Development a Novel Integrated Distributed Multi-objective Simulation-optimization Model for Coastal Aquifers Management Using NSGA-II and GMS Models

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Abstract

Groundwater is one of the most valuable water resources in the world in terms of quantity and quality. Therefore, their protection as an important issue should be considered by the operating managers. Among the types of existing groundwater aquifers, the coastal aquifers need more protection because they could be contaminated by salt in the result of seawater intrusion. Their protection is a priority based on an optimal and comprehensive management model. Increasement of demands in these areas, especially in recent years, requires sustainable and optimal management as one of the main objectives for long-term operation in the future. In order to meet this purpose, a simulation-optimization model of Bandargaz-Nokandeh coastal groundwater system that located in the north of Iran was proposed by the employment of the Groundwater Modeling System (GMS) numerical model and the Non-Dominate Sorting Genetic Algorithm-II (NSGA-II) multi-objective evolutionary optimization algorithm. In this study based on the quantitative simulated groundwater model; two managerial issues have been examined; including the control of water-table drawdown and sustainability of extraction from the wells in this aquifer. By combining these two models and implementing them, optimal withdrawal scenarios which examines different aspects of the study objectives, have been extracted. Regarding the decision-making methods of Simple Additive Weighting (SAW), Gray Relational Analysis (GRA), and Berda Aggregation method (BAM), the best scenario was determined among the points located on the optimal trade-off curve. The results show that implementations of management strategies to create a sustainable development of the Bandargaz-Nokandeh coastal aquifer, has led to a 48.45 percent decrease in water withdrawal. Also, the comparison of the groundwater table level (GWTL) under the two existing and optimal operating conditions shows a 29.54% reduction (monthly average) in the area of aquifer that contain drawdown in the GWTL. This reduction varies from 1.43% in October 2011 to 59.22% in September 2012. Based on this optimal operation policy, the consequences of excessive withdrawal, and more than the natural capacity of the aquifer, could be compensated. Besides that, in order to the sustainable development of the aquifer can be controlled the amount of water extracted from operation wells.

Extended author information available on the last page of the article

1 Introduction

The water scarcity problem is one of the most important issues in the world. Because of the growth of the world's population and the growing demand for urban, agricultural, industrial, environmental, and sanitary consumption, existing water resources do not supply today's human needs (Vaux 2011). In many parts of the world, especially in arid and semi-arid regions, the exploitation of highly sensitive groundwater resources has increased because of climate changes and the scarcity of surface water resources.

Management of freshwater resources and protection of them is an increasing necessity for natural water resource managers. Freshwater stored in coastal aquifers is one of the most important water resources for the residents of these areas (Werner et al. 2013).

Coastal aquifers beside the sea, in normal conditions, drain some of the freshwater groundwater into the sea. Under these conditions, there is a state of equilibrium between the freshwater aquifers and the below saltwater. Maintaining this balance depends on the underground flow discharge (Todd 2005). The invasion of saltwater is caused by drastic changes in groundwater levels on the coast in the long-term or short-term. These changes could be caused by over-pumping, land-use change, climate change, or sea-level fluctuations. The reduction of freshwater storage capacity and the contamination of wells are the main disturbing results of saltwater intrusion (Werner et al. 2013).

Studies on the optimal management of coastal aquifers have increased significantly in the last two decades; and many of the complex problems of groundwater, especially coastal aquifers, have been investigated in different conditions and situations.

Developing optimal management strategies in order to make the right decisions so that it fulfills the goals, requires models consisting of simulation and optimization models. These models can investigate and test the system's response to a variety of possible future scenarios and multiple scientific options (Ketabchi and Ataie-Ashtiani 2015; Zeinali et al. 2020a).

Examples of this research on groundwater resources and coastal aquifer modeling can be found in the studies such as: Rejani et al. (2008), Luyun et al. (2009), Abdullah et al. (2010), Chang et al. (2011), Trichakis et al. (2017), Banihabib et al. (2017), Akbarpour and Niksokhan (2018), Dunlop et al. (2019), Aswed El Ahmed et al. (2018), Xu et al. (2019), Zeinali et al. (2020b), Sowe et al. (2020), and Ranjbar et al. (2020).

Also, other researchers who studied the optimal and sustainable exploitation investigation of coastal aquifers are presented as follows:

Hallaji and Yazicigil (1996) studies by presenting seven management models in the field of single-objective optimization; Karterakis et al. (2007) and Ataie-Ashtiani and Ketabchi (2011) who carried out their studies to maximize the total volume of extracted freshwater by imposing limitations such as pumping capacity, prevention of infiltration of saline water into wells and hydraulic head control near pumping wells; Karatzas and Dokou (2015), with a weighted multi-objective optimization management model to maximize well extraction by controlling the intrusion of saltwater; Yihdego and Al-Weshah (2017) investigated the impact of pollution of coastal aquifers due to the entry of saline seawater using the 3-D Numerical Modelling.

Nowadays, the simulation-optimization (S-O) framework is a powerful structure that can be considered an efficient framework in the process of optimal management and decision-making in the field of coastal aquifer management (Ketabchi and Ataie-Ashtiani 2015). So far, many researchers used the S-O approach to optimal manage

coastal aquifers such as Kourakos and Mantoglou (2015), Huang and Chiu (2018), and Song et al. (2018).

Lal and Datta (2019) presented optimal pumping strategies by applying Gaussian Process Regression (GPR) metamodel based on S-O methodology to developed a multi-objective optimization model in coastal aquifer management. The result of this study shows the potential applicability of GPR metamodel based on the S-O method in the management of coastal aquifers exposed to salt water invasion.

Fan et al. (2020) presented a multi-objective optimization method to developed groundwater exploitation strategies for coastal groundwater problems. In this study, based on the variable-density groundwater numerical simulation model (SEAWAT) and NSGA-II, a management model was developed to maximize groundwater extraction and minimize seawater intrusion.

Other implications applied by Mostafaei-Avandari and Ketabchi (2020) were using of parallel-processing to make optimal extraction from coastal groundwater resources. This model is based on S-O decision model for Ajabshir plain aquifer, Iran via the SUTRA numerical model and ant colony as a simulation and an optimization tool, respectively.

Al-Maktoumi et al. (2021) presented a novel probabilistic multiperiod S-O method to obtain optimal dynamic strategies for coastal aquifer management. The results showed that the implementation of this approach can led to increased groundwater abstraction, injection, and monetary benefit compared to the commonly approaches.

The literature review reveals that most studies were performed on small hypothetical scales with many simplified assumptions. Also, provide optimal extraction policies from operation wells as one of the important management strategies for sustainable development of coastal aquifers are not considered in the previous research. Therefore, in order to improve studies on coastal aquifer management, the present study was performed aiming to develop an integrated model of fully distributed groundwater simulation model and evolutionary multi-objective optimization algorithm to evaluate management strategies and to protect coastal aquifers. Bandargaz-Nokandeh coastal groundwater system, located in the north of Iran, that affected by seawater intrusion due to over-extraction, was selected as a case study to evaluate the proposed methodology and extract the optimal operation scenarios.

By implementing the developed model can be controlled the GWTL progressive drawdown in coastal aquifers in order to sustainably exploitation. The results show the effective efficiency of the developed model in controlling the drawdown in the groundwater level and improving the quantitative status of the coastal aquifer as a result of applying optimal discharge values from the operation wells. This method could be useful in proposing management policies to extract groundwater from other aquifers, especially coastal aquifers. The major contributions of this study are as follows:

- Development of a novel integrated distributed multi-objective S-O model to improve the quantitative status of coastal aquifer using GMS and NSGA-II models
- Creation the MATLAB code to connects the fully distributed groundwater simulation model with the multi-objective optimization algorithm
- Extracting the best scenario for optimal operation of coastal aquifer wells based on SAW, GRA, BAM decision making approaches
- Proposal of the optimal amount of extraction from all operation wells to control the intrusion of seawater into coastal aquifers

2 Materials and Methods

2.1 Case Study

The study area is part of the Haraz-Qarehsu and Qarehsu-Gorgan watersheds. The aquifer of the study area, which is 192.4 Km^2, is considered as part of the Bandargaz Nokandeh plain (Fig. 1). The southern part of the region is mountainous with a cold climate and a considerable snowfall in winter. Most villages of the region are located in the southern part of Bandargaz, and almost on the edge of the heights and at close distance from each other. The lowest and highest elevation of the plain are -26 and 200 meters above sea level, respectively.

The total amount of discharge from groundwater resources in this study is 17.95 million cubic meters (MCM). According to the operation status of each discharge components, 17.49 MCM from 1019 exploited wells, 0.9 MCM from three springs, and 0.37 MCM from four qanats are being extracted. The 70%, 29%, and 1% of groundwater resources are consumed by the domestic, agricultural, and industrial sector, respectively (Fig. 2).

More than 98% of the total groundwater resources exploitation are done by wells. Examination of the position of the wells operated in the study area shows that the wells are scattered throughout the aquifer. (Fig. 3).

Investigation of spatial distribution map of the amount of exploitation by operation wells shows that in places with high concentrations of drilled wells, due to the placement of wells in each other's protection area, the rate of discharge has decreased
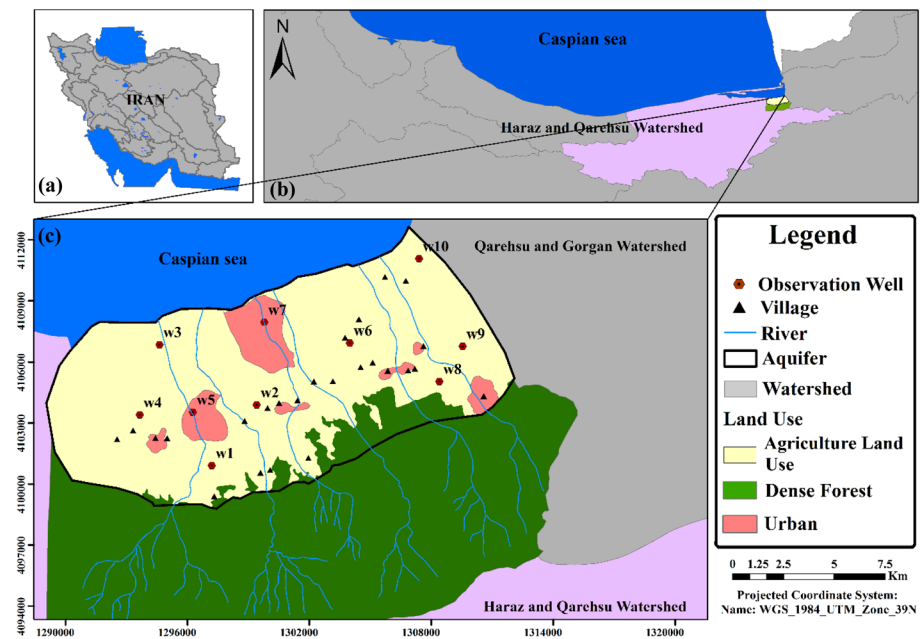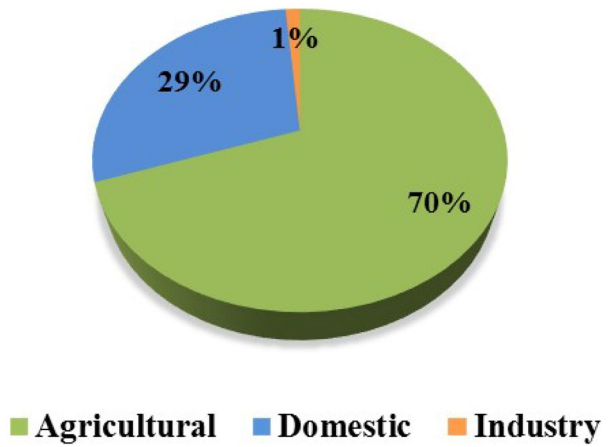

Fig. 1 (**a**) Iran's watersheds (**b**) The geographical location of case study (**c**) General specifications of the Bandargaz Nokandeh plain

Fig. 2 Pie diagram of ground-water resources exploitation in Bandargaz-Nokandeh plain

sharply (Fig. 4). Also, uncontrolled and over-capacity withdrawals of aquifer, especially in the coastal strip, has led to the intrusion of the Caspian Sea saline water into the groundwater.

2.2 Structure of the Proposed Integrated Distributed Multi-objective S-O Model

Sustainable development of aquifers as one of the most important resources of fresh water supply is a priority for planning and decision-making authorities. To achieve this, it is
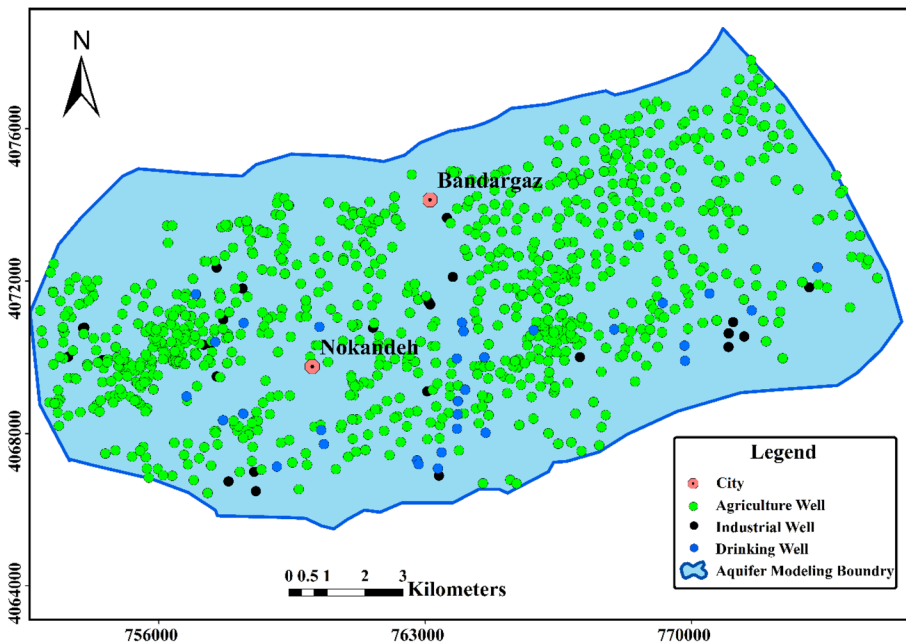

Fig. 3 Location of operation wells in Bandargaz-Nokandeh aquifer
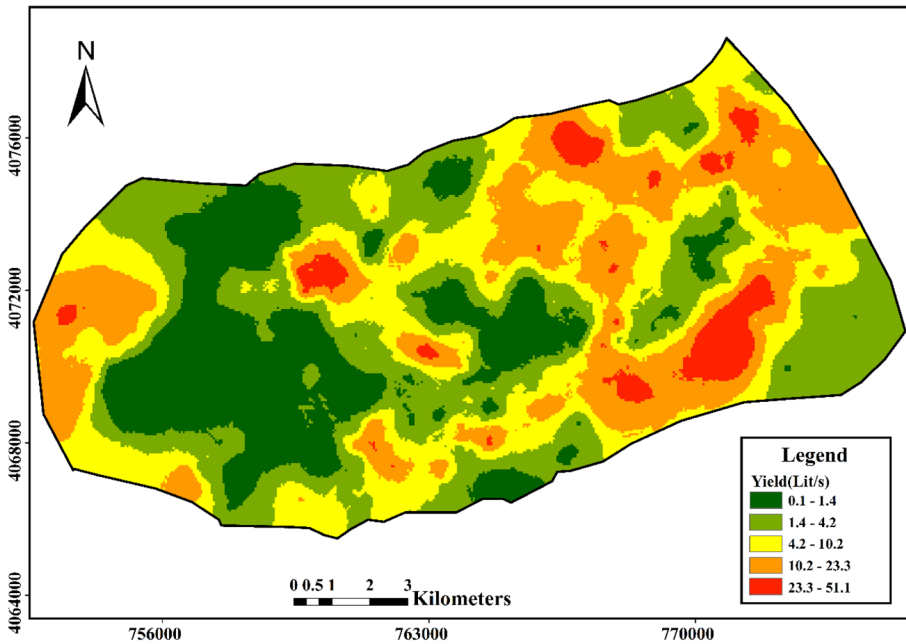
Fig. 4 The average discharge rate of operation wells in the Bandargaz-Nokandeh aquifer

crucial to have an accurate exploitive plan from the groundwater aquifers. In this paper, with the purpose of sustainable extraction of Bandargaz-Nokandeh coastal aquifer, a novel integrated distributed multi-objective S-O model was developed using the most appropriate tools (NSGA-II and GMS simulation model). For this purpose, quantitative data were collected from the hydrological and hydrogeological status of the studied plain and based on that, the quantitative simulation model of this groundwater aquifer was performed. Then, the groundwater simulation model was calibrated and verified using measured piezometric data. Based on the calibrated model, a multi-objective management model was developed in order to control progressive decline of GWTL and to extract sustainably from the wells of this aquifer.

By combining these models and implementing them, optimal scenarios for withdrawal from aquifer operation wells have been extracted.

To analyze a more acceptable scenario, the ranking of each scenario was determined by using SAW and GRA decision making methods; then, these rankings were aggregated based on the BAM decision method and ultimately the final ranking of each scenario was determined. Based on the superior scenario, the optimal operation policies of the wells, accompanied by the spatial and temporal variation of their decline, were analyzed.

The results show that the proposed methodology has been able to provide a suitable spatial and temporal distribution of operation wells in this coastal aquifer, and in a short time period, it has created a stable situation in the GWTL of aquifer. Observance of optimal extraction from wells can lead to stability in the GWTL in the long-term operation of aquifer and reduce seawater intrusion. The structure of the proposed approach is shown in Fig. 5.

To achieve the mentioned goals, it is first necessary to define the objective functions and constraints of the proposed model and present them mathematically. The objective functions are: minimizing the sum of GWTL drawdown in each of the cells in the aquifer
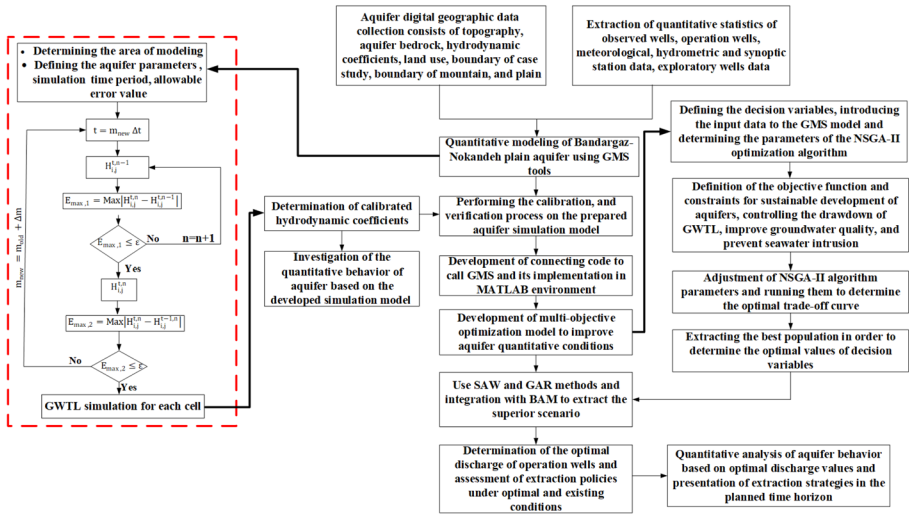
Fig. 5 The structure of a novel integrated distributed multi-objective S-O proposed model

modeling area during the study period and maximizing of water extraction from existing operating wells.

A noteworthy feature of the proposed approach is the use of the GMS distributed model in simulating the quantitative behavior of the aquifer, which unlike lump models, increased the accuracy in calculating the spatial and temporal of GWTL. Also, the constraints of the developed model have been determined and are related to the objective functions.

3 Objective Functions

$$\text{Minimize} Z_1 = \sum_{t=1}^{m} \sum_{c=1}^{\text{ncell}} \Delta H_{tc} \tag{1}$$

$$\text{Maximize } Z_2 = \sum_{t=1}^{m} \sum_{w=1}^{\text{nwell}} Qwell_{tw} \tag{2}$$

4 Constraints

$$0 \le Qwell_{tw} \le QCwell_{tw} \ , \quad w = 1,2,...,nwell, \quad t = 1,2,...,m \tag{3}$$

$$\Delta H_{tc} = H_{tc} - H_{(t-1)c} \ , \quad c = 1,2,\dots,ncell \tag{4}$$

$$H_{tc} = f\left(Qwell_{tc}, R_{tc}, H_{(t-1)c}\right) \tag{5}$$

$$Qwell_{tw} \ge 0 \ , \quad w = 1,2,...,nwell, \quad t = 1,2,...,m \tag{6}$$

$$H_{tc} > 0 \quad , \quad c = 1,2,...,ncell, \quad t = 1,2,...,m \tag{7}$$

where,

ΔH_{tc}: The GWTL drawdown related to c^{th} cells in the month t (m)

$Qwell_{tw}$: The value of water extracted from the wth well in the month t (m^3/day) (as a decision variable**)**

$QCwell_{tw}$: The existing state of water extraction from wth well in the month t (m^3/day)

R_{tc}: The natural recharge of aquifer in c^{th} cells in the month t (m/day)

H_{tc}: GWTL related to c^{th} cells in the month t (m)

f: A function that simulate the quantitative state of an aquifer. Actually, in order to calculate the value of the GWTL, the MODFLOW distributed model is used as GWTL simulator function within the optimization model.

nwell: Number of wells in the study area

m: Number of months in the horizontal plan

In this section, the explanations relevant to the presented equations are described.

In Eqs. (1) and (2), the objective functions are presented. In the first objective function (based on Eq. (1)) is considered the sum of GWTL drawdown in each of the active cells of Bandargaz-Nokandeh aquifer during the period studied. According to this Equation, initially, it is necessary to simulate the time series of GWTL by employing the aquifer calibrated model.

This GWTL simulated based on Eq. (5). This Equation works based on the GMS simulation model. In fact, it is needed to implement the aquifer simulation model in order to determine the GWTL and the drawdown in each of the active cells for each solution that provided by the optimization algorithm.

The value of simulated GWTL in Eq. (5) represent the quantitative behavior of the aquifer in faced with exploitation resources (wells) and its control can play a significant role in the stability of the groundwater and prevent the seawater intrusion. In other words, controlling the monthly GWTL drawdown in each of defined active cells at the aquifer area, in addition to reducing pumping costs, it has also been effective in improving the quality of aquifer (salinity) in the long-term. Indeed, it prevents from depletion of groundwater reserves and reduction of the saturation thickness of aquifer.

In Eq. (2), the second objective function of the proposed approach, which is maximizing the amount of water extraction from the operating wells at the aquifer area, is met. Due to the current situation of the operation wells causes to sea water intrusion towards the coastal aquifer, this over-extraction was controlled by Eq. (3). This objective function has a significant role in the water quantitative and qualitative stability of the aquifer. In this function, two priorities are preferred: long-term operation of aquifer and maintaining the stability of the aquifer in order to improve the quantitative situation and prevent the progress of seawater to the aquifer. In fact, in this objective function, the maximum water supply of the region demands has not been considered. It's worth to mention that in this area, there are considerable surface water resources, which would be useful if restrictions were implemented on the extraction of groundwater resources.

Using these two defined objective functions, which are complement each other in achieving sustainable development of aquifer, can be determine the optimal allocation values for each of the wells within the study area and based on that, it could be possible to adopt the necessary plans to meet the water supply demands of the area from other water resources (such as surface water reserves).

To solve the developed model, initially, it is needed to define the decision variables of the model. In this study, the decision variables for each month are the amount of water extraction from wells of Bandargaz-Nokandeh aquifer.

Regarding that there are 1019 active operation wells in the case study; the total number of decision variables will be equal to 12228 by considering one year of the study period.

To determine the optimal decision variables, it is necessary to use the most appropriate optimization tools. In this study, the instrument employed is the NSGA-II.

Generally, in order to extract optimal decision variables with the NSGA-II method, initially, the random values are employed for extraction from each well (decision variables). According to these values, the value of objective functions is calculated and if the penalty is due to violation of the constraints implemented on it, the production solution will be reexamined to reduce the penalty value to zero. During this process of improving the values of the decision variables, the objective functions are also evaluated to have the best value between the solutions. This process continues until the values of the objective functions remain without change. Under these conditions, it is highly likely that the value provided for the decision variables has been near to optimal and it can be used as a program to operation wells in the study area. Based on this optimal allocation to different demand sections can be develop the optimal operating policies as monthly or seasonal.

4.1 Structure of Aquifer Simulation Model

Differential equations governing groundwater flow systems cannot be solved by conventional mathematical methods, and in recent years, with the development of computer applications, numerical methods have been used to solve them. Numerical methods are divided into different groups, each of which uses hypotheses to solve the equations governing the groundwater flow. Meanwhile, two methods of finite difference and finite element have been employed in popular programs and software in solving the differential equations of groundwater systems. In this study, to solve the governing equations, the finite difference method has been considered.
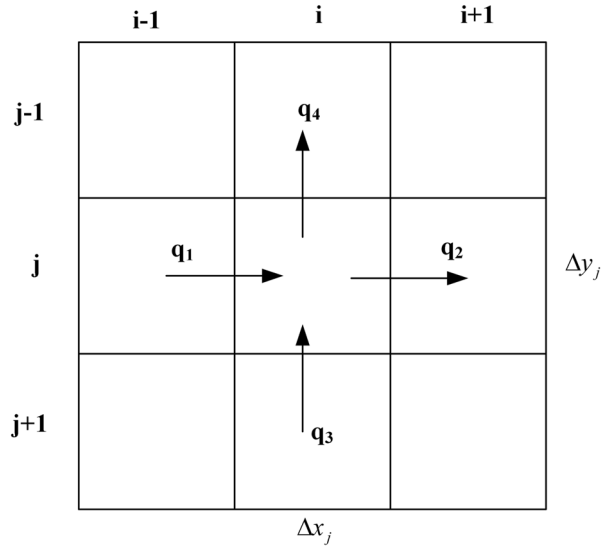
4.1.1 Solving the Equations by Finite Difference Method

In order to solve the governing equations of groundwater flow, the studied aquifer area is divided into meshes with specific dimensions (Fig. 6). Substitution of partial derivatives by finite differences in the flow equation provides a device of linear equations including the N equation and an N unknown variable. By solving it, the value of the GWTL (h) is obtained in the N cell of the mathematical model network using Eq. (9).

$$A_{i,j} = \frac{(T_{i+1,j} + T_{i,j}) \times BC_{i+1,j}}{2(\Delta x)^2}, B_{i,j} = \frac{(T_{i-1,j} + T_{i,j}) \times BC_{i-1,j}}{2(\Delta x)^2}, C_{i,j} = \frac{(T_{i,j+1} + T_{i,j}) \times BC_{i,j+1}}{2(\Delta y)^2}, D_{i,j}$$

$$= \frac{(T_{i,j-1} + T_{i,j}) \times BC_{i,j-1}}{2(\Delta y)^2}, E_{i,j} = \frac{W_{i,j}}{\Delta x \times \Delta y} + \frac{Sy_{i,j}}{\Delta t} \times h_{i,j}^{t-1}, F_{i,j} = \frac{Sy_{i,j}}{\Delta t}$$

$$(8)$$

$$h_{i,j}^t = \frac{A_{i,j} h_{i+1,j}^t + B_{i,j} h_{i-1,j}^t + C_{i,j} h_{i,j+1}^t + D_{i,j} h_{i,j-1}^t + E_{i,j}}{A_{i,j} + B_{i,j} + C_{i,j} + D_{i,j} + F_{i,j}}$$

$$(9)$$

To simulate the GWTL in each cell, the length of the simulation period is divided into specific time steps. By determining the initial conditions of the GWTL and using Eq. (9), the GWTL is simulated at the end of the first-time step. This simulated value is considered as the initial condition for this period time. This process continues for the first-time step to reach the defined error criterion. The above process that presented in Fig. 5, will continue until the period time required for aquifer simulation is covered. Further details can be found in Todd (2005). In this study, to implement the above-mentioned process for aquifer simulation, the GMS model was used.

4.2 Optimization and Decision-making Tools

Due to the complexity of the developed structure, high dimensions of decision variables, and to accelerate the achievement of the neat to global optimum solution, in this study, the NSGA-II multi-objective algorithm that proposed by Deb et al. (2000) to solve the problems of the classical genetic algorithm model, was used. It should be noted that the use of this algorithm for the operation of water resources systems has also been recommended by researchers such as Banihabib et al. (2017), Hajiabadi and Zarghami (2014), and Nemati et al. (2021). In this study, the NSGA-II algorithm was prepared and implemented in the MATLAB2018b environment to apply objective functions and constraints. More details on the NSGA-II algorithm are presented in the Tabari and Soltani (2013) research. Also, the code connecting the GMS simulation model with the multi-objective optimization model has been developed in MATLAB2018b environment.

In the optimal trade-off curve obtained from the NSGA-II algorithm, each point is assumed as a scenario (alternative) of operation of groundwater resources. Based on this trade-off curve, the decision-maker can choose one of the scenarios with regard to objective functions and extract the optimal values of withdrawal from wells. Since the points on the optimal trade-off curve cannot satisfy both objectives simultaneously, therefore, choosing the suitable points (scenario) using an appropriate decision-making method can be very helpful to facilitate the controversial scenario choice.

Due to the diversity of MCDM methods, in this study, Wang and Rangaiah (2017) proposal has opted in which the use of SAW and GRA methods are recommended. Also, in this study, the BAM method is employed to aggregate the results of mentioned decision- making methods because the results of SAW and GRA methods are different. Based on these two decision-making methods, the alternatives that generated by the NSGA-II algorithm are ranked. Then, using the BAM method, the results of these two methods are aggregated and the final ranking of each of the points located on the optimal trade-off curve is determined.

4.2.1 Berda Aggregation Method

The BAM is one of the selecting the final alternative (option) methods in a negotiation, considering the ranking of the alternatives by the voters. In Berda law, in the first step, each decision option, corresponding to the ratings allocated to that option by voters in the option ranking matrix, gets a primary score. In this study, allocated ranking in the ranking matrix are the same rankings were identified by two decision making methods of SAW and GRA. This primary score is equal to the difference between the total number of options (m) and the allocated rankings to it by one voter (the results of one of the two decision methods). Therefore, if m options are considered, the score of best option for a decision-maker will be equal to m-1, the score of second option will be m - 2 and thus the score of last option, the most unacceptable option, will be the zero. Therefore, each option will receive a primary score corresponded to the number of voters. Finally, the Berda score of each option will be equal to the sum of the primary scores obtained by that option. An option is selected as the winner of the Berda, the score of which is higher than other options (Bizhani-Manzar and Mahjouri 2013).

In order to determine the convergence criterion of the trade-off curves obtained by NSGA-II algorithm, the index presented by Chen et al. (2007) was used. Based on the values of the aggregation distance for each solution, the convergence criterion can be presented as the Eq. (10):

$$DM = \frac{d_b + d_e + \sum_{i=1}^{n-1} \left| d_i - \bar{d} \right|}{d_b + d_e + (n-1)\bar{d}} \tag{10}$$

where,

d_b, d_e: The limit values on the converged trade-off curve
d_i: The amount of aggregation distance for each solution on the trade-off curve
$\bar{d}$: Average values of the solutions aggregation distance
n: Number of points located on the converged trade-off curve
The convergence condition of the NSGA - II algorithm is obtained when the value of the DM criteria is close to zero.

5 Results and Discussion

5.1 Results of Aquifer Quantitative Simulation Model

In order to implement the proposed approach based on the integrated distributed multi-objective S-O developed model, it is necessary to simulate the Bandargaz-Nokandeh aquifer. Accordingly, based on 2011-2012 water year data, the calibration process of the GMS model has been performed and will be validated for 2012-2013 water year.

In present study, short-term operation of the aquifer has been considered due to significant variation of groundwater operation in the plains of Iran and lack of continuous quantitative and qualitative hydrogeological data. Also, in order to comply with the real conditions of aquifer operation and no changes in its hydrodynamic coefficients, the calibration and validation process has been performed for a period of one years. Applying long-term periods for aquifer modeling leads to uncertainty in the simulated parameters and increase the error of the aquifer simulation model due to significant variation in groundwater level and saturation thickness of the aquifer. Using short-term optimal policies (as a prerequisite) and re-modeling aquifer can be updated optimal operation policies based on new hydrogeological data in a short period of time, and used it for other operation periods.

To present the results of the developed model in this section, the result of groundwater simulation modeling and its calibration are presented using GMS software. The calibration process of the aquifer simulation model is performed for steady and unsteady conditions. Although, calibration is common in steady conditions, in natural conditions, the groundwater conditions are unsteady and change under the influence of human activities. Therefore, it is better to calibration the model in unsteady conditions (Anderson et al. 1992). For this purpose, the groundwater model was calibrated for a 365-day period in an unsteady state to determine the hydrodynamic coefficients. Ten observation wells were selected to compare the simulated and observed GWTL. The scatter plot between the simulated and measured GWTL values associated with the Bandargaz-Nokandeh aquifer piezometers for different time steps of calibration period are shown in Fig. 7. Based on this figure, there is a good match between the simulated and measured values of GWTL. To display a quantitative amount of simulation error during the calibration and validation period, Tables 1 have been prepared for each of the observation wells. Also, the amount of monthly simulation error using the RMSE and R^2 indicators in the two calibration and validation periods is presented in Table 2.

The accuracy of the simulation GWTL results obtained in each of the observation wells (Table 1) indicates the proper efficiency of calibrated simulation model to predict GWTL. This is also seen in the GWTL monthly prediction (Table 2). It should be noted that the amount of simulation error in piezometers 3 and 7 is slightly higher than other piezometers, but the average of prediction error in these two piezometers is less than one meter, which is acceptable in aquifer modeling.

Drawing monthly hydrograph of predicted and measured GWTL (Fig. 8) shows that calibrated hydrodynamic coefficients well represent the natural conditions governing the groundwater system of Bandargaz-Nokandeh aquifer. Also, the GWTL behavior has been correctly predicted by the GMS simulation model.

5.2 Results of the Proposed Simulation-optimization Model

Since the proper simulating of quantitative aquifer behavior in the optimization process and determination of optimal values of the decision variables are very important; therefore, in order to increase the accuracy of aquifer simulation results, a code was developed in the MATLAB2018b environment to use the results of the aquifer simulation model by the optimized model.

This code, which can call all GMS software input and output files, has the capability to model the GWTL of aquifer in a short time (for example, it takes approximately 1.25 seconds to simulate the GWTL over a one-year period). In fact, by using a file with the
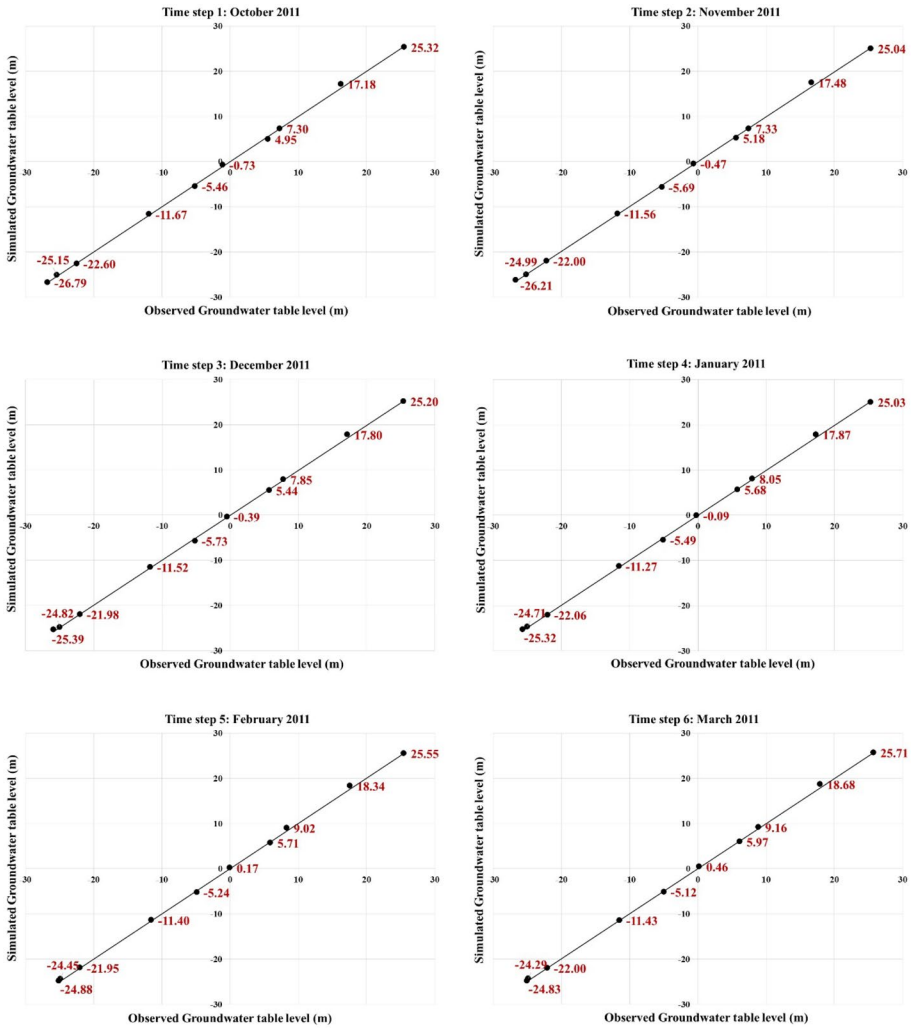
Fig. 7 Comparison between simulated and measured GWTL in different time steps after GMS model calibration (The red values are the simulated GWTL)

file name extension h5 in the GMS model, the user will be able to change the stress state (recharge or discharge) of the groundwater system, and observes the variation of GWTL with the implementation of the GMS model by the developed code.

In this code, it is needed to use a calibrated simulation model, which indicates the actual behavior of the GWTL of Bandargaz-Nokandeh aquifer. For this purpose, the GMS model was calibrated in order to determine the aquifer hydrodynamic coefficients. Then, to ensure the validity of the simulation model, the model was evaluated based on new data, which were not used in the calibration process.

Based on verified groundwater simulation model and according to defined objectives and constraints in the proposed structure, the NSGA-II algorithm with 100 chromosomes and 600 iteration was implemented. The time duration of each iteration on
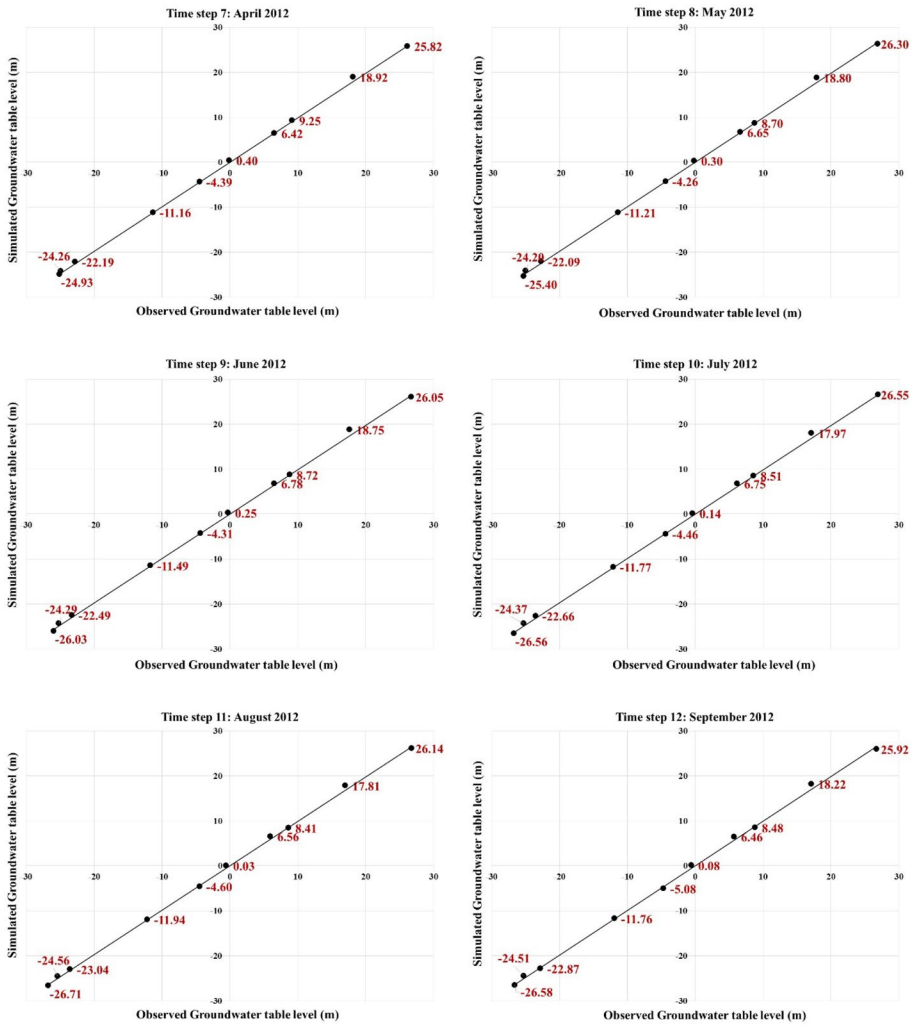
Fig. 7 (continued)

a system with Corei7- 9700 k and 16G RAM specifications is estimated equal to 125 seconds. Therefore, 20.83 hours is required to run 600 iterations.

With the implementation of the proposed approach, the optimal value of the decision variables, which is the optimal discharge from 1019 operation well in Bandargaz-Nokandeh aquifer, was extracted. According to the optimal trade-off curve (Fig. 9) and SAW, GRA, and BAM decision-making methods, the best scenario was determined from the points located on the optimal trade-off curve.

Based on Fig. 9, the values of the first and second objective functions of best scenario correspond to 438.38 meters and 9.53 MCM discharge from operation wells, respectively. Investigating the NSGA-II Algorithm conversion criteria (DM) shows that this criterion in

Table 1 The value of the RMSE and R^2 error indicators associated with each of the aquifer piezometers during the calibration and validation period

observation well	R^2		RMSE	
	2011-2012	2012-2013	2011-2012	2012-2013
1	0.94	0.67	0.44	0.67
2	0.77	0.85	0.4	0.68
3	0.34	0.6	0.63	0.6
4	0.98	0.68	0.31	0.68
5	0.85	0.65	0.4	0.64
6	0.97	0.94	0.19	0.08
7	0.81	0.33	0.43	0.44
8	0.96	0.71	0.84	0.64
9	0.91	0.89	0.25	1.1
10	0.96	0.91	0.25	0.26

this study is equal to 0.0929. This indicates that the non-dominate fronts are converging to the optimal trade-off curve between the objectives.

To analyze the results of the developed management model, the GWTL drawdown situation in coastal areas with a significant drawdown was investigated under two conditions of exploitation in the existing situation and apply of optimal operation policies on wells. For example, the position of the cells that has a progressive drawdown in GWTL of operation wells are shown in Fig. 10. Also, to evaluate the efficiency of the developed model, spatial and temporal variation of the GWTL drawdown in case study aquifer was produced using the ArcGIS10.2 software. This investigation demonstrated the quantitative improvement of aquifer status and the creation of an appropriate policy for moving towards sustainable operation from this aquifer.

Based on optimal decision variables, the monthly optimal extraction from each of the operation wells and the monthly average extraction from these wells were analyzed and compared with the existing state of exploitation in order to determine the amount of determine the amount of over-exploitation of this coastal aquifer.

Table 2 The monthly value of the RMSE and R^2 error indicators during the calibration and validation period

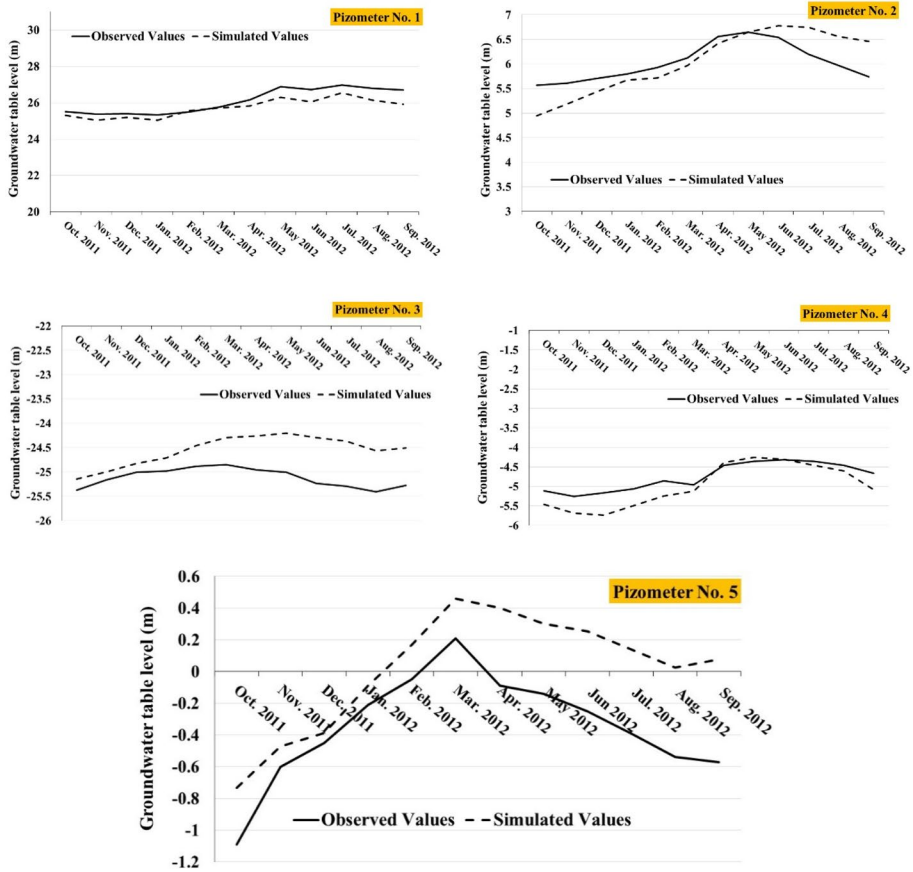| Month	R^2		RMSE	
	2011-2012	2012-2013	2011-2012	2012-2013
October	0.99	0.99	0.4	0.68
November	0.99	0.99	0.38	0.76
December	0.99	0.99	0.33	0.6
January	0.99	0.99	0.3	0.66
February	0.99	0.99	0.39	0.4
March	0.99	0.99	0.33	0.46
April	0.99	0.99	0.43	0.48
May	0.99	0.99	0.48	0.61
June	0.99	0.99	0.6	0.63
July	0.99	0.99	0.55	0.59
August	0.99	0.99	0.52	0.59
September	0.99	0.99	0.6	0.7

Fig. 8 The hydrograph of predicted and measured GWTL in each of the piezometers during the calibration period of the GMS model

The obtained optimal exploitation value from 1019 operation wells imply that the GWTL in all wells are rising from the middle of the winter season because of the uniform distribution of exploitation and its decentralization on certain areas of the aquifer. This type of allocation leads to relative stability in the aquifer. To view the variation of GWTL in the specified areas in Fig. 10, comparatively, the GWTL hydrograph for each zone is presented in Fig. 11 under current and optimal conditions.

A quantitative investigation of GWTL behavior under these two operating conditions indicates a significant improvement in coastal wells in terms of increasing GWTL and preventing seawater intrusion towards this coastal aquifer in most months of the water year. It should be noted that this condition is not significant in autumn season due to the low water demand and reduction of extraction from the coastal aquifer.

The calculation of the average value of GWTL rise due to the optimal extraction of wells being exploited in the ten zones shows that on average the GWTL has risen 1.61
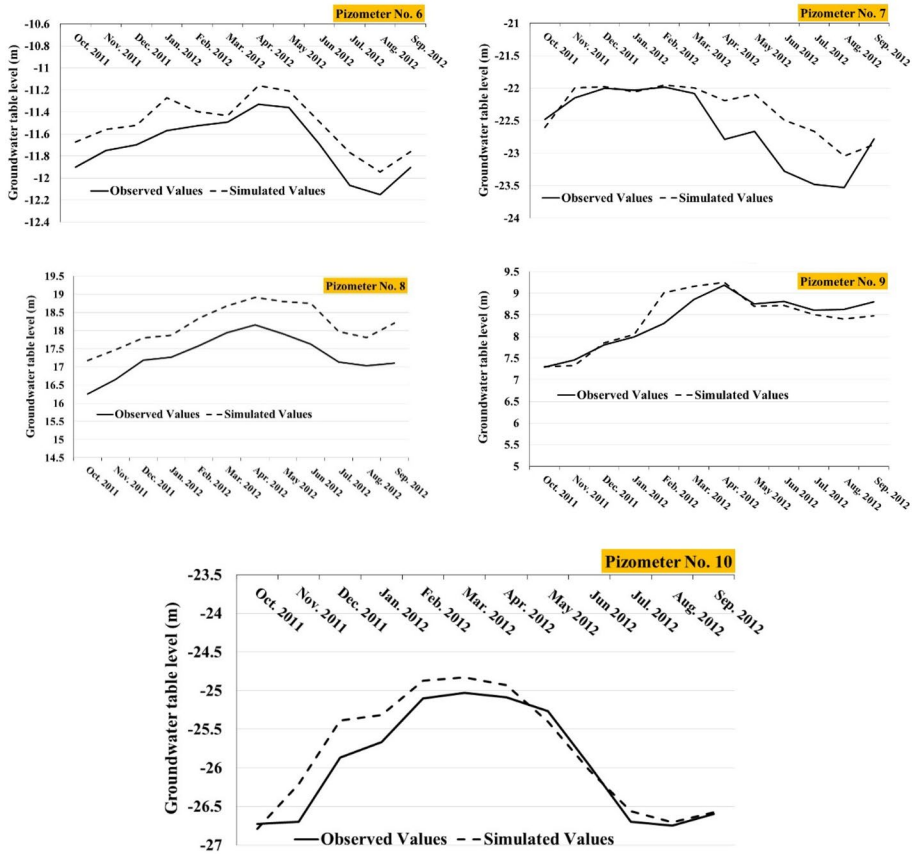
Fig. 8 (continued)

meters in this coastal aquifer. Continuing this process of exploitation via aquifers can lead to the quantitative and qualitative stability of the aquifer in a long-term (Fig. 12).

The remarkable feature of the optimal extraction rate obtained from the proposed approach is that in the developed model, the effort has been made to extract all the wells drilled at the aquifer area and from the focusing and the excessive extraction in a specific region has been prevented. This extracting policy not only can supply the water demands of the plain, but it also prevents a GWTL progressive drawdown in aquifer (especially coastal aquifers that are prone to salinization).

To investigate the spatial and temporal variation of the monthly GWTL, the simulated cellular results for the periods when the intensity of exploitation of the aquifer is noticeable, were drawn in Fig. 13. As can be seen, most of the shoreline of Bandargaz-Nokandeh aquifer has passed the catastrophic conditions of vast GWTL drawdown and has experienced more appropriate conditions in the increase of the saturation thickness of the aquifer resulted from the application of optimal extracting policies.
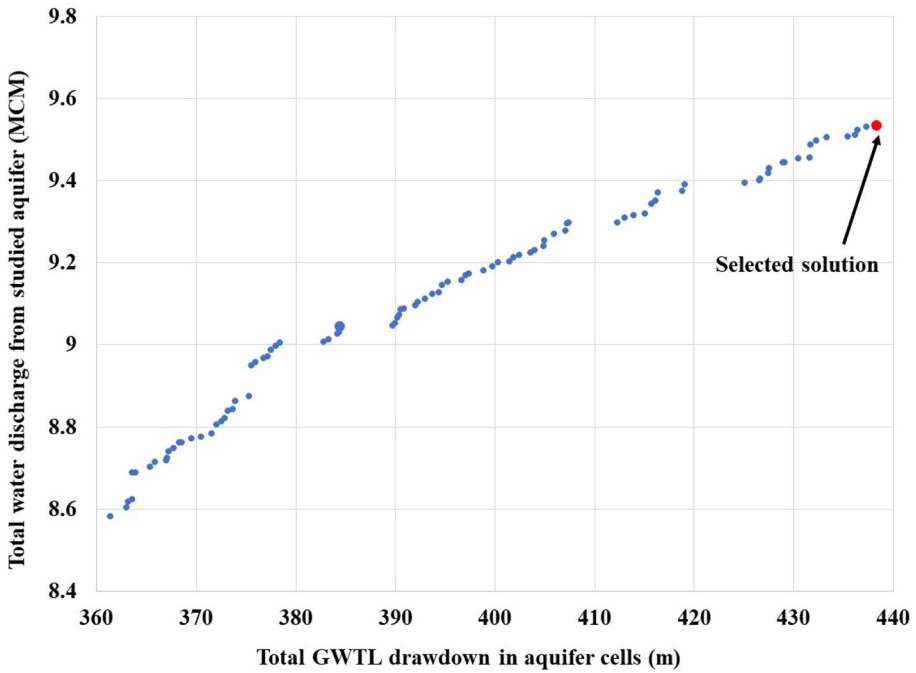
Fig. 9 Selected solution extracted from the scenarios located on the optimal trade-off curve

Due to the positive effects of optimal operation of wells and its spread throughout the aquifer, a comparative drawing of areas where is suffering from a drawdown in GWTL is illustrated in Fig. 14 under current and optimized operating conditions. According to the
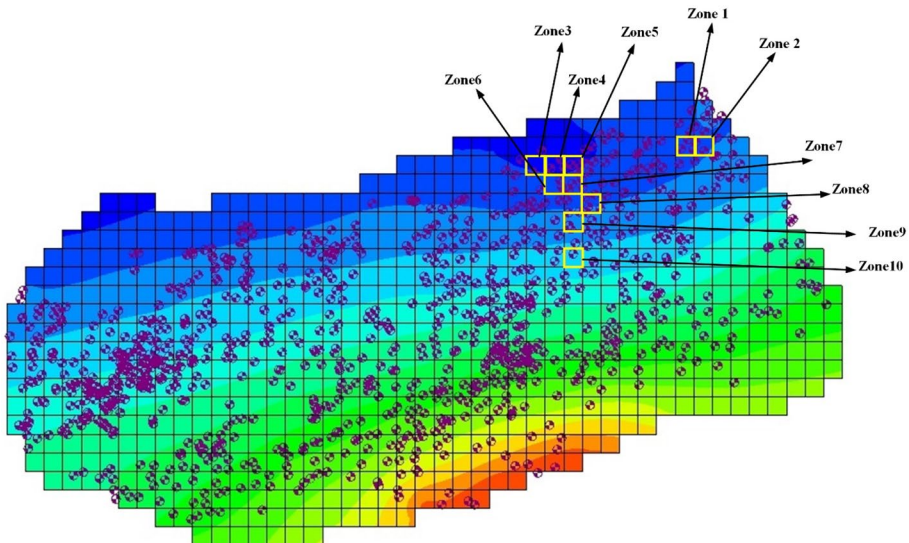

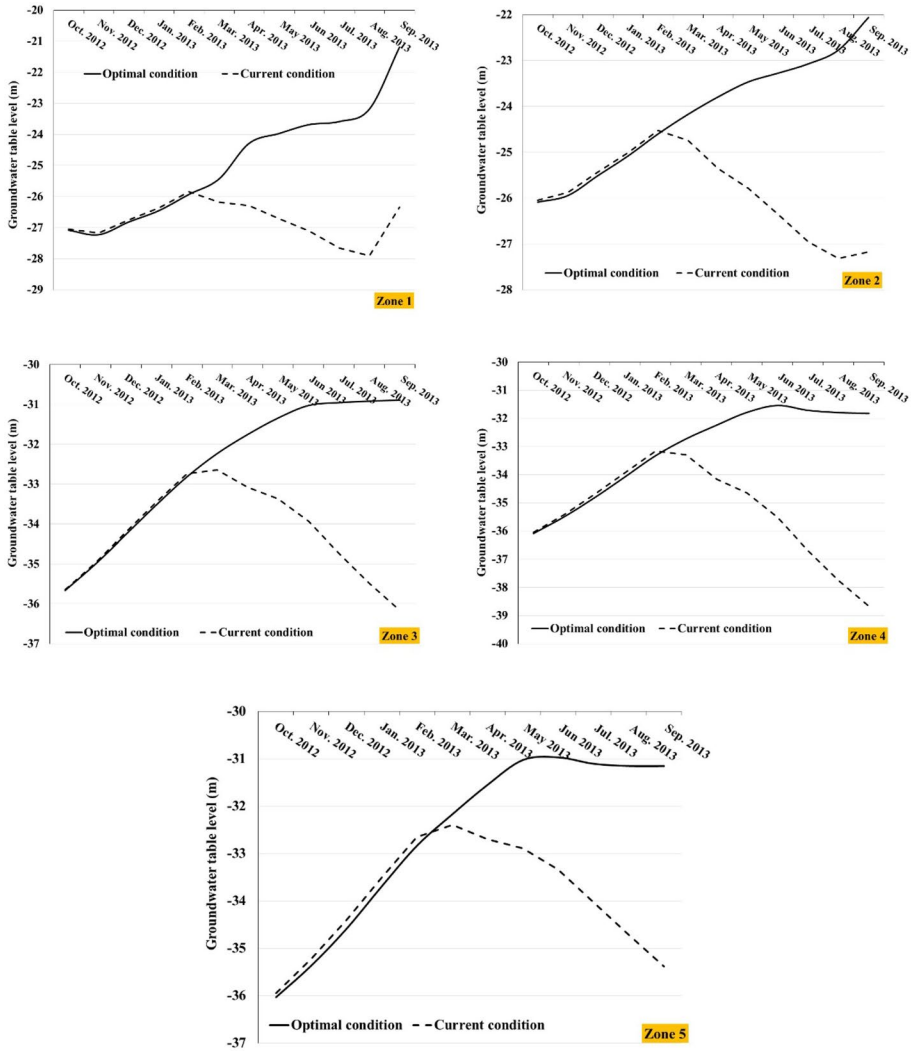**Fig. 10** Location of areas with a significant GWTL drawdown into operation wells

Fig. 11 Comparison of the monthly simulated GWTL of wells located in zone 1 under current and optimal operation conditions

obtained results and comparison of the GWTL under two mentioned conditions can be found that there is a 29.54% decrease (monthly average) in the area of aquifer that contain drawdown in the GWTL. This reduction varies from 1.43% in October 2011 to 59.22% in September 2012. So, by applying the optimal policies of operation and their continuity over several years could be compensated the dire consequences of over-exploitation, which is more than the natural capacity of the aquifer. These policies can also control the extraction from the wells and be used for sustainable development of aquifer.
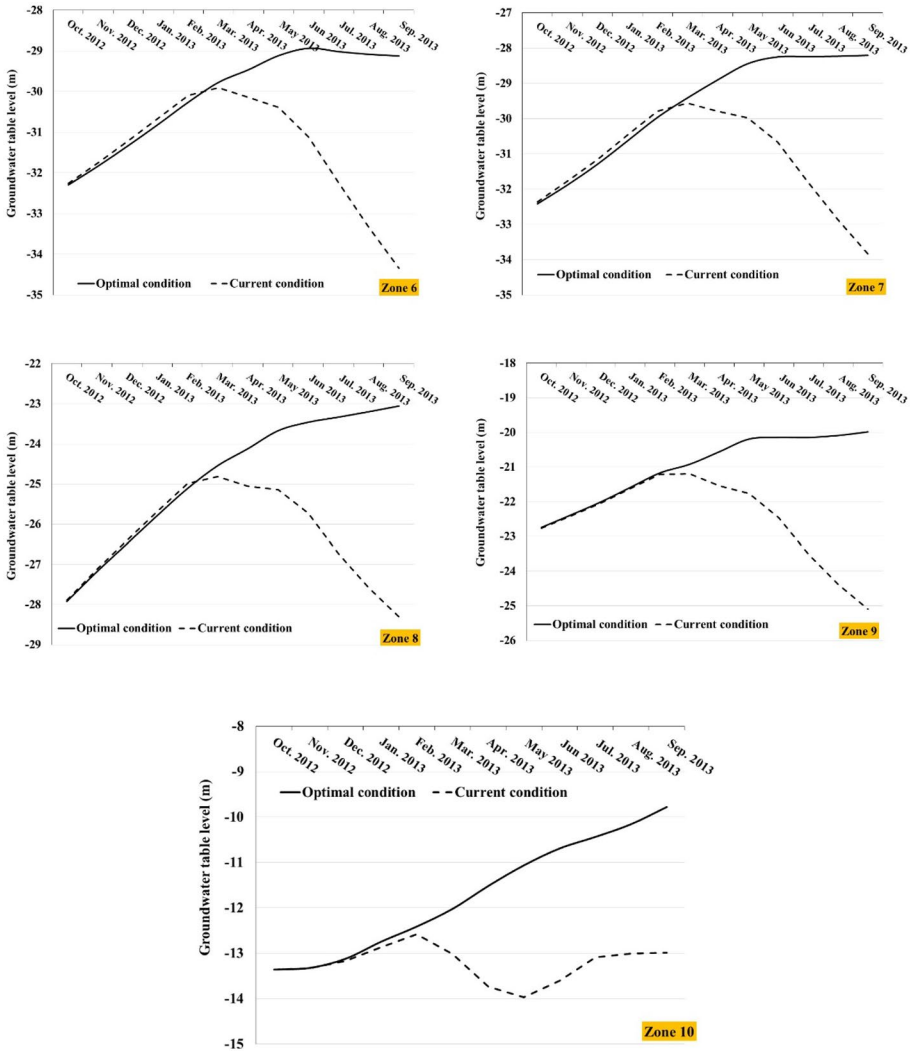
Fig. 11 (continued)

According to the optimal value of the decision variables, the time series of the optimal extraction rate can be determined. To compare the amount of over-extraction by the operating wells, Fig. 15 is plotted. The results show that the optimal extraction rate is 9.53 MCM, which shows a 45.48 percent decrease compared to the existing extraction situation (17.49 MCM). It should be noted that the number of illegal wells has increased sharply in this region due to agricultural development and the growing extraction of groundwater resources. This has led to the salinity of coastal wells due to the saltwater intrusion from the Caspian Sea.

Comparison of the discharge rate of wells under optimal and existing situation can provide a good view of the unfavorable operating conditions under non-optimal utilization of this coastal aquifer. For this purpose, for example, the operation status of the aquifer
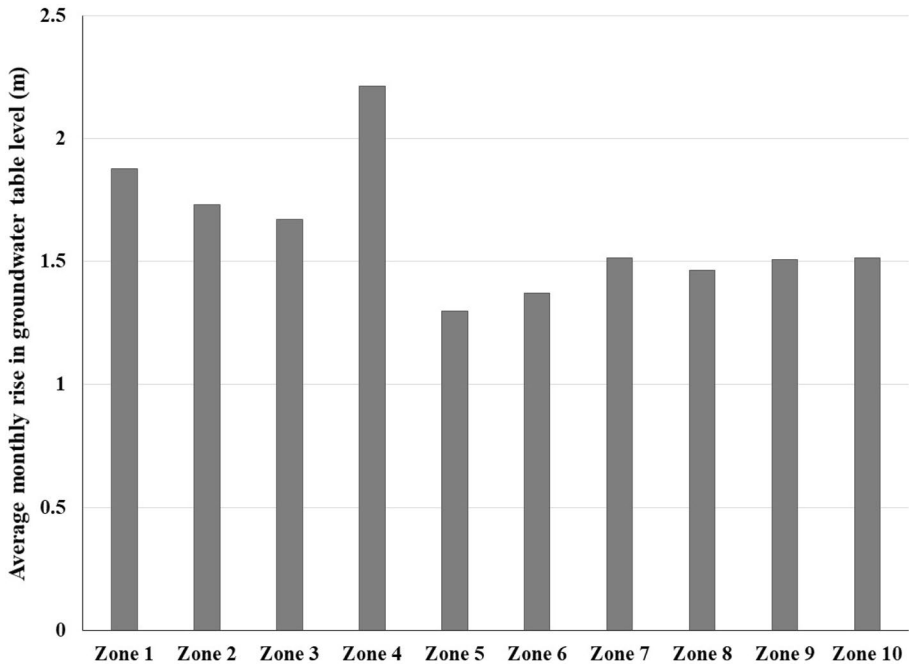
Fig. 12 The monthly average of GWTL rise in the wells being exploited in the ten zone

during 4 months of October 2012, January 2012, April 2013 and July 2013 are illustrated in Figs. 16, 17, 18 and 19. It can be found that a considerable part of the existing extractions was uncontrolled and caused instability in GWTL. Based on optimal exploitation values can be stated that in order to protect the stability of the Bandargaz-Nokandeh aquifer, it is necessary to reduce the permissible amount of extraction from 17 liters per second to 10 liters per second from wells in this area. It could only be provided by taking executive activities to restrain the extractions from the wells and issuing legal permission in which the permissible amount of extraction is specified in it. Certainly, the proper implementation of these laws needs the regular surveillance of extractions from the wells by the in-charge authorities.

In order to operational implementation of the optimal exploitation policies, it is necessary to clearly determine the exploitation instructions from each well according to the optimal values and be provided to the well owner in the form of an allocation permit. This permit includes the monthly operation schedule, the number of exploitation days per month, penalties for violations of allocation permit conditions, incentive and supportive policies from well owners as a result of implement water conservation programs and increase water use efficiency. It is also necessary to control the allocated permits, installation online water consumption measurement devices, patrolling and monitoring of the active wells, informing to well water consumers about the consequences of abstraction of groundwater and familiarize them with the incentive policies considered by the responsible organizations. In this regard, it is necessary to allocate an appropriate budget for the implementation of aquifer sustainable exploitation policies.
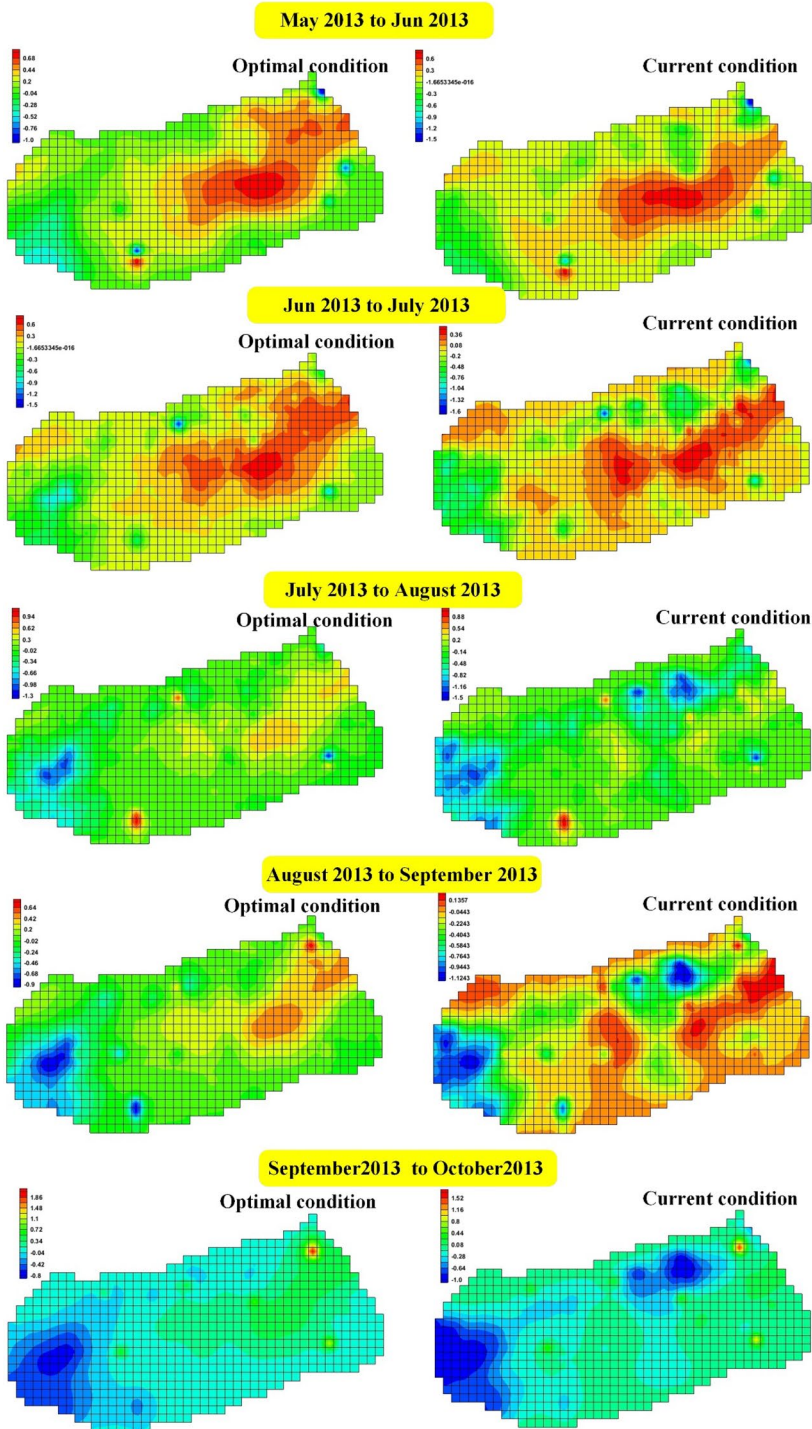
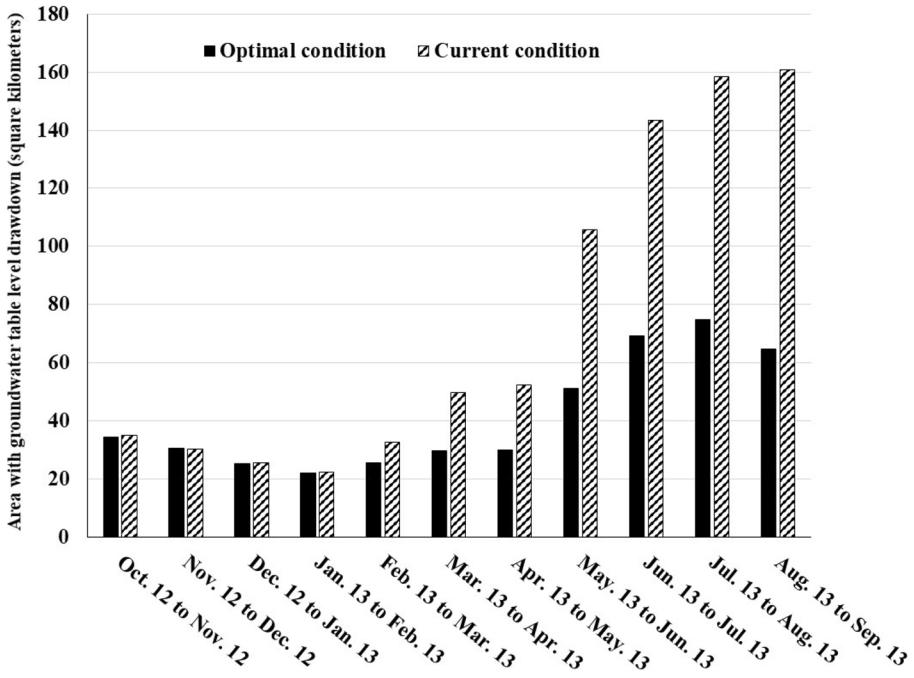**Fig. 13** Spatial and temporal variation of the monthly GWTL drawdown under current and optimal status

Fig. 14 Monthly variation of areas with the GWTL drawdown under current and optimal status
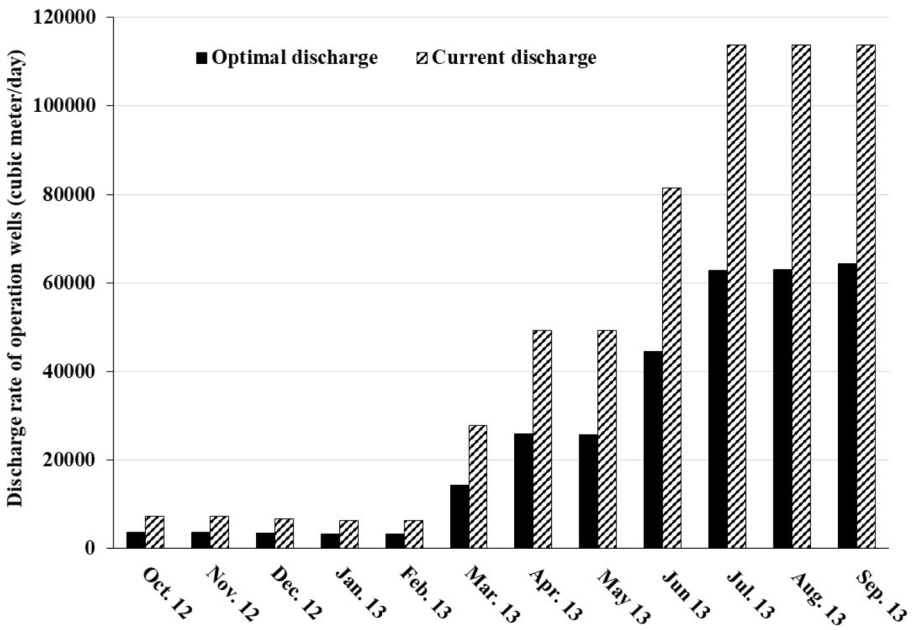

Fig. 15 Monthly variation of wells discharge in Bandargaz-Nokandeh aquifer in the two existing conditions and optimal extraction
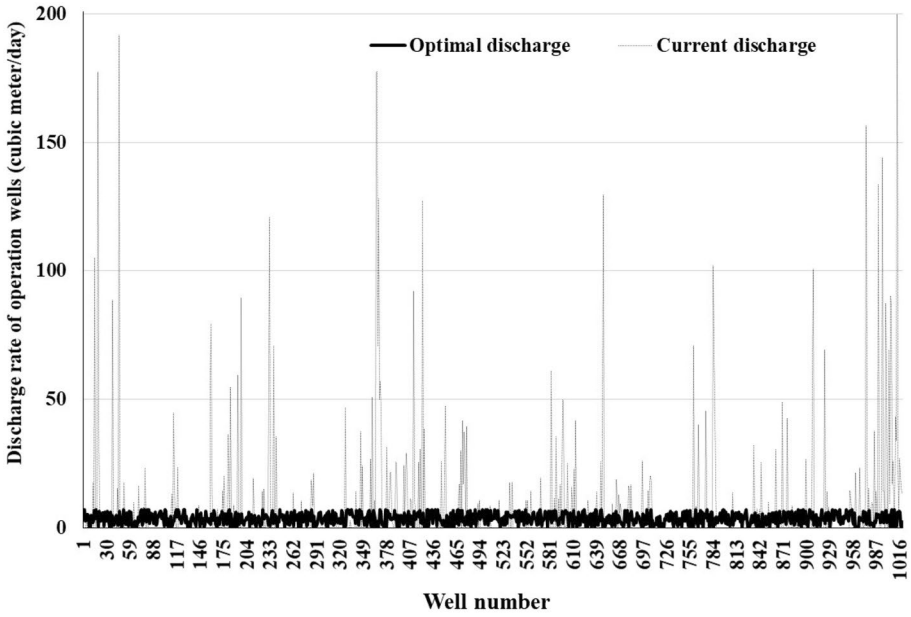
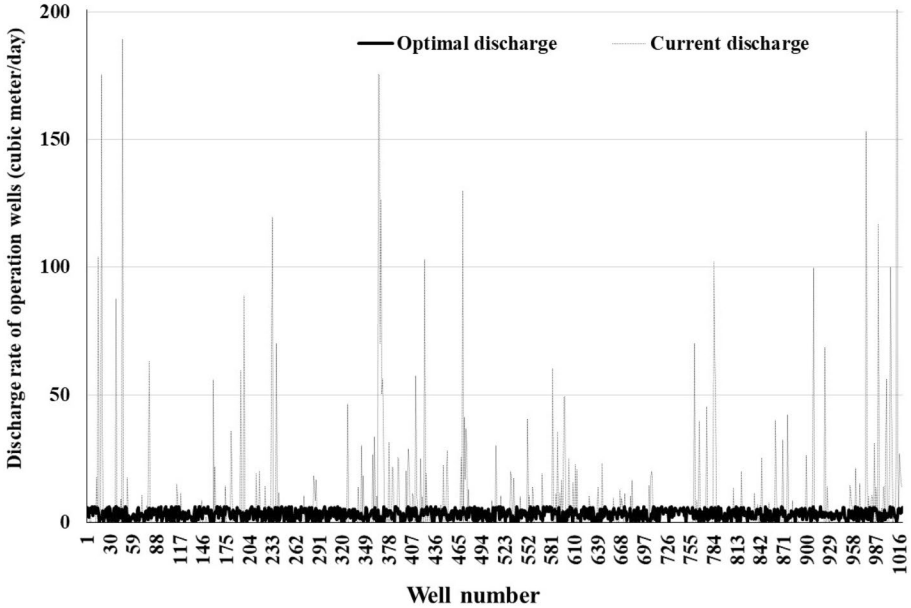**Fig. 16** Comparison of wells discharge under existing and optimal operating status in October 2012

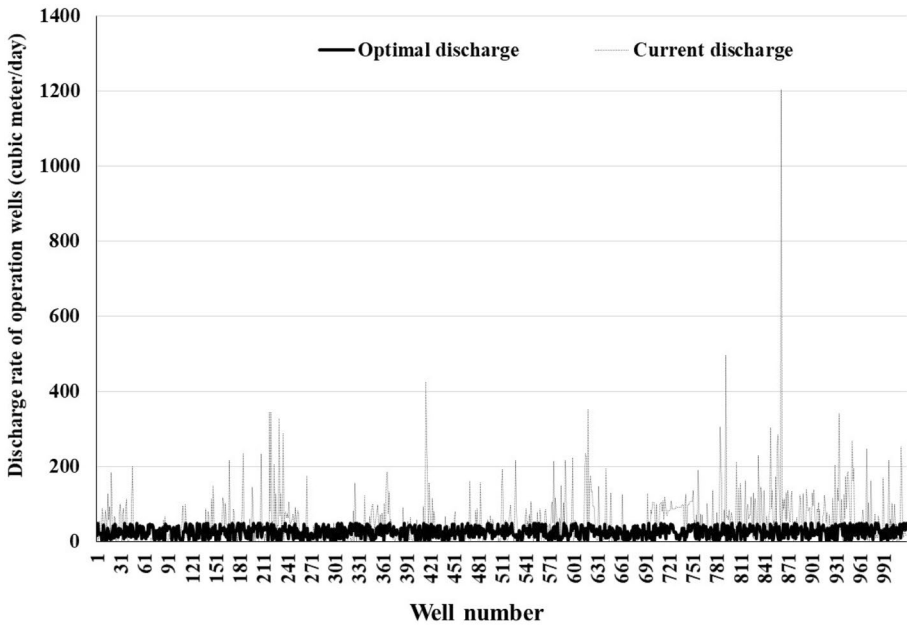**Fig. 17** Comparison of wells discharge under existing and optimal operating status in January 2012

Fig. 18 Comparison of wells discharge under existing and optimal operating status in April 2013
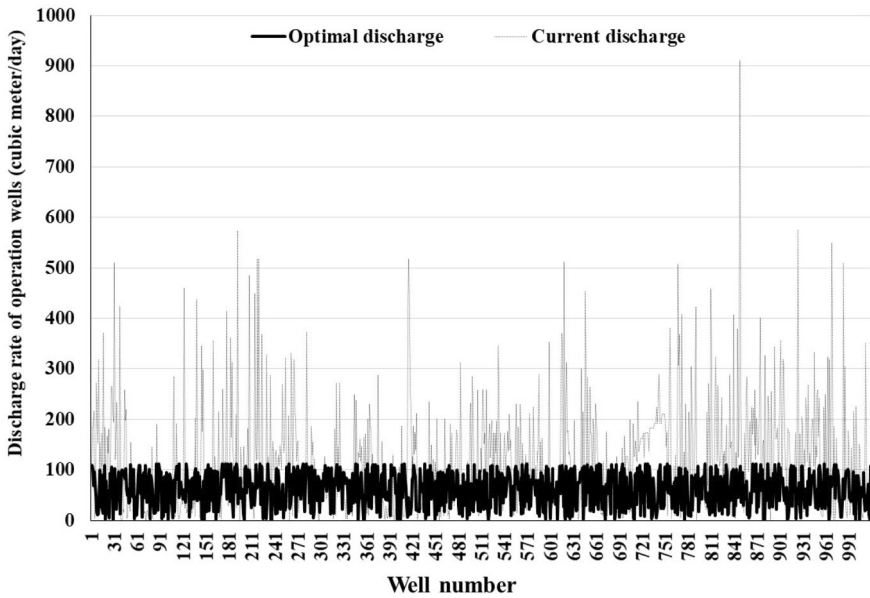

Fig. 19 Comparison of wells discharge under existing and optimal operating status in July 2013

6 Conclusion

In this research, a novel integrated distributed multi-objective S-O model have developed to determine exploitation management strategies that can create stability in coastal aquifer exposed to saltwater invasion. In this regard, the MODFLOW-2000 mathematical model under GMS simulation model was used to simulate the quantitative behavior of the Bandargaz-Nokandeh aquifer. After simulating the model in the unsteady condition, the aquifer was calibrated for a 12-month stress period (2011-2012) to determine the hydrodynamic coefficients of aquifer. The validation of the GMS model was also examined for a period of one year (2012-2013).

To use the results of the aquifer simulation model in the developed multi-objective S-O management model, the interface code was prepared in MATLAB2018b environment. Minimizing the sum of GWTL drawdown in each of the cells in aquifer modeling area during the study period and maximizing of water extraction from existing operating wells at the aquifer are considered as the objective functions of the proposed management model.

Using the NSGA-II multi-objective algorithm and its implementation, optimal aquifer operation scenarios were determined from each of the wells. Each of the scenarios located on the optimal trade-off curve represents different aspects of the objectives studied. Then, the SAW, GRA, and BAM decision-making methods were used to extract the superior scenario.

The results of the proposed approach show that most of the coastline of Bandargaz-Nokandeh plain aquifer is in critical condition. By applying optimal discharge from wells, in addition to raising the GWTL in the coastal strip, the quality conditions of the aquifer are controlled seawater intrusion in the short-term.

Also, according to the obtained results and comparison of the GWTL under two mentioned conditions can be found that there is a 29.54% decrease in the area of aquifer that contain drawdown in the GWTL. This reduction varies from 1.43% in October 2011 to 59.22% in September 2012. The results of this study showed that the structure of the proposed management model is a powerful tool for the management of coastal groundwater resources. This method can present useful executive instructions in extracting groundwater from other aquifers, especially coastal aquifers. In order to develop the results of this study, it is suggested that quality parameters and surface water resources be used to improve and increase the accuracy of exploitation policies. Also, the effects of uncertainty of quantitative and qualitative parameters are better to be considered in the development of operating instructions.

Declarations

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