



Distributed Simulation-optimization Model for Conjunctive Use of Groundwater and Surface Water Under Environmental and Sustainability Restrictions

Mulu Sewinet Kerebih¹  · Ashok K. Keshari²

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Abstract

Evolving optimal management strategies are essential for the sustainable development of water resources. A coupled simulation-optimization model that links the simulation and optimization models internally through a response matrix approach is developed for the conjunctive use of groundwater and surface water in meeting irrigation water demand and municipal water supply, while ensuring groundwater sustainability and maintaining environmental flow in river. It incorporates the stream-aquifer interactions, and the aquifer response matrix is generated from a numerical groundwater model. The optimization model is solved by using MATLAB. The developed model has been applied to the Hormat-Golina valley alluvial stream-aquifer system, Ethiopia, and the optimal pumping schedules were obtained for the existing 43 wells under two different scenarios representing with and without restrictions on stream flow depletion, and satisfying the physical, operational and managerial constraints arising due to hydrological configuration, sustainability and ecological services. The study reveals that the total annual optimal pumping is reduced by 19.75 % due to restrictions on stream flow depletion. It is observed that the groundwater pumping from the aquifer has a significant effect on the stream flow depletion and the optimal conjunctive water use plays a great role in preventing groundwater depletion caused by the extensive pumping for various purposes. The groundwater contribution in optimal conjunctive water use is very high having a value of 92 % because of limited capacity of canal. The findings would be useful to the planners and decision makers for ensuring long-term water sustainability.

Keywords Optimization model · Conjunctive use · Sustainable development · Stream-aquifer interaction

✉ Mulu Sewinet Kerebih
mulusewt@gmail.com

1 Introduction

Growing water demand due to intensified agriculture, population increase, urbanization, and industrial development leads to increase hydraulic stresses on the water resources systems (De Fraiture and Wichelns 2010). This has been worsening in the arid and semi-arid regions where the surface water resources are already scarce. The availability of fresh water resources has long been recognized as a limiting factor in the development of most arid and semi-arid regions, and as a result, irrigated agriculture is threatened by the water shortage caused by droughts and water mismanagement (Mays 2013; Kahil et al. 2015). The increasing water demand for various purposes and reducing fresh water availability have forced engineers and planners to propose more comprehensive and complex strategic management plans for the sustainable development of water resources in the water scarce areas. The literature review shows that the optimization techniques can be effectively employed to chalk out strategic management plans for tangible outcomes as it enables to account operational limitations and restrictions to avoid the undesirable consequences. Keshari and Datta (1996a) presented a nonlinear simulation-optimization model for integrated management of groundwater pollution and withdrawal in a confined aquifer under different scenarios characterizing heterogeneity, anisotropy and boundary conditions. Later a multiobjective nonlinear optimization model was developed by Keshari and Datta (1996b) to manage a contaminated aquifer for agricultural use wherein irrigation demands can be met partly or fully by the groundwater. In this study, groundwater simulation and optimization models were linked internally through an embedding technique. Safavi et al. (2010) presented an application of simulation-optimization model for conjunctive use of surface water and groundwater to minimize the shortage in meeting irrigation demand with control on the cumulative drawdown of the underlying water table. Kamali and Niksokhan (2017) presented a multiobjective simulation embedded optimization model and used particle swarm optimization for sustainable management of groundwater. Perea et al. (2020) presented a multiobjective genetic algorithm to optimize the daily abstraction of groundwater from multiple sources in water scarce regions. The coordinated operation of groundwater and surface water systems is used to increase the yield and reliability of total water supplies by using groundwater when surface water supplies are scarce or vice versa (Liu et al. 2013; Dogan et al. 2019). However, the coordinated management of water resources requires better understanding of how groundwater pumping and surface water diversions affect the flow conditions in a stream-aquifer system and sustainability in the region. The excessive withdrawal of groundwater can cause a decline in groundwater level as well as depletion of hydraulically connected stream, and thereby environmental issues may arise because of the adverse effects that impinge on aquatic and riparian ecosystem due to reduction in the stream flow (Huang et al. 2018; Flores et al. 2020).

The recent literature shows growing interest in the use of optimization techniques for managing groundwater resources, although they differ significantly in terms of optimization technique, hydrological processes involved, scale of detailing and complexity, and application area (Refsgaard et al. 2010; Safavi et al. 2010; Sedki and Ouaza 2011; Kamali and Niksokhan 2017; Perea et al. 2020). The demand for new models still exists because the conjunctive management problems are always associated with large scale physical systems involving complicated hydrological processes and connected environmental consequences, multiple goals, time varying operational conditions, and a long time horizon. These aspects become prominent particularly in the areas characterized by water scarcity, hydraulically connected stream-aquifer systems, hydrological uncertainty, and increased human intervention.

Keeping the above in view, the objective of this paper is to present a distributed simulation-optimization model for conjunctive water use in a hydraulically connected stream-aquifer system and involving environmental and sustainability restrictions. The optimization framework incorporates the hydrologic response of the stream-aquifer system due to external stresses as well as restrictions to deal with diverse concerns of various stakeholders while determining optimal strategies for sustainable groundwater withdrawal rates. The present study is aimed to demonstrate the efficacy of the coupled application of simulation and optimization models in developing efficient strategies for the sustainable management of groundwater and surface water resources conjunctively in a river basin with dominant stream-aquifer interactions. The simulation model uses finite difference based numerical technique to describe the aquifer system and determine the hydraulic head and the water budget of the aquifer system under the external stresses, whereas the optimization model evolves optimal management strategies under imposed restrictions and operational constraints from a set of feasible strategic options. The developed simulation-optimization model has been applied to a real aquifer system, the Hormat-Golina valley in Ethiopia to test the applicability of the model. In this study area, the high dependency on groundwater for irrigation has placed relentless stresses on the aquifer system which may cause adverse cumulative effect in the long-run. The present study is first of its kind in the study area and aimed to evolve optimal water management strategies to meet the current and future water demands in a sustainable manner while satisfying the physical, managerial and environmental flow constraints.

2 Formulation of Simulation-Optimization Model

The formulated model consists of four components; decision variables, that can be considered as quantifiable controls in the planning and management of surface water and groundwater in an integrated manner, an objective function to measure the performance of the planning or management process, a set of constraints from diverse viewpoints that impose restrictions on the values of decision variables that can be taken by the decision or policy makers and the agencies involved in the water withdrawal and water policy regulators, and a response matrix, obtained from the groundwater flow simulation model which links up the simulation and optimization model internally in a single framework of the optimal water management model. The model is designed for the conjunctive water use in a river basin having strong hydraulic connectivity between stream and aquifer and characterized by considerable spatial variability. The schematic diagram of the conceptualized model showing various physical processes that influences hydrological variables is shown in Fig. 1. The groundwater is recharged naturally from rainfall as well as from the irrigation return flow and canal seepage as quantified through conveyance loss. The interaction between river and aquifer is simulated through subsurface flow. The model is conceptualized for the optimal utilization of groundwater and surface water for irrigation and municipal water supply while maintaining groundwater drawdown to avoid water scarcity and minimum stream flow requirement at the downstream for drought proofing and environmental or ecological purposes. The model uses deterministic optimization to provide a set of optimal stream flow diversion and distributed groundwater pumping rates based on a series of historical hydrologic data.

The developed model incorporates simulation model within the framework of the optimization model using the response matrix technique for decision making. Thereby, a groundwater flow simulation model by using MODFLOW (McDonald and Harbaugh 1988) was first

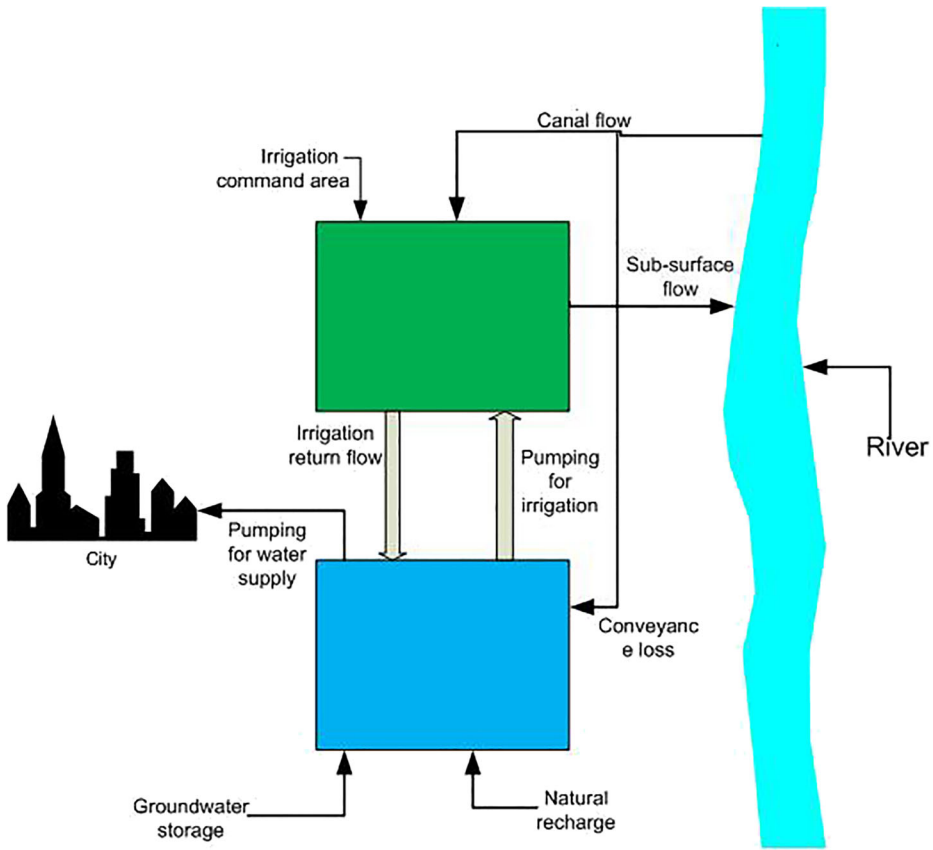


Fig. 1 Schematic diagram of conjunctive water use simulation-optimization model

constructed and calibrated to simulate the hydrological response of the Hormat-Golina valley aquifer system. The simulation model calibrated for the study area under consideration was used to develop the unit response matrices.

The optimization model is formulated with an objective to maximize the total groundwater withdrawal from pumping wells in the aquifer and water diversion from the stream with physical and managerial constraints placed on various hydrological variables. Thus, the objective of the conjunctive water use management model is to maximize the sum of total groundwater withdrawal and surface water diversion from the alluvial stream-aquifer system within a defined time horizon for irrigation and municipal water supply. The objective function can be expressed as:

$$\text{Maximize } Z = \sum_{k=1}^{N_p} \sum_{\xi=1}^{N_{pw}} (\Delta t_p)_k (Q_{gw})_{\xi,k} + \sum_{k=1}^{N_p} \sum_{l=1}^{N_R} (\Delta t_d)_k (Q_{SD})_{l,k} \quad (1)$$

Where Z is the total water supply in a planning horizon (pumpage from existing wells and diverted from a stream) (L^3); $(Q_{gw})_{\xi,k}$ is the groundwater extraction from cell ξ in time period

k (L^3/T); $(Q_{SD})_{l,k}$ is the stream diversion from reach l in time period k (L^3/T); N_{pw} is the number of groundwater pumping cells; N_R is the number of stream diversion reaches; N_{tp} is the number of time periods in a time horizon; $(\Delta t_p)_k$ is the pumping time in the k^{th} time period (for example, no. of days of groundwater pumping in the k^{th} month); $(\Delta t_d)_k$ is the diversion time in the k^{th} time period (for example, no. of days of stream diversion in the k^{th} month); k is an index for the time period (for example, $k = 1$ for January; $k = 2$ for February; $k = 3$ for March and so on); ξ is an index for the well number; and l is an index for the stream flow diversion site.

2.1 Physical and Managerial Constraints

The physical constraints describe the hydrologic relationships prevailing in the basin. It includes the response of the aquifer system and stream-aquifer restrictions under hydraulic/hydrologic stresses due to groundwater pumping and other prevailing hydrological processes. In addition to these sets of constraints, the optimal solution should also satisfy the managerial constraints that arise in meeting irrigation and water supply demands; and restrictions for environmental flow and water sustainability. These constraints have been developed for the conjunctive water use model and are presented below. Further, the constraints that none of the decision variables being negative are implied in the optimization.

2.1.1 Constraints Expressing Stream–Aquifer System Responses

To express stream-aquifer system responses, an external numerical groundwater flow model is used to estimate and compile the aquifer’s responses over time to unit stresses applied at pumping/recharge locations. These unit responses are stored in a database called a response matrix. The unit response functions are incorporated into the conjunctive water use optimization model as physical constraints. In this study, influence coefficients are used in the constraint equation to describe the hydraulic head in the aquifer and stream reach outflow. Mathematically, they can be expressed as:

$$s_{o,n}^s = \sum_{k=1}^n \left[\sum_{\xi=1}^{N_{pw}} \delta_{o,\xi,n-k+1}^h (Q_{gw})_{\xi,k} + \sum_{l=1}^{N_R} \beta_{o,l,n-k+1}^h (Q_{SD})_{l,k} \right] \tag{2}$$

$$q_{u,n}^s = \sum_{k=1}^n \left[\sum_{\xi=1}^{N_{pw}} \delta_{u,\xi,n-k+1}^s (Q_{gw})_{\xi,k} + \sum_{l=1}^{N_R} \beta_{u,l,n-k+1}^s (Q_{SD})_{l,k} \right] \tag{3}$$

Where $s_{o,n}^s$ is the groundwater head drawdown at cell \hat{o} at the end of period n (L); $\delta_{o,\xi,n-k+1}^h$ is the influence coefficient describing the effect of groundwater pumping at cell ξ resulting from a unit pumping in stress period k on the potentiometric surface elevation at cell \hat{o} by the end of n^{th} time period ($L/L^3/T$); $(Q_{gw})_{\xi,k}$ is the quantity of pumped water from ξ cell during k^{th} time period (L^3/T); $\beta_{o,l,n-k+1}^h$ is the influence coefficient describing the effect of water diversion from reservoir/stream at a location l resulting from a unit diversion in stress period

k on the potentiometric surface elevation at cell \hat{o} by the end of n^{th} time period $\left(\frac{L}{L^3/T}\right)$; $(Q_{SD})_{l,k}$ is the quantity of water diverted from reservoir/stream in reach l during k^{th} time period (L^3/T) ; $q_{u,n}^s$ is the stream flow depletion rate in reach \hat{u} at the end of time period n (L^3/T) ; $\delta_{u,\xi,n-k+1}^s$ is the influence coefficient describing the effect of groundwater pumping at cell ξ resulting from a unit pumping in stress period k on the stream outflow in reach \hat{u} at the end of n^{th} time period $\left(\frac{L}{L^3/T}\right)$; $\beta_{u,l,n-k+1}^s$ is the influence coefficient describing the effect of diverted water from the reservoir in reach l resulting from a unit diversion in the stress period k on the stream outflow at reach \hat{u} in the end of n^{th} time period $\left(\frac{L}{L^3/T}\right)$; N_{pw} is the number of groundwater pumping cells; and N_R is the number of stream diversion reaches. The change of head at \hat{o} at the end of time period k due to the management strategy is given by $h_{o,k+1} - h_{o,k}$; and Q_{gw} is taken positive for pumping. Q_{gw} is a general source/sink term with $Q_{gw} > 0$ for pumping and $Q_{gw} < 0$ for recharge.

2.1.2 Constraints Expressing Environmental and Sustainability Restrictions

The environmental and sustainability restrictions are incorporated into the set of constraints as bounds on the decision variables. The environmental restriction is incorporated as an upper bound on the stream flow diversion from the river so that a minimum discharge close to the environmental flow is maintained at the downstream of the diversion site located on the river. This is done to allow the river to do the ecological services. The sustainability restriction is incorporated into the set of constraints as an upper bound on the groundwater pumping so that the groundwater level does not decline at an alarming rate and result into a drought condition or becomes unavailable on a long term basis for utilization.

Thus, the lower and upper bounds on groundwater pumping and stream diversion at a specific location must be satisfied at every point in the system where withdrawals from the wells and diversions from the stream reaches are made. This set of constraints also implies that diversions for water supply/irrigation will not be greater than the natural flow. In no case, the upper bound on the groundwater pumping from a well can be more than the maximum capacity of individual pumping well. Similarly, the upper bounds on the stream flow diversion cannot be more than the full or design capacity of the canal. Further, the groundwater pumping from the individual wells and the diverted canal water from the stream should be positive. Mathematically, it can be described as follows:

$$0 \leq (Q_{gw})_{\xi,k} \leq (Q_{gw}^{up})_{\xi,k} \quad \begin{matrix} \xi = 1, \dots, N_{pw} \\ k = 1, \dots, N_{tp} \end{matrix} \tag{4}$$

$$0 \leq (Q_{SD})_{l,k} \leq (Q_{SD}^{up})_{l,k} \quad \begin{matrix} l = 1, \dots, N_R \\ k = 1, \dots, N_{tp} \end{matrix} \tag{5}$$

Where $(Q_{gw}^{up})_{\xi,k}$ is the upper bound on the groundwater pumping from the individual wells and $(Q_{SD}^{up})_{l,k}$ is the upper bound on the stream flow diversion.

2.1.3 Water Demand Constraints

The water withdrawn from the groundwater and diverted from the streams is used for a number of purposes in the region. Mainly, it is used to irrigate agricultural fields and for municipal water supply of the nearby town. Therefore, the amount of water which is diverted from the streams and pumped from the aquifer should satisfy all these water demands. The constraints for irrigation water demand can be expressed as:

$$\sum_{\xi \in \Omega_{is}}^{N_{pw}} (Q_{gw})_{\xi,k}^{is} + \sum_{l \in \mathcal{L}_j}^{N_R} (Q_{SD})_{l,k}^{is} \geq (Q_D)_k^{is} \quad (Q_{SD})_{l,k}^{ms} \geq (Q_D)_k^{ms} \quad k = 1, \dots, N_{tp} \quad (6)$$

$$\Omega_{ms} = \left\{ \xi_1^{ms}, \xi_2^{ms}, \xi_3^{ms}, \dots, \xi_{N_{pw}}^{ms} \right\} \text{ and } m_s = \left\{ l_1^{ms}, l_2^{ms}, l_3^{ms}, \dots, l_{N_R}^{ms} \right\}$$

Where $(Q_D)_k^{ms}$ is the municipal water supply demand at time period k, and Ω_{ms} and m_s are, respectively, set of all groundwater pumping wells and stream diversion reach locations in a basin from which water is supplied for the municipal use.

2.2 Generation of Response Matrices

In the response matrix technique, analytical or numerical model is used to generate response function which is used to estimate and compile the aquifer response per unit pumping at a location over the planning period (Barlow et al. 2003; Sedki and Ouaza 2011). In the present study, a numerical groundwater flow simulation model as discussed earlier was used to generate the unit response matrix. By using a response matrix, the drawdown is predicted at the pumping well site and at the surrounding wells as a result of pumping from the individual wells. In fact, this is a prerequisite for the proper planning and sustainable management of surface and groundwater resources in the stream-aquifer system. The groundwater flow equation describing the transient flow through a non-homogeneous anisotropic aquifer in the numerical model can be represented as (McDonald and Harbaugh 1988):

$$\frac{\partial}{\partial x} \left(k_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(k_{zz} \frac{\partial h}{\partial z} \right) = ss \frac{\partial h}{\partial t} + W \quad (8)$$

Where K_{xx} , K_{yy} and K_{zz} denote hydraulic conductivity along x, y and z coordinate axes, and are assumed to be parallel to the major axes of hydraulic conductivity; h, W, S_s and t denote potentiometric head, volumetric flux per unit volume representing sources and/or sinks, specific storage of the porous material, and time, respectively.

The numerical simulation model used for the generation of unit response matrix was designed to simulate a dynamic equilibrium over a 1-year cycle of average monthly hydrologic conditions. This assumption was made as the cycle of average monthly hydrologic conditions repeats from one year to the next year. The unit response matrix represents the response of the aquifer when one unit of pumping is applied at a location. The transient response function in discrete form may be written as (Maddock 1972):

$$s_{o,n}^- = \sum_{\xi=1}^{N_{pw}} \sum_{k=1}^n \beta_{o,\xi,n-k+1} (Q_{gw})_{\xi,k} \quad (9)$$

Where $\widehat{s}_{o,n}$ is the drawdown at \widehat{o}^{th} cell at the end of k^{th} time period (L); the unit response function $\widehat{\beta}_{o,\xi,n-k+1}$ is the change in the drawdown (unit drawdown) in the \widehat{o}^{th} cell at the end of k^{th} time period due to a unit pumpage from the ξ^{th} cell during the k^{th} time period (T/L^2);

$(Q_{gw})_{\xi,k}$ is the quantity of water pumped from the ξ^{th} cell during the k^{th} time period (L^3/T); and N_{pw} is the number of pumping cells. Eq. (9) as presented applies to a case of an isolated aquifer. In the present case, the model is developed for the stream-aquifer system, and thus the groundwater withdrawal has an effect on the stream depletion and the diversion of the stream also influences the drawdown in the aquifer in this case.

The stream-aquifer interaction is established through the leakage to or from the aquifer to the river and vice versa (Belaineh et al. 1999; Barlow et al. 2003). This model uses a technique referred as the discrete kernel approach in groundwater modeling literature. The discrete kernel formulation for the average cell drawdown in terms of the response resulting from river leakage and multiple pumping wells for the combined stream-aquifer system can be algebraically expressed as:

$$S_{o,n} = \sum_{\xi=1}^{N_{pw}} \sum_{k=1}^n \widehat{\beta}_{o,\xi,n-k+1} (Q_{gw})_{\xi,k} + \sum_{K=1}^{N_R} \sum_{k=1}^n \widehat{\beta}_{o,l,n-k+1} h(QSD)_{l,k} \tag{10}$$

Where $\widehat{s}_{o,n}$ is the drawdown at \widehat{o}^{th} cell at the end of k^{th} time period (L) due to the combined effect of groundwater pumping and stream flow diversion in a stream-aquifer system. The unit response function $\widehat{\beta}_{o,l,n-k+1}^h$ is the change in drawdown (unit drawdown) in the \widehat{o}^{th} cell at the end of k^{th} time period due to unit water diversion from the stream at a stream reach location l during the k^{th} time period (T/L^2); $(Q_{SD})_{l,k}$ is the continuous leakage function from a stream reach l during the k^{th} time period (L^3/T); and N_R is the number of stream reach cells.

The stream flow depletion response coefficient ($\widehat{\delta}_{u,\xi,n-k+1}^s$) at the stream flow constraint site is defined in terms of groundwater pumping (Belaineh et al. 1999; Barlow et al. 2003), and its value can be calculated by using numerical model:

$$\widehat{\delta}_{u,\xi,n-k+1}^s = \frac{q_{u,n}^*}{(Q_{gw})_{\xi,k}} \tag{11}$$

Where $q_{u,n}^*$ is the stream flow depletion at a stream reach site \widehat{u} at the end of k^{th} time period in response to a unit pumping $(Q_{gw})_{\xi,k}$ at well ξ . The total stream flow depletion at each constraint site in each month can be calculated by the summation of the individual stream flow depletions caused by each well. This summation is written for each stream reach site \widehat{u} at the end of k^{th} time period as:

$$q_{u,n}^s = \sum_{\xi=1}^{N_{pw}} \sum_{k=1}^n \widehat{\delta}_{u,\xi,n-k+1}^s (Q_{gw})_{\xi,k} \tag{12}$$

Where $q_{u,n}^s$ is the total stream flow depletion at stream reach constraint site \widehat{u} .

The transient response functions $\widehat{\beta}_{o,\xi,n-k+1}$ and $\widehat{\delta}_{u,\xi,n-k+1}^s$ for drawdown and stream flow depletion were generated from the repeated runs of the transient simulation model for a planning horizon of one year with monthly time step by subjecting each of the pumping well to a discharge of 1 l/s for the first pumping period and zero unit for the rest of the periods.

2.3 Estimation of Irrigation Water Demand

In the present study, a computer program known as CROPWAT 8.0 has been used for the estimation of irrigation water demand. CROPWAT 8.0 uses the FAO-56 Penman-Monteith method to estimate the reference evapotranspiration (ET_o) based on the meteorological data (Smith 1992). The Penman-Monteith method has advantages over many other methods because it can be used globally without local calibration and it has well documented equations tested extensively with a variety of lysimeters (Doorenbos and Pruitt 1977). The irrigation water requirements for various crops (ET_{crop}) are estimated by the following expression:

$$ET_{crop} = K_c * ET_o \quad (13)$$

Where K_c is the crop coefficient, and ET_o is the reference evapotranspiration.

3 Description of the Study Area

The study area considered for the application of the developed conjunctive water use model is located in the northern part of Ethiopia. It is geographically situated in between $11^{\circ} 59' 00''$ to $12^{\circ} 09' 00''$ north latitude and $39^{\circ} 36' 00''$ to $39^{\circ} 46' 00''$ east longitudes (Fig. 2). It covers a total area of 145 km² and is mostly plain area with flat topography having an elevation ranging from 1640 m to 1339 m (a.m.s.l). The Hormat-Golina valley plain area is characterized as a semi-arid climate and the average annual temperature ranges from 17.5 °C to 26 °C. The mean annual rainfall in the study area is 798.4 mm.

3.1 Hydrogeological Setting

The main aquifer in the valley is unconsolidated sediment. As evident from the geological log of boreholes, the alluvial deposits are composed of intercalating layers of gravel, gravely sands, silty sands, clay, and silty clay with increasing coarser material towards the top. The hydraulic conductivity of the aquifer was estimated from the aquifer test data of 38 boreholes drilled in the study area. The aquifer hydraulic conductivity ranges from 0.08 m/day to 44.9 m/day. The transmissivity of the aquifer was calculated by multiplying the hydraulic conductivity and the aquifer saturated thickness.

The recharges from rainfall and subsurface seepage from the western volcanic aquifer to the alluvial valley are considered as 52.00 mm/year and 34.38 MCM/year, respectively (Mamo 2007). The recharge from rainfall was applied to the top active cells of the model as a specified flux to the upper most active layer in the model. The rate of leakage between the stream and the aquifer was estimated using the head difference between the stream and the aquifer.

3.2 Irrigation Development and Cropping Pattern

The low lying valley part of the Kobo watershed has been known as the most drought prone region in Ethiopia. As a result, the traditional irrigation system has been practiced since long years ago as a supplement to rainfall. The irrigation is practiced by diverting the water from the

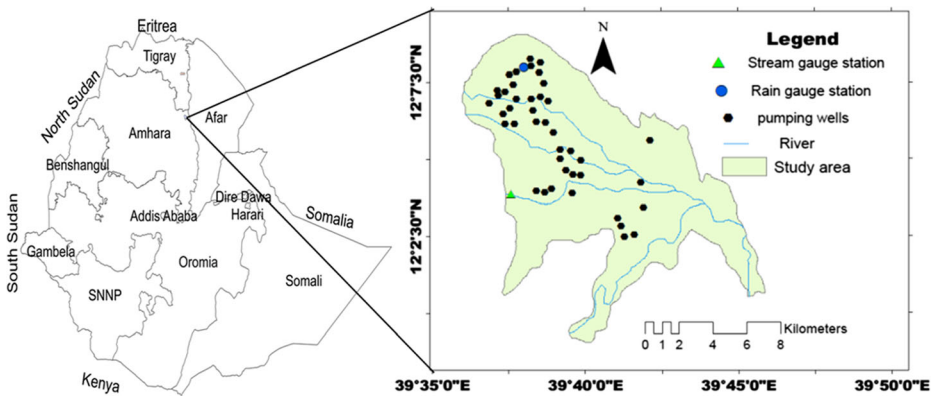


Fig. 2 Location map of the study area

nearby rivers of Alawuha and Golina. However, the modern irrigation has been given emphasis since 1999 in the Kobo valley due to scarcity of rainfall in the area (Co-SAERAR, unpublished report, 1999); and thereby 17,000 ha of land is being proposed and start to practiced for irrigation mostly from groundwater sources.

In the area, the cropping pattern is dominated by annual food crops, the cereals (sorghum, maize and teff), pulses (chick pea, haricot bean, mug bean), vegetables (onion, tomato, pepper and sweet potato) and oil crops (sesame and groundnut).

4 Results and Discussion

4.1 Numerical Model Design

The modeled area contains the entire alluvial aquifer system of the Hormat-Golina basin for which the groundwater flow modeling has been carried out using a grid cell size of 90.47 m x 92.38 m. The aquifer is discretized vertically in one layer depending upon the hydrogeological stratification of the aquifer. The vertical aquifer thickness corresponds to the alluvial sediment and ranges from around 50 m near to the water divide to 270 m in the downstream area with an average thickness of 160 m. The top boundary layer of the unconfined aquifer is water level of the aquifer. The bottom of alluvial sediment was considered as the bottom boundary.

No flow boundaries are assigned to the model at the contact areas of alluvial sediment and surrounding mountainous strata except for the fractured zones and stream bed boundaries, assuming that no groundwater enters into the modeled area from the ridges. The head dependent flux boundary is assumed at the localities of the fracture zones of the surrounding ridges along valley channels and gullies. The head values of general head boundaries were interpolated based on the measured water levels in the nearby monitoring wells. The boundary conductance values were initially based on the hydraulic conductivity of the aquifer and the necessary adjustment was made during the model calibration procedure. The top boundary of the model was simulated as specified flux boundary cells to allow recharge from the rainfall. The Golina stream was simulated with stream (STR) module.

4.2 Calibration of the Simulation Model

The groundwater flow model was calibrated for the study area based on the water level measurement of 34 wells. The model calibration was carried out using trial and error method of adjusting initial estimates of aquifer properties, namely, hydraulic conductivity and stream bed conductivity to get the best match between the simulated and the measured water levels. It is the most preferred calibration technique by practitioners (Anderson and Woessner 1992; Kerebih and Keshari 2016).

The values of various hydraulic parameters were repeatedly adjusted till the simulated and the observed heads are matched. The calibrated values of river bed conductivity and specific yield are 3.1 m/day and 0.2, respectively. The observed and the calculated hydraulic head values are presented on 1:1 line, with 95 % confidence interval as shown in Fig. 3. It is evident from this figure that the calculated and the observed values are in good agreement.

4.3 Irrigation Water Demand

Crops grown in the command area are categorized into dry season and wet season crops. The monthly irrigation water demand for the dry and wet season crops were estimated by using CROPWAT model is shown in the Fig. 4. The total irrigation water demand comes out to be, respectively, 8.28 Mm³ and 4.70 Mm³ for the dry and wet season crops in the command area.

4.4 Optimal Water Resources Management

The developed model was applied to the study area to determine the optimal strategies for water resources management in the Hormat-Golina valley stream-aquifer system. The optimization model was run by incorporating the generated transient response functions from the simulation model to estimate the optimal pumping rates of 43 existing wells located in the modeled area (Fig. 2). The response matrix coefficients of the transient response functions were generated using the procedure as discussed earlier. The aquifer response equations are incorporated as equality constraints in the coupled simulation-optimization model to evolve conjunctive use management plans of surface and groundwater for sustainable development of water resources in the river basin. Thus, the simulation and optimization models are linked internally through a response matrix approach. These constraints are expressed in terms of decision variables and the drawdown resulting from the unit hydraulic stresses, termed as the response matrix coefficients. The hydraulic stresses may be groundwater pumping or stream flow diversion, or a combination of them. The drawdown response matrix coefficients of these equality constraints were generated from the groundwater flow simulation model, MODFLOW. During the optimization search process, this simulation model is linked with the optimization model internally through the computed response matrix to predict the optimal pumping rates from the existing wells. The optimization model was solved by using MATLAB programming software. The computer codes were written in MATLAB using optimization functions or M-files were written using optimization toolbox to solve the formulated optimization problem for the study area under consideration. For more description on the optimization toolbox, readers may refer Coleman et al. (1999).

A planning horizon of one year with monthly pumping time step was considered for the application of the developed model. The drawdowns at 43 pumping wells and stream flow depletion at one control point were monitored over the 12 months of pumping period. The

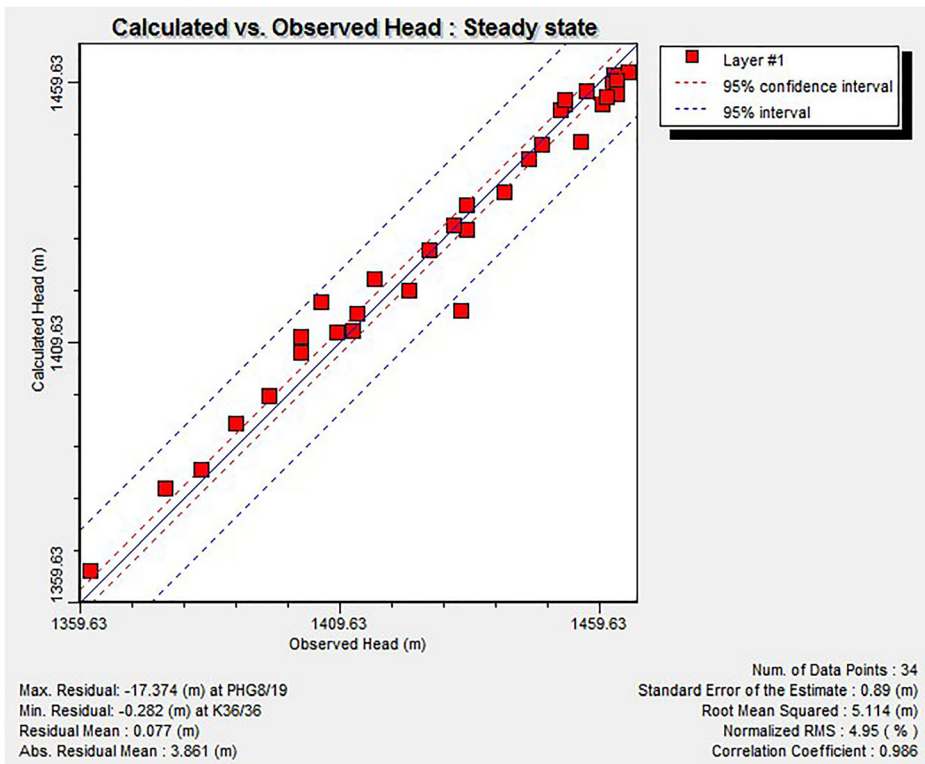


Fig. 3 Comparison of simulated and observed heads for steady state flow simulation

drawdown response functions with a total of 23,232 from these 43 pumping well sites and one stream flow control point were generated from the groundwater flow simulation model and were assembled to form the drawdown and stream depletion response matrices. The maximum and the minimum capacities of individual pumping wells, the permissible drawdown, the minimum stream flow depletion at constraint site, and the irrigation water demand are the inputs of the optimization model. The minimum pumping rate value should be positive (i.e.

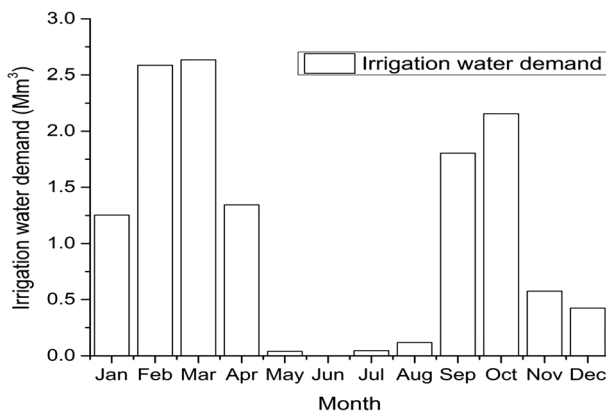


Fig. 4 Monthly irrigation water demand

greater than zero), whereas the maximum pumping rate of individual wells was determined by considering the maximum pumping capacity of each well (Table 1). The pumping from individual wells should not exceed their allowable limit.

The maximum drawdown usually occurs at the pumping well sites, and it reduces towards the peripheral area of the influence. In the model, the drawdowns were constrained that the drawdown should not exceed the maximum permissible value at these localities. In the present study, the drawdown values of individual wells during the dry seasons were considered as the maximum allowable drawdown as shown in Table 2. The optimal withdrawal strategies were determined for one year under two different scenarios representing with and without stream flow depletion constraint.

4.4.1 Optimal Groundwater Pumpage Without Stream Flow Depletion Constraint

The first scenario (Scenario I) represents the optimal groundwater pumping schedules from the existing wells without imposing any restriction on the stream flow depletion. In this scenario, the objective function has 516 decision variables (pumping rates of wells), 516 drawdown constraints (43 sites with a monthly time step, $43 \times 12 = 516$), 12 demand constraints (monthly basis) in one year planning period, and 516 lower and upper bounds representing environmental and sustainability constraints, which are described by Eqs. 2, 4, 5 and 6. The drawdown response coefficients were generated from the simulation model runs for the unit stresses applied at the pumping well location successively in each pumping wells.

It was observed that the model solution is infeasible when the optimization model was run to meet the monthly water demands with the prescribed maximum drawdown values. This indicates that the drawdown must be larger than the permissible limit which was recorded during the dry periods. Hence, to make the model converge and obtain optimal pumping rates from the existing wells in the well field, adjustments have been made on the maximum drawdown constraints during the dry periods. Subsequently, the optimization model was executed with several runs to obtain the best optimal pumping rates with reasonable drawdown.

Results obtained from the developed model for monthly optimal pumping from 43 existing wells in the study area are shown in Fig. 5. It is evident from Fig. 5 that the value of optimal pumpage is highest in March (2.64 Mm³) and February (2.64 Mm³), and it may be attributed to the need for relatively high irrigation water demand. Since these months are dry, the crop water

Table 1 Maximum pumping capacity of wells in Hornmat-Golina valley

Well	Q _{max} (m ³ /s)	Well	Q _{max} (m ³ /s)	Well	Q _{max} (m ³ /s)	Well	Q _{max} (m ³ /s)
HG1	0.05	HG4	0.05	PHG5	0.05	THG1	0.04
HG10	0.05	HG5	0.05	PHG6	0.05	THG2	0.05
HG11	0.05	HG6	0.05	PHG7	0.05	THG3	0.05
HG12	0.05	HG7	0.05	PHG8	0.045	THG4	0.05
HG13	0.05	HG8	0.028	PHG9	0.05	TK7	0.05
HG14	0.05	HG9	0.01	PK1	0.05	TW1	0.038
HG16	0.025	PHG1	0.05	PK2	0.05	Zel1	0.05
HG17	0.05	PHG10	0.05	PK6	0.04	Zel2	0.05
HG18	0.05	PHG2	0.045	PK7	0.04	K33	0.04
HG2	0.05	PHG3	0.05	PK8	0.05	K34	0.04
HG3	0.02	PHG4	0.045	PK9	0.05		

Table 2 Maximum permissible drawdown (S_{\max}) values in Hormat-Golina valley

Site	S_{\max}	Site	S_{\max}	Site	S_{\max}	Site	S_{\max}
HG1	6.5	HG4	5.16	PHG5	2.99	THG1	3.21
HG10	4.75	HG5	2.26	PHG6	2.44	THG2	1.46
HG11	4.75	HG6	7.38	PHG7	3.49	THG3	1.6
HG12	5.48	HG7	9.14	PHG8	1.56	THG4	2
HG13	5.34	HG8	4.47	PHG9	1.1	TK7	7.91
HG14	4.58	HG9	3.42	PK1	6.5	TW1	11
HG16	1.85	PHG1	4.34	PK2	8.79	ZEL1	5
HG17	2.03	PHG10	0.7	PK6	4.74	ZEL2	4.35
HG18	1.99	PHG2	3.5	PK7	5.51	K33	5.15
HG2	6.22	PHG3	5.11	PK8	5.15	K34	9.01
HG3	4.01	PHG4	5.28	PK9	5.13		

requirements of various crops are met from the irrigation water. The optimal pumping is lowest in July (1.4Mm³) and August (1.3 Mm³). Hence, rain water is mostly used to grow crops in these rainy seasons and the irrigation water is used as a supplement. In June, crops are not grown in the command area. Therefore, the irrigation water demand is zero, and the pumping of groundwater is null. Results obtained reveal that the depletion of groundwater level in the aquifer is generally observed during dry seasons as a result of high groundwater pumpage.

4.4.2 Optimal Groundwater Pumpage with Stream Flow Depletion Constraint

The second scenario (Scenario II) represents the optimal groundwater pumping schedules from the existing wells with restrictions imposed on the stream flow depletion. In this scenario, the number of decision variables in the objective function is same as that in scenario I (516), because the second scenario differs from the first scenario only due to the addition of stream flow depletion constraints at the stream outlet control point. Hence, it has 516 drawdown constraints (at 43 sites with 12 months), 12 monthly stream flow depletion constraints at one control point, 12 monthly demand constraints, and 516 each of lower and upper bounds representing environmental and sustainability constraints, which are described by Eqs. 2–7 as discussed earlier. In this scenario, the management model was run to meet the monthly water demands with the same prescribed maximum drawdown values as used in the first scenario and the permissible stream flow depletion in each month. The stream flow depletion constraint described by Eq. 5 was set at the downgradient end of the Golina main stream outlet point. The minimum monthly permissible stream flow depletions at the stream flow constraint site were set by trial and error following an iterative procedure. The first trial of the stream flow depletion was set by multiplying the optimal pumping obtained during scenario I with per unit pumping stream flow depletion coefficient, which was estimated by using the simulation model output in the excel spreadsheet. Then after, several iterations with a 2.5 % reduction interval from the calculated value were made to find out the best optimal pumping with the least stream flow depletion until the model converges. Finally, the obtained monthly stream flow depletions as shown in Fig. 6 were set as the specified least amount. It was observed that the model could not converge with the lesser values of these specified minimum monthly stream flow depletion.

The maximum stream flow depletions in the dry months, at the end of February, March, April, May, September and October were constrained to be less than or equal to 3–15 % of the

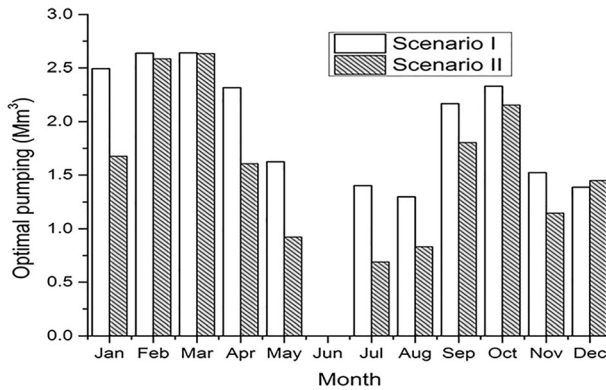


Fig. 5 Monthly optimal groundwater pumping

stream flow rates that occur in the absence of any groundwater withdrawals and stream flow diversion. The specified stream flow depletion amounts for these months were relatively high because they generally coincide with the time of year when the irrigation water requirements (demand) are largest and the stream flows are simultaneously lowest in these months. Relatively higher stream flow depletion is specified in March since the irrigation demand is relatively high, and the minimum specified stream flow depletion is in August.

The optimization model was run successively and monthly optimal pumpage from individual wells was determined. In scenario II, a decrease of the optimal pumping rate is observed particularly in some of the wells located nearby to the stream boundary due to the control of stream flow depletion caused by groundwater pumping. It is observed that the total annual optimal pumping in scenario II decreases by 19.75 % as compared to the optimal pumping in scenario I, which indicates that the groundwater pumping from the aquifer has a significant effect on the stream flow depletion.

The monthly variation of optimal total pumping from various wells in the study area for scenario II is shown along with that in scenario I in Fig. 6. It is evident from this figure that the maximum optimal pumping is observed in February (2.59 Mm³) and March (2.63 Mm³) in scenario II, which show a decrease by 1.89 % and 0.38 %, respectively, from the optimal values in the scenario I. The post optimal pumping was carried out by using the optimal pumping rates as input to the simulation model again. The optimal pumping rate of each well

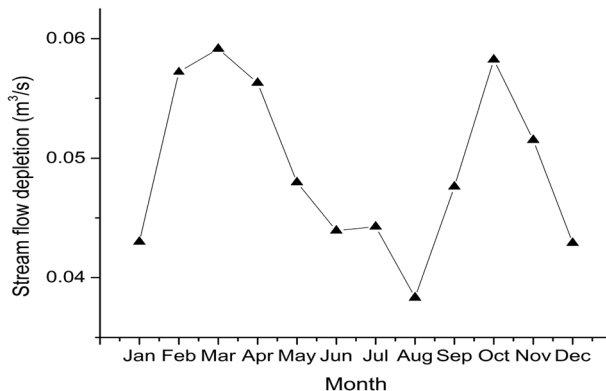


Fig. 6 Monthly stream flow depletion

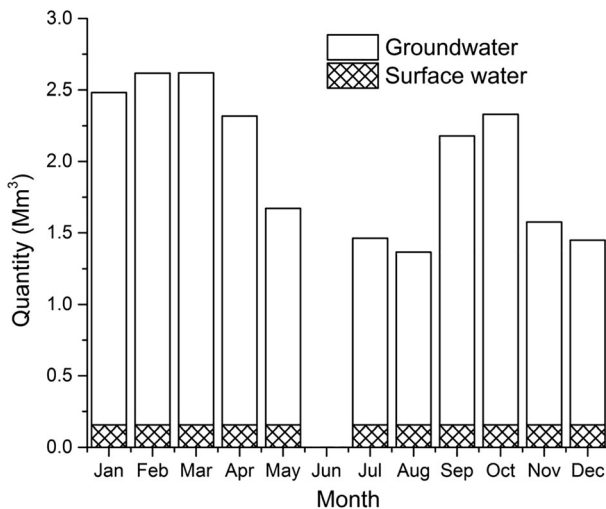


Fig. 7 Optimal groundwater pumping and surface water diversion

was calculated from the coupled simulation-optimization model by linking drawdown response generated from the simulation model of each well per unit pumping. The optimal pumping rate of each well found from the optimization model was used as an input to the simulation model and then the simulation model was run to simulate the groundwater levels. The average maximum drawdown obtained from the simulation model is 5.7 m. The simulated drawdown of each well obtained from the simulation model was cross-checked with the specified drawdown constraint value used in the optimization model. The difference between the maximum simulated drawdown and the specified maximum drawdown constraint value varies from 0.09 to 2.5 m in most of the wells.

4.4.3 Conjunctive Use Scenarios of Groundwater and Surface Water

To obtain the optimal conjunctive use scenarios of groundwater and surface water, the drawdown coefficients per unit stream flow diversion at the stream flow diversion constraint site were generated and compiled together with the drawdown coefficients per unit pumping obtained from the simulation model. It is observed that the drawdown coefficients per unit stream flow diversion at the stream flow diversion constraint site are insignificant, and it is zero in most of the wells because the groundwater flow is from the well to the stream and diversion from the stream has not that much significant effect on the aquifer drawdown. At some of the drawdown constraint sites which are located near the stream boundary, the drawdown values per unit stream diversion are small and this has a marginal effect on the cumulative drawdown. By compiling those drawdown coefficients caused by per unit pumping and stream flow diversion at each constraint site, the optimization model was run to maximize both the groundwater pumping and stream flow diversions incorporating all the constraints which are described by Eqs. 2, 4, 5 and 6. The maximum capacity of stream flow diversion (canal flow) was set based on the current canal capacity condition (60 l/s).

Results show that the optimal canal flow is at its full capacity (60 l/s) and its contribution is only 7.9 % of the optimal value of total conjunctive water use as evident from Fig. 7. It is because of the limitation of the canal capacity, and the remaining 92.1 % is from the

groundwater pumping. The total optimal groundwater pumping obtained from this conjunctive use optimization model reduces by 0.43 % as compared to the total optimal pumping which was obtained when only the groundwater source is used. The results obtained for the integrated use of surface water and groundwater show an average reduction of maximum groundwater drawdown by 0.5 m. Hence, the conjunctive optimal use of surface water and groundwater will play a great role in the reduction of groundwater depletion. This will be more effective when surface water is used when it is plenty or sufficiently available, and it will facilitate to preserve groundwater to be utilized in case of deficiency.

5 Conclusions

Incorporating both surface water and groundwater for managing water resources on a basin scale is very crucial to meet the upcoming water challenges in a sustainable manner. In this study, a coupled simulation-optimization based conjunctive water use model has been developed for the sustainable development of groundwater and surface water. It incorporates stream-aquifer interactions and operational and ecological constraints. The simulation model is linked internally with the optimization model using a response matrix approach, and the aquifer response is obtained from a three dimensional numerical groundwater model known as MODFLOW. The optimization model is solved using MATLAB. The developed model was successfully applied to the Hormat-Golina valley alluvial stream-aquifer system, Ethiopia. Optimal solutions were obtained for the conjunctive use of groundwater and river water in meeting municipal water supply and irrigation water demand while ensuring long term sustainability.

The optimal solutions of the simulation-optimization model were obtained for two scenarios representing with and without stream flow depletion constraint. The optimal pumpage of the 43 existing wells obtained from the model was found to be highest in February and March months for both scenarios, and most of the pumping wells operate at their full capacity during these months. The maximum allowable groundwater withdrawals are estimated as 2.64 Mm³ and 2.64 Mm³ in the first scenario and 2.59 Mm³ and 2.63 Mm³ in the second scenario in the months of February and March, respectively. The minimum allowable groundwater withdrawals are estimated as 1.3 Mm³ in August in the first scenario and 0.69 Mm³ in July in the second scenario. The total annual optimal pumping in the scenario II decreases by 19.75 % as compared to that in the scenario I because of the decrease in the optimal pumping rate in some of the wells, particularly located at the stream boundary due to the regulation of minimum stream flow depletion. Because of the limited canal capacity, the contribution of groundwater in optimal conjunctive water use is very high, being equal to 92 %. It is observed that the groundwater pumping from the alluvial aquifer has a significant effect on the stream flow depletion. The optimal conjunctive water use of surface water and groundwater plays a great role in preventing groundwater depletion caused by the extensive pumping of groundwater for irrigation and municipal water supply.

The study reveals that the findings obtained from the coupled simulation-optimization model would be useful to the planners and decision makers in order to ensure sustainable water resources development in the basin. The developed model and the findings obtained in this study are generic and would be of significant interest worldwide in decision making for sustainable water management. Although the application is shown for an Ethiopian aquifer system, the developed model and the approach presented in this study could be applied or replicated successfully in other regions.

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Data Availability Some or all data that support the findings are available from the corresponding author upon reasonable request.

Declarations

Ethical Approval The manuscript is original and has not been submitted elsewhere for the consideration. Results are presented clearly, honestly, and without fabrication, falsification or inappropriate data manipulation. No data, text, or theories by others are presented.

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Affiliations

Mulu Sewinet Kerebih¹ · Ashok K. Keshari²

Ashok K. Keshari
akeshari@hotmail.com; akeshari@civil.iitd.ac.in

¹ Department of Hydraulic Engineering, Debre Markos University, Debre Markos 269, Ethiopia

² Department of Civil Engineering, Indian Institute of Technology Delhi, Hauz Khas, New Delhi 110016, India