

Optimal pumping policy from well field connected with a stream

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Received: 26 December 2023 / Accepted: 21 March 2024

Published online: 09 April 2024

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Abstract

Conjunctive use management of water resources is of paramount importance in the backdrop of the growing demand for freshwater resources. With this viewpoint, this study is aimed to present a methodological approach utilizing the combined use of simulation and optimization models for evolving strategies or policies for the management of water resources in a well-field connected to a stream. The proposed methodology incorporates the coupling of the groundwater simulation model with the optimization model for decision-making through the response matrix method. In this study, a numerical groundwater flow model using MODFLOW was used to simulate the response of stream-aquifer interactions. A linear optimization model was formulated to account for the best optimal groundwater withdrawal taking into consideration the allowable drawdown, permissible stream flow depletion, and satisfaction of the water demands. Such management options permit the investigation of alternative strategies for groundwater abstraction in a well-field hydraulically connected to a stream for sustainable development of water resources. The model was applied in a hypothetical well field study area hydraulically connected to a stream and satisfactory results were obtained. The methodology was also very important to understand the tradeoff between groundwater withdrawal and the depletion of flow to the nearby stream. This approach was applied to the Aynalem well field stream-aquifer system which is located in Northern Ethiopia. Results show that groundwater extraction from the Aynalem well field triggers stream flow depletion and it is possible to decrease the stream flow depletion by 3.5–4.5% by adjusting current groundwater withdrawal schedules and configuration of existing wells.

Keywords Simulation–Optimization · Conjunctive use management · Groundwater · Stream pumping policy

1 Introduction

Groundwater is one of the most valuable natural resources, which plays a vital role in economic development and ecological diversity [1]. In recent years, the use of groundwater has been increasing due to the rise of water demand for drinking water supplies and food production for the growing population. Globally, groundwater aquifers are being over-exploited by 20% leading to serious consequences such as a decline in groundwater levels, stream flow depletion, water shortages, land subsidence, and saltwater intrusion in coastal areas [2]. Besides, groundwater supplies in the basin have been depleted due to a long-term decrease in precipitation and a lack of coordinated use of surface water and groundwater resources [2–4]. In order to sustain groundwater yield in a basin therefore it is imperative to evolve optimal water use management strategies that include conjunctive use of water resources particularly, in regions where freshwater is scarce.

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Conjunctive use involves the systematic use of surface water systems and groundwater aquifers to increase the yield and reliability of water supplies for sustainable development [5, 6]. Thereby, interest has recently grown up to understand surface water and groundwater interactions and to establish a rational basis for the development and conjunctive use of both resources in a basin. However, the representation of both system responses, interaction, and the development of management strategies that address the simultaneous regulation of aquifers and surface water systems has become more difficult [2]. Therefore, it is imperative to develop a methodology incorporating the complex behavior of the physical stream-aquifer systems and their management strategies for the sustainable development of water resources.

Several new models and techniques are also emerging to address various groundwater management problems that consider interactions among surface water, groundwater, and water resources use and environmental consequences. Among these, numerical groundwater simulation models are useful tools to simulate the response of the aquifer system and develop groundwater management strategies. The simulation model attempts to address the complexity of real-world physical systems by integrating the hydrogeologic system, climatic effects, and anthropogenic stresses and provide a means to evaluate and reconcile competing management alternatives [7]. However, various groundwater management alternatives may not be achieved by the use of simulation techniques alone. In this case, a couple of applications of simulation and optimization model approaches are essential to incorporate the complex behavior of the groundwater and surface water flow systems and identify the best management strategies. A couple of application of an optimization model and a simulation model of the aquifer system describes the response of the physical aquifer system due to various external stresses and provides various water resources management strategies [8–10].

Many attempts have been made by researchers to apply a combined simulation–optimization model to address groundwater management issues, although they vary significantly in terms of optimization method, hydrological processes, complexity, and model application region [11–17]. However, the demand for updating methods still exists since groundwater management issues are associated with complex systems incorporating stream-aquifer interactions, ecological issues, long-time horizons, conflicting interests, and economic constraints [18].

The objective of the present study is to describe a simulation–optimization modeling approach for determining the optimal pumping policy for a well-field hydraulically connected to a stream for sustainable development. The simulation–optimization modeling approach is a coupling application of a simulation model and optimization techniques for the simultaneous management of stream-aquifer systems. In this study, a simulation model uses numerical techniques to simulate the physical behavior of a stream-aquifer system using a three-dimensional finite-difference groundwater flow model (MODFLOW) whereas the optimization model accounts for management aspects by incorporating physical and managerial constraints. A coupling application of simulation and optimization modeling approach provides management strategies to maintain aquifer yield sustainability and reduction of stream flow depletion [10, 19].

The simulation–optimization modeling approach in the present study is applied (1) to a hypothetical study area to demonstrate the simulation of the stream-aquifer physical system and management issues incorporating groundwater withdrawal schedules and stream flow for downstream users and ecological purposes in a typical stream-aquifer system. (2) a real stream-aquifer system (Aynalem well field, located in northern Ethiopia) was used to test the feasibility of the modeling procedures for practical applications and to evaluate explicit management alternatives related to rising groundwater withdrawal rates and stream flow depletion cases.

2 Simulation–optimization modeling approach

A combined application of an optimization model and a simulation model of the stream-aquifer system can be a useful approach to determine optimal groundwater development strategies because they provide an effective tool to evaluate the relations among minimum stream flow criteria, satisfied water-supply demands to different stakeholders, and sustainable ground-water withdrawal rates. A simulation model uses numerical techniques to describe and predict the aquifer response of the physical nature of stream-aquifer systems and they are used as inputs to the groundwater management model due to their predictive capability [11]. In this study, transient numerical models using MODFLOW [20] were used to evaluate the response of stream-aquifer interactions.

The optimization model accounts for management aspects of the water resources system. A linear optimization technique was formulated and used in this study since the objective and constraints are linear. The objective of the optimization model is to maximize the total groundwater withdrawal from the stream-aquifer system by incorporating environmental and sustainability restrictions. In the present study, the response matrix technique was used to couple the simulation model with the optimization model.

An external groundwater simulation model was used to generate unit responses in the response matrix approach [21]. The unit response describes the influence of unit stresses applied at pumping/recharge locations. The unit responses are assembled to construct the response matrix, which is included in the management model. A transient response function in the discrete form is given by [22]:

$$s_{\hat{o},n} = \sum_{\xi=1}^{N_{pw}} \sum_{k=1}^n \delta_{\hat{o},\xi,n-k+1}^h (Q_{gw})_{\xi,k} \quad (1)$$

where $s_{\hat{o},n}$ is drawdown at the cell \hat{o} at the end of period n (L); $\delta_{\hat{o},\xi,n-k+1}^h$ is the influence coefficients $(L/L^3/T)$; $(Q_{gw})_{\xi,k}$ is the amount of groundwater withdrawal from ξ cell during the k^{th} period (L^3/T);

The stream flow depletion response coefficient ($\delta_{\hat{u},\xi,n-k+1}^s$) in a stream reach can be described in terms of groundwater withdrawal as Eq. (2) [19, 21].

$$\delta_{\hat{u},\xi,n-k+1}^s = \frac{q_{\hat{u},n}^*}{(Q_{gw})_{\xi,k}} \quad (2)$$

where $q_{\hat{u},n}^*$ is the stream flow depletion at stream controlling site \hat{u} at the end of the n^{th} period due to a unit groundwater withdrawal (L^3/T); The response coefficients are dimensionless and range from 0.0 to 1.0.

The summation of stream flow depletion at each constraint site is written as:

$$q_{\hat{u},n}^s = \sum_{\xi=1}^{N_{pw}} \sum_{k=1}^n \delta_{\hat{u},\xi,n-k+1}^s (Q_{gw})_{\xi,k} \quad (3)$$

The assumption of the response matrix technique is applicable when the groundwater system behaves linearly within the relevant ranges [23, 24]. The saturated thickness of confined aquifers does not vary with pumping; hence the head response of the confined aquifer varies linearly and this makes linear programming more attractive. On the other hand, the saturated thickness and transmissivity do change with pumping in unconfined aquifers and for this reason the head response of the unconfined aquifer varies non-linearly. However, unconfined aquifers can use a confined flow equation when head changes in unconfined aquifers are small compared to the saturated thickness of the aquifer and in this case, the linearity assumption is often realistic in groundwater flow modeling [25–29].

This technique has been used successively by many researchers for groundwater management [8, 19, 21, 30–32]. In this study, linear programming is formulated since both objectives and constraints are linear. The study areas where the model has been applied (Aynalem well field stream-aquifer) are unconfined. Hence, the assumption of linearity was considered valid because the saturated thickness is large and head changes are small compared with the aquifers thickness. The system of linearity was also tested by a post-optimality analysis [33] that is the resulting pumping rates derived from the optimization model were verified with the results obtained from the application of optimal management plans to the simulation model.

In this study, a 1 year planning period corresponding to monthly time steps was considered in the management model. Consequently, drawdown and stream flow depletion transient response functions were generated from the developed numerical groundwater flow simulation model by subjecting each of the pumping wells to unit discharge for the first stress period and zero units for the rest of the periods.

2.1 Simulation of the hypothetical problem

The simulation module is essential to model the hydrologic aquifer responses, the stream-aquifer interactions, and the developing influence coefficients for the aquifer system. In this study, the transient numerical groundwater flow model MODFLOW was used to simulate the hydrologic response and used to develop the influence coefficients per unit pumping from the hypothetical study area of the stream-aquifer system. The hypothetical system study represents the abstraction of groundwater from a single unconfined aquifer that is hydraulically connected with a stream in which limited drawdown and permissible stream flow depletion are allowed in the control site. The topography of the hypothetical study area is relatively flat with an average elevation of 60 m above mean sea level. The local topography slopes towards the stream which is located almost at the center of the area. The stream depletion monitoring location (control

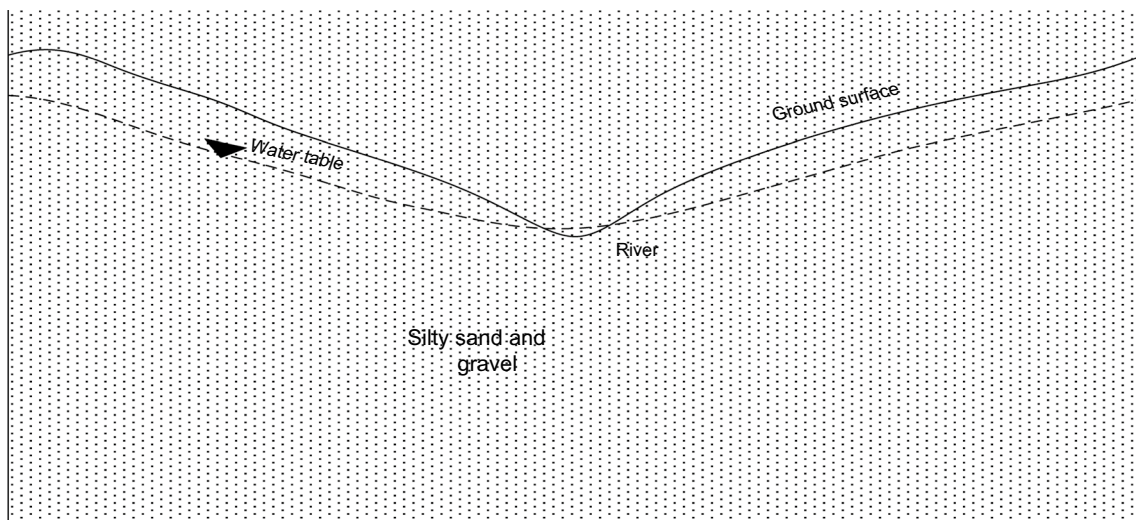
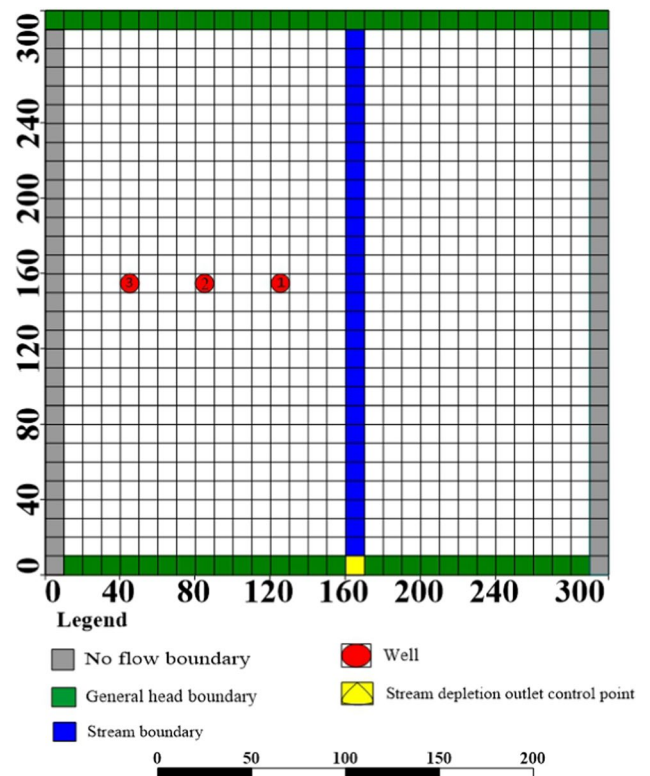


Fig. 1 Cross-sectional view of the hypothetical area

Fig. 2 Discretization view of the hypothetical study area



location) is located at the downstream end of the stream to ensure a specified amount of depletion for ecological and downstream purposes (Fig. 2). The stream flows from north to south direction with a surface water elevation that ranges from 52 to 53 m above mean sea level in the north to 51–52 m above mean sea level in the south. The average depth of the stream is approximately 1.0 m. The hypothetical aquifer is underlain by relatively homogeneous silty sand and gravel. The aquifer depth is 30 m below the ground surface. The water table is flat which generally follows the topography of the surface (Fig. 1). The stream-aquifer interaction was simulated as a head-dependent flow boundary and was simulated by the use of the stream routing package in MODFLOW [34]. The streambed conductance is assumed to be 46.45 m²/day. A monthly stream flow discharge was specified at the first stream cell along the northern boundary of the model. The

aquifer has an average horizontal hydraulic conductivity of 3.048 m/day, a ratio of vertical to horizontal conductivity of 1:10, specific storage of 0.0164, a specific yield of 0.20, and effective porosity of 0.20.

2.1.1 Model area discretization and boundary conditions

The Model area of the aquifer is discretized into a grid of 30 rows and 30 columns and one layer (Fig. 2). Grid cells were a uniform length of 10 m. Boundary conditions for the hypothetical model consisted of the water table, specified flows, and head-dependent flow conditions. No flow boundary condition is assigned to the west and east side of the area assuming negligible groundwater fluxes across the water divide. The groundwater flow and outflow from the hypothetical study area is from the north to south direction based on the hydraulic gradient. The head-dependent boundary was assumed to account for the seepage from the upstream side (north). A general head boundary condition is also assumed for the head-dependent flow towards the upstream side (northern) and the downstream side (southern) of the aquifer system. The seasonal recharge amount was applied at the uppermost top boundary at each stress period. Monthly recharge rates i.e. 9% of rainfall for the 23 years (1993–2016) were determined based on the daily rainfall record in the Aynalem watershed area [35]. The no-flow boundary is assigned to the bottom boundary. The stream is 6.5 m wide and located in the middle of the model design area. Since the stream acts as a local groundwater flow divide and is modeled with a head-dependent flow boundary condition at the stream.

2.2 Formulation of an optimization model

The objective of the formulated optimization model is to maximize the total groundwater withdrawal from the aquifer that is hydraulically connected to a stream considering physical and managerial constraints. The objective function of the optimization can be expressed as:

$$\text{Maximize } Z = \sum_{k=1}^{N_{tp}} \sum_{\xi=1}^{N_{pw}} (\Delta t_p)_k (Q_{gw})_{\xi,k} \quad (4)$$

where Z = Total withdrawal from pumping wells in a planning horizon (L^3); $(Q_{gw})_{\xi,k}$ = Groundwater extraction from cell ξ in period k (L^3/T); N_{pw} = Number of groundwater pumping cells; N_{tp} = Number of periods in a time horizon; $(\Delta t_p)_k$ = pumping time in the k^{th} period; k = period index; ξ = index for well number.

2.2.1 Stream–aquifer system responses constraints

In the proposed study, influence coefficients are used as constraints to describe stream-aquifer system responses. Each influence coefficient is assembled into a response matrix and incorporated into the drawdown and stream flow depletion constraints of the optimization model.

At the location of pumping well sites, the drawdown must not exceed the maximum permissible values for all time steps and can be expressed as [22]:

$$\sum_{\xi=1}^{N_{pw}} \sum_{k=1}^n \delta_{\hat{o},\xi,n-k+1}^h (Q_{gw})_{\xi,k} \leq (s_{\hat{o},n})_{max}; \forall \hat{o}, n \quad (5)$$

where $(s_{\hat{o},n})_{max}$ = maximum allowable drawdown at \hat{o}^{th} site (L).

The stream flow depletion at the constraint site (outlet reach) must not exceed the maximum permissible stream flow depletion values for all time steps and can be expressed as:

$$\sum_{\xi=1}^{N_{pw}} \sum_{k=1}^n \delta_{\hat{u},\xi,n-k+1}^s (Q_{gw})_{\xi,k} \leq (q_{\hat{u},n}^s)_{max}; \forall \hat{u}, n \quad (6)$$

where $(q_{\hat{u},n}^s)_{max}$ = maximum allowed rate of streamflow depletion at the site \hat{u} , in n period (L^3/T).

2.2.2 Maximum and minimum pumping rate constraint

This group of constraints indicates that the maximum amount of pumping from each well must not be greater than the capacity of the well. Similarly, the minimum amount of pumping from each well should not be less than its prescribed minimum value. This requirement must be satisfied at each well in the system where withdrawals from wells are made. The upper bound of the pumping rate in each well can be determined by the capacity of the pump, yield of the aquifer, and water requirement amount. Mathematically it can be described as:

$$(Q_{lb})_{\xi,k} \leq (Q_{gw})_{\xi,k} \leq (Q_{up})_{\xi,k} \quad \xi = 1, \dots, N_{pw} \tag{7}$$

$$k = 1, \dots, N_{tp}$$

where $(Q_{lb})_{\xi,k}$ and $(Q_{up})_{\xi,k}$ are lower and upper bounds of pumping rates in (L³/T).

2.2.3 Water supply demand constraints

The withdrawal of groundwater from the aquifer should satisfy the water demands for meeting the municipal water supply of the nearby towns. Mathematically, the demand constraint can be described as follows:

$$\sum_{\xi \in \Omega_{ms}}^{N_{pw}} (Q_{gw})_{\xi,k}^{ms} \geq (Q_D)_k^{ms} \quad k = 1, \dots, N_{tp} \tag{8}$$

$$\Omega_{ms} = \{ \xi_1^{ms}, \xi_2^{ms}, \xi_3^{ms}, \dots, \xi_{N_{pw}}^{ms} \}$$

where $(Q_D)_k^{ms}$ = municipal water supply demand at period k, Ω_{ms} is a set of all groundwater pumping well in a basin from which water is supplied for municipal use.

2.3 Model application

The developed model was first applied to a hypothetical study area (Fig. 2). The initial application of the model was tested by placing three pumping wells in the hypothetical study area and withdrawal of groundwater from the aquifer was allowed by these wells. A planning horizon of 1 year (12 months) was considered with four stress periods starting in January and ending in December. The stress periods have 90 and 92 days in length. Consequently transient influence coefficient ($\delta_{\xi,n-k+1}^h$) describing the effect of groundwater pumping on the potentiometric surface elevation was generated from the numerical groundwater flow simulation model for each stress period by subjecting each pumping well to a unit discharge for the first stress period and zero discharge for the rest of the stress periods successively. Drawdowns of three pumping wells sites and stream flow depletion at the downstream end control point (outlet) were simulated over a 1 year planning horizon. The unit response coefficients were assembled to form the transient response matrix expressing the effect of pumping on the hydrologic response of the stream-aquifer system.

The maximum permissible drawdowns (s_{max}) at three pumping well sites, stream flow depletion due to the withdrawal of water from a well field nearby to the stream, water demand, and maximum permissible pumping rate were input of the hydraulic management model. The maximum permissible drawdown at the pumping well site could be determined based on the consideration of pumping cost, land subsidence, practical evidence of aquifer property, and scientific factors. The maximum permissible stream flow depletion at the downstream control point is also determined with the consideration of minimum stream flow requirement to the downstream users and ecological purposes, particularly within dry seasons. In this study, the maximum allowed stream flow depletion is 0.039 m³/2*10⁻² which is the minimum average discharge observed in February. In this study, the specified maximum permissible drawdown at each pumping well site and allowable stream flow depletion are summarized in Table 1. The maximum allowable pumping rate from each well and at each stress period was specified in consideration of pump capacity, well field yield availability, and other scientific factors.

Table 1 Permissible drawdown and stream flow depletion of a hypothetical study area

I. Drawdown		II. Stream flow depletion	
site	Maximum drawdown (m)	site	Maximum allowed stream flow depletion (m^3/s)* 10^{-2}
S ₁	3.6	q ₁	0.039
S ₂	4.5		
S ₃	5.4		

2.4 A conjunctive use optimization model for Aynalem well field aquifer system

The developed conjunctive simulation–optimization model has been applied to the Aynalem well field which is located 770 km north of Addis Ababa (capital of Ethiopia) (Fig. 3). It is the main water supply source of Mekele City, the Capital of Tigray regional state, Ethiopia. This well field is an area of greater interest as groundwater development has been carried out without considering its sustainability. Groundwater is over-exploited through discharging wells to meet the water needs, and this practice has caused a considerable decline in the groundwater table and consequently depletion of the Aynalem stream. Therefore, there is a need of investigating the long-term effects of groundwater pumping practices, regulation on groundwater draft, and determination of optimized pumping rates for the sustainability of groundwater development.

A groundwater flow model of the Aynalem well field was developed to simulate the physical stream-aquifer system using Visual MODFLOW and linked externally to the optimization model using a response matrix technique. The model was calibrated and validated to capture realistic conditions. The sensitivity analysis was carried out to evaluate the importance of aquifer parameters. The details of the numerical groundwater flow model of the Aynalem well field aquifer could be found in [36]. The unit responses were generated for repeated runs from the calibrated and validated numerical simulation model to develop a transient response matrix and linked externally to the optimization model.

2.4.1 Groundwater level and stream discharge

Close monitoring of groundwater level helps in the evaluation of spatial and temporal fluctuation of the groundwater level in the aquifer and to understand the response of the aquifer to groundwater withdrawal. Commonly, the temporal and spatial fluctuation of groundwater in the aquifer is indicative of how the aquifer changes as a result of groundwater recharge and discharge. Assessment of groundwater level fluctuation in the Aynalem well field was carried out through a field inventory program. During the field inventory program, most of the springs and shallow

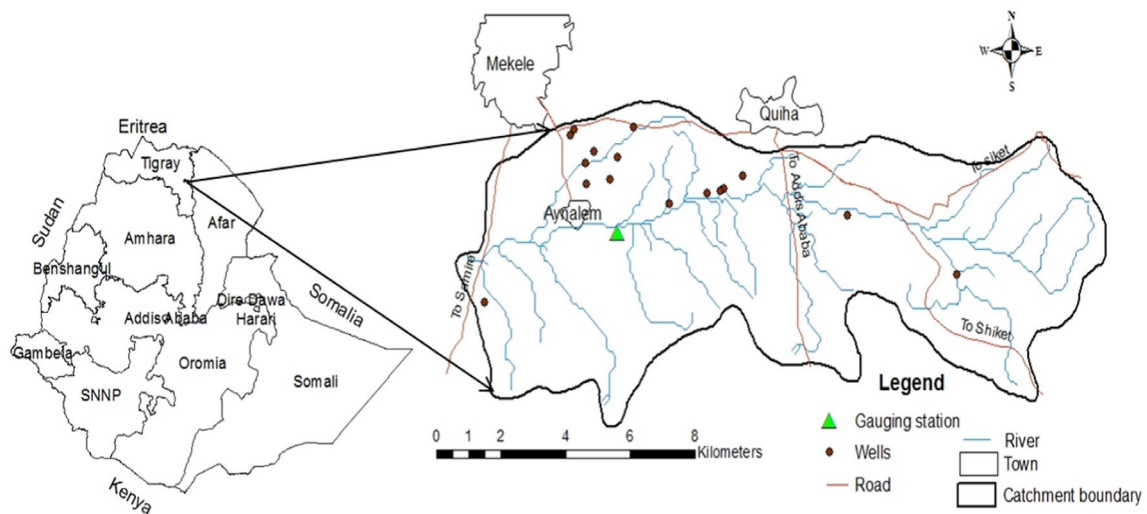


Fig. 3 Location of Aynalem well yield stream-aquifer system

Fig. 4 Water level variation at various wells of the Aynalem well field

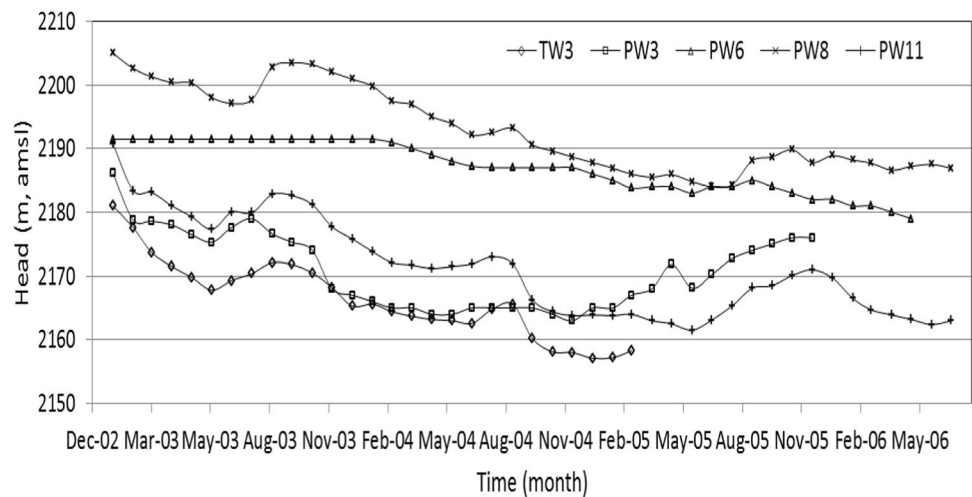
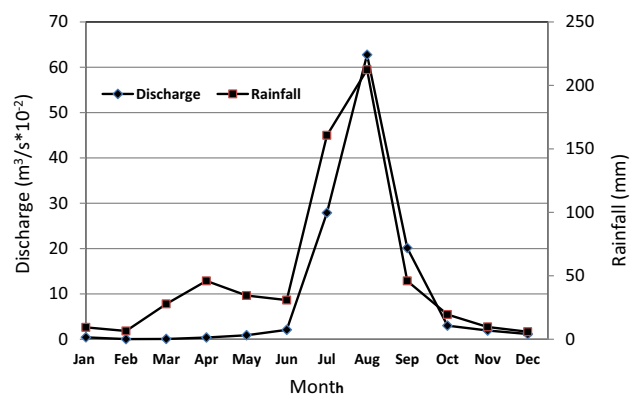


Fig. 5 Average monthly rainfall and stream flow discharge



hand-dug wells in the well field were already dried up. Some of the boreholes which were drilled in the 1990s are also getting abandoned due to the decline of groundwater level. A 4 year (2003–2006) groundwater level monitoring data of five wells were collected from the Mekelle Water Supply and Sewerage Service Office (MWSSO) (Fig. 4). The groundwater level records were taken from pumping wells, due to the absence of independent groundwater level monitoring wells during that period. This may give some measurement errors due to the continuous pumpage of the production wells. As a result of the excessive abstraction rate of groundwater and variable recharge rate, a dynamic fluctuation of groundwater level is observed in the Aynalem well field aquifer system. The trend of the groundwater level data from the wells indicates that a significant decline in groundwater level is observed in wells from time to time.

The time series records of the stream flow are quite important for a better understanding of the stream-aquifer response [37]. The daily rainfall data and the daily streamflow data for 23 years (1993–2016) were collected from the National Meteorological Agency and Ministry of Water and Energy, Addis Ababa, Ethiopia respectively (Fig. 5). The rainfall is used to estimate the recharge rate of the aquifer. The stream gauging station covers only the upstream of 69 km² of the total catchment area. The daily streamflow data were analyzed to calculate the average monthly and annual streamflow. The discharge is maximum in August and minimum in February.

2.4.2 Permissible drawdown at constraint sites

Pumping cost, land subsidence, and other local and socio-scientific factors are considered to determine the maximum permissible drawdown values at a site [38]. In the Aynalem well field, the drawdown values of each well during the dry periods were considered the maximum allowable drawdown (Table 2). The drawdowns were observed at the end of the calibration period. The maximum drawdown values of constraint well sites PW7, MU, and PW12 are higher than the other wells because they are sited in a more groundwater-depleted area.

Table 2 Maximum permissible Drawdown (S_{max}) of wells

Site	Maximum drawdown (m)	Site	Maximum drawdown (m)
Myshibt	7	PW4	11
PW11	17	PW7	28
PW3	13	TW5	16
PW6	8	PW12	20
PW8	16	Pw2	17
MU	18	TW3	15

3 Results and discussion

3.1 A conjunctive use optimization model for the hypothetical stream-aquifer system

3.1.1 Optimal groundwater withdrawal

The conjunctive use optimization modeling approach was first applied to a representative study area. Groundwater is withdrawn from an unconfined aquifer that is hydraulically connected to a stream. Three groundwater withdrawal wells which are located at a distance of 33, 73, and 113 m from the stream boundary (Fig. 2) were considered for analysis. The management model has an annual planning horizon, corresponding to four stress periods. The optimization model was linked to the simulation model to estimate the optimal withdrawal rates of wells. The optimization model is solved using MATLAB by writing optimization code. The optimal solutions were obtained for two scenarios namely; with and without stream flow depletion constraints.

The maximum optimal pumping (0.357 Mm^3) was estimated in the third stress period (July–September) and the minimum (0.33 Mm^3) was estimated in the first stress period (January–March) respectively (Fig. 6). The maximum optimal pumping obtained in the third stress period includes July, August, and September which are the rainfall seasons in the year and groundwater recharge is more in these months of the year. The first stress period includes January, February, and March, in which minimum pumping was recorded and it is relatively the driest period within the year.

The comparison of the total annual optimal pumping of each well with stream flow depletion constraints and without stream flow constraint is shown in Fig. 7. Results obtained show that the optimal pumping of well 1 which is located near

Fig. 6 Optimal pumping of wells in a hypothetical study area

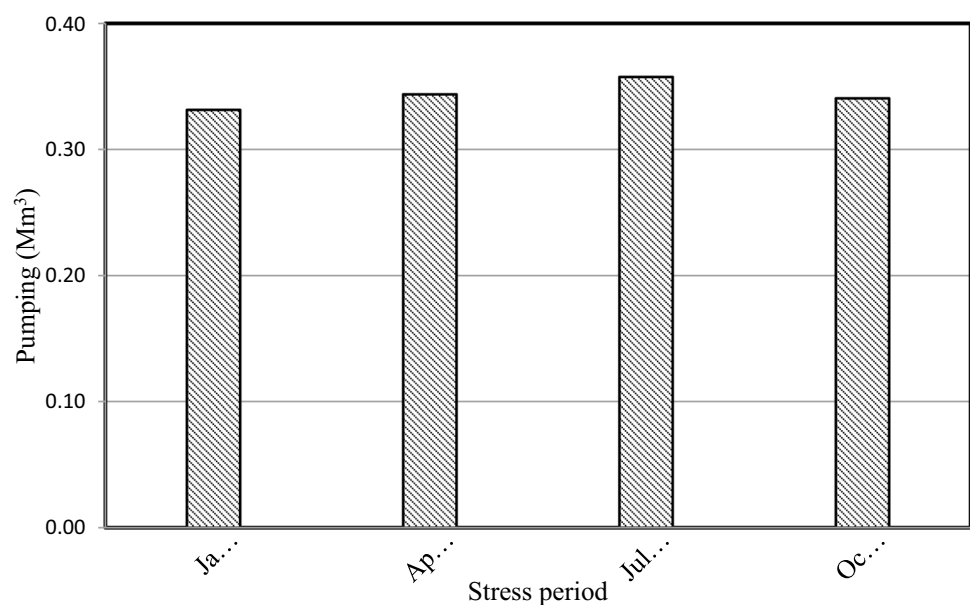
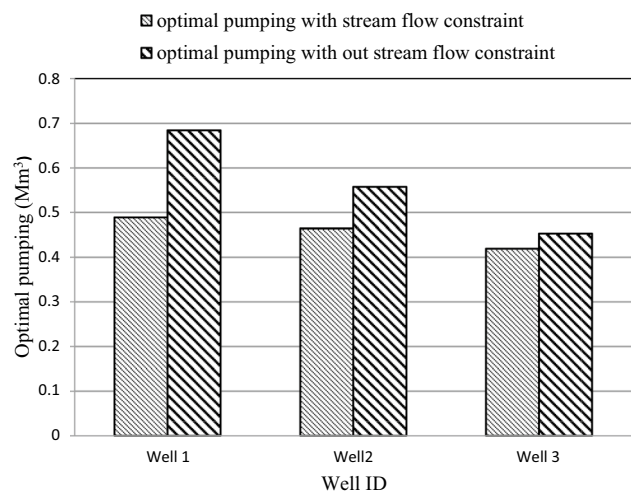


Fig. 7 Optimal pumping with and without stream flow depletion



the stream boundary is higher than the others in both cases. Well 2 is located in between Well 1 and Well 3 and the optimal pumping is next to well 1. The least optimal pumping is observed at well 3 which is found far away from the stream boundary. The optimal pumping without stream flow constraint at well 1 is 40% larger than the optimal pumping with stream flow constraint whereas the optimal pumping without stream flow depletion constraint of well 2 and well 3 are increased by 20 and 8%, respectively than optimal pumping considering stream flow depletion as a constraint. Results of the model indicate that substantial increases in total optimal pumping from the aquifer without considering stream flow depletion as a constraint are possibly from the nearby stream. This indicates that stream flow is more affected by wells located nearby streams and the withdrawal of water from the stream aquifer system should be assisted by optimal pumping policy to reduce unplanned stream flow depletion by wells.

3.1.2 Evaluating drawdown and stream flow changes in pumping

In the simulation–optimization model, the effect of the change of drawdown and stream flow depletion constraints on the optimal pumpage was evaluated. The change of drawdown constraints showed that the model solution was found to be infeasible when the drawdown at well 1, well 2, and well 3 should be less than 3.6, 4.5, and 5.4 m, respectively because these represent the highest value that has been set. The optimization model was also infeasible when the stream flow depletion constraint at the control point was less than the specified value (33.69 m³/day).

The drawdown constraint was evaluated by increasing the drawdown value in the range of 5–30% with an interval increase of 5%. Figure 8 shows the tradeoff curve between the total maximum optimal pumpage versus the percentage increase of drawdown within the planning horizon. As is shown in the figure, the drawdown increases the withdrawal of groundwater also increases. The increase in total pumping is 3.86, 7.72, 11.58, 15.45, 19.31, and 23.04% for drawdown change of 5, 10, 15, 20, 25, and 30% respectively. This indicates that uncontrolled groundwater withdrawal from a well field brings the aquifer drawdown.

The effect of change of each control point (drawdown site) was performed separately with an increase of only one control point and no change of others (Fig. 9). It can be seen from the figure that drawdown change at site 3 is more and thus control point 3 is more sensitive to drawdown than the others. The effect of change of stream flow depletion in the management model was also evaluated (Fig. 10). It has been seen from the figure that a 10% increase in stream flow depletion increases the groundwater withdrawal rate by 3% than the optimal. The conjunctive use management model indicates that substantial increases in total withdrawal from the stream-aquifer are possible for the increased rates of stream flow depletion of a nearby stream and aquifer uncontrolled drawdown.

3.2 A conjunctive use optimization model for Aynalem well field aquifer system

A conjunctive simulation- optimization model was developed to address the water demand and aquifer and stream flow depletion issues in the Aynalem stream aquifer system. Groundwater flow and its interaction with surface water in the Aynalem Well field was simulated by a transient numerical groundwater flow model with average monthly hydrologic conditions [36]. Drawdowns at 12 pumping well sites and stream flow depletion per unit pumping at one stream flow

Fig. 8 Effect of drawdown change in pumping

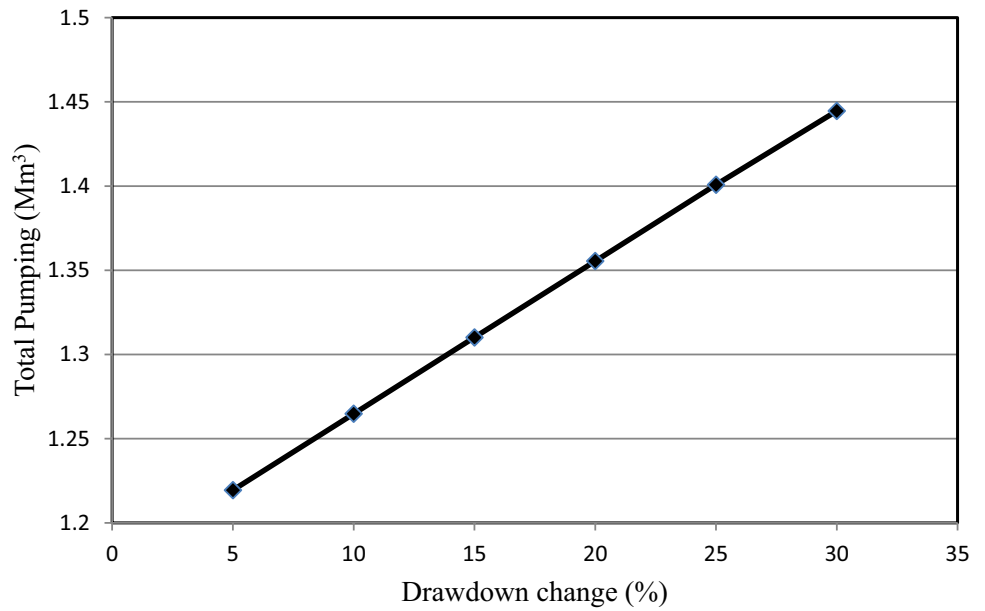


Fig. 9 Effect of pumping on drawdown change at each site

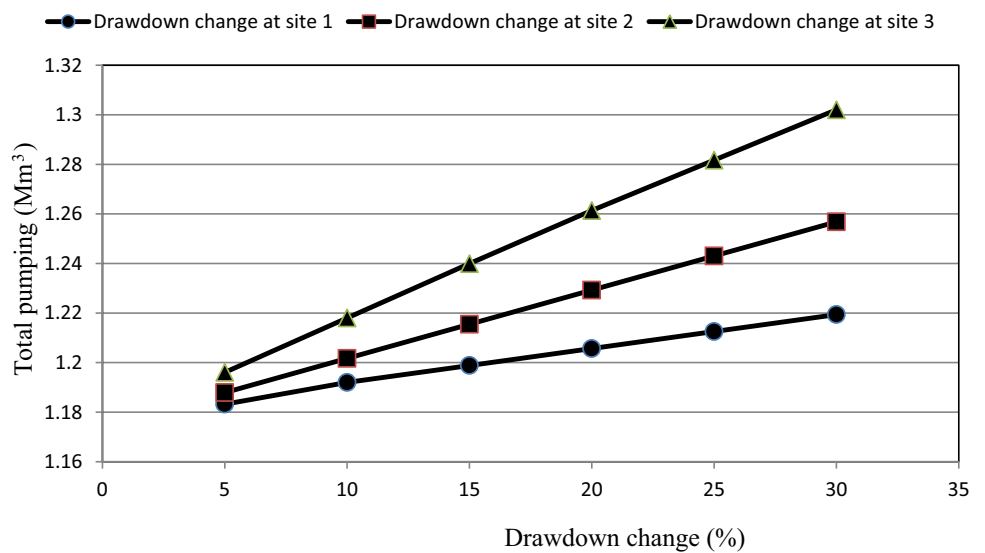
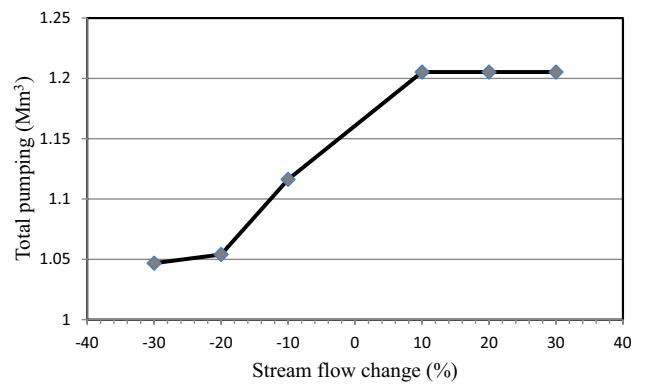


Fig. 10 Stream flow depletion change in pumping



site were monitored simultaneously from the simulation model of the Aynalem well field over the 12 months of the planning period by assuming average hydrologic conditions. The average hydrologic conditions of the Aynalem aquifer were used in the simulation model to generate the drawdown and stream flow depletion per unit pumping responses. Then after, the drawdown response matrix coefficients were generated from repeated runs of the simulation model for a planning period by successively subjecting each of the pumping wells to a unit discharge for the first stress period and zero discharge for the rest of the stress periods. Subsequently, the drawdown response functions with a total of 1728 from 12 pumping well sites of the Aynalem well field were obtained. These values are then assembled and used to form the response matrix.

The generated drawdown and stream flow depletion per unit pumping responses from the simulation model was incorporated into the optimization model, and solved in MATLAB programming by writing optimization function code. The management model has an annual planning horizon, corresponding to monthly pumping time steps. The optimal solutions were obtained for two scenarios namely, with and without stream flow depletion constraints.

3.2.1 Optimal pumping without stream flow depletion restriction

In the first case of this scenario, the optimization model was run to meet the average monthly water demands extracted from 12 existing wells with prescribed maximum drawdown values obtained from dry periods and having no stream flow depletion constraints. The monthly average water demands are the observed amounts from 12 existing pumping wells from 2003 to 2006. In the first trial of the optimization model run, with demand constraints, the model solution was found to be infeasible because of the lesser amount of assumed drawdown values to meet average monthly demands during dry periods. An adjustment in maximum drawdown was allowed to take place by trial and error to make the model converge with demand constraints. Through several trials of the optimization model run, the assumed drawdown value during dry periods in each of the wells has been increased by 10% to converge the optimization model, and the optimal solution was obtained under this permissible drawdown.

The comparison of monthly annual pumping and non-optimal pumping (observed) is shown in Fig. 11. It indicates that the optimal pumping in all the months is higher than the non-optimal pumping. However, the optimal pumping in some of the wells (Myshibt, PW3, PW8, TW3, and MU) is less than the non-optimal pumping (Fig. 12). This indicates overexploitation of water has been taken in these wells. These wells are mostly located at the lower right bank of the well field and a high drawdown is observed in this locality. On the other hand, in the rest of the wells, the optimal pumping is more than the non-optimal pumping. It indicates that the extracted water during the analyzed period is almost less than or equal to the optimum value and it is possible to say that the pumping of water from these wells is safe. It is evident from the overall results that inefficient pumping has been taking place in wells located at the lower right bank of the well field where more wells are concentrated in this locality. Therefore, the pumping of water from this locality of the well field may not be secure for the long-run well development of the aquifer unless precautionary measures are taken.

3.2.2 Optimal pumping with stream flow depletion restriction scenario

Results were also obtained to investigate the variations in the optimal pumping strategies with and without stream flow depletion scenarios characterizing environmental flow restrictions. The stream flow depletion responses at a stream flow constraint site located at the downstream end of the Aynalem river were generated from repeated runs of the simulation

Fig. 11 Comparison of total annual optimal and non-optimal pumping for 6 months (January–June)

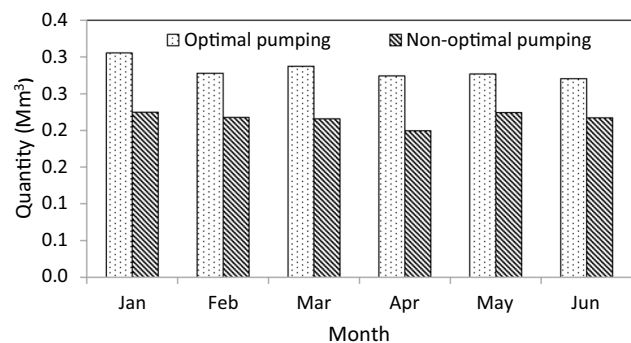
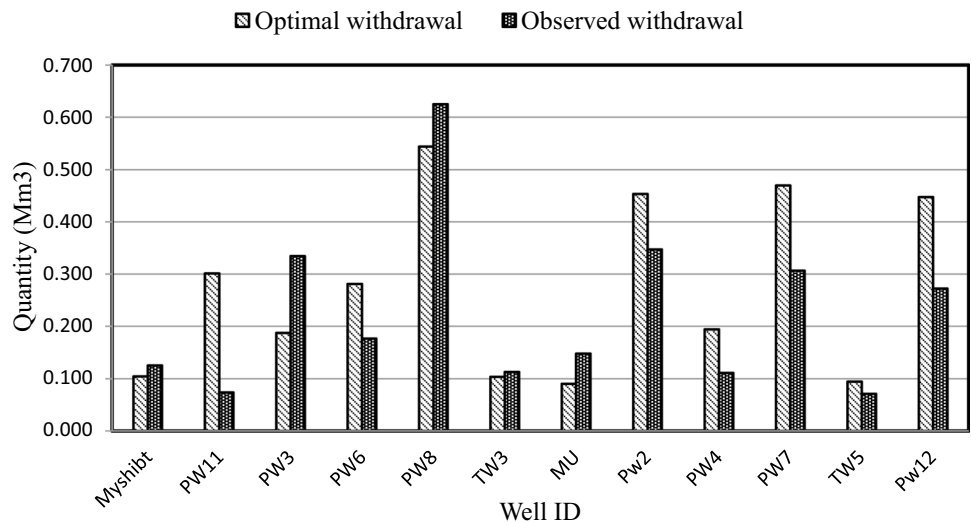


Fig. 12 Optimal and non-optimal (observed withdrawal of each well

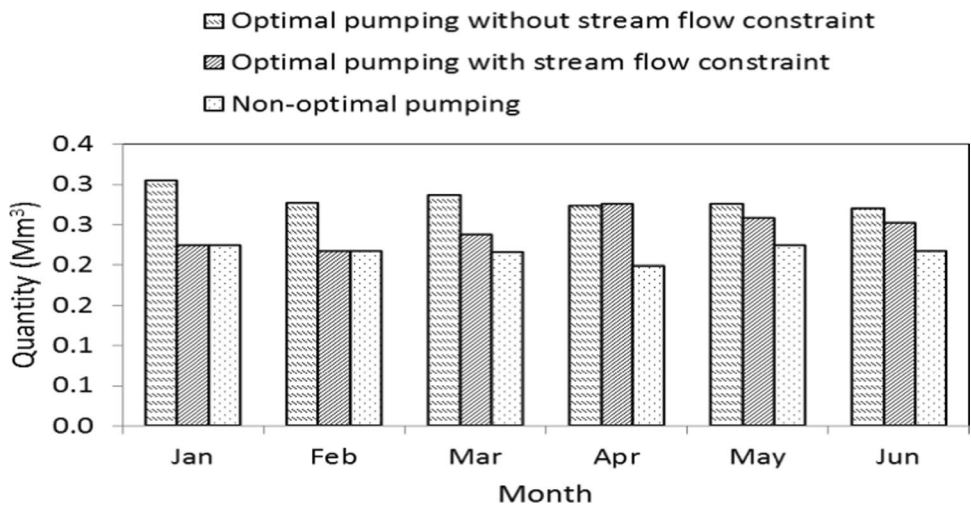


model. Two configurations of groundwater withdrawal wells were tested. This configuration consists of 12 existing pumping wells and their associated optimal pumping rates obtained from the first optimization model.

The maximum rate of stream flow depletion rate was first estimated by multiplying the average monthly observed pumping rates of 12 existing well by the unit response matrix of stream flow depletion in the Excel spreadsheet. Then by using this result as an initial input to the optimization model, several trials of optimization model runs were made to reduce the maximum stream flow depletion rates in meeting average monthly demand and to obtain optimum pumping during dry months (January–June). After many trials, the maximum stream flow depletion was reduced by 6% from the first trial estimate and this value was specified as the maximum allowable stream flow depletion for each dry month of the year. This decision was made by sequentially lowering the values of the first estimate of stream flow depletion of the Aynalem river during dry months (January–June) by uniform percentage reduction in a series of model runs. The maximum reduction was determined when the next reduction beyond 6% made the model infeasible for an optimal solution.

The comparison of average monthly optimal pumpings without stream flow constraint, with stream flow constraint, and existing pumping is shown in Fig. 13. Results reveal that the total optimal pumping with stream flow depletion as a constraint is decreased by 14% from the total optimal pumping with no stream flow depletion constraint. In January, the optimal pumping with stream flow depletion constraint is 35% smaller than the optimal pumping with no stream flow depletion constraint. The optimal pumping with stream flow depletion constraint is maximum (0.276 Mm³) in April. The minimum optimal pumping with stream flow depletion constraint is estimated as (0.22 Mm³) during February and it is decreased by 21.55% from the optimal pumping obtained without stream flow depletion constraint.

Fig. 13 Comparison of average monthly optimal and non-optimal pumping with and without stream flow depletion constraints



The optimal pumping from some of the wells (PW6, PW8, TW3, and PW7) reduces when the stream flow constraints are imposed. In the remaining wells, pumping is almost equal to or higher than optimal pumping when stream flow constraints are imposed.

Results of model runs reveal that the substantial increase in the withdrawal of wells from the aquifer during dry months triggered the Aynalem stream flow depletion. Hence, two alternatives were evaluated by using the conjunctive water management model to reduce the maximum allowable stream flow depletion rates caused by the unplanned groundwater pumping and to allow minimum flow requirement downstream for the ecological purpose during dry months (January–June). The first alternative is made by modifying the current withdrawal schedules of existing wells. In this alternative, determinations were made by increasing the withdrawal capacity of the wells (PW11, TW5, and PW12) which are located relatively far away from the stream boundary and have less effect on stream flow depletion. Increasing the withdrawal capacity of these wells by 15% and regulating the effect of this discharge on the other wells, results in the decrease of stream flow depletion by 4.5% from the specified value. The second alternative was made by reducing the withdrawal capacity of wells, which would result in a decrease in stream flow depletion. In this alternative, decreasing the withdrawal capacity of the wells by 10% decreases the stream flow depletion rate by 3.5%.

3.2.3 Post-optimal pumping analysis

The post-optimal pumping analysis was performed using the optimal pumping rates obtained from the optimization model as input to the simulation model again. The calibrated simulation model of the Aynalem well field was run to simulate the groundwater levels. The maximum drawdown which is obtained from the simulation model is 28.3 m at well PW7 and the minimum drawdown of 7.7 m at well Myshibt (Fig. 14). The simulated drawdowns of each well obtained from the simulation model were cross-checked with the specified drawdown values which were used in the optimization model. The difference between the maximum simulated drawdowns and specified maximum drawdown constraints of each well is less than 10% and this indicates the validity of the simulation–optimization model.

4 Conclusion

There is a need for the comprehensive use of management models incorporating both surface water and groundwater sources in a river basin or watershed to meet the upcoming water challenge sustainably. For this purpose, a combined simulation–optimization model is developed for sustainable water resources development strategies in a well field with hydraulically connected to a stream. The simulation model better reflects the hydraulic and hydrologic response of the

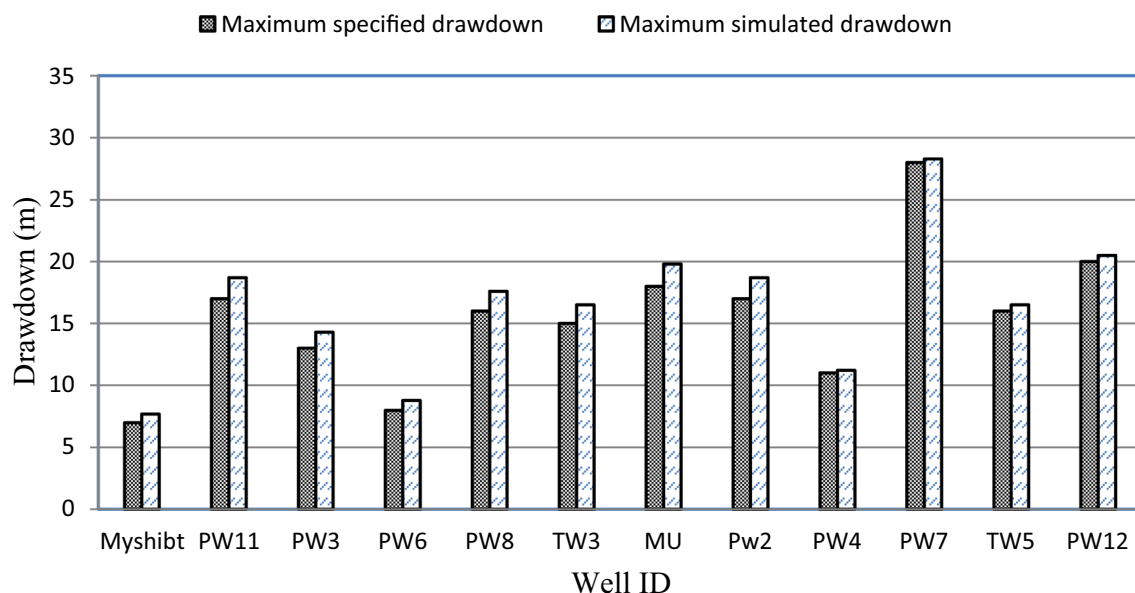


Fig. 14 Maximum specified and simulated drawdown

stream-aquifer interaction system with groundwater pumping and the optimization model looks for the best water resources management strategy taking into consideration the allowable drawdown, permissible stream flow depletion, and satisfaction of the water demands. The simulation–optimization model computes optimal groundwater withdrawal from a well field in consideration of aquifer head hydraulics, and stream flow depletion.

The model was first applied in a representative stream-aquifer system hydraulically connected to streams and is capable of evolving the strategic placement of extraction well locations in consideration of manageable aquifer drawdown and stream flow depletion in a well-field connected with a stream. This approach was applied to the Aynalem well field stream-aquifer system, in Northern Ethiopia. Model results show that groundwater pumping triggers stream flow depletion in the Aynalem well field and it is possible to decrease stream flow depletion by 3.5–4.5% by modifying current withdrawal schedules, the number and configuration of existing wells. Generally, the findings of this study would be very useful to planners and decision-makers to ensure sustainable water resource development in a basin.

Acknowledgements The authors wish to express their thanks to the National Ministry of Water and Energy, Meteorology Agency of Ethiopia, and Mekele City Water Supply and Drainage Office for providing the necessary data free of charge. The financial support for the field visit from Debre Markos University is also gratefully acknowledged.

Author contributions All authors contributed to the study's conception and design. Material preparation, data analysis were performed by the second author (Solomon Bogale). Drafting the work or revising it critically for important intellectual content was carried out by the first author (Mulu Sewinet Kerebih), and critical data analysis, writing, and review were done by a third author (Ashok K. Keshari). All authors read and approved the final manuscript.

Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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