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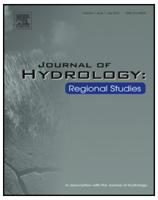

Recharge variability and sensitivity to climate: The example of Gidabo River Basin, Main Ethiopian Rift

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ABSTRACT

Study region: Gidabo River Basin, located in the south eastern Main Ethiopian Rift (MER).
Study focus: The focus is to characterize the spatial and temporal variability of groundwater recharge, identify the drivers that govern its distribution, and to improve the understanding of its sensitivity to precipitation and temperature in the MER by applying the semi-distributed hydrological model, Soil and Water Assessment Tool (SWAT).
New hydrological insights for the region: The average annual recharge for 1998–2010 reveals a remarkable decrease from the highland (410 mm/year) towards the rift floor (25 mm/year). Both the spatial and temporal recharge variability is mainly controlled by the climate. In the rift floor, recharge is found to occur only when annual precipitation exceeds a threshold of approximately 800 mm. A sensitivity analysis reveals that annual recharge is very sensitive to variations in precipitation and moderately sensitive to temperature changes. The relative sensitivity increases from the highland to the rift floor across the watershed. Increases in both precipitation and temperature, as suggested by climate change projections for Ethiopia, appear to have an overall positive impact on recharge in the majority of the catchment. These findings have implications also for other catchments where recharge is spatially nonuniform and provide a basis for further investigations into the assessment of groundwater resources and their vulnerability to climate change at the watershed and sub-watershed scale.

1. Introduction

For long Ethiopia's groundwater potential is believed to be of limited extent when compared to surface water resources, yet compared to other countries the total exploitable groundwater potential is high (Awulachew et al., 2007; Kebede, 2013). However the distribution, availability and accessibility of this groundwater are erratic both in space and time (Calow et al., 2010). This variability is directly linked to recharge, the entry of water into the saturated zone (Freeze and Cherry, 1979). The total annual recharge for the entire Ethiopia is estimated to be 36 billion m^3/year (Kebede, 2013). The distribution of this recharge however significantly varies spatially and temporally as it depends on a wide variety of factors such as climate, topography, vegetation, soil, and geology. Therefore, understanding the spatial and temporal variability of groundwater recharge is critical for sustainable development and management of groundwater resources. Although groundwater research has been done at a variety of different scales in Ethiopia, there have been few attempts (Chernet, 1993; Tilahun and Broder,

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2009) to quantify the spatial and temporal variability of recharge. As a result the fundamental aspects of groundwater recharge such as its timing, magnitude and distribution have not been well defined.

Likewise, the potential impact of future climate change on groundwater recharge is almost ignored in Ethiopia, although the potential effects of climate change on water resources, in general, have been of great concern. The existing assessments of climate change impacts (e.g. Legesse et al., 2003; Bates et al., 2008; Abeye et al., 2009; Elshamy et al., 2009; Beyene et al., 2010; Taye et al., 2011; START, 2013; Mengistu and Sorteberg, 2012; Faramarzi et al., 2012; IPCC, 2007, 2013; Kebede et al., 2013; Tekle and Tadele, 2014; Aich et al., 2014; Taye et al., 2015) have mainly focused on surface water and comparatively little is known about the potential impacts on groundwater recharge. Yet, the impacts on groundwater recharge are far reaching and need to be investigated, particularly in Ethiopia, where most people rely on groundwater as a source of potable water for drinking and other domestic uses. Changes in groundwater recharge due to climate change might cause decreasing groundwater levels in shallow unconfined aquifers and thus potentially can cause the drying up of springs and shallow boreholes. Similarly, groundwater recharge has immense importance for sustaining baseflow and therefore for the existence of many surface water resources such as lakes and rivers, e.g., in the Ethiopian Rift. A first water balance estimation indicates that around 50% of the total inflow to terminal lakes is groundwater coming through large open faults (Ayenew, 1998). However, fissured aquifers are highly vulnerable to variations in recharge, due to their low storativity, which may represent only three years of average infiltration (Wyns et al., 2004). Groundwater is a vital water resource and awareness needs to be raised on its vulnerability to overexploitation, pollution and climate change.

The spatial distribution of groundwater recharge and also the potential impact of climate change on groundwater recharge are likely to be most diverse in regions with highly variable physiographic characteristics such as the Main Ethiopian Rift (MER) (Fig. 1). In particular, climatic parameters such as precipitation and air temperature vary strongly from the rift floor towards the escarpment and the highland. Tilahun and Broder (2009) obtained an estimated average recharge of 28 mm per year for the Dire Dawa basin, a semi-arid area at the eastern margin of the northern MER. However, 80% of this recharge was found to occur in the escarpment, where local recharge rates were estimated to be up to 200 mm per year. Runoff generation and recharge mechanisms vary greatly within the different physiographic regions of the MER. Consequently, the sensitivity of groundwater recharge to climate change is also likely to show high spatial variability.

The goal of this study is (i) to characterize the spatial and temporal variability of recharge and identify the various drivers that govern its distribution and (ii) to improve the understanding of the response/sensitivity of groundwater recharge to changes in precipitation and air temperature in the MER. For this purpose, the Gidabo River Basin, which is located in the southern MER, is considered as the study area.

To account for the spatial heterogeneity of the watershed in terms of soil, land-use and slope characteristics, the semi-distributed hydrologic model SWAT (Arnold et al., 1998; Neitsch et al., 2011) is employed. Besides other water balance components, the spatial and temporal distribution of groundwater recharge is obtained from the model output. While other, more direct methods for recharge estimation are available (for an overview see e.g. Scanlon et al., 2002; Sophocleous, 2004), their application at the watershed scale appears to be impracticable in the given case. In addition, the model-based estimation of groundwater recharge allows examining the sensitivity of groundwater recharge to changes in air temperature and precipitation. This represents a first step towards an assessment of the aquifers' vulnerability to climate change. Scenario-based assessments, where a hydrological model is driven by climate change scenarios derived from downscaled GCMs have been found to result in high uncertainty of the projected recharge (Kurylyk and MacQuarrie, 2013). Motivated by the "alternate approach" suggested by Brown and Wilby (2012) the focus of this work is shifted to the hydrological system and its general sensitivity to changes in climatic parameters. The results from this sensitivity study will then be discussed in the light of existing projections of climate change.

2. Study area

The Gidabo River Basin is located in the south-eastern MER (Fig. 1). The River Gidabo winds through forested and agricultural land of escarpment and rift floor, finally terminating in Lake Abaya, the largest lake in the rift valley. The river is approximately 120 km in length with an estimated 3302 km^2 contributing source area. It originates on the north-eastern mountains of Soka Sonicha.

The area is covered by a variety of volcanic rocks (basalt, ignimbrites, rhyolites, trachytes and pyroclast) and to a minor part by lacustrine sediments (AG consult, 2004; Mechal, 2007; Halcrow, 2008; GSE, 2012). These rocks are highly affected by the late tertiary rifting activity and erosional processes (Wolde Gabriel et al., 2000) which resulted in a wide range of elevations from 1175 m a.s.l. at Lake Abaya in the west to about 3200 m a.s.l. at the Gelala summit in the north east. As a result of typical rift morphology the three major physiographic regions, rift floor, escarpment and highland are obvious.

Climate in the Gidabo River Basin ranges from semi-arid in the rift floor to humid in the mountains of the escarpment (Fig. 2). In the highlands and escarpment bounding the rift floor precipitation exceeds 1600 mm/year, whilst at the lowest altitude in the rift floor precipitation is often below 800 mm/year. Precipitation is characterized by a bimodal pattern with maximum peaks during April and May ("small rainy" season) and during September and October in the "main rainy" season. Like in most parts of Ethiopia, the diurnal variation of air temperature in the basin is more visible than its seasonal variation. Average monthly temperature varies from 21 °C to 25 °C in the rift floor to less than 11.5 °C to 13.5 °C in the high altitude plateau (highland).

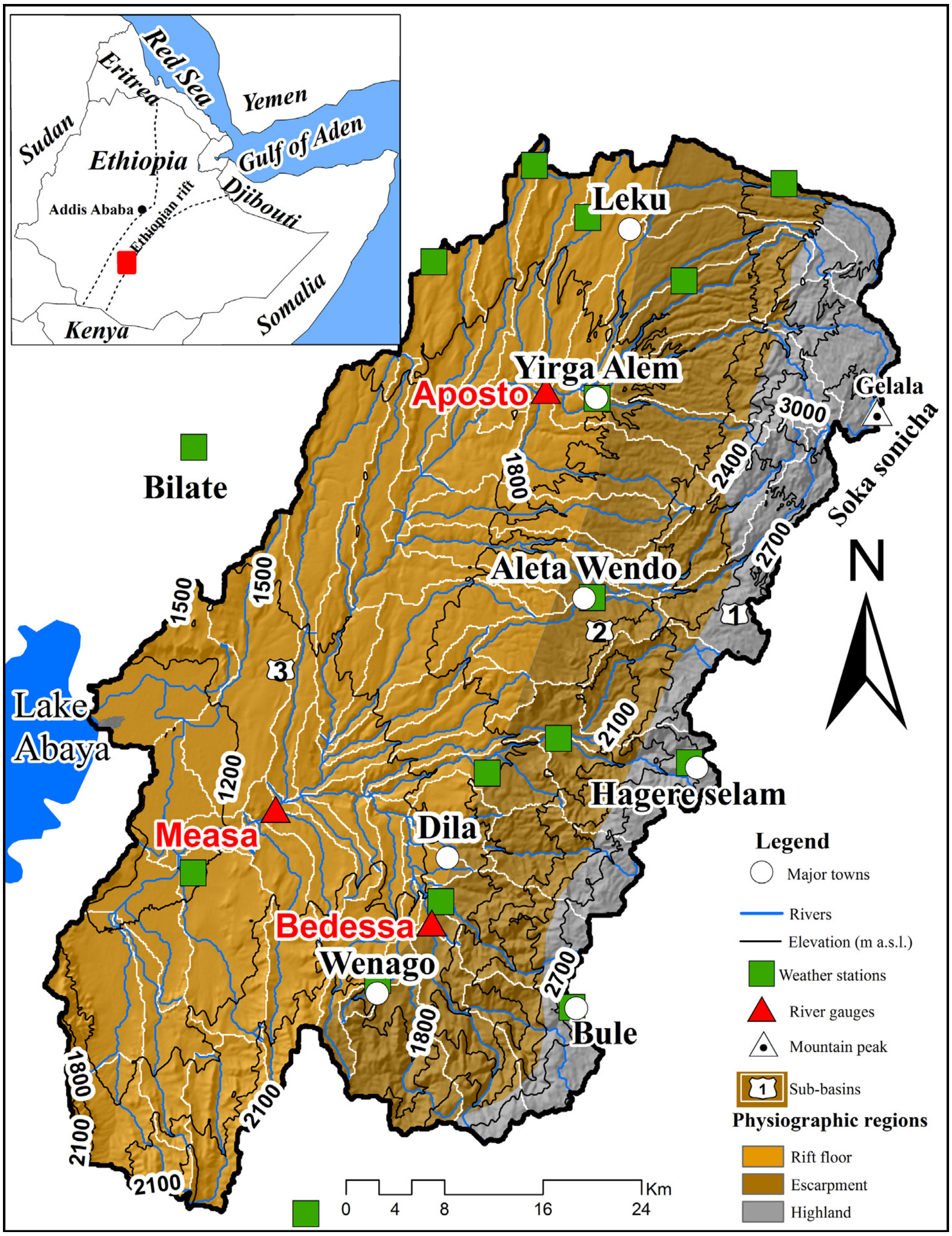

Fig. 1. Location map of the Gidabo River Basin showing topography, weather stations, river gauges, river network, the sub-basins including the three sub-watersheds representing the highland (1), escarpment (2) and rift floor (3) and the physiographic regions. Highland, escarpment and rift floor approximately coincide to the following elevation ranges 2400–3207, 1800–2400, and 1170–1800, respectively. The inset map shows the location of the Gidabo River Basin (red polygon) within the Ethiopian rift. The names belongs to either to the towns (black) or river gauging stations (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3. Methods

The "Soil and Water Assessment Tool" SWAT (Arnold et al., 1998) and the calibration and uncertainty program "Sequential Uncertainty Fitting Algorithm version 2" SUFI-II (Abbaspour et al., 2004, 2007) were applied to the Gidabo watershed. SWAT is a physically based long-term continuous time watershed-scale model developed initially to predict the impact of agricultural or land management practices on water, sediment and agricultural chemical yields in large complex watersheds. It is also capable of predicting water yield, nutrient, and sediment loading under climate-change scenarios (Neitsch et al., 2011). SWAT is a semi-distributed model operating on a daily time-step. A high level of spatial variability can be simulated, since SWAT allows the division of the watershed into a large number of sub watersheds, which are then further subdivided into unique combinations of soil, land use and slope characteristic areas called hydrological response units (HRUs). The HRUs

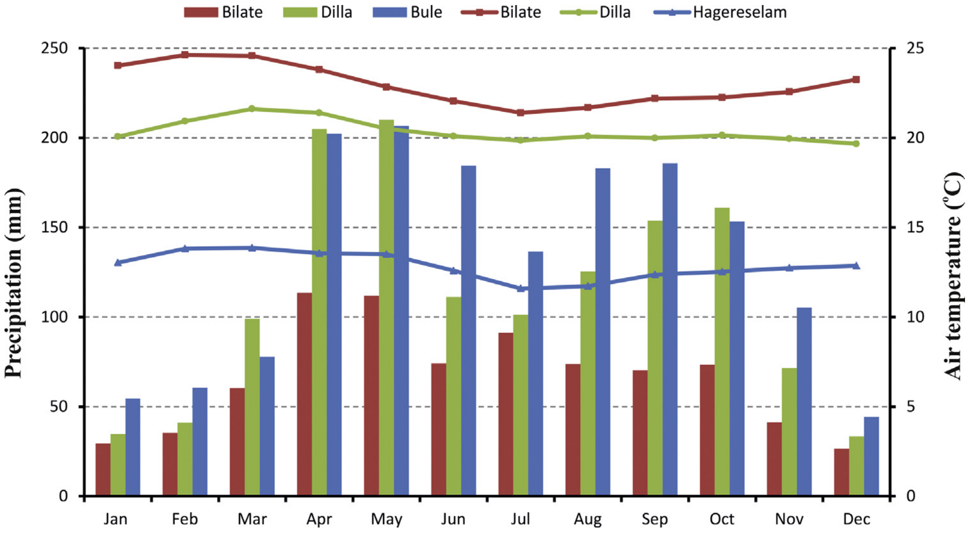

Fig. 2. Mean monthly precipitation and air temperature data at four selected stations in the Gidabo River Basin (Bilate in the rift floor, Dilla in the escarpment and Bule and Hagere selam in the highland).

are used to describe spatial heterogeneity in terms of land cover, soil type and slope class within a watershed. The HRUs are defined by means of a coupled GIS (geographical information system) tool based on a digital elevation model (DEM), land cover and soil maps. The water balance is the main driving force in SWAT. For each HRU the water balance is represented by five storage components: canopy interception, snow, soil profile, shallow aquifer, and deep aquifer.

The hydrological processes simulated by SWAT include precipitation, interception, infiltration, surface runoff, evapotranspiration, percolation, and lateral subsurface flow within both the soil and the aquifer (Arnold et al., 1998; Neitsch et al., 2011). Surface runoff was estimated using a modified Soil Conservation Service (SCS) curve number method (USDA Soil Conservation Service, 1972). Due to a lack of sufficient climate data, the Hargreaves method (Hargreaves and Samani, 1982) was applied to estimate potential evapotranspiration (PET) instead of the more data-demanding Penman–Monteith (Allen, 1986; Allen et al., 1989; Monteith, 1965) and Priestley–Taylor (Priestly and Taylor, 1972) methods available in SWAT. Oudin et al. (2005) demonstrated that rainfall-runoff models using such parsimonious temperature-based methods may perform similarly well or even better in terms of model fit than more data-demanding approaches. Nevertheless, the accuracy of the PET calculation deserves further consideration, particularly with regard to the semi-arid parts of the model area.

The excess water available after initial abstractions and surface runoff infiltrates into the soil. The soil profile is subdivided into several layers. Percolation is simulated for each layer in the soil profile. When the soil water in the layer exceeds field capacity, downward flow occurs and its rate is governed by the saturated hydraulic conductivity. The flow through each soil layer is simulated using a storage routing technique. Lateral subsurface flow in the soil profile is calculated simultaneously with percolation using a kinematic storage routing technique based on slope, slope length, and saturated conductivity. Likewise, the upward flow of plant water uptake and soil water evaporation between layers is simulated using a depth distribution approach. Water that moves past the bottom of the soil profile by percolation enters and flows through the vadose zone before becoming aquifer recharge. An exponential decay weighting function is utilized to account for the time delay in aquifer recharge once the water exits the soil profile. SWAT partitions groundwater into two aquifers systems: a shallow aquifer which contributes return flow to streams within the watershed and a deep aquifer which contributes to return flow to streams outside the watershed. The recharge is accordingly subdivided into shallow and deep aquifer recharge. Neitsch et al. (2011) describe the implementation of the aforementioned hydrological processes in SWAT in more detail.

Calibration and validation is performed by SWAT-CUP (Calibration and Uncertainty Program) using the SUFI-2 algorithm, as it represents uncertainties of all sources (e.g., data, model, etc.) (Yang et al., 2008) and can perform parameter sensitivity analysis to identify those parameters that contribute most to the output variance. A comprehensive description of the SUFI-2 algorithm can be found in Abbaspour (2011). Since the SWAT model is calibrated using measured stream flow data, the recharge estimation is based on surface-water studies and numerical modelling according to the classification by Scanlon et al. (2002). Thus, recharge is estimated as a residual term in the water balance equation. Therefore, the accuracy of the estimate is controlled by the accuracy of the measured water balance components—see Scanlon et al. (2002) and the references provided therein for a more detailed discussion.

3.1. Model input

The Shuttle Radar Topographic Mission (SRTM) DEM data with 90 m resolution (Jarvis et al., 2006) was used to delineate the Gidabo River watershed into 63 sub-basins (Fig. 1). The sub-watersheds are delineated such that they represent

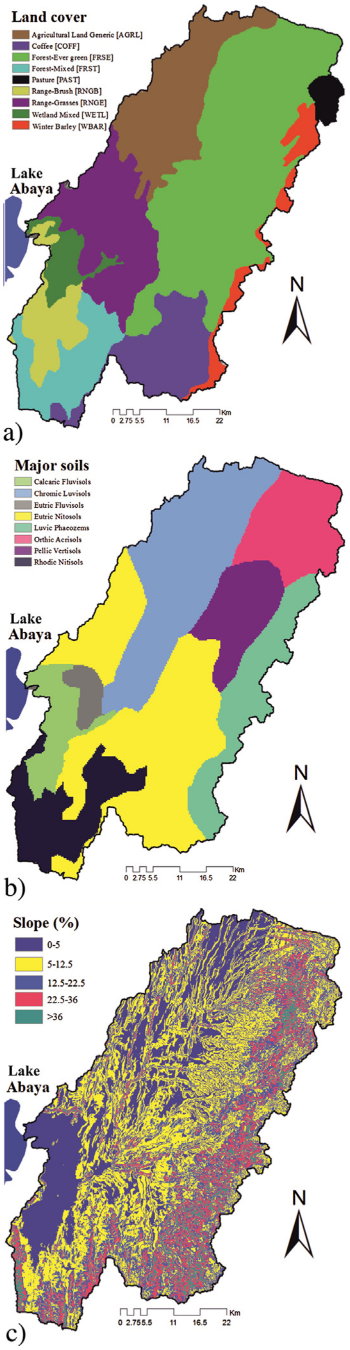

Fig. 3. Soil types (a), land cover (b) and slope (c) maps of the Gidabo River Basin.

the physiographic regions (highland, escarpment and rift floor). The land cover data obtained from the Ministry of Water Resources of Ethiopia (Halcrow, 2008) were used for parameterizing the SWAT model. The land uses were divided into nine major groups (Fig. 3a): Forest-Ever Green (FRSE, 38.5%), Agricultural Land Generic (AGRL, 14.6%), Range-Brush (RNGB, 14.6%), Coffee (COFF, 9.7%), Forest-Mixed (FRST, 8.1%), Range-Grasses (RNGE, 5.6%), Winter Barley (WBAR, 4.0%), Wetland Mixed (WETL, 3.4%), and Pasture (PAST, 1.5%). Soil physical and chemical properties such as soil texture, available water content, hydraulic conductivity, bulk density and organic carbon content for different layers of each soil type were obtained from Halcrow (2008), Raunet (1977) and WWDSE (2007). Major soil types in the basin are Eutric Nitosols (30.5%), Chromic Luvisols (22.9%), Orthic Acrisols (10.5%), Luvic Phaeozems (10.2%), Rhodic Nitisols (10.0%), Pellic Vertisols (8.1%), Calcaric Fluvisols (5.8%), and Eutric Fluvisols (2.0%) (Fig. 3b). The land use, soil and slope (Fig. 3c) data sets were imported, overlaid

Table 1
The 12 most sensitive parameters and their relative sensitivity; parameter ranges and calibrated value (spatially constant parameters) or relative change (distributed parameters) used during calibration processes.

Parameter	Definition	Relative sensitivity [−]	Paramter range	Calibrated value/change
ESCO	Soil evaporation compensation coefficient, modifying the depth distribution of the evaporation demand within the soil [−]	0.28	0.7–1	0.90
CN2	SCS runoff curve number for average moisture (moisture condition II) [−]	0.12	±0.25%	−0.03%
ALPHA_BF	Base flow recession constant [1/day]	0.12	0–1	0.41
REVAPMN	Threshold water level in shallow aquifer for, water movement from the aquifer into the soil in response to water deficiencies (“revap”) [mm H_2O]	0.10	1–500	55.45
CANMX	Maximum canopy storage [mm H_2O]	0.08	0–10	0.23
SOL_AWC	Available water capacity [mm H_2O/mm soil]	0.07	±0.25%	−0.19%
GWQMN	Threshold water level in shallow aquifer for base flow [mm H_2O]	0.06	0–5000	57.25
RCHG_DP	Aquifer percolation coefficient, defining the portion of the recharge moving into the deep aquifer [−]	0.05	0–1	0.14
SOL_Z	Soil thickness [mm]	0.05	±0.25%	−0.08%
GW_REVAP	Revap coefficient, defining the maximum amount of water (relative to potential evapotranspiration) moving from shallow aquifer into soil [−]	0.04	0.02–0.2	0.10
CH_K2	Effective hydraulic conductivity of channel [mm/hr]	0.01	0–250	67.50
SOL_K	Saturated hydraulic conductivity [mm/hr]	0.01	±0.25%	−0.02%

and linked with the SWAT databases. Threshold values of 20% land use, 10% soil and 20% slope were used to discretize the sub-watersheds into 278HRUs.

The weather variables used for driving the water balance are daily precipitation, minimum and maximum daily air temperature. These data were obtained from the Ethiopian National Meteorological Agency (NMA) for weather stations located within and in close proximity to the watershed (Fig. 1). In the rift center where there is a lack of meteorological stations, daily precipitation and temperature data were obtained from the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) website (http://globalweather.tamu.edu/). During simulation each sub-basin is linked to the nearest weather station. Daily stream flow data of three gauging stations (Fig. 1) obtained from the Hydrology Department of the Ministry of Water Resources of Ethiopia was used for model calibration and validation.

3.2. *Sensitivity analysis*

A parameter sensitivity analysis was done using the ArcSWAT interface and the built-in SWAT sensitivity analysis tool (Van Griensven et al., 2002; Van Griensven and Bauwens, 2005). As suggested by Neitsch et al. (2011), the sensitivity of the simulated stream flow to twenty eight hydrological parameters was tested using the default lower and upper bound parameter values. Based on the sensitivity test, 12 parameters have considerable effect on stream flow simulation, which means that they have a relative sensitivity of more than or equal to 0.01 (Table 1). These parameters were selected for the calibration process. A detailed description of all hydrological parameters is given in the ArcSWAT interface for SWAT user’s manual (Neitsch et al., 2011).

3.3. *Calibration and validation*

Hydrological models usually contain parameters that need to be estimated through calibration so that observed and predicted output values are in agreement (Tolson and Shoemaker, 2007; Zhang et al., 2009, 2011). A regionally varied auto-calibration procedure is followed using monthly river discharges from three stations, so that around 75% of the watershed is accounted for (Fig. 1). The parameter distributions initially estimated based on soil type, land use, and slope were calibrated using global modification terms. In other words, the initial values of each parameter were changed either by the same percentage within the entire watershed or by adding a fixed value. The first three years of the available data from 1995 to 1997 were used as warm-up period to mitigate the unknown initial conditions and were excluded from the analysis. The period from 1998 to 2005 was used for calibration and the period from 2006 to 2010 for validation. As Gidabo at Measa station has no data for 2006–2010, no model validation was carried out in this case.

Following the recommendation of Gan (1998) both manual and automatic calibration procedures were employed. The model was calibrated manually following a multi-step procedure recommended by Neitsch et al. (2011). The upper watersheds (Fig. 1) (Gidabo at Aposto and Bedessa) were separately calibrated at first, and the parameters in those sub-watersheds were then held constant while the lower watershed (Gidabo at Measa) was calibrated. During the calibration, the parameters were allowed to vary within given ranges to obtain the optimal parameter values or relative changes in the case of spatially varying parameters (Table 1) to minimize the differences between observed and simulated flows and to reproduce the seasonal characteristics. Finally, the Sequential Uncertainty Fitting Program (SUFI-2) of the SWAT-CUP package was used for parameter optimization. During the calibration processes the parameters were allowed to vary within given ranges to

Table 2
Evaluation of the hydrological goodness of fit of the monthly streamflow of three gauging stations (Aposto, Bedessa and Meassa) in the studied basin.

	Gauging station		
	Aposto	Bedessa	Measa
Warm up period	1995–1997		
Calibration period	1998–2005		
Coefficient of determination (R^2)	0.60	0.65	0.70
Nash-Sutcliffe coefficient (NSE)	0.70	0.54	0.80
Percent bias (PBIAS)	3.60	−16.00	−17.50
Validation period	2006–2010		
Coefficient of determination (R^2)	0.71	0.80	–
Nash-Sutcliffe coefficient (NSE)	0.65	0.70	–
Percent bias (PBIAS)	10.00	−14.50	

- No data available.

obtain the optimal parameter values or relative changes in the case of spatially varying parameters (Table 1). The parameter ranges are based on the recommendations given in the SWAT documentation of Neitsch et al. (2011).

For goodness-of-fit judgment of the model, the coefficient of determination (R^2), the Nash-Sutcliffe Efficiency (NSE) (Krause et al., 2005) and percent bias (PBIAS) (Gupta et al., 1999) were calculated (Table 2). The model shows slight overestimation during high flow (Fig. 4). At least partly, this might be related to the quality of the input data sets, in particular precipitation and soil properties, used during the modeling processes. The weather stations are mainly assembled along the foot of the escarpment (Fig. 1); as a result the spatial variability of rainfall in the catchment is not very well represented in the model. Similarly the area is covered by heterogeneous soil with different properties (Halcrow, 2008) such as soil texture, thickness and hydraulic conductivity. However, the existing soil data have regional character and lack spatial resolution (Fig. 3b). In addition, river flow measurement errors also contribute to uncertainties during high flow periods. Since medium and low flow at Bedessa and Measa are well reproduced by the model, the overestimation of high flows results in a negative percent bias for these stations (Table 2). In contrast, the overestimation of the high flows is more than compensated by an underestimation of low flows at Aposto, such that the overall percent bias is slightly positive. While the good agreement with the observed baseflow recession at Bedessa and Measa indicates that the simplified linear-storage representation of groundwater in SWAT is adequate for large parts of the catchment, it might be the cause of the deviations apparent during low flow at Aposto. Nevertheless, the overall model performance is found to be satisfactory for all discharge stations for both calibration and validation periods (Table 2 and Fig. 4). The calibrated parameters are also used for the ungauged part of the watershed. Recharge was computed at the HRU scale and the results aggregated to the sub-basin scale. Due to a lack of groundwater level monitoring wells in the watershed, it was not possible to compare the simulated recharge with groundwater level fluctuations.

3.4. Climate sensitivity analyses

Climate sensitivity analyses were performed by perturbing the meteorological input parameters (precipitation and temperature) of the baseline SWAT model. The objective of this approach is not to determine with any degree of confidence what specifically would or will happen in the future as a result of climate change, but to examine the general behavior of the hydrological system and, in particular, the responsiveness of groundwater recharge to possible changes in climatic input parameters. Nevertheless, the overall range of the perturbations is based on results from climate projection studies (e.g. Bates et al., 2008; McSweeney et al., 2008; Conway, 2009; Elshamy et al., 2009; Beyene et al., 2010; Taye et al., 2011; Williams and Funk, 2011; Conway and Schipper, 2011; Diro et al., 2008; James and Washington, 2012; Faramarzi et al., 2012; IPCC, 2007, 2013; Aich et al., 2014; Taye et al., 2015) within Ethiopia, east Africa and Africa in general. These studies reported that temperature is expected to rise for all seasons in all regions of Ethiopia within the next 100 years. The rising in temperature has been consistent among climate models (e.g. Elshamy et al., 2009; James and Washington, 2012; IPCC 2007; 2013; Kebede et al., 2013). Within the ranges of high and low emission scenarios, the average warming across all models shows temperature increases of approximately 1 to 4 °C by the end of the century. On the contrary, modifications of rainfall patterns are expected both in intensity and in total amount. However, the projected change in rainfall varies seasonally and does not manifest a systematic increasing or decreasing trend all over the year (Conway et al., 2007; Bates et al., 2008; Abdo et al., 2009; Elshamy et al., 2009). Moreover, precipitation projections over Ethiopia indicate a wide range of spatial pattern (Conway and Schipper, 2011; McSweeney et al., 2008). Nevertheless, in general, the projection studies are broadly consistent in indicating an overall increase in annual rainfall with annual changes reaching up to +20%, in some places even more. The increase is largely a result of increasing rainfall in the wet seasons and less severe droughts during dry season (McSweeney et al., 2008).

Based on climate projection studies, the perturbations applied are precipitation changes of +10% and +20% and temperature increases of +1, +2, +3 and +4 °C and combination of the above temperature and precipitation conditions. Predicting the change of climate variables in the future generally involves high uncertainty due to internal variability of the climate system, future greenhouse gas and aerosol emissions, translation of these emissions into climate change by global climate models

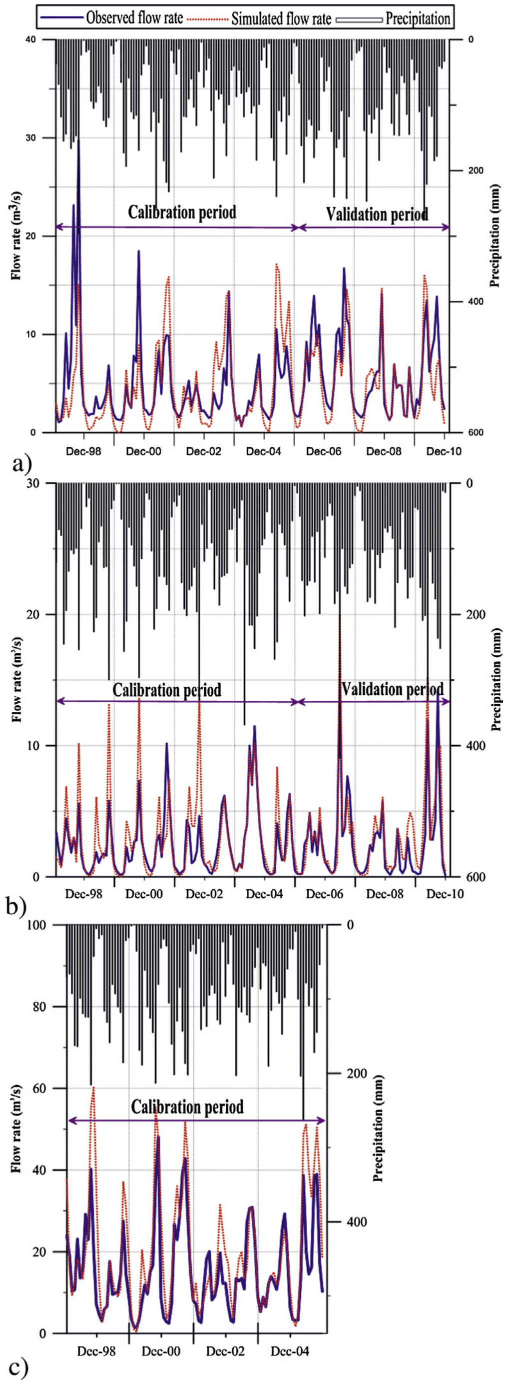

Fig. 4. Simulated versus measured monthly flow rates and precipitation of Aposto (a), Bedessa (b) and Measa (c) rivers during the calibration and validation period.

and downscaling from the GCMs to the scale of a hydrologic model. Taking these uncertainties into account and for better understanding of the system's sensitivity to climate a potential decrease in precipitation (−10% and −20%) and temperature (−1 and −2 °C) were also considered in the analysis. Precipitation, temperature and potential evapotranspiration vary seasonally in the area of study (Fig. 2; Mechal, 2007), and as a consequence the sensitivity of recharge to these parameters can be highly different between dry and wet periods (e.g. Jyrkama and Sykes, 2007; Mileham et al., 2009). Therefore one additional scenario with a seasonally varying change in precipitation (−10% within the dry season, +10% within the wet season) is

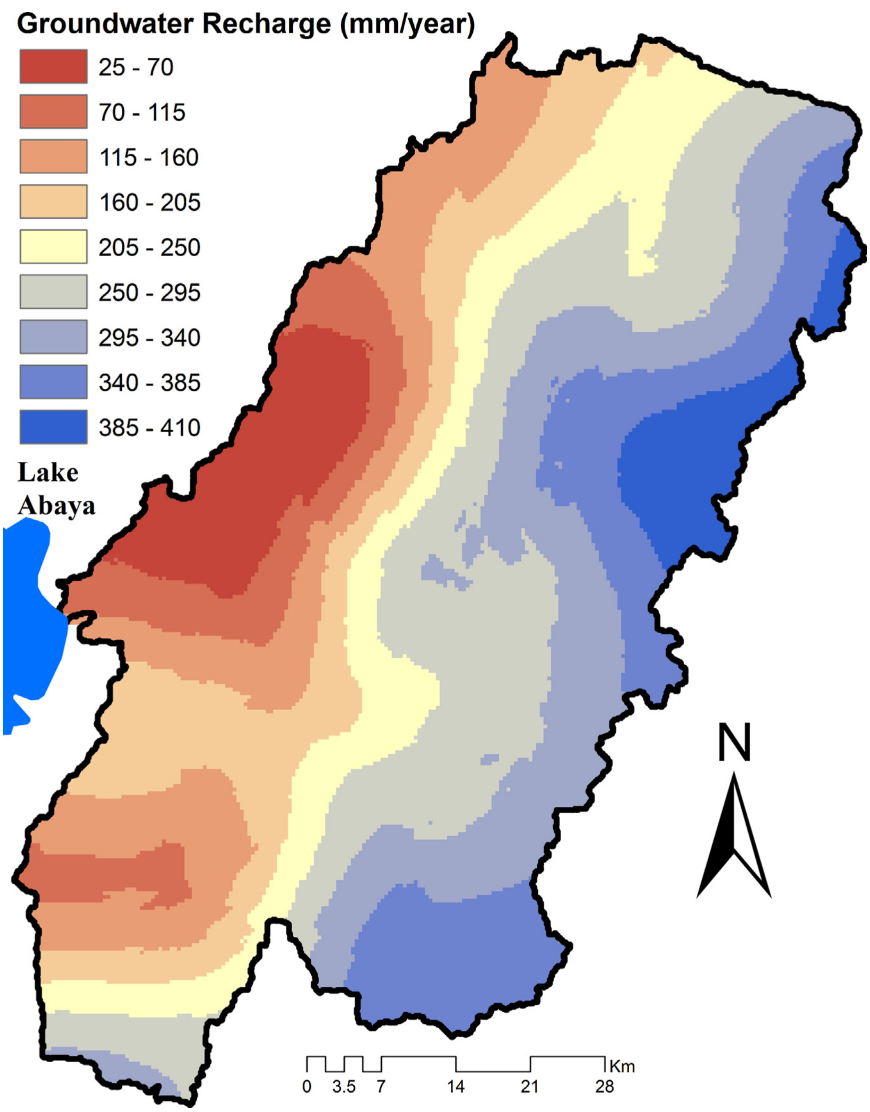

Fig. 5. Spatial variation of simulated long term average annual recharge in the Gidabo River Basin.

considered for comparison. Climatic variables such as relative humidity, wind speed, cloud cover and solar radiation were considered to be unchanged.

4. Results and discussion

4.1. Current recharge variability

4.1.1. Spatial recharge variability

The long term average annual recharge (1998–2010) obtained from the SWAT model for the whole Gidabo River Basin is estimated to be approximately 236 mm/year with a standard deviation (STD) of 99 mm/year. Yet the spatial distribution shown in Fig. 5 reveals a clear spatial pattern with a remarkable decrease of recharge from the highland (410 mm/year) towards the rift floor (25 mm/year) reflecting the great differences in climatic conditions as well as soil and land use characteristics in the three distinct physiographic regions. The obtained recharge for the three physiographic regions highland, escarpment and rift floor (Fig. 1) are 358 mm/year (STD 35 mm/year), 308 mm/year (STD 49 mm/year), and 174 mm/year (STD 76 mm/year), respectively. The high variability of the recharge in the rift floor is shown by a high standard deviation which is due to the greater variability in land use, soil, slope and climate variables within this largest physiographic region (Figs. 1, 3).

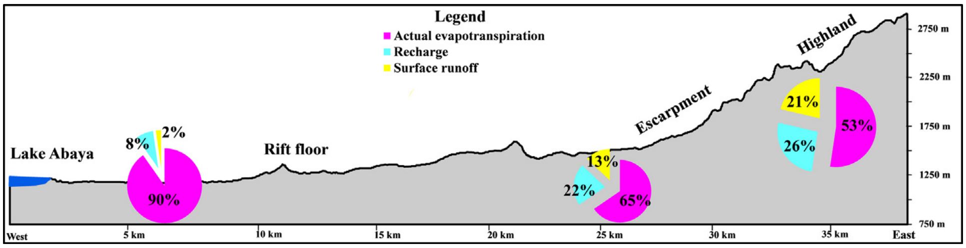

Fig. 6. Partitioning of the mean annual rainfall into actual evapotranspiration, recharge and surface runoff within the three physiographic regions of the watershed.

Since SWAT considers only soil moisture excess recharge, the simulated recharge might be underestimated where there would be a focused recharge along open faults in the rift floor instead leading to higher surface runoff. This is consistent with (and might partly explain) the frequent overestimation of peak flows apparent in the simulated hydrographs (see Fig. 4 and related discussion in Section 3.3). The spatial pattern of recharge in the watershed was found to be similar in different years, although the magnitudes of the annual recharge differed (see Section 4.1.2 on temporal recharge variability).

The systematic decrease in precipitation and increase in temperature from the highland towards the rift floor (Fig. 2) indicates that the spatial variability of recharge across the watershed is mainly controlled by climate rather than by soil and land use. Evapotranspiration is a major source of water loss in the water balance of the watershed and accordingly, beside precipitation, a major control on the recharge distribution. On average evapotranspiration accounts for more than 50% of precipitation, but in the rift floor it may reach up to 90% of precipitation (Fig. 6). However, within each physiographic region, relief and the climatic parameters precipitation and temperature are rather similar such that topography and climate are less significant than land cover and soil type in influencing the internal spatial recharge distribution. For instance, in the southeast of the watershed (comprising highland and escarpment), recharge is relatively low despite significant rainfall. This is attributed to the low saturated hydraulic conductivity of the Eutric Nitosols and the high evapotranspiration rates in the coffee cover. Similarly, in the rift floor close to Lake Abaya, recharge is relatively high as a result of the high hydraulic conductivities and high infiltration rates in the Calcaric Fluvisols. Thus, the overall pattern of the recharge distribution is mainly controlled by the climatic variability across the watershed. However, the small scale pattern is modified by variations in soil and land use.

4.1.2. *Temporal recharge variability*

Recharge is found to vary both inter-annually and intra-annually within the Gidabo River Basin. To examine the recharge variability across the watershed, three representative sub-watersheds were selected in each physiographic region (sub-basin 1 - highland; sub-basin 2 - escarpment; sub-basin 3 - rift floor) (Fig. 1). Fig. 7a shows the relationship between annual recharge and precipitation from 1998 to 2010 in the three physiographic regions. Years of high recharge are clearly associated with years of high rainfall. Following the general trend in precipitation, a slight increase in recharge is observed within this period. In the highland and escarpment recharge occurred in all years, whereas in the rift floor recharge occurred only when annual precipitation exceeded approximately 800 mm. This suggests a threshold related to the extremely high evapotranspiration in the rift floor that needs to be exceeded to allow recharge (Fig. 6).

Intra-annual recharge variability is evident and significant, with the amount of variability largely dictated by the temporal distribution of precipitation (Fig. 7b). Recharge follows a bimodal annual cycle of wet and dry periods and is highest in the wet periods of August to October for the highland and escarpment and April to June for the rift floor. Even though the amount of recharge is variable, in the highland and escarpment recharge occurs throughout the year. In contrast, in the rift floor recharge occurs only in the rainy season from April to October.

4.1. *Sensitivity of recharge to climate parameters*

4.2.1. *Sensitivity to precipitation changes*

The sensitivity of annual groundwater recharge to changes in precipitation is found to be non-uniform across the watershed (Figs. 8 a, b and 9 a). The relative change of recharge increases from the highland toward the rift floor. A reduction of precipitation by 20% causes a higher relative change in recharge ranging from a decrease by approximately 40% in the highland to a decrease by more than 80% in the rift floor. A 20% increase in precipitation even produces increases in recharge ranging from approximately 30% in the highland to more than 100% in the rift floor.

As precipitation within the rift floor appears to be close to a threshold that needs to be exceeded to cause recharge, increased precipitation is expected to have a pronounced positive impact on groundwater recharge in the rift floor (Figs. 8 b and 9 a). In contrast to the plain rift floor, the highland and escarpment are characterized by much higher precipitation and by steep slopes. Therefore, any further increase in precipitation only partly contributes to recharge, as it also increases surface runoff and lateral flow in the soil layers.

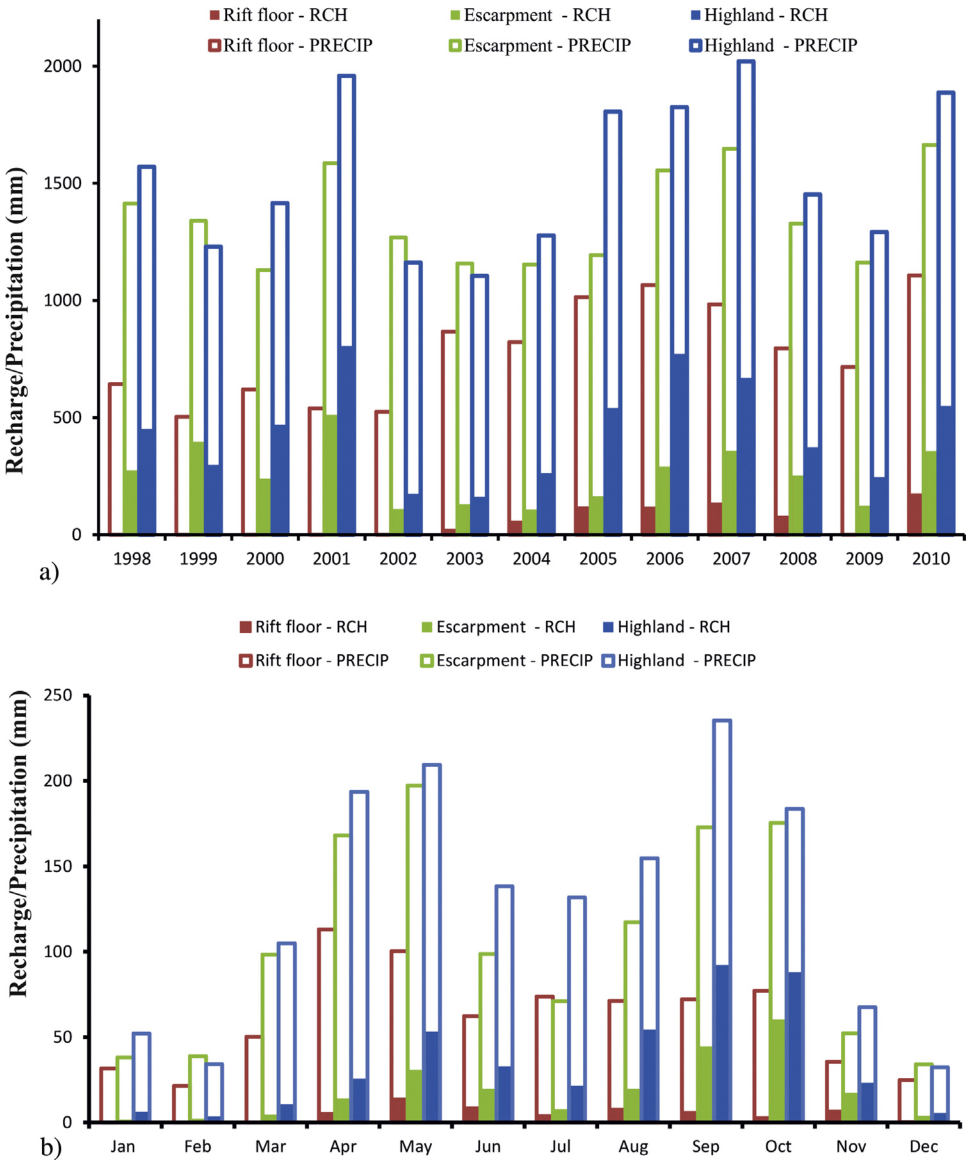

Fig. 7. Estimated (a) annual recharge and (b) long term (1998–2010) monthly recharge of the rift floor, escarpment and highland based on three representative sub-watersheds.

The Gidabo River Basin has a large number of springs, almost all of which are discharging water throughout a year, including dry seasons. However, there is high seasonal yield fluctuation and dry seasons flow is quite low, usually below 0.5 l/s (Mechal, 2007). These springs emerge from shallow aquifer systems characterized by low storage. Thus, the current sustained outflow is due to continuous supply by recharge from precipitation. Reduced precipitation would have significant impact on the discharge of these springs especially in the highland and escarpment where the majority of rural communities rely on them for drinking and other domestic uses. Moreover, the calibrated model shows that the highland and escarpment sections of the rivers gain water from the shallow aquifers, suggesting that the recharge in these parts of the watershed is also responsible for sustaining a continuous flow of water in the rivers throughout the year. A drop in recharge due to a decrease in precipitation would have significant impact on river baseflow and consequently the volume of surface water flowing to Lake Abaya.

As shown in the Section 4.1.2 the seasonal variability of recharge is largely determined by the temporal distribution of precipitation (Fig. 7b). In the watershed the driest period of a year is December–February, while the wettest period is August–October for the highland and escarpment and April–June for the rift floor. During the dry season the rift floor receives almost no recharge, whereas the escarpment and highland receive 3% to 4% of the annual recharge. More than 50% of the recharge in the watershed comes from the wettest period of a year. A similar seasonal variation in river flow is observed in

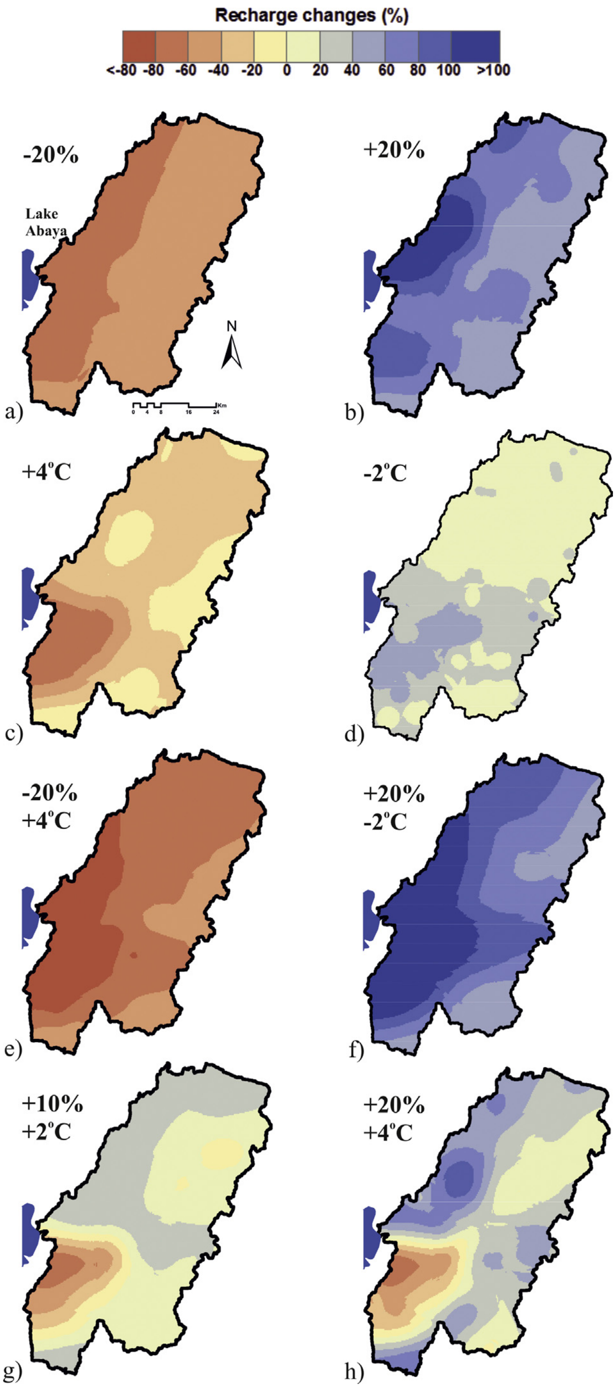

Fig. 8. Spatial long term average annual recharge changes due to (a) −20% precipitation change, (b) +20% precipitation change, (c) **+**4 °C temperature change, (d) −2 °C temperature change, (e) combination of −20% precipitation and +4 °C temperature change, (f) combination of +20% precipitation and −2 °C temperature change, (g) combination of +10% precipitation and +2 °C temperature change and (h) combination of +20% precipitation and +4 °C temperature change.

upper Blue Nile Basin, western Ethiopia (Taye and Willems, 2011, 2012, 2013). It is therefore expected that the effects of precipitation changes on recharge vary throughout the year.

To investigate how the sensitivity of recharge to changes in precipitation varies seasonally and to explore how it is affected by seasonally varying changes in precipitation, we compare the monthly recharge resulting from the two above-considered model runs with annually constant precipitation changes of −10% and +10%, respectively, with that from a scenario with −10% precipitation change in the dry period and +10% precipitation change in the wet period (Table 3; Fig. 10).

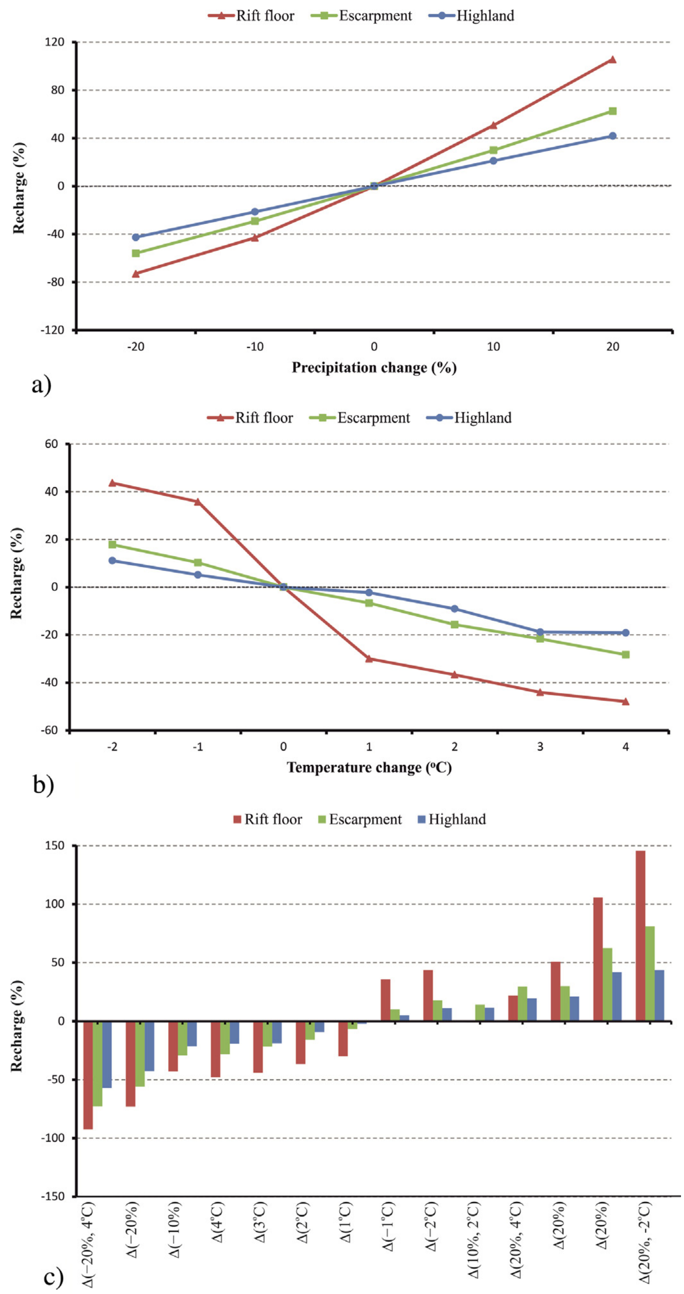

Fig. 9. Long term average annual recharge changes (%) due to changes in precipitation (a), temperature (b), and combined precipitation and temperature (c) in the rift floor, escarpment and highland.

As recharge in the rift floor is close to zero in the dry season, any change in precipitation causes a large relative change in recharge (see Figs. 8 b and 9 a). Nonetheless, the absolute change in monthly recharge and their contribution to the annual change is low (Table 3). In the escarpment and highland recharge occurs throughout the entire year and therefore the impact of changes in precipitation within the dry season is more important as compared to the rift floor. However, the absolute changes of the monthly recharge are still much higher in the wet season. Consequently, it becomes clear that the absolute recharge change in the dry season is by far lower than that in the wet season. In other words, the annual recharge is highly sensitive to precipitation changes in the wet season, while a change in the dry season has little effect.

Table 3 and Fig. 10 further show how the calculated changes in monthly recharge are influenced by the seasonal pattern of precipitation changes. In the scenario with an increase of precipitation only during the wet season the recharge change in the wet season is lower than that in the scenario with the same precipitation increase during the entire year. This difference is related to the soil moisture storage and thus most pronounced at the beginning of the wet season. As a result, the recharge

Table 3
Absolute change of recharge compared to the calibrated model due to changes in precipitation (seasonally constant changes of +10% and −10% and seasonally varying change of −10% during the dry season and +10% during the wet season) for the three physiographic regions. Dry period is from December to February; wet period is from April to June in the rift floor and from August to October in the Escarpment and the Highland. The highlighted cells compare the change in the dry (orange) and wet (blue) season of a scenario where seasonal change is considered to that of the corresponding scenario with constant precipitation change of −10% and +10%, respectively. Green cells indicate the time period with unchanged precipitation in the scenario with seasonally varying changes.

	Scenario	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Annual	Dry period	Wet period
Rift floor	Seasonal (mm)	0.03	0.00	-0.18	-0.29	-0.03	2.57	5.60	2.42	0.16	0.32	0.03	0.11	11.75	-0.47	10.60
	+10% (mm)	2.09	0.03	0.62	0.29	1.37	6.85	7.88	2.48	1.41	2.94	2.16	2.57	30.68	0.94	17.21
	-10% (mm)	-2.52	-0.03	-0.18	-0.35	-0.03	-3.72	-5.67	-3.19	-1.16	-4.05	-2.23	-1.21	-24.35	-0.57	-12.58
Escarpment	Seasonal (mm)	0.86	-0.69	-0.47	-0.40	-0.20	-0.01	-0.43	-0.11	-0.06	4.30	7.70	16.67	27.16	-1.56	28.67
	+10% (mm)	3.12	2.11	1.73	0.40	1.54	3.42	12.54	8.20	3.97	11.46	11.23	24.76	84.47	4.24	47.44
	-10% (mm)	-5.84	-0.81	-0.51	-0.42	-1.45	-3.20	-9.80	-5.90	-2.78	-5.84	-14.30	-7.32	-58.17	-1.74	-27.47
Highland	Seasonal (mm)	0.79	-1.12	-1.44	-0.76	-0.51	-0.21	-0.03	-0.24	0.08	5.52	10.80	8.93	21.82	-3.32	25.25
	+10% (mm)	4.07	1.41	1.80	0.78	2.16	6.72	10.35	8.53	6.95	8.77	12.67	9.28	73.50	3.99	30.73
	-10% (mm)	-3.85	-1.32	-1.47	-0.76	-2.06	-6.54	-10.81	-8.63	-5.06	-9.43	-15.89	-10.71	-76.52	-3.56	-36.03

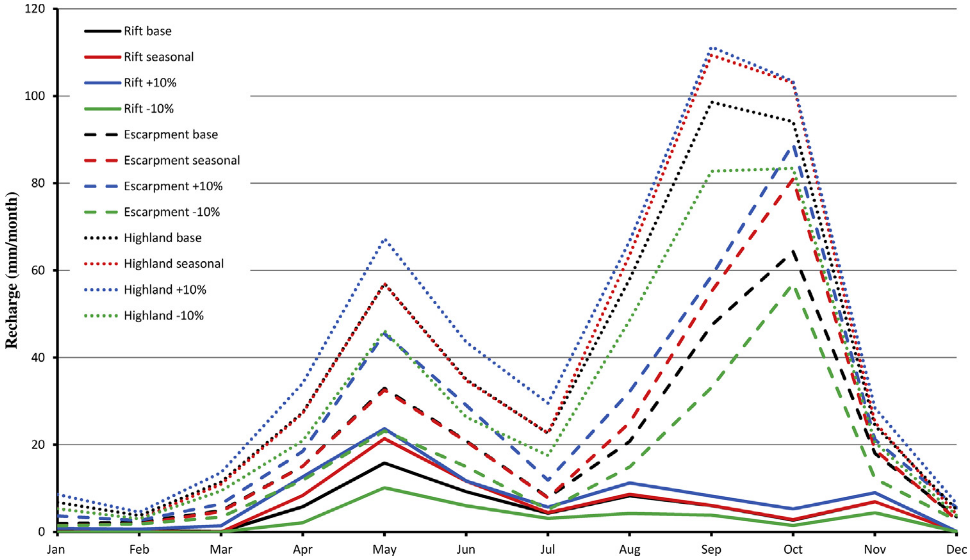

Fig. 10. Seasonal variation of recharge for the three physiographic regions in scenarios with different precipitation change: Base—no change, constant change of +10% or −10%, and seasonally varying change of −10% during the dry season (December–February) and +10% during the wet season (April–June in the rift floor; August– October in the Escarpment and Highland).

change in the wet season of the scenario with an increase in precipitation throughout the entire year is higher but still similar to that of the scenario with a seasonally varying change. The calculated changes in the dry season are found to be even less affected by the seasonal pattern of change; the changes resulting from the scenario with a decrease in precipitation throughout the entire year are very close to those from the scenario with a decrease only in the dry season (Table. 3).

4.2.2. Sensitivity to temperature changes

The relative sensitivity of recharge to changes in temperature is relatively modest in the entire watershed. Nevertheless, for increased or lowered temperature, the changes in recharge will be greater in the rift floor than in the escarpment and highland. The spatial pattern shown in Fig. 8c indicates that an increase in temperature of +4 °C may cause a reduction in recharge of up to 75% in parts of the rift floor, while the decrease is less than 10% in parts of the highland. Conversely, a decrease in temperature by 2 °C causes an increase of recharge of up to 50% in part of the rift floor, but almost no change in some areas located in the escarpment and highland (Fig. 8d). The recharge shows the highest sensitivity to temperature changes within the range from −1 °C to +1 °C in the rift floor (Fig. 9b). Outside this range, the sensitivity of recharge to changes of temperature in the rift floor is similar to that in the other physiographic regions. This suggests that under the current climate the hydrological system within the rift floor is close to a threshold where slight changes in air temperature have strong impact on groundwater recharge. Under the current conditions, precipitation and actual evapotranspiration within the rift floor are found to be nearly balanced such that recharge fluctuates around low average rates that can be zero over time periods of up to several years (see Figs. 6 and 7). As a result, a slight decrease or increase in temperature tends to shift recharge rates from zero to positive values or from positive values to zero, respectively, which results in the observed overall high sensitivity to temperature. In this sense, the high sensitivity to temperature changes is closely related to the aforementioned threshold of 800 mm in annual precipitation, which needs to be exceeded to cause recharge in the rift floor.

Thus, temperature change impacts are more significant in areas where evapotranspiration is an important part of the hydrologic cycle. The study results show that under high or low warming trends a very slight proportional change in evapotranspiration results in a high relative change in recharge and surface runoff. For instance in the rift floor where evapotranspiration is extremely high, +4 °C change in temperature causes only 3% change in actual evapotranspiration; however, this change causes a more than 30% drop in recharge and surface runoff. This shows a substantial influence of evapotranspiration on recharge in the studied watershed. Increasing temperatures will have most significant impacts in the rift floor where potential evapotranspiration is much higher than the available rainfall. The low recharge values estimated under current situations might even approach zero and lead to increased water stress in the region.

However, it is important to note that the accuracy of the residual approach employed here for estimating groundwater recharge is limited by the accuracy of the determination of the other water balance components (see Section Methods). This not only concerns the measured precipitation and stream discharge but also the approach for calculating evapotranspiration. In the present study, potential evapotranspiration is estimated based on temperature data only. As our study reveals a high sensitivity of recharge to changes in evapotranspiration within the rift floor, the recharge estimates in this part of the watershed should be further substantiated using other techniques for calculating potential evapotranspiration.

4.2.3. Sensitivity to the combined effects of temperature and precipitation

A combination of reduced precipitation and increased temperature has negative impact on recharge within the entire watershed (Figs. 8 e and 9 c), whereas a combination of increased precipitation and decreased temperature leads to a general increase in recharge (Figs. 8 f and 9 c). Yet the latest IPCC projections indicate an increase of both temperature and rainfall in Ethiopia by the end of the century, likely ranging from +0.5 °C to +4 °C and +10% to +20%, respectively (IPCC, 2013). IPCC (2013) addresses more the larger region. Nevertheless, the data might give some idea about potential changes in the watershed considered here. The results from the sensitivity analysis suggest that such possible future climatic conditions would have a positive impact on recharge within large parts of Gidabo River Basin but not in the south-western part, where recharge is found to decrease (Fig. 8g, h). This suggests that in most parts of the watershed temperature effects are offset by the projected increase in future precipitation leading overall to an increase in the available groundwater resources, while recharge is reduced in some parts of the rift floor where evapotranspiration is extremely high. However, the above discussed scenario of seasonally varying changes in precipitation (Section 4.2.1) reveals that the recharge is most sensitive to precipitation changes in the wet season. Applying the same annual increase of precipitation especially to the wet season will produce higher recharge estimates. Hence, the approach of applying constant perturbations to climate parameters needs to be seen only as a first step towards system understanding and not as a quantitative climate impact study.

5. Conclusions

In this study the well-established semi-distributed hydrological model SWAT and the calibration procedure SUFI-2 were applied to quantify the groundwater recharge and its sensitivity to climate parameters of the Gidabo River Basin, MER. The modelled recharge varies substantially in space and time over the simulation period (1998–2010). The long term annual average recharge pattern reveals a remarkable decrease of recharge from the highland (410 mm/year) towards the rift floor (25 mm/year) reflecting the great differences in climatic conditions as well as soil and land use characteristics in the three distinct physiographic regions highland, escarpment and rift floor. Recharge variability across the watershed is mainly controlled by climate; however within the physiographic regions it is attributed to soil and land use. Simulation results also suggest that recharge is highly correlated to the annual rainfall pattern and follows a bimodal annual cycle of the wet and dry periods. In addition, recharge varies considerably in different years, particularly within the rift floor where recharge is found to occur only if the annual precipitation exceeds a threshold of approximately 800 mm. The study shows that the use of a single recharge estimate for the entire basin is inappropriate when assessing the water resources in the MER area.

The sensitivity of recharge to meteorological parameters was examined by perturbing the SWAT model input parameters taking into account a potential parameter range suggested by climate change projections for Ethiopia. As a step towards a first assessment of the aquifer's vulnerability to changes in climate variables, we considered a constant change over dry and wet periods. Though this neglects seasonally variable changes in precipitation and temperature, the comparison with one scenario assuming opposite changes in precipitation in different seasons suggests that it may serve as a reasonable first approximation. The sensitivity of annual groundwater recharge to changes in precipitation or temperature as well as to a combination of both is found to be non-uniform across the watershed and the relative change of recharge increases from the highland toward the rift floor. Within the rift floor a slight change in evapotranspiration and precipitation results in relatively much higher changes in recharge compared to the other physiographic regions. Under the current state of climatic conditions the hydrological system within the rift floor is close to a threshold where slight changes in air temperature and precipitation have strong impact on groundwater recharge. In general, the annual recharge within the watershed is found to be very sensitive to variations in precipitation and moderately sensitive to temperature changes within the likely range of parameter values. The likely increase in both precipitation and air temperature as projected by IPCC appears to have a positive impact on recharge in the majority of the catchment, where the effects caused by higher temperatures may be more than offset by a projected increase in future precipitation leading to an overall increase in the available groundwater resource. However in some parts of the rift floor evapotranspiration is extremely high, which might give rise to reduced recharge despite the increased precipitation.

It must be pointed out that the sensitivity of recharge to changes of climate variables in the current study were assessed using only one hydrological model and two forcing variables (precipitation and temperature), neglecting potential changes in other variables such as vegetation, soil parameters, or radiation, which might affect the hydrological processes. Nevertheless, the findings from this study provide a basis for further research. In particular, the high sensitivity of groundwater recharge to climate variables within the rift floor as found in this study points to the need for further investigations into the groundwater recharge processes within this area addressing also future climate change impacts using regional climate model projections.

Conflict of interest

The authors declares no conflict of interest.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ejrh.2015.09.001.

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