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Enhancing smallholder agricultural production through sustainable use of shallow groundwater in the Borkena catchment, Awash River Basin, Ethiopia

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ABSTRACT

With increasing shallow groundwater use for agricultural purposes, understanding the spatiotemporal variability in recharge rates, storage capacity, and its interaction with surface waters becomes crucial for its sustainable management. An integrated SWAT–MODFLOW model is developed to assess shallow groundwater availability in the Borkena catchment. The model is calibrated using streamflow and static groundwater level data. Results show that groundwater recharge in the catchment is 85 mm/a, representing 11% of the mean annual rainfall. Shallow groundwater resources exist across nearly 42% of the Borkena catchment. The percentage of shallow groundwater withdrawal to groundwater recharge is very low (0.1%), signifying the potential for increased shallow groundwater development. However, caution must be taken as its uncontrolled expansion may result in a high risk of depletion. This integrated modeling is one of the few efforts conducted to provide important information regarding shallow groundwater potential in the Borkena catchment, which is essential for the resilience of small-scale producers in the continued growing water demand and climate change.

Key words: Awash River Basin, Borkena catchment, shallow groundwater storage, SWAT–MODFLOW, water budget

HIGHLIGHTS

- An integrated SWAT–MODFLOW model for the Borkena catchment was developed.
- At least 650 mm of annual rainfall is necessary for groundwater recharge to occur in the Borkena catchment.
- Shallow groundwater resources cover nearly 42% of the Borkena catchment area.
- Increasing the use of shallow groundwater resources has the potential to bring more land under irrigation.

1. INTRODUCTION

Groundwater plays a crucial role in global water supply and sustaining livelihoods. It accounts for 43% of irrigation (Siebert *et al.* 2010) and 50% of worldwide drinking water use (Smith *et al.* 2016). It is also important for securing the biodiversity of ecosystems. A major advantage of groundwater as a source of water supply arises from the buffering effect of aquifers to climatic variability and change in contrast to the much more rapid response of surface waters (World Bank 2000; Shah 2020). Furthermore, the scale of groundwater development at the level of individual farmers or small collective groups has offered greater flexibility in irrigation scheduling and much simpler distribution systems, resulting in higher crop yields and irrigation water productivity (World Bank 2000). Compared to communal large irrigation schemes, shallow groundwater irrigation is believed to be more attractive to farmers due to the individual modes of uptake and operation (Villholth 2013). Given the growing dependence on this resource, its sustainable management is becoming more important.

Groundwater from shallow aquifers (<30 m) has transformed irrigation in many poor rural communities (e.g., producing higher-value crops) (Curry & Seaber 1990). These aquifers, accessible through shallow or hand-dug wells, are often unconfined and recharge quickly. They serve as an important rural water supply source, support small-scale irrigation, maintain streamflow during dry periods, and sustain wetland and riparian ecosystems (Dillon & Simmers 1998). In India, the exploitation of shallow hard rock aquifers has resulted in a boom in irrigation and agriculture (Fishman *et al.* 2011). Similarly, in Bangladesh, the rapid expansion of groundwater irrigation due to government policies supporting low-lift power pumps and shallow and deep tube wells has radically transformed the production of dry-season rice and substantially contributed to food security (Hossain 2009).

In Ethiopia, the use of shallow groundwater for irrigation is gaining attention from the government and farmers. The Ethiopian Agricultural Transformation Agency (ATA) mapped shallow groundwater in parts of three regional states in Ethiopia, encompassing a total area of 38,253 km^2 (Gachet *et al.* 2014). Additional estimates of shallow groundwater in the Tana-Beles and Taramber-Maychew basins cover 27,080 km^2 (83.5% of total area) and 9,070 km^2 (69.8% of total area), respectively. According to ATA (2023), the shallow groundwater resources distibuted across Ethiopia have the potenial to irrigate nearly 1.2 million hectares of land at the household levels. While shallow groundwater has huge irrigation potential, specific information on their geographic availability is limited, as is the capacity to develop them as irrigation sources (ATA 2023).

This study considers the Awash River basin, an important River basin in Ethiopia that supports the national economy by utilizing water resources for agriculture, agro-industries, and factories (MoWE 2019). The basin is characterized by complex hydro-climatological conditions, a variety of water users, and intricate water governance (Taye *et al.* 2018). In addition to large-scale state farms, most of the basin's population can be categorized as small-scale agricultural producers (SSPs) who are dependent on rain-fed agriculture. Multiple environmental, social, and economic drivers exacerbate the vulnerability of SSPs to changes in climatic and other anthropogenic conditions. Approaches that can avert localized water shortages, improve agricultural productivity, and reduce the impacts of rainfall variability will be crucial to SSPs resilience to the changing climate. With this background, the potential of shallow groundwater is explored, using the Borkena catchment as a case study. Among several approaches used to enhance smallholder agricultural production through shallow groundwater resources such as (1) shallow groundwater availability assessment in space and time, (2) adopting efficient irrigation practices, (3) crop selection, and (4) empowering smallholder farmers to utilize shallow groundwater effectively, this study focused on resource base assessment.

Scientific evidence supporting the availability of shallow groundwater in the Borkena catchment remains scarce. While some studies, e.g., Azeref & Bushira (2020) and Gobezie *et al.*(2023), have estimated recharge rates, they have not adequately quantified spatial-temporal rates, spatiotemporal water storage variations, or safe recharge percentages for sustainable utilization. Addressing these gaps is essential for effective water resources planning in the catchment and supporting SSPs. To this end, an integrated modeling approach was developed to quantify shallow groundwater availability in the Borkena catchment. This study responds to the following research questions:

1. How much shallow groundwater is available that can support irrigation for small-scale producers?
2. Where is shallow groundwater found in Borkena catchment?

2. STUDY AREA

The Borkena catchment is the sub-basins of Awash River Basin, with a catchment area of 3,200 km^2 (Figure 1). It is home to an estimated 1 million people. The catchment elevation ranges from 553 to 3,500 m above mean sea level (m, amsl). The average catchment slope is 21%. The mean annual rainfall is 920 mm. The annual rainfall ranges from 505 to 1,095 mm and shows strong inter-annual variability. The mean temperature is 23 °C. The potential annual evapotranspiration is 2,480 mm. The long-term mean annual streamflow [1997–2002] at the Borkena swamp outlet gauging station is 13.4 m^3/s (422 million cubic meters per annum), and approximately 49% of the annual flow occurs in August. Leptosols are the dominant soil type, covering 72% of the catchment area. The dominant soil texture is clay, covering 69% of the catchment area. Based on a land use/land cover map produced using a Landsat remote sensing image of 2000, the Borkena catchment is covered by cropland (42%), forest and trees (26%), shrubland (17%), grassland (9%) and other land cover types such as built-up area, bare land, and water bodies together cover only 6% of the catchment area.

Geologically, the Tarmaber Basalt (Tarmaber Megeze Formation) and Ashangi Basalt cover 35 and 31% of the Borkena catchment, respectively. In most of the study area, Tarmaber Basalt is overlayed on the Ashangi Basalt. The alluvial deposits comprise the low-lying valley of the study areas and constitute 9% of the catchment area. According to Kebede (2013), the Ethiopian flood basalts are generally characterized by four different stratigraphic units: from bottom to top, Ashangie, Aiba, Alaji, and Termaber Basalts. The younger trap basalts are reported to have higher aquifer productivity than the older, but both the older and younger volcanic basalts show a decreasing aquifer productivity trend with increasing depth (Kebede 2013). For more details, please refer to the Electronic Supplementary Material (ESM).

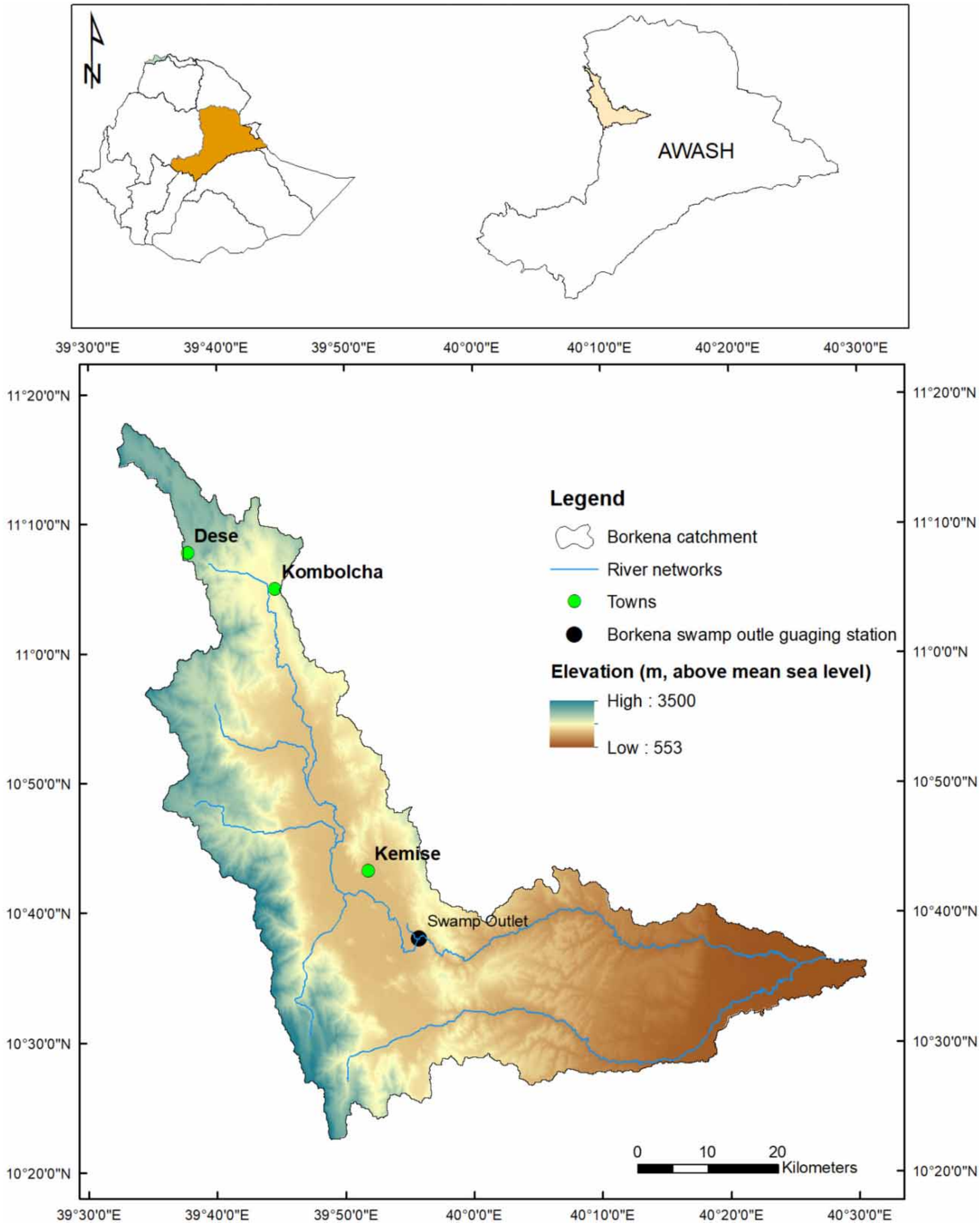

Figure 1 | Study area location and digital elevation model.

Hydrogeologically, the study area (Figure 2) is characterized by four aquifers: high-productive fracture rock aquifer, low-productive fracture rock aquifer, moderate-productive intergranular aquifer, and moderate-productive fracture rock aquifer (Chernet 1993). Groundwater in Borkena, or Awash River Basin, generally occurs in a complex, heterogeneous geologic environment. The study area is characterized by a volcanic rock aquifer (i.e., Basaltic rock aquifers) under the regolith aquifer. Regolith, consisting of soil, alluvium, and weathered rock material, overlies most geologic units throughout the study area.

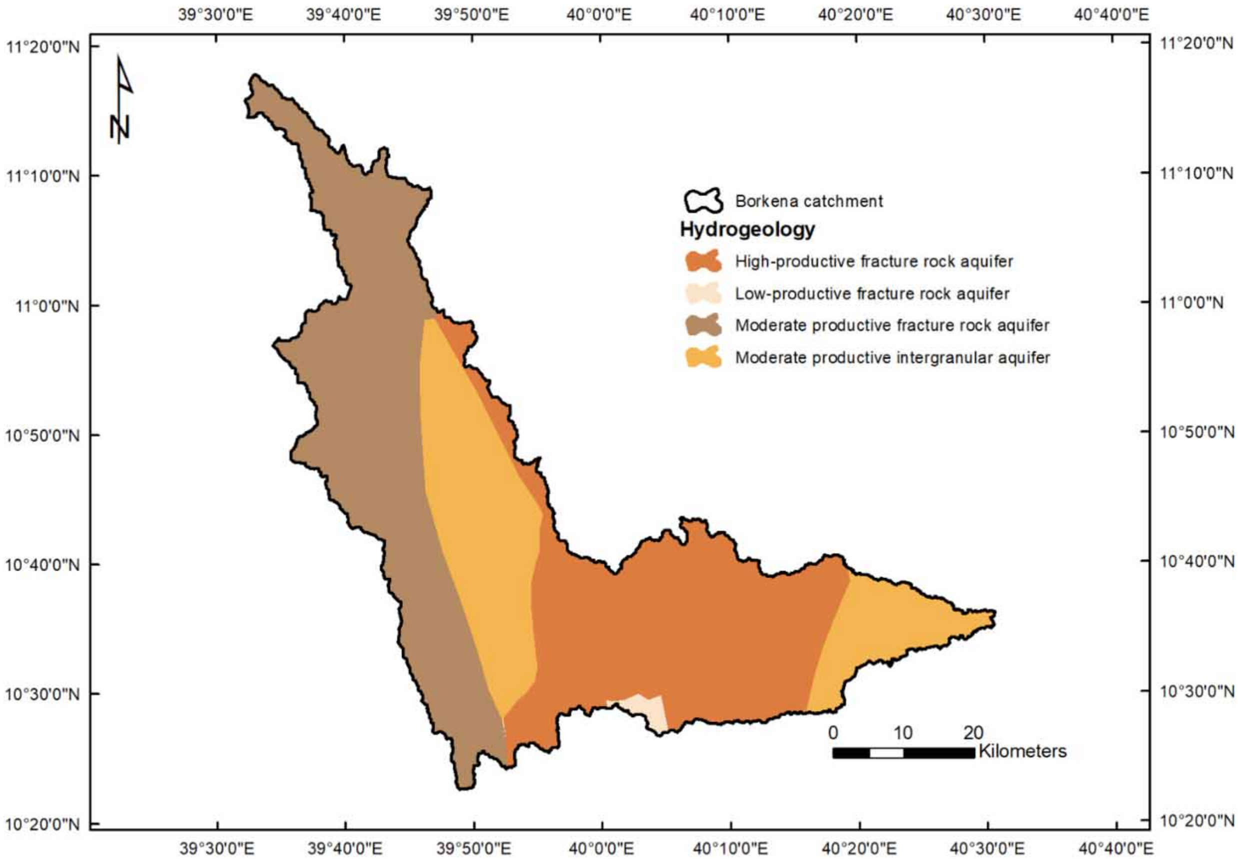

Figure 2 | Hydrogeology of the study area (Source Chernet (1988)).

3. METHODS

An integrated SWAT–MODFLOW model was developed to estimate shallow groundwater availability in the Borkena catchment. Integrated models account for feedback processes that affect the timing and rate of evapotranspiration, surface runoff, and groundwater-surface water interactions. Hence, they contribute substantially to our understanding of the hydrology of watersheds, rivers, and aquifers. They are also useful for developing conjunctive surface and groundwater resource management plans and test water management scenarios that consider complex interactions of the hydrological system, particularly in a changing climate. The methodological framework for the SWAT–MODFLOW modeling for the Borkena catchment is presented in Figure 3.

3.1. SWAT–MODFLOW model description

SWAT–MODFLOW is a loosely coupled model of SWAT and MODFLOW developed to simulate surface and groundwater hydrology. In the SWAT–MODFLOW, the SWAT groundwater conceptual model is replaced by MODFLOW, which can provide a more dynamic and temporally detailed groundwater balance. The coupled SWAT–MODFLOW model developed by Bailey *et al.* (2016) was used for the present study. Integrating the SWAT–MODFLOW model requires values of state variables (i.e., variables that define the state of a dynamic system) to be passed from SWAT to MODFLOW and from MODFLOW back to SWAT. This includes (i) Recharge from SWAT hydrologic response units (HRUs) to MODFLOW grid cells, (ii) difference between potential evapotranspiration and actual evapotranspiration from SWAT HRUs to MODFLOW grid cells, (iii) sub-basin channel stage from the SWAT sub-basin channel to MODFLOW river cells, and (iv) groundwater-stream exchange rates from the MODFLOW River cells to SWAT sub-basin channels.

The riverbed conductance and riverbed elevation defined in the MODFLOW river package are used throughout the simulation, but the river stage provided by SWAT sub-basin channels replaces the river stage of the MODFLOW river package. Recharge values from SWAT HRU replace those used in the Recharge package of MODFLOW during the

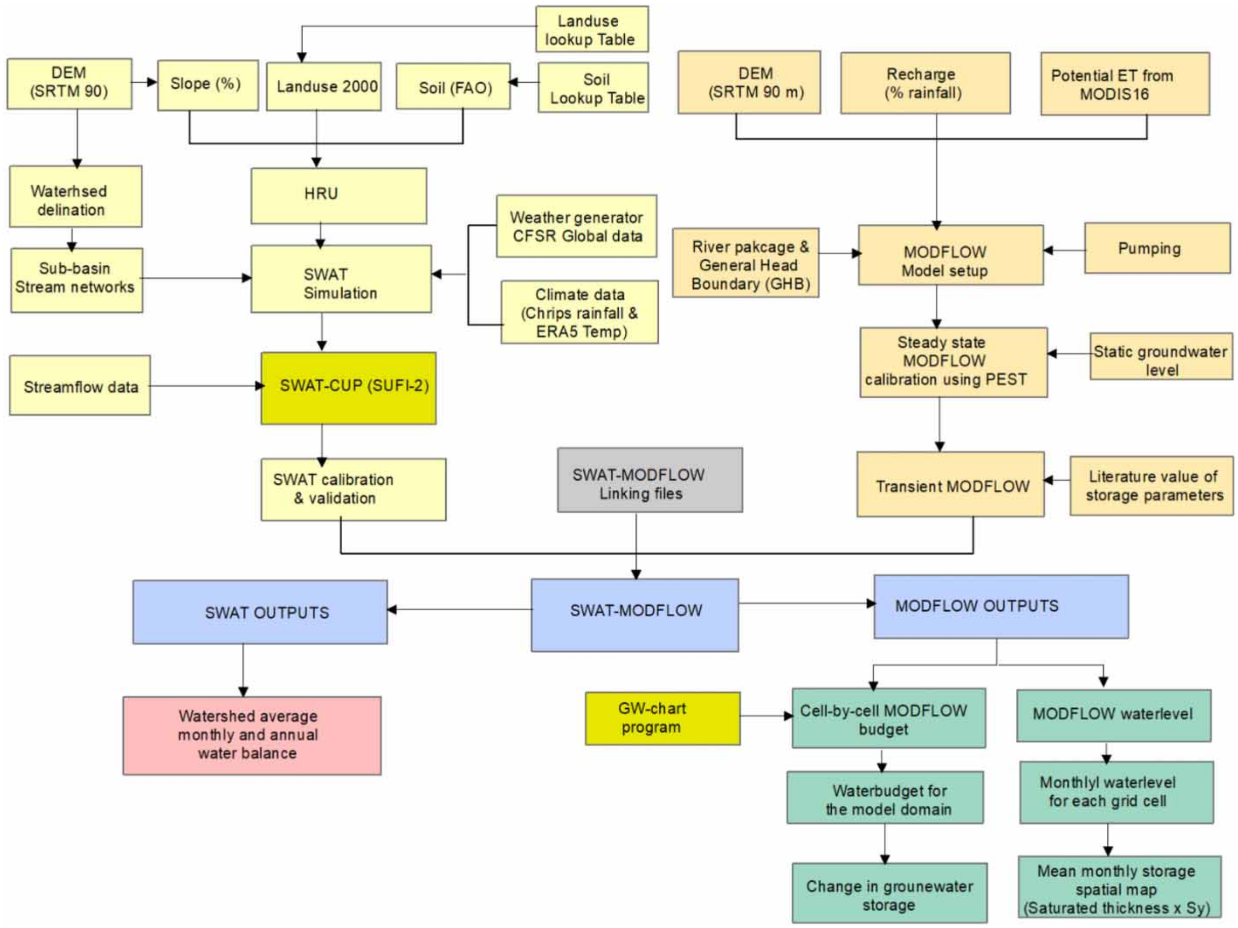

Figure 3 | A modelling framework for the SWAT–MODFLOW model.

SWAT–MODFLOW simulation. Thus, the value in the Recharge package of MODFLOW will not affect the SWAT–MODFLOW results. In the SWAT–MODFLOW, the evapotranspiration (ET) surface in the MODFLOW ET package is replaced by ground surface elevation. The evapotranspiration rates are replaced by the difference between potential ET and actual ET simulated by SWAT. This residual ET can be removed from the saturated zone of the aquifer if the water table is above the extinction depth. Extinction depth refers to the maximum depth to which plant roots penetrate the soil.

3.1.1. SWAT model setup and input data

The SWAT model for Borkena was divided into 22 sub-basins and 635 HRUs. The ARC-SWAT interface was used to automate the SWAT setup. The SWAT sub-basins, land use, soil, and slope maps used in SWAT are presented in the ESM. The land use map is 30 m resolution from Landsat images. Soil data were based on the FAO soil map, and the slope was based on the Shuttle Radar Topography Mission (SRTM) 90 m Digital Elevation Model (DEM). Rainfall data were obtained from Climate Hazards Group InfraRed Precipitation with Station data (CHIRPs) (Funk *et al.* 2014), a quasi-global rainfall dataset at a spatial resolution of 0.05° (~5.5×5.5 km). This is because the station rainfall data contained significant missing data and gaps, limiting its usability in our modeling efforts. We rigorously validated CHIRPS data against station rainfall data. We found a very good correlation ($R = 0.78$), aligning with the findings by Ayehu *et al.* (2018) and Belete *et al.* (2020) in the Blue Nile basin, reporting strong correlations ($R > 0.8$) between monthly CHIRPS and station data, supporting the validity of our remote sensing approach. Temperature and windspeed data were obtained from the fifth-generation European Centre for Medium-Range Weather Forecast (ECMWF) atmospheric reanalysis (ERA5 global climate at a spatial resolution of 0.25° (~28×28 km)). Solar radiation and relative humidity were assigned as simulated.

3.1.2. SWAT model calibration and validation

The SWAT model was calibrated and validated using streamflow data at the Borkena swamp outlet gauging station from 1996 to 2002. Following established practices (Arnold *et al.* 2012), the first five years (1990–1995) were used as the warmup period. We divided the remaining data (1996–2002), ensuring a statistically representative distribution of wet, moderate, and dry years across both calibration (two-thirds, 1996–2000) and validation (one-third, 2001–2002) periods. This is because more recent streamflow data beyond 2002 for the Borkena Swamp outlet gauging station was unavailable. Streamflow data for recent years have not been available for most river gauging stations in Ethiopia due to the problem of converting water level data to discharge (Taye *et al.* 2022b). The calibration was carried out using SWAT CUP (SWAT Calibration and Uncertainty Programs) with the SUFI-2 (Sequential Uncertainty Fitting version 2) algorithm (Abbaspour 2015). The SWAT model's most common hydrological model calibration parameters related to runoff generation, evapotranspiration, soil, and groundwater characteristics are CN2, AWC, ESCO, SURLAG, GW-ALPHA, GW_DELAY, and GW_REVAP (Arnold *et al.* 2012). For the present study, we selected eleven parameters for model calibration, including the seven listed as common parameters and four additional parameters based on model sensitivity analysis (i.e., GWQMN, SOL_K, EPCO, and SURLAG). Parameter ranges and calibrated values are presented in Table 1. Performance statistics for the calibration and validation periods were assessed using Nash-Sutcliffe coefficients (NSE). According to Moriasi *et al.* (2015), model performance is 'satisfactory' for flow simulations at a monthly time step if NSE > 0.5.

3.1.3. MODFLOW model setup

The groundwater flow system was modeled using MODFLOW-NWT using the Model Muse modeling environment/user interface (Winston 2009). The MODFLOW model domain is discretized into a uniform grid size of 200 m × 200 m, and vertically, the model is discretized into two layers, representing the very shallow aquifer system (<30 m) and the relatively deeper weathered and fractured aquifer (30–100 m). Hard rock aquifers form typically within the first 100 m of the Earth's surface, within weathering profiles, and open fractures decrease with depth (Lachassagne *et al.* 2021). The alluvial sediments in the Borkena catchment are located in the Dese, Kombolcha, and Cheffa areas, have a thickness ranging from 30 to 100 m, and contain the most important aquifers (Ketema 1980).

Shallow aquifers considered in this study include the regolith aquifer (unconsolidated sand and gravel aquifers) and the uppermost bedrock (i.e., the weathered shallow aquifer); see Section S11 and Tables S1–S5 of the ESM. The top layer coincides with the land surface elevation, determined by the SRTM DEM. The elevation of the bottom layers was defined

Table 1 | SWAT parameters selected for calibration and their calibrated values

Parameter name	Description	Parameter ranges		Fitted value
		Lower	Upper	
r__CN2.mgt	The SCS curve number for moisture condition II (%). It is a function of the soil's permeability, land use, and antecedent soil water conditions.	− 0.3	0.3	− 0.07
v__ALPHA_BF.gw	Baseflow alpha factor (1/days).	0.2	0.8	0.42
v__GW_DELAY.gw	Groundwater delay time (days).	0	450	22.05
v__GWQMN.gw	The threshold depth of water in the shallow aquifer is required for return flow to occur (mm H_2O).	0	500	356.50
v__ESCO.hru	Soil evaporation compensation factor [-].	0	1	0.30
r__SOL_AWC.sol	Available water capacity of the soil layer (mm H_2O).	− 0.25	0.25	0.24
r__SOL_K.sol	Saturated hydraulic conductivity (mm/h).	− 0.25	0.25	0.06
v__EPCO.hru	Plant uptake compensation factor [-].	0	1	0.34
v__GW_REVAP.gw	Groundwater 'revap' coefficient [-]. 'revap' is water in a shallow aquifer returning to the root zone (mm H_2O).	0.02	0.2	0.13
v__REVAPMN.gw	Threshold depth of water in the shallow aquifer for 'revap' or percolation to the deep aquifer to occur (mm H_2O).	0	500	156.50
V__SURLAG.bsn	Surface runoff lag coefficient.	0.05	24	6.68

by subtracting a constant aquifer thickness of 30 and 100 m from the top elevation defined using DEM. The shallow groundwater boundary is assumed to follow the surface water divide (Ayenew *et al.* 2008). Therefore, we used no flow boundaries for the lateral boundaries that coincide with the watershed boundary except at the catchment outlet, where we defined the General Head Boundary (GHB) to simulate water entering and leaving the model domain. The head outside the model boundary for the GHB was assigned based on the observed groundwater data. The conductance term of the GHB was estimated using model calibration. The top layer was simulated as an unconfined aquifer, and the bottom layer was assumed to be convertible (Kebede 2013). If a layer is convertible, the code checks whether the head in the lower level is above or below the top of the layer as the simulation progresses and treats the layer as confined or unconfined, accordingly.

Temporally, the 33-year simulation period (1990–2022) was divided into 396 monthly stress periods, including the warmup periods. A stress period is an interval over which specified inputs are constant. The simulation period was determined by streamflow data availability (1996–2002) for model calibration and validation, coupled with the need to assess long-term water balance trends. The monthly stress period was selected to simulate seasonal change in groundwater use, recharge, evapotranspiration, and seasonal aquifer storage. Since information on the rate of groundwater pumping at individual wells was not available, groundwater abstraction rates were estimated using literature values of average groundwater yields for volcanic rocks (MacDonald & Davies 2000). A 1.5 l/s abstraction rate was assumed at individual shallow motorized pumping wells (Moges 2019). The yield data in liters per second were converted to cubic meters per day, assuming an average daily pumping of 8 h (i.e., 43 m^3/d). The usual assumption for urban water supply wells' pumping duration is 10 h per day, but we used a more conservative assumption of 8 h for shallow wells (Walker *et al.* 2019). Pumping from the shallow aquifer through hand-dug wells was assumed to be 10 m^3/d (MacDonald *et al.* 2009). Thirty-two pumping wells were incorporated into the model to simulate groundwater pumping from the shallow aquifer. Well distribution across model layers was determined using borehole depth and static groundwater levels. The total pumping in the first layer is 160 m^3/d (16×10 m^3/d). For the second layer, it equals 688 m^3/d (16×43 m^3/d).

Recharge rates for the steady-state model were estimated as a fraction of precipitation. The multiplying factor was estimated based on SWAT simulated recharge. Groundwater Evapotranspiration is simulated using the Evapotranspiration (ET) Package. The potential evapotranspiration rate is determined based on long-term mean annual potential ET [2000–2013] from MODIS16. Evapotranspiration extinction depth was determined based on soil type and land cover from Shah *et al.* (2007) and was set to be 3 m. Groundwater-surface water flux exchange was simulated using the River Package. River bottom elevation was estimated based on DEM. Based on a previous study, a constant river stage of 0.25 m was assumed (Gobezie *et al.* 2023). The conductance of the riverbed was estimated by model calibration. After coupling, recharge, ET from Groundwater (GWET), and river stage used in MODFLOW will be replaced by SWAT simulated recharge, GWET, and river stages.

3.1.4. Steady-state MODFLOW model calibration

The steady-state MODFLOW model was calibrated using static groundwater level data in 23 shallow wells (irrespective of the date). During model calibration, hydraulic conductivity, anisotropy factor, riverbed, and GHB conductance were adjusted until the simulated head matched the observed values. Automatic calibration was performed using PEST (Model-Independent Parameter Estimation and Uncertainty Analysis code) (Doherty *et al.* 1994). Initial estimates of horizontal hydraulic conductivity values were made based on pumping test data (See Table S6 of the ESM), past studies in the study area (Ketema 1980; Azeref & Bushira 2020), and other literature on weathered-fractured basaltic rock aquifers (Pande *et al.* 2022). Vertical hydraulic conductivities are assumed to be one-tenth of the horizontal hydraulic conductivities (Cook 2003). The specified likely parameter range and final calibrated values are presented in Table 2.

3.1.5. Transient MODFLOW model calibration

The transient model aims to simulate transient storage due to changes in stresses associated with changes in climate, land use, and other scenarios. A transient MODFLOW model needs to be developed to couple the MODFLOW model with SWAT in the SWAT–MODFLOW framework. The same aquifer hydraulic properties determined from the steady-state model were used in the transient MODFLOW simulations. However, due to a lack of time-varying groundwater level time-series data, calibration of the transient MODLOW model was not possible. Therefore, the monthly transient model is developed based on literature values of storage parameters representative of the regolith aquifer and weathered and fractured basaltic formation (Specific yield (Sy) of 0.09 and 0.01, respectively) (Kebede 2013; Gowing *et al.* 2020; Tilahun *et al.* 2020). A decrease in Sy with depth is reported (Lachassagne *et al.* 2021).

Table 2 | MODFLOW parameters selected for calibration and their calibrated values

Parameter	Units	Layer 1	Layer 2
Hydraulic conductivity (Kx) zone 1: Moderate-productive intergranular Aquifer (unconsolidated sediments)- 1 Moderate	m/d	0.6	0.27
Hydraulic conductivity (Kx) zone 2: High-productive fracture rock aquifer (Volcanic Rocks: Basalt, Rhyolites, Trachyte)-3 High Productive	m/d	1.57	0.6
Hydraulic conductivity (Kx) zone 3: Moderate-productive fracture rock aquifer (Volcanic Rocks: Basalt, Rhyolites, Trachyte)- 3 Moderate	m/d	0.5	0.27
Hydraulic conductivity (Kx) zone 4[a]: Low-productive fracture rock aquifer (Volcanic Rocks: Basalt, Rhyolites, Trachyte)-3 Low Pro	m/d	0.57	0.027
Horizontal anisotropy (Ky/Kx)	–	1	1
Vertical anisotropy (ratio of horizontal (Kx) to vertical hydraulic conductivity (Kz)	–	10	10
Specific yield (Sy)	–	0.09	0.01
Specific storage (Ss)	–	1.0×10^{-5}	1.0×10^{-5}
Recharge multiplier (calculated from SWAT recharge sub-basin output). A recharge rate was applied to the uppermost active cell.	–	0.11	
Riverbed conductance	m^2/d	100	
General Head Boundary conductance (GHB)	m^2/d	1,000	

[a]Kx in zone 4 is insensitive as there is no water level data to constrain it.

3.2. SWAT–MODFLOW coupling

Linking files and coupling of SWAT–MODFLOW were made following Bailey & Park's (2019) approaches. Since SWAT HRUs do not have designated geographic locations, SWAT HRUs are disaggregated using GIS (Geographic Information System). Disaggregation splits an HRU into individual polygons with a specific geographic area**.** These Disaggregated HRUs (DHRUs) are then intersected with MODFLOW grid cells to pass state variables between SWAT and MODFLOW (Bailey & Park 2019). After the HRUs were disaggregated, four linking files were created that link DHRUs to MODFLOW grid cells so that the state variable could be transferred from SWAT to MODFLOW and vice versa.

4. RESULTS

4.1. SWAT–MODFLOW model calibration and validation results

The NSE for the SWAT model calibration period was 0.88, and for the validation period it was 0.70. The simulated hydrograph captures the temporal dynamics reasonably well (Figure 4). The calibration and validation of the SWAT model performance is good enough for its intended use and further coupling with the MODFLOW model.

Figure 5 illustrates the agreement between the simulated and observed groundwater levels at 23 shallow wells in the Borkena catchment obtained during steady-state MODFLOW model calibration. The Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) values between the observed and simulated groundwater level values were 9.9 and 7.2 m, respectively. The large model calibration error is likely due to local heterogeneity, which could not be resolved during model calibration. Catchment-scale groundwater models might not perfectly match groundwater levels, especially in areas where groundwater levels change significantly across the region (Cao *et al.* 2013). Residuals are randomly distributed across the sites as Hill (1998) recommended. The Normalized Root Mean square error is less than 10%, and the mass balance error is less than 1%, which is acceptable (ASTM Standard D5447 2010). The calibrated parameter values are within the range of literature values.

Our model calibration yielded hydraulic conductivity (K) values consistent with previous findings in the region. For unconsolidated sediments, our K range (0.27–0.6 m/d) aligns with Ketema's (1980) estimate (1.08–3.1 m/d). Similarly, the K range for fractured rock aquifers (basalt, rhyolite, trachyte) falls within the range reported by Azeref & Bushira (2020) for the Borkena area (0.6–7.5 m/d). Even a specific value for a basalt aquifer in India (1.5 m/d, Pande *et al.* 2022) fits within our calibrated range. The broader K variation observed in pumping tests (0.001–32 m/d, Table S6, ESM) is worth noting,

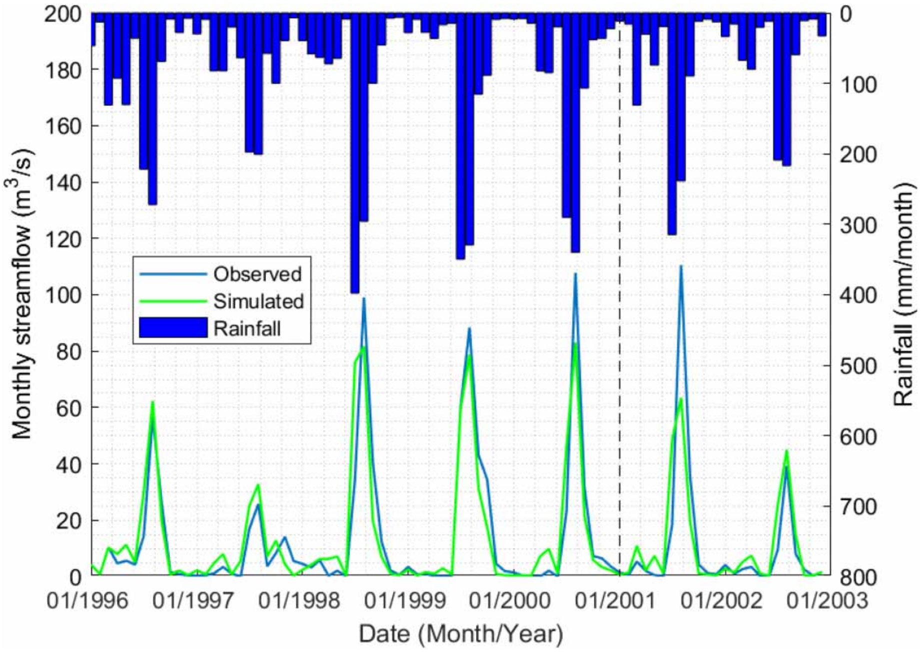

Figure 4 | Observed and simulated hydrographs at the Borkena swamp outlet gauging station and catchment average rainfall for 1996–2003 of Borkena catchment (vertical black dotted line separates the calibration and validation period, 1996–2000 and 2002–2003, respectively).

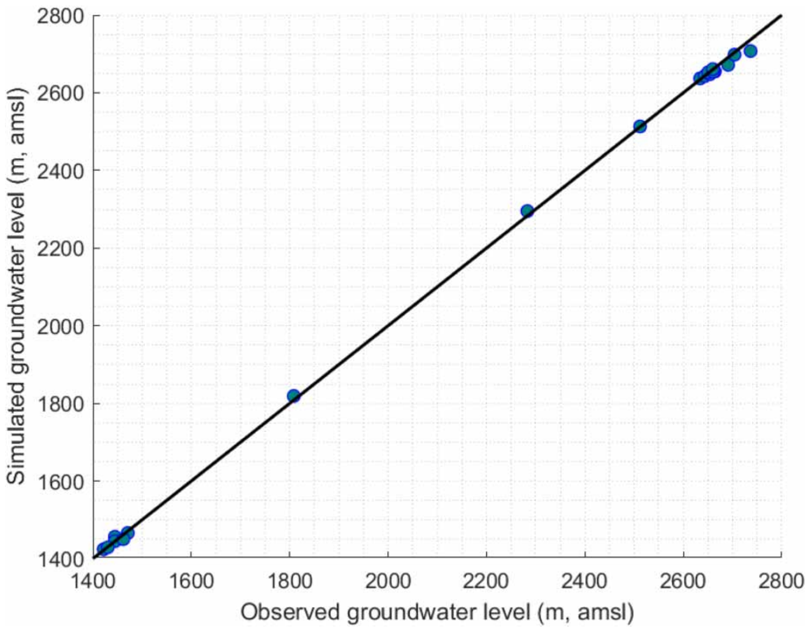

Figure 5 | Observed and simulated groundwater levels at 23 shallow wells in the Borkena catchment using a steady-state MODFLOW model.

highlighting potential variability within the aquifer system. Independently calibrated SWAT and MODFLOW models were coupled without further calibration, similar to Chunn *et al.* (2019).

4.2. Water balance

The mean annual water budget simulated using the SWAT–MODFLOW mode for the simulation period 1996–2022 is presented schematically in Figure 6. The mean annual simulated evapotranspiration is about 74% of the mean annual

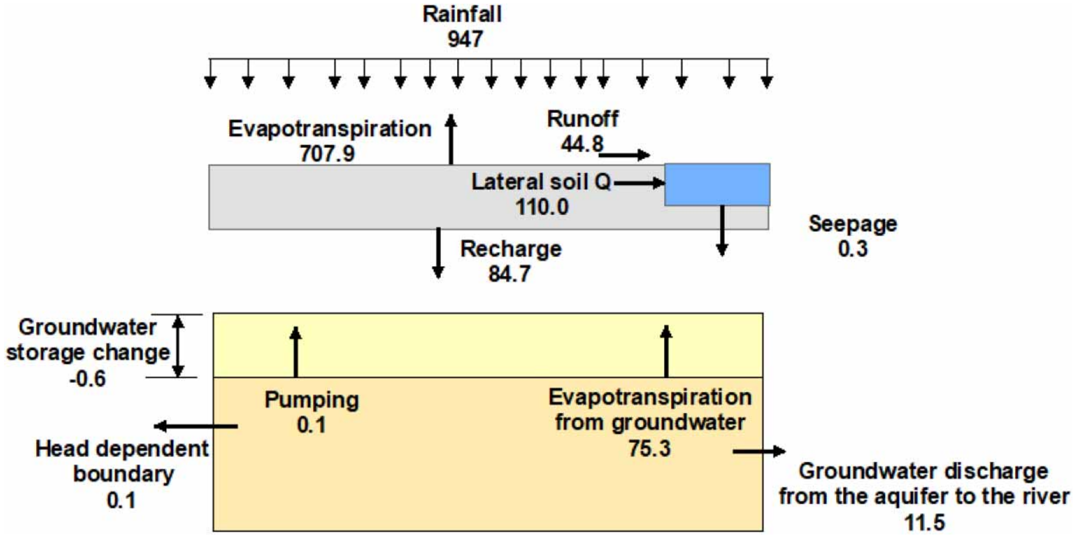

Figure 6 | Borkena catchment mean annual water budget for the simulation period 1996–2022 (mm/year).

rainfall. While this value is higher than the 58% reported by Gobezie *et al.* (2023) in the study area, it falls within the range observed in other studies of semi-arid regions (e.g., Taye *et al.* (2022a)). The mean annual recharge over the entire Borkena catchment is 85 mm, representing 11% of the mean annual rainfall. This finding aligns with recharge rates reported in previous studies by Azeref & Bushira (2020) and Gobezie *et al.* (2023) within the same area and also falls within the broader range of 10–20% of annual rainfall estimated for Ethiopia's central and northwestern highlands by Ayenew *et al.* (2008). Evapotranspiration directly from groundwater accounts for 75 mm/year, about 89% of the recharge. The mean annual surface runoff is 5% of the mean annual rainfall. Our analysis estimates interflow to contribute significantly to the Borkena Catchment's water yield, accounting for 66% of the total and representing 11.6% of the mean annual rainfall. This value is higher than the estimate of lateral flow (6.6% of mean annual rainfall) reported by Gobezie *et al.* (2023) in the same area. The change in soil moisture is likely to be small compared to the total water balance for an annual time scale and can be neglected.

4.3. Temporal variability in groundwater recharge

There is significant inter-annual variability in groundwater recharge (Figure 7). The annual recharge varies from 2.5 to 166 mm. The maximum and minimum recharge occurs in 1998 and 2015, respectively, matching the wettest and driest years in the basin. The coefficient of variation in annual recharge is 1.9. Recharge occurs predominantly in a few wet years, i.e., 1998, 2000, 2007, 2010, and 2016 (Figure 7). It was shown that infrequent but high-intensity rainfall events significantly impact groundwater recharge in semi-arid regions (Smith *et al.* 2016). This study found the correlation (R^2) between recharge and rainfall to be 0.66. Recharge in the Borkena catchment occurs when the annual rainfall is greater than 650 mm (Figure 8). Kotchoni *et al.* (2019) reported a lower groundwater recharge threshold than our study. Their findings suggest that recharge begins above 140 and 250 mm/a of annual rainfall, while our results indicate a higher threshold. This shows that the temporal viability of recharge rates is controlled by climate variability. While both rainfall and temperature influence groundwater levels over time, temperature has a stronger effect on shallow groundwater (Chen *et al.* 2004). Groundwater recharge exhibits significant variability based on the geological setting. Recharge rates for shallow aquifers composed of unconsolidated sediments are significantly higher than weathered and fractured rock aquifers (Kotchoni *et al.* 2019).

4.4. Shallow groundwater availability in Borkena catchment

Shallow groundwater in the Borkena catchment is spatially variable (Figure 9). Results show that 42% of the Borkena catchment area is underlain by shallow groundwater. The shallow groundwater is near the land surface in stream valleys and low-lying regions, where the rocks are weathered and fractured. Shallow groundwater in the Borkena catchment is predominantly found in low-lying areas (slope 0–10%). Figure 9 shows areas where groundwater is easily accessible using hand-dug wells,

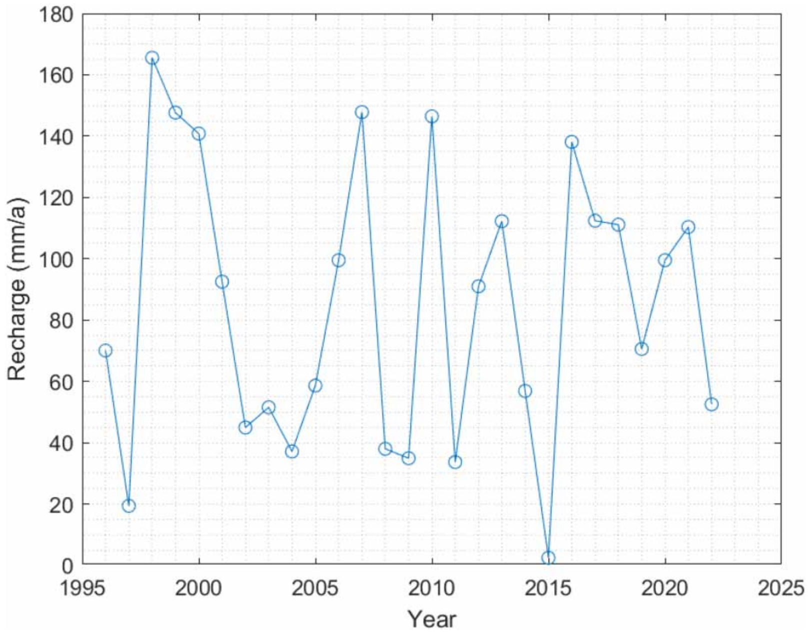

Figure 7 | Catchment average mean annual recharge for 1996–2022.

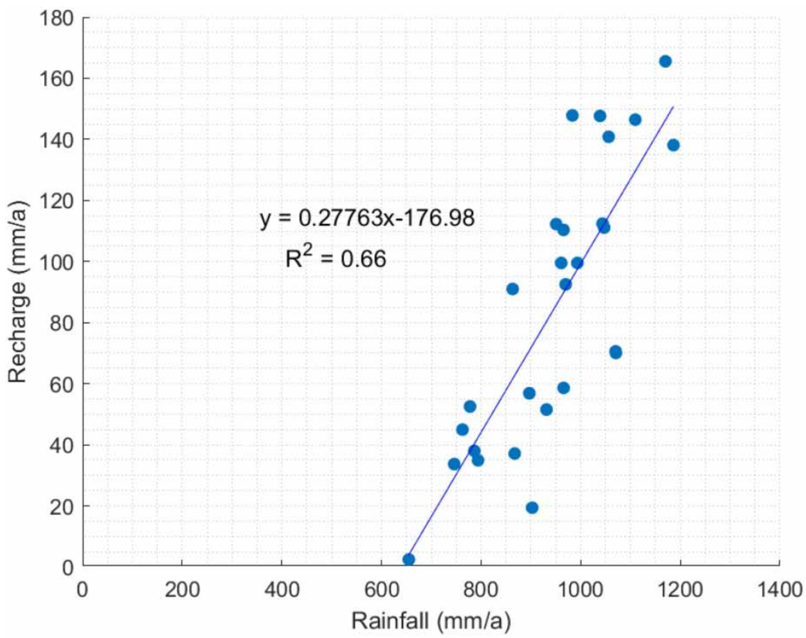

Figure 8 | Correlation between annual rainfall and annual recharge for the period 1996–2022.

represented by light blue. These areas typically have shallow groundwater within 6 m of the surface. Groundwater naturally flows downhill and accumulates in depressions. This explains why water table depth is often heavily influenced by local topography as much as, or even more than, regional climate (Fan *et al.* 2017). We calculated the Topographic Wetness Index (TWI) to validate our model results. TWI indicates the likelihood of saturation, and areas with high TWIs often have high groundwater levels (Rinderer *et al.* 2014). TWI was found to be significantly correlated with depth to groundwater, exhibiting a strong positive correlation coefficient ($R = 0.71$) (Sörensen *et al.* 2006). Due to the strong connection between topography

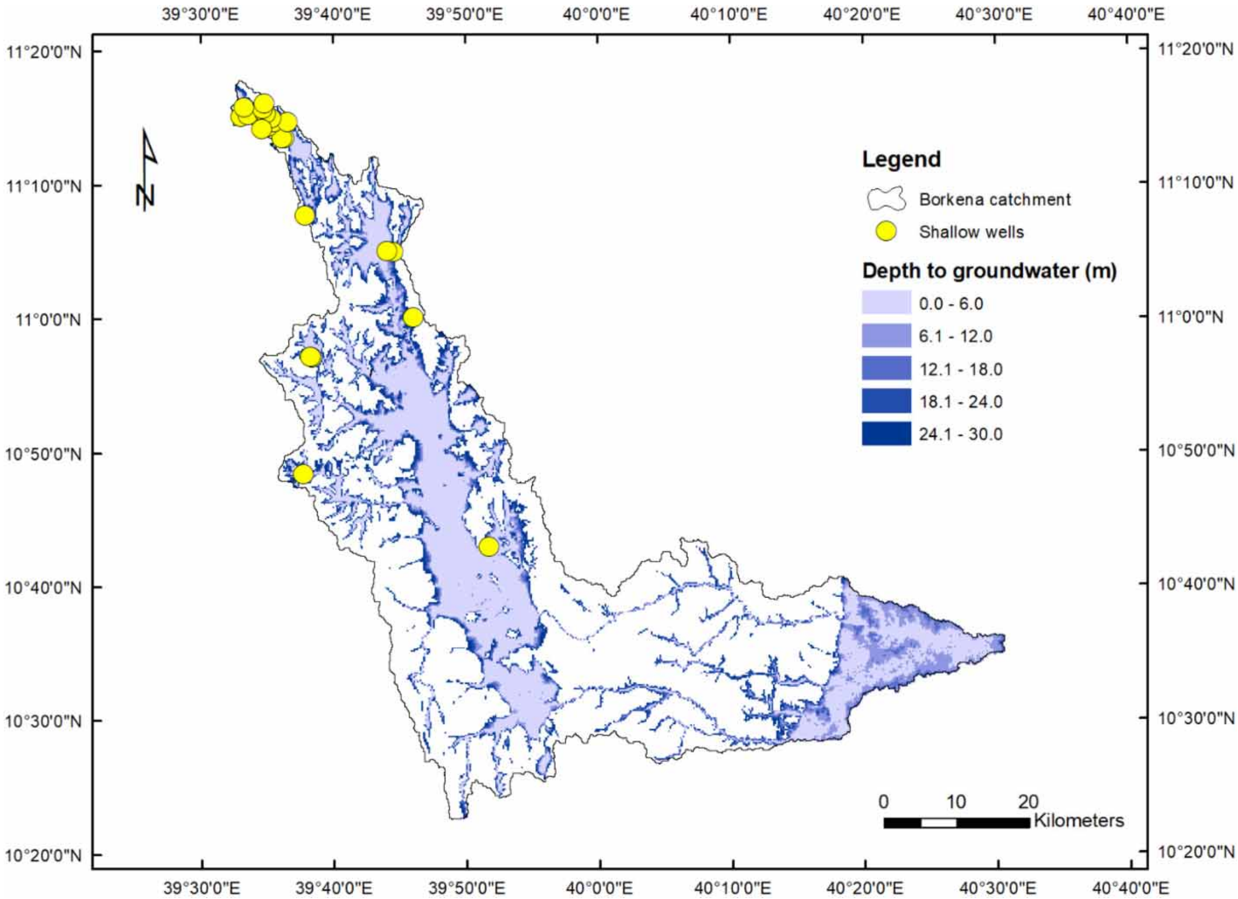

Figure 9 | Shallow groundwater availability map in the Borkena catchment (<30 m) estimated based on long-term average depth to groundwater over the period from 1996 to 2022 overlaid with existing shallow wells. The white areas on the map indicate regions where shallow groundwater does not occur within 30 m below the ground surface.

and groundwater level, TWI has proven effective in predicting the spatial distribution of shallow groundwater. Our SWAT–MODFLOW model and TWI analysis consistently identify similar areas with a high potential for shallow groundwater, see Section S13 of the ESM.

5. DISCUSSION

Shallow groundwater has long been promoted in the Borkena catchment and Ethiopia in general but has rarely been systematically assessed. Thus, this is believed to be the first comprehensive model-based shallow groundwater assessment for the Borkena catchment, providing a crucial foundation for advancing shallow groundwater planning and management. The analysis has generated at least four key findings.

The long-term mean annual recharge for 1996–2022 is 84.7 $\pm$ 45.6 mm. In volumetric terms, the annual recharge is 258 $\pm$ 138 Mm^3 during 1996–2022. This recharge rate broadly agrees with previous study estimates (Ayenew *et al.* 2008; Azeref & Bushira 2020; Gobezie *et al.* 2023). According to UNESCO (2011), more than 85% of the recharge contributes to the shallow aquifer, and less than 15% of the groundwater recharge reaches the deep-lying aquifers. However, assuming all the recharge water can be used by pumping is unrealistic. If groundwater use is equal to recharge, groundwater is at risk of overexploitation, and streams, springs, and wetlands may eventually dry up. For instance, greater irrigation access, driven by the expansion of tube wells, has led India to severe groundwater depletion (Jain *et al.* 2021). Ponce (2007) recommended 40% of annual recharge as a sustainable groundwater abstraction. If we take 40% of shallow aquifer recharge, the shallow groundwater volume available in the catchment is approximately 88 Mm^3.

The water budget analysis shows lateral flow is greater than direct runoff in the catchment (Figure 6). The steep topography and the prevalence of Leptosols, shallow soils over hard rock (Jones *et al.* 2013) in the study area contribute to increased lateral flow. This is primarily due to the limited vertical movement of water in the shallow soil layer, the impeding downward percolation of water through the hard rock, and the reduced soil anchoring ability of the shallow root systems. The combination of these factors, along with watershed management practices like terracing, has likely promoted lateral flow (Mekuria *et al.* 2023). Research has shown that interflow is a dominant flow process in forested mountain watersheds (Chanasyk & Verschuren 1983). Sloan & Moore (1984) reported lateral flow as high as 75–97% of the storm flow volume. Lateral flow accounted for 89% of the total water flow in the Keynes Catchment, South Australia (Hardie *et al.* 2012). Sanchez-Gomez *et al.* (2023) also reported the dominance of interflow in sloppy areas. Lateral flow is also likely large in watersheds with high soil hydraulic conductivity and an impermeable or semipermeable layer at shallow depths that can support a perched water table (Sloan & Moore 1984; Weiler *et al.* 2006). In addition, decayed root holes, animal burrows, wormholes, and other structural channels make a highly porous medium for rapid water flow in all directions (Sloan & Moore 1984). In Shallow soils overlying hard rock, large roots may not penetrate the underlying hard rock, leading to lateral root growth. As the roots decay and create larger pores, a connected network of pipes can form, facilitating a significant amount of lateral water flow (McDonnell 1990) .In steep catchments with shallow bedrock, lateral flow can be described as a two-part process: rapid flow through vertical cracks (macropores) and slower flow through the soil matrix (McDonnell 1990; Hardie *et al.* 2012).

The shallow groundwater storage potential in the Borkena catchment is relatively good. Approximately 42% of the catchment area has shallow groundwater (Figure 9). In this context, developing shallow groundwater for smallholder irrigation holds good potential for improving food security. Shallow groundwater can help smallholder farmers intensify their agriculture through irrigation, produce higher-value crops, diversify their income, and reduce their vulnerability to droughts (Qureshi *et al.* 2010). With reliable water access, farmers can diversify their crops. However, its uncontrolled expansion may result in a high risk of shallow groundwater depletion. Hence, maintaining the balance of abstraction and recharge is key for the long-term sustainability of shallow groundwater use.

As shown in Figure 6, the percentage of total groundwater abstraction to groundwater recharge is about 0.1%, indicating that abstraction is far less than recharge. Increasing shallow groundwater use in the Borkena catchment has the potential to bring more land under irrigation. According to FAO (2012), maize is a major irrigated crop in Borkena (~37% of the irrigated area). The dominant irrigation method in the Borkena catchment is furrow irrigation. Assuming a 600 mm per season irrigation requirement for maize and irrigation efficiency of 60% (Jurriens & Lenselink 2001), the total water demand to irrigate one hectare of land is around 10,000 m^3. This means approximately 8,800 ha of land will come under irrigation with the available shallow groundwater of 88 Mm^3, nearly 90% of the existing irrigated area in the Borkena catchment (i.e., 9,650 ha); see Section S14 of the ESM. Therefore, promoting shallow groundwater irrigation for smallholder farmers in the Borkena catchment holds promise for poverty reduction and increased food security. Access to shallow groundwater increases agricultural productivity and income.

6. LIMITATIONS

The known limitations in the present analysis include: (1) Due to a lack of groundwater level time-series data, transient MODFLOW model calibration was not possible. The transient MODFLOW model was developed with an assumed specific yield from the literature. As the specific yield values vary in a narrow range, the error introduced due to this assumption is minimal. (2) Some areas mapped with good shallow groundwater potential may be swamp areas and may not be suitable for farming. Any development of shallow groundwater for irrigation will require further location-specific analysis, and this study can be used as a basis. (3) Given the critical role of shallow groundwater for both irrigation and domestic water supply in rural areas, it is important to acknowledge that this study primarily focuses on the smallholder irrigation component. By concentrating solely on smallholder irrigation, we implicitly assume that sufficient water is available for domestic needs. However, this simplification may not accurately reflect the complex interplay between these two water uses, potentially leading to an overestimation of available water for irrigation. Therefore, a comprehensive assessment of both irrigation and domestic water demands would be necessary for a more holistic understanding of the system.

7. CONCLUSIONS AND RECOMMENDATIONS

In the Borkena catchment and Ethiopia in general, shallow groundwater use is promoted to improve smallholder farmers' food security. However, there are yet limited evidence bases to inform shallow groundwater-related planning. An improved understanding of shallow groundwater availability and replenishment rates is lacking, hampering sustainable shallow groundwater development and governance. An integrated SWAT–MODFLOW model was developed to support shallow groundwater availability assessment in the catchment. Results of the analysis show that nearly 42% of the catchment has shallow groundwater that smallholder farmers can easily access using shallow or hand-dug wells. The current shallow groundwater use is low compared to the estimated recharge; hence, increasing shallow groundwater for small-scale producers holds promise, strengthening livelihoods and improving food security. However, as shallow groundwater systems are hydraulically connected with surface water, uncontrolled development of shallow groundwater typically reduces the flow to surface water, adversely affecting aquatic and riparian ecosystems. There are no existing groundwater observation wells within the Borkena catchment. Hence, establishing dedicated monitoring wells is essential to address this critical knowledge gap. These wells would provide crucial data on groundwater availability and movement in the area. Furthermore, further research is recommended to investigate the impact of water quality, especially the salinity issues that restrict shallow groundwater development in the lower Awash Bain and the impact of climate change on shallow groundwater availability.

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AUTHOR CONTRIBUTIONS

G.Y.E. contributed to conceptualization, methodology, software, validation, formal analysis, investigation, writing – original draft, visualization. M.T.T. contributed to conceptualization, methodology, writing review, and editing. A.S. contributed to conceptualization, project administration, writing review, and editing. S.T. contributed to methodology, data curation and writing review, and editing.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Abbaspour, K. C. (2015) *SWAT-CUP: SWAT Calibration and Uncertainty Programs – A User Manual*. Dübendorf, Switzerland: Eawag, pp. 16–70.

Arnold, J. G., Moriasi, D. N., Gassman, P. W., Abbaspour, K. C., White, M. J., Srinivasan, R., Santhi, C., Harmel, R., Van Griensven, A. & Van Liew, M. W. (2012) SWAT: Model use, calibration, and validation, *Transactions of the ASABE*, **55** (4), 1491–1508. doi:10.13031/2013.42256.

ASTM Standard D5447. (2010) *Standard Guide for Application of A Groundwater Flow Model to A Site-Specific Problem*.

ATA. (2023) *Shallow Ground Water Mapping*. Available from: https://www.ata.gov.et/programs/highlighted-deliverables/input-voucher-sales-system-ivs/ [Accessed Aug 2023].

Ayehu, G. T., Tadesse, T., Gessesse, B. & Dinku, T. (2018) Validation of new satellite rainfall products over the Upper Blue Nile Basin, Ethiopia, *Atmospheric Measurement Techniques*, **11** (4), 1921–1936.

Ayenew, T., Demlie, M. & Wohnlich, S. (2008) Hydrogeological framework and occurrence of groundwater in the Ethiopian aquifers, *Journal of African Earth Sciences*, **52** (3), 97–113. https://doi.org/10.1016/j.jafrearsci.2008.06.006.

Azeref, B. G. & Bushira, K. M. (2020) Numerical groundwater flow modeling of the Kombolcha catchment northern Ethiopia, *Modeling Earth Systems and Environment*, **6**, 1233–1244. https://doi.org/10.1007/s40808-020-00753-6.

Bailey, R. & Park, S. (2019) *SWAT-MODFLOW Tutorial Version 3 Documentation for Preparing and Running SWAT-MODFLOW Simulations*.

Bailey, R. T., Wible, T. C., Arabi, M., Records, R. M. & Ditty, J. (2016) Assessing regional-scale spatio-temporal patterns of groundwater–surface water interactions using a coupled SWAT-MODFLOW model, *Hydrological Processes*, **30** (23), 4420–4433. https://doi.org/10.1002/hyp.10933l.

Belete, M., Deng, J., Wang, K., Zhou, M., Zhu, E., Shifaw, E. & Bayissa, Y. (2020) Evaluation of satellite rainfall products for modeling water yield over the source region of Blue Nile Basin, *Science of the Total Environment*, **708**, 134834.

Cao, G., Zheng, C., Scanlon, B. R., Liu, J. & Li, W. (2013) Use of flow modeling to assess sustainability of groundwater resources in the North China Plain, *Water Resources Research*, **49** (1), 159–175. https://doi.org/10.1029/2012WR011899.

Chanasyk, D. & Verschuren, J. (1983) An interflow model: I. Model development, *Canadian Water Resources Journal*, **8** (1), 106–119. https://doi.org/10.4296/cwrj0801106.

Chen, Z., Grasby, S. E. & Osadetz, K. G. (2004) Relation between climate variability and groundwater levels in the upper carbonate aquifer, southern Manitoba, Canada, *Journal of Hydrology*, **290** (1–2), 43–62.

Chernet, T. (1988) *Hydrogeology of Ethiopia*. Ethiopia: Ethiopian Institute of Geological Surveys Addis Abeba.

Chernet, T. (1993) *Hydrogeology of Ethiopia and Water Resources Development, Ethiopian Institute of Geological Surveys Ministry of Mines and Energy*.

Chunn, D., Faramarzi, M., Smerdon, B. & Alessi, D. S. (2019) Application of an integrated SWAT–MODFLOW model to evaluate potential impacts of climate change and water withdrawals on groundwater–surface water interactions in West-Central Alberta, *Water*, **11** (1), 110. https://doi.org/10.3390/w11010110.

Cook, P. G. (2003) *A Guide to Regional Groundwater Flow in Fractured Rock Aquifers*.

Curry, B. B. & Seaber, P. R. (1990) *Hydrogeology of Shallow Groundwater Resources, Kane County, Illinois. Contract/Grant Report 1990-01*.

Dillon, P. & Simmers, I. (1998) *Shallow Groundwater Systems: IAH International Contributions to Hydrogeology 18*. CRC Press, London.

Doherty, J., Brebber, L. & Whyte, P. (1994) PEST: Model-independent parameter estimation. Watermark Computing, Corinda, Australia, 122: 336.

Fan, Y., Miguez-Macho, G., Jobbágy, E. G., Jackson, R. B. & Otero-Casal, C. (2017) Hydrologic regulation of plant rooting depth, *Proceedings of the National Academy of Sciences*, **114** (40), 10572–10577.

FAO. (2012) *Coping with Water Scarcity-the Role of Agriculture Developing A Water Audit for Awash Basin with Emphasis on Agricultural Water Management*.

Fishman, R. M., Siegfried, T., Raj, P., Modi, V. & Lall, U. (2011) Over-extraction from shallow bedrock versus deep alluvial aquifers: Reliability versus sustainability considerations for India's groundwater irrigation, *Water Resources Research*, **47** (6). https://doi.org/10.1029/2011WR010617.

Funk, C. C., Peterson, P. J., Landsfeld, M. F., Pedreros, D. H., Verdin, J. P., Rowland, J. D., Romero, B. E., Husak, G. J., Michaelsen, J. C. & Verdin, A. P. (2014) A quasi-global precipitation time series for drought monitoring. 2327-638X, US Geological Survey. https://dx.doi.org/10.3133/ds832.

Gachet, A., Sevestre, D., Kebede, S., Ketemab, A., Asratb, A. & Haile, T. (2014) A National Shallow Groundwater Mapping Exercise, Pilot Phase: Central Ethiopia, Including Woredas in Oromiya and Southern Regions: Radar Technologies International.

Gobezie, W. J., Teferi, E., Dile, Y. T., Bayabil, H. K., Ayele, G. T. & Ebrahim, G. Y. (2023) Modeling surface water–groundwater interactions: Evidence from Borkena Catchment, Awash River Basin, Ethiopia, *Hydrology*, **10** (2), 42. https://doi.org/10.3390/hydrology10020042.

Gowing, J., Walker, D., Parkin, G., Forsythe, N., Haile, A. T. & Ayenew, D. A. (2020) Can shallow groundwater sustain small-scale irrigated agriculture in sub-Saharan Africa? Evidence from NW Ethiopia, *Groundwater for Sustainable Development*, **10**, 100290. https://doi.org/10.1016/j.gsd.2019.100290.

Hardie, M. A., Doyle, R. B., Cotching, W. E. & Lisson, S. (2012) Subsurface lateral flow in texture-contrast (duplex) soils and catchments with shallow bedrock, *Applied and Environmental Soil Science*, **2012** (1), 861358.

Hill, M. C. (1998) *Methods and Guidelines for Effective Model Calibration*. CO, USA: US Geological Survey Denver.

Hossain, M. (2009) *The Impact of Shallow Tubewells and Boro Rice on Food Security in Bangladesh, 917*. International Food Policy Research Institute, Washington, DC.

Jain, M., Fishman, R., Mondal, P., Galford, G. L., Bhattarai, N., Naeem, S., Lall, U., Singh, B. & DeFries, R. S. (2021) Groundwater depletion will reduce cropping intensity in India, *Science Advances*, **7** (9), eabd2849. doi:10.1126/sciadv.abd2849.

Jones, A., Breuning-Madsen, H., Brossard, M., Dampha, A., Deckers, J., Dewitte, O., Gallali, T., Hallett, S., Jones, R. & Kilasara, M. (2013) *Soil Atlas of Africa*. Publications Office of the European Union, Luxembourg.

Jurriens, M. & Lenselink, K. (2001) Straightforward furrow irrigation can be 70% efficient, *Irrigation and Drainage: The Journal of the International Commission on Irrigation and Drainage*, **50** (3), 195–204.

Kebede, S. (2013) *Groundwater in Ethiopia: Features, Numbers and Opportunities*. Springer Science & Business Media, Heidelberg.

Ketema, T. (1980) *Hydrogeology of the Borkena River Basin, Wollo, Ethiopia*. *MSc Thesis*, School of Graduate Study, Addis Ababa University.

Kotchoni, D. V., Vouillamoz, J.-M., Lawson, F. M., Adjomayi, P., Boukari, M. & Taylor, R. G. (2019) Relationships between rainfall and groundwater recharge in seasonally humid Benin: A comparative analysis of long-term hydrographs in sedimentary and crystalline aquifers, *Hydrogeology Journal*, **27**, 447–457.

Lachassagne, P., Dewandel, B. & Wyns, R. (2021) Hydrogeology of weathered crystalline/hard-rock aquifers – guidelines for the operational survey and management of their groundwater resources, *Hydrogeology Journal*, **29** (8), 2561–2594.

MacDonald, A. & Davies, J. (2000) *A Brief Review of Groundwater for Rural Water Supply in sub-Saharan Africa*. Available from: https://nora.nerc.ac.uk/id/eprint/501047

MacDonald, A. M., Calow, R. C., MacDonald, D. M., Darling, W. G. & Dochartaigh, B. E. (2009) What impact will climate change have on rural groundwater supplies in Africa?, *Hydrological Sciences Journal*, **54** (4), 690–703. https://doi.org/10.1623/hysj.54.4.690.

McDonnell, J. J. (1990) A rationale for old water discharge through macropores in a steep, humid catchment, *Water Resources Research*, **26** (11), 2821–2832.

Mekuria, W., Tadesse, M., Admassu, W., Asmame, B., Tessema, A., Abebe, S., Shibiru, E., Yirga, M., Jorgi, Y. & Abdu, F. (2023) The role of landscape management practices to address natural resource degradation and human vulnerability in Awash River basin, Ethiopia, *Current Research in Environmental Sustainability*, **6**, 100237.

Moges, S. (2019) Agricultural use of groundwater in Ethiopia: Assessment of potential and analysis of economics, policies, constraints, and opportunities, *Gates Open Res*, **3** (136), 136.

Moriasi, D. N., Gitau, M. W., Pai, N. & Daggupati, P. (2015) Hydrologic and water quality models: Performance measures and evaluation criteria, *Transactions of the ASABE*, **58** (6), 1763–1785. doi:10.13031/trans.58.10715.

MoWE. (2019) *Towards Identification of Water Based Growth Corridors. Part II: Land Suitability Evaluation and Growth Corridors Identification and Mapping*. Ministry of Water and Energy Addis Ababa.

Pande, C. B., Moharir, K. N., Singh, S. K., Elbeltagi, A., Pham, Q. B., Panneerselvam, B., Varade, A. M. & Kouadri, S. (2022) Groundwater flow modeling in the basaltic hard rock area of Maharashtra, India, *Applied Water Science*, **12**, 1–14. https://doi.org/10.1007/s13201-021-01525-y.

Ponce, V. M. (2007) Sustainable Yield of Groundwater. Available from: https://ponce.sdsu.edu/groundwater_sustainable_yield.html

Qureshi, A. S., McCornick, P. G., Sarwar, A. & Sharma, B. R. (2010) Challenges and prospects of sustainable groundwater management in the Indus Basin, Pakistan, *Water Resources Management*, **24** (8), 1551–1569. https://doi.org/10.1007/s11269-009-9513-3.

Rinderer, M., Van Meerveld, H. & Seibert, J. (2014) Topographic controls on shallow groundwater levels in a steep, prealpine catchment: When are the TWI assumptions valid?, *Water Resources Research*, **50** (7), 6067–6080.

Sanchez-Gomez, A., Martinez-Perez, S., Leduc, S., Sastre-Merlin, A. & Molina-Navarro, E. (2023) Streamflow components and climate change: Lessons learnt and energy implications after hydrological modeling experiences in catchments with a Mediterranean climate, *Energy Reports*, **9**, 277–291. https://doi.org/10.1016/j.egyr.2022.11.191.

Shah, T. (2020) Climate change and groundwater: India's opportunities for mitigation and adaptation, Water resources policies in South Asia. Routledge India, pp. 213-243.

Shah, N., Nachabe, M. & Ross, M. (2007) Extinction depth and evapotranspiration from ground water under selected land covers, *Groundwater*, **45** (3), 329–338. https://doi.org/10.1111/j.1745-6584.2007.00302.x.

Siebert, S., Burke, J., Faures, J.-M., Frenken, K., Hoogeveen, J., Döll, P. & Portmann, F. T. (2010) Groundwater use for irrigation–a global inventory, *Hydrology and Earth System sciences*, **14** (10), 1863–1880. https://doi.org/10.5194/hess-14-1863-2010.

Sloan, P. G. & Moore, I. D. (1984) Modeling subsurface stormflow on steeply sloping forested watersheds, *Water Resources research*, **20** (12), 1815–1822. https://doi.org/10.1029/WR020i012p01815.

Smith, M., Cross, K., Paden, M. & Laban, P. (2016) *Spring–Managing Groundwater Sustainably*. Gland, Switzerland: IUCN, .

Sörensen, R., Zinko, U. & Seibert, J. (2006) On the calculation of the topographic wetness index: Evaluation of different methods based on field observations, *Hydrology and Earth System Sciences*, **10** (1), 101–112.

Taye, M., Dyer, E., Hirpa, F. A. & Charles, K. (2018) Climate change impact on water resources in the Awash Basin, Ethiopia, *Water*, **10** (11), 1560. https://doi.org/10.3390/w10111560.

Taye, M. T., Ebrahim, G. Y., Nigussie, L., Hagos, F., Uhlenbrook, S. & Schmitter, P. (2022a) Integrated water availability modelling to assess sustainable agricultural intensification options in the Meki catchment, Central Rift Valley, Ethiopia, *Hydrological Sciences Journal*, **67** (15), 2271–2293.

Taye, M. T., Haile, A. T., Genet, A., Geremew, Y., Wassie, S., Abebe, B. & Alemayehu, B. (2022b) Data quality deterioration in the Lake Tana Sub-basin, Ethiopia: scoping study to provide streamflow and water withdrawal data, 204. International Water Management Institute (IWMI).

Tilahun, S. A., Yilak, D. L., Schmitter, P., Zimale, F. A., Langan, S., Barron, J., Parlange, J. Y. & Steenhuis, T. S. (2020) Establishing irrigation potential of a hillside aquifer in the African highlands, *Hydrological Processes*, **34** (8), 1741–1753. https://doi.org/10.1002/hyp.13659.

UNESCO. (2011) Groundwater for Emergency Situation: A methodological Guide, Edited by Jaroslav Vrba and Balthzzar Th.Verhagen.

Villholth, K. G. (2013) Groundwater irrigation for smallholders in Sub-Saharan Africa–a synthesis of current knowledge to guide sustainable outcomes, *Water International*, **38** (4), 369–391. https://doi.org/10.1080/02508060.2013.821644.

Walker, D., Parkin, G., Gowing, J. & Haile, A. T. (2019) Development of a hydrogeological conceptual model for shallow aquifers in the data scarce upper Blue Nile basin, *Hydrology*, **6** (2), 43.

Weiler, M., McDonnell, J. J., Tromp-van Meerveld, I. & Uchida, T. (2006) *Subsurface Stormflow. Encyclopedia of Hydrological Sciences*.

Winston, R. B. (2009) *ModelMuse: A Graphical User Interface for MODFLOW-2005 and PHAST*. US Geological Survey, Reston. Available from: https://doi.org/pubs.usgs.gov/tm/tm6A29

World Bank. (2000) *Groundwater in Rural Development Facing the Challenges of Supply and Resource Sustainability*.

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