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Evaluating the potential of Nature-based solutions to mitigate land use and climate change impacts on the hydrology of the Gefersa and Legedadi watersheds in Ethiopia

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ABSTRACT

Study region: Surface water supply source of Addis Ababa, the capital city of Ethiopia, relies primarily on the small reservoirs in Gefersa and Legedadi water supply systems located upstream of Little and Big Akaki rivers. Thus, Gefersa and Legedadi are the study watersheds of this research.
Study focus: This study evaluates the impacts of land use and climate changes on surface water availability and the benefits of nature-based solutions (NbS) to enhance the water supply and the life of the dams in the Gefersa and Legedadi small watersheds that supply water to Addis Ababa city, Ethiopia. Several land use and climate change scenarios have been developed and integrated into baseline hydrological model to assess their impact on water balance components and sediment yield. Extreme climate change scenarios were developed using the combination of the 5th, 50th and 95th percentiles of future precipitation and temperature changes.
New hydrological insights for the region: The results of the land use change analysis revealed a shift between 2012, 2022 and 2042, with a significant expansion of urban settlements and a decline in forestland and vegetation cover. Under climate change scenario, the simulations project that drier seasons become drier and wet seasons become wetter. Overall, this study highlights the potential benefits of NbS in enhancing water availability, particularly during the dry season, promoting dry season farming and increasing the water supply to meet the water demand. The approach followed in this study can be adapted to other watersheds with access to more recent and good quality datasets for future research.

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1. Introduction

Anthropogenic activities and other drivers play a significant role in global land use/land cover change. Natural landscapes are extensively transformed into different human-dominated ecosystems, such as urbanized areas, expanded agricultural land, pastural land and artificial water bodies due to deforestation (Dadashpoor et al., 2019; Gelli et al., 2023). The available records indicate that 60 % of total land use change is attributed to direct intervention by human actions, while the remaining portion is driven by indirect factors such as climate change (Song et al., 2018). According to Winkler et al. (2021), there has been a global reduction in forest area of 0.8 million km^2 associated with the expansion of cropland and pastural/range areas of 1 million km^2 and 0.9 million km^2, respectively. Over 50 % of the new agricultural land in tropical regions resulted from the conversion of forestland, whereas an additional 28 % originated from forest disturbance from 1980 to 2000 (Lambin, and Meyfroidt, 2011). This conversion of land use from one form to another may have significant impacts on the global water cycle, with potential change in evaporation rates, groundwater recharge, and surface runoff, leading to the occurrence of extreme events such as floods, droughts, and shifts in regional climate patterns (Calijuri et al., 2015, Lei et al., 2022, de Mello et al., 2020). For instance, the conversion of vegetation cover into agricultural or urban areas reduces soil permeability due to the expansion of impermeable surfaces and decreased canopy interception. This shift can result in increased surface runoff, reduced soil moisture, and groundwater recharge. Consequently, water flow becomes more concentrated in rivers, elevating flood risks and depleting groundwater reserves. Additionally, the loss of vegetation deceases evapotranspiration, disrupting local humidity and temperature, which can influence rainfall patterns and further modify regional hydrological cycles.

On the other hand, climate change also indirectly triggers the conversion of land use types, and the loss of vegetation cover due to changes in climatic variables (Li et al., 2015). According to the latest synthesis report from the Intergovernmental Panel on Climate Change (IPCC), global surface temperature has risen by 1.1°C compared to the pre-industrial period (1850–1900) because of increased greenhouse gas emissions (IPCC, 2023). Global warming due to an increase in temperature can instigate forest fires and forest droughts in many tropical regions (Camia et al., 2017). Climate change further exacerbates the challenges facing surface water availability in the region. Changes in precipitation patterns, increased temperatures, and the intensification of extreme weather events such as droughts and floods disrupt the hydrological cycle, leading to fluctuations in surface water availability and quality (Mimikou et al., 2000). These changes have a diversified local-scale impact on agriculture, water resources, human health, ecosystem disruption and economic growth. Thus, it is crucial to implement climate change mitigation strategies to minimize these effects on vulnerable sectors.

Ethiopia is experiencing considerable urbanization and population growth, which leads to an increase in water demand for both domestic and industrial purposes that surpasses the available water supply from surface and subsurface flows. This situation is particularly pronounced in major cities such as Addis Ababa, the capital city of Ethiopia. The estimated population of the city reached approximately 5.5 million in 2023, with an average annual growth rate of 4.5 % (WPR, 2024). The population projections indicate that this growth trajectory is likely to continue, and the population is expected to double by 2040 (WPR, 2024). Growth is driven primarily by migration and informal settlements in search of better opportunities. Similarly, the area of the city is expanding at an alarming rate to accommodate the rise in population. The available figures indicate unprecedented expansion in urban areas from 49 km^2 in 1974–343 km^2 in 2014 in the upper Awash Basin, which encompasses Addis Ababa (Shawul and Chakma, 2019). The basin has experienced substantial land use changes, primarily the conversion of forest, shrubland and pastureland to cropland and settlement. The comparison of remote sensing images and land use maps in the past 10 years (2021–2022) revealed more than 10 % expansion of settlements in the Gefersa and Legedadi watersheds (Negash et al., 2023) in the upper Awash basin that serve as the two surface water supply sources of Addis Ababa. Land use change has a substantial impact on water availability and quality (Anteneh et al., 2018), while unplanned population growth increases the water demand for domestic, industrial, and other uses.

The gap between the city's water supply and demand continues to grow despite the city administration continuing to expand water supply development projects from both surface and groundwater sources. As per the 2020 report from the Addis Ababa Water and Sewage Authority (AAWSA, 2020), the city receives an estimated 225,000 m^3/day of potable water from the Legedadi (195, 000 m^3/day) and Gefersa (30,000 m^3/day) surface water supply systems and 374,000 m^3/day of groundwater from the Akaki Wells field. Compared with the total estimated water demand in 2020 (1.2 million m^3/day), the surface water supply accounts for 18 %, the groundwater supply accounts for 31 % and the remaining 51 % represents unmet demand (AAWSA, 2020). Model scenario analysis examining rapid population growth and urbanization has projected a 48 % increase in unmet water demand by 2030 (Alemu and Dioha, 2020). Climate change, poor watershed management and a lack of implementation of nature-based solutions (NbS) exacerbate water scarcity, water quality deterioration and reservoir siltation (Tefera et al., 2023). According to the United Nations Environment Programme (UNEP, 2022), NbS are sustainable approaches that involve managing, protecting, and restoring ecosystems to address social, economic, and environmental challenges effectively. The potential benefits of NbS such as Agroforestry, Area closure, detention/retention basins, terraces and bund, ponds and wetlands, check dams, contour farming, and cover crops have been tested in various watersheds and their benefits on environmental sustainability have been reported (2011; Seddon et al., 2020). Despite significant challenges related to land degradation and water quality deterioration in the Gefersa and Legedadi watersheds, the implementation of NbS remains limited. These watersheds face increasing pressure from environmental degradation, yet practical efforts to introduce sustainable interventions have not been widely adopted.

The primary factors contributing to soil erosion in watersheds include land use changes such as urbanization, deforestation, agricultural expansion, overgrazing, and shifts in rainfall patterns (Tsegaye, 2019). Sediment deposition is a major constraint in reservoir impoundment, potentially reducing the water storage capacity of reservoirs and negatively impacting the surface water supply for Addis Ababa city (Elala, 2011). For example, soil erosion and water quality are issues in the Gefersa and Legedadi watersheds, where the reservoirs have experienced remarkable sediment inflow and water quality deterioration due to several factors, such as poor watershed management practices and urban encroachment. An estimated 46,390 and 127,250 tons of sediment load is expected to inflow annually to the main Gefersa and Legedadi reservoirs, respectively (Megersa, 2017; Tefera et al., 2023). Thus, soil erosion has caused the storage capacities of the Legedadi and Gefersa reservoirs to decrease by ~4.5 % and ~6 %, respectively, with data analyzed from 1979 to 1998 (Daba, 2017; DAR AL OMRAN, 2011). The rate of decline in reservoir storage capacity has likely accelerated recently in the watersheds because of significant urban expansion, increased bare land areas, and the effects of climate change.

Despite the urgency of these issues, there is a limited focus on watershed interventions through the implementation of both structural and non-structural NbS in these watersheds, owing to various socioeconomic, environmental, and other factors. Recent stakeholder engagement meetings and field visits to the two study watersheds revealed the absence of NbS interventions, except for minimal efforts at fruit tree plantations in areas less than 5 ha in size in each watershed, as part of the Green Legacy Initiative by the Ethiopian government. Additionally, there is a research gap at the local scale in terms of assessing the potential impacts of land use and climate changes on water availability. Specifically, there is a need for studies exploring how NbS interventions can enhance water quantity, improve water quality, and support environmental sustainability. Current research lacks robust, localized evidence on the effectiveness of NbS in mitigating the impacts of environmental degradation, climate variability, and water stress. Filling this gap is essential for developing evidence-based policies and ensuring that future NbS implementations are context-specific and aligned with watershed needs to grant water security.

Therefore, this research focuses on scenario-based biophysical model simulations to (i) assess the impacts of historical and future land use changes on water quantity and quality, ii) evaluate climate change impacts on water balance components, iii) identify potential NbS through stakeholder engagement and suitable land for interventions using GIS-based multicriteria analysis, and iii) assess the potential benefits of interventions for improving water availability and water quality in the Gefersa and Legedadi watersheds. The SWAT hydrological model and remote sensing products were primarily used as approaches and data sources to address the objectives of this research.

2. Materials and methods

2.1. Study area

The Little Akaki River and Big Akaki River are the two major rivers that originate from the highlands and traverse Addis Ababa city boundary. These rivers are tributaries of the Awash River, which ranks among Ethiopia's largest rivers. The city's surface water supply source relies primarily on the small reservoirs in Gefersa and Legedadi water supply systems located upstream of Little and Big Akaki rivers (Fig. 1). The Gefersa watershed is located upstream of the Little-Akaki River approximately 18 km west of Addis Ababa. Its catchment area covers approximately 55 km^2. The elevation varies between 1126 and 1210 m in the watershed, with highlands in the

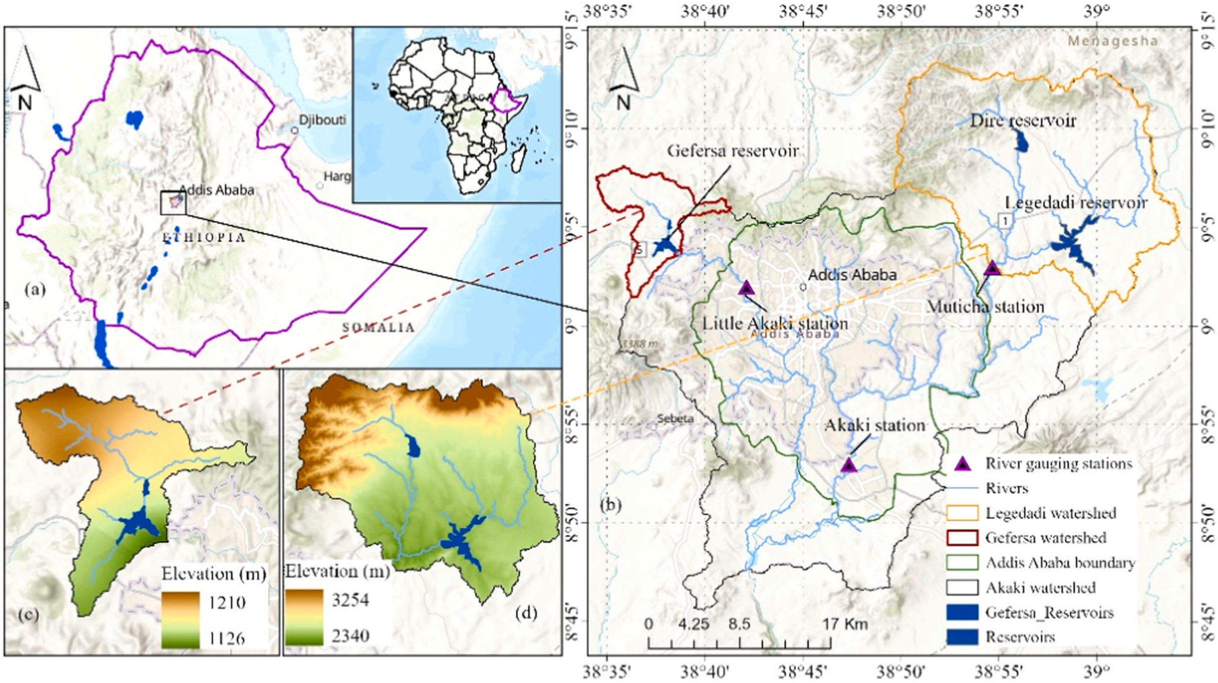

Fig. 1. Location maps of the Akaki, Gefersa and Legedadi watersheds (a & b) with respect to City of Addis Ababa. Elevation maps are also shown for the Gefersa (c) and Legedadi (d) watersheds.

northwest and lowlands in the southern parts. The annual rainfall and average temperature range from 1050–1345 mm and 12–18°C, respectively. The majority area in each watershed is dominated by slope gradients less than 15 % and agricultural land use type. While the Legedadi watershed is located upstream of the Big Akaki River, with a catchment area of ~394 km^2 upstream of the Muticha River gauging station. The elevation in the Gefersa watershed varies between 2340 and 3254 m, with highlands in the northern and northwestern regions and lowlands in the southern and southeastern parts of the watershed. According to the traditional agroecological zone classification of the Ministry of Agriculture of Ethiopia (Hurni et al., 2016), the Gefersa and Legedadi watersheds are categorized under the "Moist Dega" agroecological zone based on elevation (2300–3200 m), annual rainfall (900–1400 mm) and average temperature (12–18°c). The main Gefersa water supply dam was built in 1938 and renovated in 1954, with an increased water storage capacity of 6.5 Mm^3. Later, a small embankment dam was built to serve as both a silt trap and an auxiliary water storage facility just upstream of the main reservoir (800 m). The Legedadi surface water supply system is implemented in the Legedadi watershed, and the system comprises two dams, namely, Legedadi and Dire Dams (Fig. 1b). The Dire earthen dam is used as an auxiliary water storage dam for the Legedadi treatment plant.

2.2. Data used

2.2.1. Climate data

The Gefersa and Legedadi watersheds are considered ungauged watersheds with scarce observed climate data. To fill this gap, remote sensing-based rainfall and maximum and minimum temperature data were acquired from the Climate Hazards Group InfraRed Precipitation/Temperature with Station data (CHIRPS and CHIRTS). The CHIRPS/CHIRTS products integrate rainfall and temperature data collected from various stations to increase the accuracy of the data. Several studies have evaluated satellite rainfall products and demonstrated the effectiveness of CHIRPS in many watersheds in Ethiopia (e.g., Bayissa et al., 2017; Gebremicael et al., 2019; Dinku et al., 2018). CHIRPS and CHIRTS products have been used for further applications, such as drought monitoring (Bayissa et al., 2019; Demisse et al., 2017). The daily rainfall and temperature data (1983–2020) with 5 km spatial resolution were processed for the two watersheds. Importantly, CHIRTS data from 2017 to 2020 have not yet been made publicly available. Consequently, data were generated via the Climate Data Store (CDS) daily statistics calculator for this period.

The RCM data were extracted from the Intergovernmental Panel on Climate Change (IPCC) Working Group I (WGI) Interactive Atlas portal (https://interactive-atlas.ipcc.ch/). The CMIP6 model was used for the WGI reference regional set with a reference baseline period from 1995 to 2014. The monthly average 5th, 50th and 95th percentile values of total precipitation and average temperature changes were obtained for SSP2–4.5 and SSP5–8.5, representing the usual and worst-case scenarios, respectively, in the near-term (2021–2040) projection. These percentile values were calculated using over 32 RCMs forced by different global circulation models (GCMs).

2.2.2. Hydrological data

In the Akaki watershed, there are three river gauging stations (Fig. 1b) with daily and monthly streamflow data from 1990 to 2004. These data were acquired from the Ministry of Water, Irrigation, and Energy (MoWIE) of Ethiopia. As shown in Fig. 1b, two of the

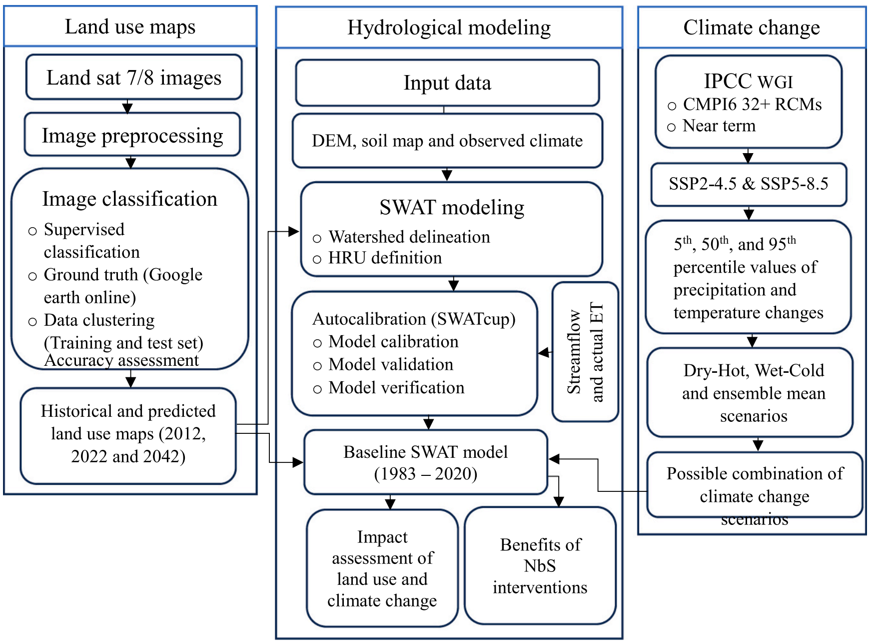

Fig. 2. Methodological workflow chart shows the major steps followed to address the objectives of this study.

stations (i.e., Muticha and Akaki) are located in the Big Akaki River downstream of the Legedadi water supply system, whereas the third station (i.e., Little Akaki) is located downstream of the Gefersa watershed. As confirmed by the hydrology department of the MoWIE, recent data since 2005 are not accessible. Data related to the water supply and demand and dam characteristics were obtained from AAWSA.

2.2.3. Spatial biophysical data

A digital elevation model (DEM) at a spatial resolution of 30 m was acquired from the Shuttle Radar Topography Mission for the Gefersa (Fig. 1c) and Legedadi (Fig. 1e) watersheds. In addition, gridded soil data at 250 m spatial resolution and data on soil properties (e.g., sand, silt, and clay fractions; coarse fragments; and organic carbon) for six soil layers were obtained from the Africa Soil Information Service (AfSIS). Similarly, maps of historical and future land use were developed using Landsat 7 and 8 images with a 30 m spatial resolution. The actual evapotranspiration (ET) values of the 8-day composite and 500 m spatial resolution MODIS product (MOD16A2) were extracted at the subbasin scale from the Google Earth Engine (GEE) platform. The time series data were extracted from 2000 to 2020 and used to verify the SWAT subbasin output of the actual ET.

2.3. Method

The workflow chart illustrates the method followed in this research is presented in Fig. 2. Overall, four model simulation scenarios are proposed to assess the impacts of biophysical and climate changes on the surface water supply in the two watersheds. These scenarios include the baseline model simulation scenario, land use change scenario, climate change scenario, and NbS scenario.

2.3.1. Baseline model simulation scenario

The SWAT model was used to develop the baseline hydrological model to simulate the water balance components. The model is widely applied to predict the impacts of land management practices, climate change, sediment yield, and water pollution on water resources and environmental sustainability from small watersheds to large and complex spatial scales (Neitsch et al., 2011). The model uses different physical algorithms to estimate the water balance components at the hydrological response unit (HRU) scale using input climatic and biophysical data. Many researchers have proven the model's effectiveness and potential applications (Fukunaga et al., 2015; Bayissa et al., 2018; Akoko et al., 2021; Tamm et al., 2018; Costa et al., 2024). For example, Kiros et al. (2015) reviewed the performance of the SWAT model for land use and land cover changes under semiarid climatic conditions. They reported that the model was effective in evaluating the effects of land use on runoff and sediment losses because of its ability to integrate and simulate a wide variety of conservation practices.

Separate SWAT models were developed for the Gefersa and Legedadi watersheds using the input climatic and biophysical parameters to simulate the baseline water balance components from 1983 to 2020. The watersheds were further discretized into subbasins and HRUs using a unique combination of land use, soil, and slope. After the model simulation runs, a sensitivity analysis was conducted to identify the sensitive model parameters that control flow and sediment yield (Arnold et al., 2012). Accordingly, a total of 13 model parameters were identified and used to calibrate the model. The flow control parameters were first calibrated, followed by calibrating the sediment parameters as suggested by Arnold et al. (2012). The default values of these model parameters were first fine-tuned manually and then auto-calibrated using sequential uncertainty fitting (SUFI-2) in SWAT-CUP.

Since the rivers upstream of the Gefersa and Legedadi reservoirs are ungauged, the model was calibrated with observed streamflow measured at downstream gauging stations (i.e., Little Akaki and Big Akaki). Muticha station was not used because of the poor quality of the data. The model was simulated at monthly time steps with warmup (1996–1998), calibration (1999–2004) and validation (1991–1995) periods. Compared with those in the validation period, the data used for model calibration included high-, low-, and normal-flow events.

Commonly and widely used statistical metrics, including the Nash–Sutcliffe efficiency (NSE), coefficient of determination (bR^2), Kling–Gupta efficiency coefficient (KGE) and percent bias (PBIAS), were used to evaluate model performance. Eqs. (1)–(4) show the mathematical representations of these model evaluation metrics.

$$\mathrm{NSE} = 1 - \left[\frac{\sum_{i=1}^{n}(\mathrm{Obs}_i - \mathrm{Sim}_i)^2}{\sum_{i=1}^{n}(\mathrm{Obs}_i - \overline{\mathrm{Obs}})^2}\right] \tag{1}$$

$$\mathrm{bR}^2 = b\left\{\frac{\sum_{i=1}^{n}(\mathrm{Obs}_i - \overline{\mathrm{Obs}})(\mathrm{Sim}_i - \overline{\mathrm{Obs}})}{\left[\sum_{i=1}^{n}(\mathrm{Obs}_i - \overline{\mathrm{Obs}})^2\right]^{0.5}\left[\sum_{i=1}^{n}(\mathrm{Sim} - \overline{\mathrm{Sim}})^2\right]^{0.5}}\right\}^2 \tag{2}$$

$$\mathrm{KGE} = 1 - \sqrt{(r-1)^2 + (\alpha-1)^2 + (\beta-1)^2} \tag{3}$$

$$\alpha = \frac{\overline{Sim}}{\overline{Obs}}, \beta = \frac{\sigma_{sim}}{\sigma_{Obs}}$$

$$PBIAS = \left[\frac{\sum_{i=1}^{n} (Obs_i - Sim_i)}{\sum_{i=1}^{n} Obs_i} * 100 \right] \quad (4)$$

where Obs_i is the observed variable, Sim_i is the simulated variable, $\overline{Obs}$ and $\overline{Sim}$ are the average observed and simulated values of the entire observation (n), σ_{sim}andσ_{Obs} indicates the standard deviation of the simulated and observed values, and n is the total number of observations.

Furthermore, the calibrated model output of actual ET was compared with an independent MODIS-based actual ET product. First, the time series MODIS actual ET was extracted for each subbasin from 2000 to 2020 and then compared with the SWAT output using the coefficient of determination (R^2). This statistical matrix measures any similarities in the temporal patterns between the two actual ET estimates.

2.3.2. Land use change scenario

The impact assessment of land use on water balance components involves developing high resolution land use maps for historical and future time periods. The selection of the years depends on the availability of good-quality satellite observation data, normal climate years and research interest in future projection periods. Accordingly, detailed land use and land cover maps were developed for historical (i.e., 2012 and 2022) and future (2042) time periods using the Landsat 8 and Landsat 7 products. The primary image dates for the historical period were May 12, 2012, and May 22, 2022. The sensor malfunction issue stems from the failure of the Scan Line Corrector (SLC) on the Landsat 7 satellite was treated by following the temporal images composite approach to fill the missing pixel values. Thus, images collection from January to December of 2012 were used in developing the land use map for 2012. A supervised image classification approach was used to identify major land use types for the Gefersa and Legedadi watersheds. Landsat images of 30 m spatial resolution, accessible through the Google Earth Engine (GEE) platform, were utilized to generate training samples for classifying various land use types using a machine learning approach. The data clustering assigned 80 % of the random samples for model training and 20 % to test or evaluate the model. High-resolution background imagery from the Google Earth platform was used to identify the training sample points in each land use type. The ensemble learning image classification approach of the Smile random forest regressor was applied to train the model by constructing multiple regression trees during image classification (Theres and Selvakumar, 2022). The accuracy of the classification was evaluated using widely accepted qualitative procedures, such as user accuracy and kappa statistics, by generating a confusion matrix. For land use prediction, independent and dependent variables were used to predict land use for 2042. The independent variables include elevation, slope, hillshade, aspect, distance to the river and distance to the roads while land use maps developed for 2022 and 2012 were used as dependent variables to predict the land use in 2042. The independent variables were selected based on data availability and became less variable with time. Similar model training approaches and machine learning technique were followed to predict the land use map. The model first learns to detect shifts in land use patterns to extrapolate future changes based on historical trends. The model assumes stationarity of the land use patterns, which can be considered as a limitation particularly in a rapidly changing regions or where new policies affect land use. This study acknowledges predicting future land use inherently involves uncertainty not only due to data quality and uncertainty in algorithms but also due to unforeseen factors (e.g., policy changes, urban development) may alter land use patterns in unexpected ways.

Once the calibration and verification of the baseline SWAT model were completed using the 2022 land use map, the baseline land use data were subsequently replaced with the 2042 land use map to simulate water balance components while maintaining constant model parameters and other input data. A comparison between selected water balance components under the baseline and future land use change scenarios was subsequently performed to assess changes in the future.

2.3.3. Climate change scenario

Based on the 5th, 50th and 95th percentile values, extreme climate change scenarios were developed for each SSP2–4.5 and SSP5–8.5 emission scenario. The 5th percentile values often represent the lowest or minimum values, which indicates "dry" conditions for precipitation and "cold" conditions for temperature. Conversely, the 95th percentile values represent the highest or maximum values, indicating "wet" conditions for precipitation and "hot" conditions for temperature. To create an extreme scenario called "dry-hot", we combined the 5th percentile of the change in precipitation with the 95th percentile of the change in temperature. Similarly, we derived the "wet-cold" scenario by combining the 95th percentile of precipitation with the 5th percentile of temperature. Additionally, the ensemble mean scenario was derived using the arithmetic mean values of 32 climate models for precipitation and 34 models for

Table 1
Climate models scenarios description.

Source	Group	Scenarios
Global Climate Models from IPCC AR6	Dry-Hot	P5T95–4.5
		P5T95–8.5
	Ensemble	P50T50–4.5
		P50T50–8.5
	Wet-Cold	P95T5–4.5
		P95T5–8.5

temperature (Costa et al., 2024; Wu et al., 2021). In total, six climate change scenarios (Table 1) were simulated to assess their impacts on water balance components and quantify water availability in the near term. These climate change scenarios were selected to capture a broad range of potential future conditions and assess their implications for water availability and balance. The selection of such scenarios ensures the research can quantify potential risks under both moderate and extreme conditions, helping to guide adaptive water resource management and improve policy planning in the near term.

2.3.4. Model simulation scenarios with NbS

The method used to assess the potential intervention of NbS in the Gefersa and Legedadi watersheds involves the selection of both structural and nonstructural solutions based on a literature review, previous experience, expert judgment and stakeholder engagement. Accordingly, a list of potential NbS (i.e., soil and stone bunds, terraces, ponds, check dams and retention and detention basins) were identified, and their benefits in improving water availability and quality in the watershed were assessed. Some of these interventions are widely used in Ethiopia and their performance in reducing soil erosion and water conservation was verified from the implementing organizations although their performance highly relies on routine maintenance. In addition, feedback from the stakeholders and expert opinions were gathered on each solution during the field visits in the watersheds. Stakeholder feedback was incorporated by actively engaging experts mainly from AWSSA to provide feedback on erosion hotspot areas and appropriate NbS suggested by the research team. Next, the suitable location for each solution was identified in the watersheds using GIS-based multicriteria analysis. Slope, soil depth, soil texture and land use were considered the key factors for site selection for the interventions. However, the coarse resolution of the available rainfall and runoff coefficient data limited the ability to capture the spatial variability in the watersheds. The suitability classes of each intervention were adapted as per the suggestions of the Ministry of Agriculture and other studies (Krois and Schulte, 2014; Ammar et al., 2016; Rahmati et al., 2019) and the suitability level is presented as a supplementary material (supplementary 1).

The integration of these interventions into the SWAT model was performed by adjusting the model parameters based on previous studies conducted using field experiments and hydrological modeling at the watershed scale in Ethiopia (Table 2). In addition, whenever expert judgment was required to refine the model parameters, we drew upon the vast experience of our research team to properly represent the interventions in the model. The model parameters were modified by editing HRU input tables, which used mainly management files. Soil and stone bunds are implemented mainly in agricultural lands to control sheet erosion and gully head formation by slowing runoff. In SWAT, key model parameters including curve number (CN2), USLE_P, slope length (SL_SUBBSN) and slope steepness (HRU_SLP) were adjusted to reflect reduced runoff, sediment yield, and slope impact. For optimally suitable agricultural HRUs, CN2 decreased by 3–6 units, USLE_P by 40 %, SL_SUBBSN by 83 % (0–10 % slope) and 58 % (10–20 % slope), and HRU_SLP by 25 % (> 8 % slope) from the calibrated values (Betrie et al., 2011, Lemma et al., 2019). Similarly, there is built in function in SWAT to implement terraces by adjusting CN2, USLE_P and slope to agricultural HRUs in the highlands and lowlands. CN2 decreased by 6 unit and USLE_P calibrated values replaced by 0.1 (2–8 % slope), 0.14 (8–15 % slope) and (> 15 % slope) in optimally suitable land (Arabi et al., 2008; Silva et al., 2024). The model doesn't have the flexibility to integrate the design features and density of terraces as they appear on the ground. Ponds were implemented upstream of the watershed as part of the river, with areas ranging between 1 and 2 ha. An upstream drainage area of 20–40 km^2 should drain the pond as part of the criteria. There is an option to add ponds and reservoirs at suitable locations in the SWAT model. A similar approach was used to incorporate detention and retention basins, with adjustments made to their size and placement to manage urban runoff downstream of built-up areas. The option to estimate the dimensions of these structures by the model was selected using the estimated peak flow and total runoff for a design storm. Checkdams were represented as a small reservoir by specifying the surface area ranging from 0.1 to 1 ha with an average depth of 1 m to simulate the water holding and sediment trapping effects. Model parameters including seepage coefficient (RES_K: lower to

Table 2
Model parameters modified to represent NbS practices in SWAT model.

NbS types	Model parameters	Slope (%)	Adjustment
Soil and stone bunds	CN2 (mgt)		Reduced by 3–6 units from the calibrated values
	USLE_P		Reduced by 40 % from the calibrated values
	SL_SUBBSN	0–10	Reduced by 83 % from the calibrated values
		10–20	Reduced by 58 % from the calibrated values
		> 20	No change
	HRU_SLP	> 8	Reduced by 25 % from the calibrated values
Terraces	CN2 (mgt)		Reduced by 6 units from the calibrated values
	USLE_P	2–8	Reduced by 0.1 from the calibrated values
		8–15	Reduced by 0.14 from the calibrated values
		> 15	Reduced by 0.14 from the calibrated values
Ponds			1–2 ha area pond for upstream drainage area of 20–40 km^2
Detention and retention basins			Size determined using peak flow and design storm: option to estimate the dimensions by the model is selected
Checkdams	RES_K		lower to 0.01–0.1
	SED_TRAP		adjusted b/n 0.5–0.8
	CH_COV1 and CH_COV2		increased by 0.1–0.3
	ALPHA_BF		Increased by 5–10 % of the calibrated values

0.01–0.1), sediment trapping efficiency (SED_TRAP: adjusted b/n 0.5–0.8), channel cover factors (CH_COV1 and CH_COV2: increased by 0.1–0.3) and baseflow (ALPHA_BF: increased 5–10 %) and revap (GW_REVAP: increased 5–10 %) factors were adjusted.

3. Result and discussion

3.1. Baseline model simulation scenario

The sensitivity analysis, model parameter ranks and fitted values are presented in the supplementary material (supplementary 2). Model parameters such as curve number (CN2), maximum canopy storage (CANMX), and the threshold depth of water in the shallow aquifer (GWQMN) were identified as the most sensitive parameters, with p values less than 0.01 and t statistics greater than 20. Conversely, the threshold depth of water in the shallow aquifer for "revap" to occur (REVAPMN), lateral flow travel time (LAT_TIME), and deep aquifer percolation fraction (RCHRG_DP) were determined to be less sensitive, showing an insignificant impact on the model output.

The goodness-of-fit values of the model performance values are presented in Table 3 for both the monthly calibration and validation periods at the Little Akaki and Big Akaki gauging stations. The model performance statistics generally depict good model performance, with NSE, R^2 and KGE values greater than 0.6 in both watersheds during the model calibration period. Comparatively, the model performance somewhat decreased during the validation period, particularly the KGE value in the Big Akaki watershed. However, the model still satisfies the good model performance criteria per the recommendation of Moriasi et al. (2015) and Arnold et al. (2012), with criteria of NSE > 0.5 and $R^2 > 0.6$. The model PBIAS is also within an acceptable range, particularly during the calibration period (< 16 %). The uncertainty analysis measured by p- and r-factors supported good model performance, which implies that the model can be further used for impact assessment. The p factor indicates the percentage of the observed data within the 95PPU, 80 % and 82 % during calibration for the Little Akaki and Big Akaki watersheds, respectively. This shows that approximately 80 % of the observed data are within the 95PPU uncertainty bound. Similarly, the r-factor, which represents the average thickness of the uncertainty band, was less than 0.5, which supports good model performance (Abbaspour, 2015). Similar model performance is observed at the hypothetical stations at the outlets of the Gefersa and Legedadi watersheds, with streamflow data transferred from downstream stations using the area ratio approach. The results from these hypothetical stations are not included to avoid redundancy, as the model performance values obtained were very similar. The time series plots of the observed and simulated monthly flow for the calibration and validation periods at Little and Big Akaki are presented in the supplementary material (supplementary 3). However, the quality of the streamflow data, the lack of observed climate data within the watersheds, uncertainties in the model structure, and the assumptions of homogeneity and lumped parametrization within each HRU may introduce errors in the model output. Thus, conducting uncertainty analysis and addressing data quality issues and model assumptions could improve the results in future studies.

An independent remote sensing-based MODIS actual ET product is used to verify and compare model-estimated actual ET to assess the accuracy of the model. The coefficient of determination (R^2) is used to measure the temporal patterns of the subbasin average model output and the MODIS-based actual ET. In general, the results indicate good agreement between the SWAT-simulated and MODIS-based actual ET in all subbasins in the Gefersa watershed and Legedadi watersheds (supplementary 3).

3.2. Impact of land use change

The spatial patterns of the resulting land use maps for the Gefersa and Legedadi watersheds are shown in Fig. 3 and Table 3. The performance evaluation of the land use classification, based on the confusion matrix, demonstrated good agreement as measured with user accuracy and kappa values of 0.88 and 0.86, respectively, for both 2012 and 2022. A marked shift is evident between 2012 and 2022 land use maps, indicating a significant expansion of urban settlements (65 %) and bareland (18 %) within a decade and reductions in agricultural land (5 %), forestland (4 %) and grassland and shrubland cover (7 %) in Gefersa watershed. Similarly, there is an expansion in urban settlement (51 %) and bareland (40 %) in Legedadi watershed. Conversely, agricultural land, forestland and grassland and shrubland cover showed a decreasing pattern with 7 %, 5 % and 13 %, respectively in this watershed. Rapid urbanization leading to the conversion of natural landscapes might severely impact biodiversity and disrupt essential hydrological processes, potentially compromising the watershed's ecological balance and resilience.

The spatial distributions of the land use types projected for 2042 are also shown in Fig. 3a and b for the Gefersa and Legedadi

Table 3
Model performance evaluation metrics for the model calibration and validation periods at Little Akaki/Gefersa and Big Akaki.

Performance	Little Akaki		Big Akaki	
metrics	Calibration	Validation	Calibration	Validation
NSE	0.75	0.70	0.79	0.60
R^2	0.87	0.77	0.83	0.81
KGE	0.61	0.61	0.75	0.40
PBIAS (%)	6.00	15.00	4.30	4.00
p-factor	0.8	0.78	0.82	0.80
r-factor	0.41	0.45	0.46	0.48

Model verification using MODIS actual ET data

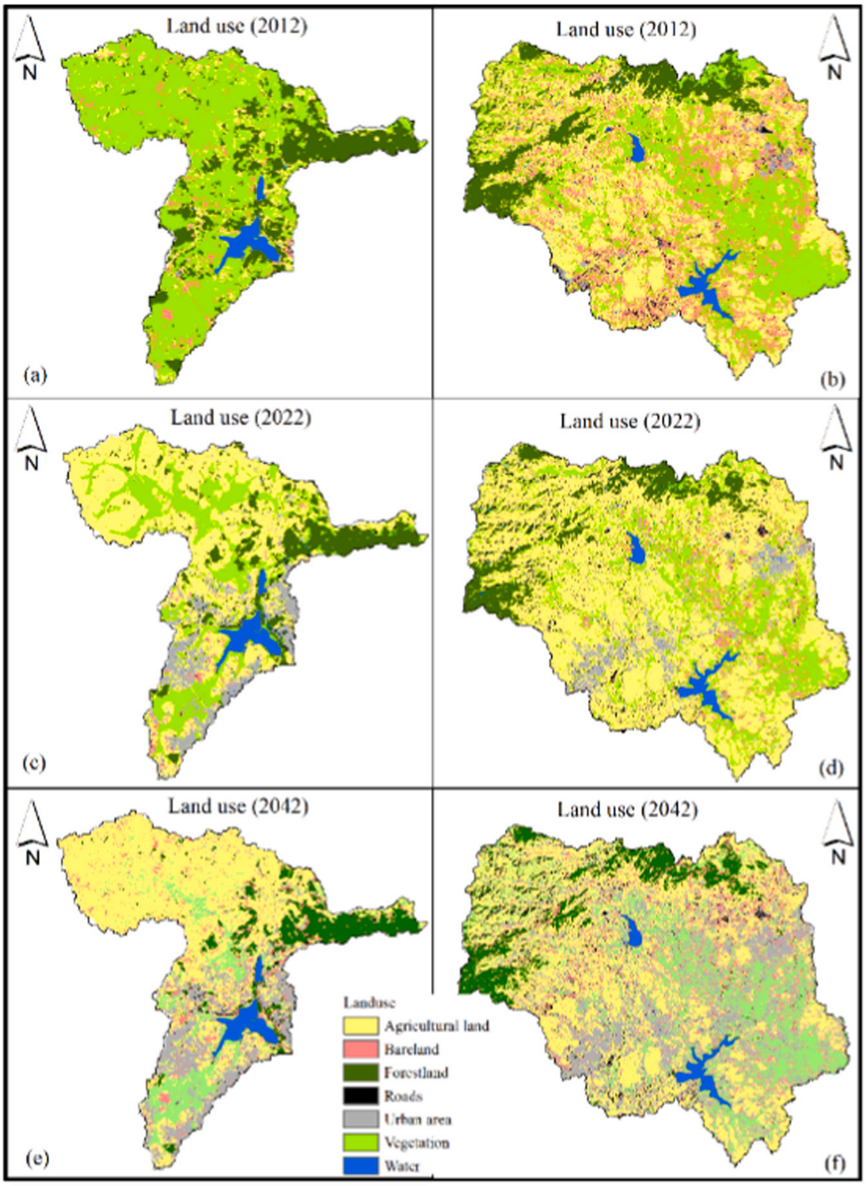

Fig. 3. Land use dynamics for the Gefersa and Legedadi watersheds in 2012 (a and b), 2022 (c and d) and 2042 (e and f). All the land use maps in the left panels are for the Gefersa watershed, and those in the right panels are for the Legedadi watershed.

watersheds, respectively. A summary of the percentage change and area coverage (ha) of each land use type is presented in Table 4. Over the past decade, urbanization in these watersheds has expanded by approximately 75 %, driven by factors such as population growth, economic development, potential loopholes in government policies and planning, socioeconomic dynamics, and other contributing elements. The prediction accuracy of the model was reasonable, as it was illustrated with a user accuracy and kappa values of 0.86 and 0.84, respectively. This indicates the reliability of the model in capturing the anticipated changes in land use dynamics. The distribution of the predicted land use map of 2042 depicts significant expansion of the urban area, with 52 % and 41 % increases compared with the urban area in 2022 in both watersheds. The road network and bare land areas are expected to expand by 63 % and 34 %, respectively, in the Gefersa watershed and by 49 % and 55 %, respectively, in the Legedadi watershed by 2042. Conversely, agricultural land and grassland and shrubland cover are anticipated to decrease by 6 % and 7 %, respectively, in Gefersa and by 7 % and 13 %, respectively, in Legedadi. Forestland is also expected to decrease by 7 % and 5 % in the Gefersa and Legedadi watersheds, respectively. It is evident that cross validating these land use maps with ground observations may be required to enhance their overall accuracy.

Previous studies have similarly highlighted the expansion of urbanization particularly in Akaki watershed. For instance, Birhanu et al. (2016) reported an approximate 10 % increase in urbanization in the broader Akaki watershed, while Arsiso et al. (2018)

Table 4
Percentage change and area coverage of each land use type between 2022 and 2042 in the Gefersa and Legedadi watersheds. The percentage values were calculated by dividing the difference between each land use type in 2042 and 2022 by the 2022 value. Thus, negative values indicate a decrease, and positive values indicate an increase within this time frame.

Land use types	Gefersa watershed					Legedadi watershed				
	Area (ha)			LU change (%)		Area (ha)			LU change (%)	
	2012	2022	2042	(2022–2012)	(2042–2022)	2012	2022	2042	(2022–2012)	(2042–2022)
Agriculture	2733	2585	2425	−5	−6	22433	21722	20256	−3	−7
Bareland	122	144	194	18	34	1267	1775	2743	40	55
Forestland	759	730	676	−4	−7	3355	3255	3100	−3	−5
Roads	31	48	79	55	63	1007	1430	2130	42	49
Urban	363	600	914	65	52	1790	2707	3809	51	41
Grassland and shrubland	1510	1411	1310	−7	−7	9970	8933	7784	−10	−13
Water	120	120	120	0	0	491	491	491	0	0

documented an increase of 121.88 km^2 in built-up areas over the past 25 years. Despite the specific rates of urbanization and land use changes vary across studies, there is a consistent agreement on the trend of urban expansion in the Akaki watershed and other watersheds in Ethiopia (Yohannes et al., 2024; Maru et al., 2023). Erasu Tufa and Lika Megento (2022) reported a significant reduction of farmland due to unplanned expansion of built-up areas in Addis Ababa. Their study revealed that 90 % of the farmland was converted into urban settlements between 1987 and 2020. Tefera et al. (2023) also reported significant expansion of urbanization in three major cities including Addis Ababa. Other studies supported significant expansion of urbanization with the consequence of reduced agricultural land and other landuses in the study watersheds and other similar watersheds in Ethiopia (Talema and Nigusie, 2023; Tilahun et al., 2022; Argaie et al., 2022). This expansion of urban areas has far-reaching consequences, including an increase in stormwater runoff and soil erosion while reducing groundwater recharge. In addition, urbanization prompts more wastewater to be discharged into local streams and eventually to reservoirs. Thus, sustainable land management and urban planning strategies are essential to mitigate the impacts of rapid urbanization on natural resources and ecosystems.

The land use of 2022 is used to develop the baseline model to simulate the water balance components. The projected land use for 2042 is subsequently replaced with this baseline model while maintaining consistency in all other model parameters and input values to assess the impacts of land use. After model simulation from 1984 to 2020, a comparative analysis of the areal average model outputs of selected water balance components was conducted, and the resulting bar plots are presented in Fig. 4 for the Gefersa (left panels) and Legedadi (right panels) watersheds.

Changes in actual ET due to future land use changes were minimal throughout the simulation period, with average reductions of 3 % and 10 % for the Gefersa (Fig. 4a) and Legedadi (Fig. 4b) watersheds, respectively. Conversely, surface runoff is projected to increase by 12 % and 14 % in Gefersa (Fig. 4c) and Legedadi (Fig. 4d), respectively. Similarly, groundwater recharge is expected to decrease by 7 % and 4 % in both watersheds (Fig. 4e and f). The increase in surface runoff and decrease in groundwater are attributed to the expansion of urbanization in both watersheds at the expense of vegetation cover and other land use types that support increased water storage. Potential intensification of extreme events such as high flow, potentially leading to flash floods during the rainy season and reduced low flow during the dry season. The flow during the dry season heavily depends on groundwater contributions in the form of baseflow, which is likely to decrease due to land use changes. The combined effect of increased surface runoff, sedimentation and decreased groundwater reduces both annual volume of water storage and dry season water availability.

Additionally, sediment yield is predicted to increase significantly in both watersheds (Fig. 4g and h). Previous studies have also reported an increase in sediment with a negative consequence of decreasing the active storage of reservoirs (Tefera et al., 2023; DAR AL OMRAN, 2011; Daba, 2017; Yohannes et al., 2024). The primary factors contributing to soil erosion in watersheds include changes in land use, deforestation, upstream expansion of agriculture, overgrazing, and shifts in rainfall patterns. The extensive farming practices on steep and undulating slopes in the watershed exacerbate soil erosion and land degradation. As a result, there is a high concentration of sediment in the water, leading to the transportation of nutrients that can deteriorate the water quality. Based on meetings with stakeholders, the inflow of manganese and other chemicals to reservoirs has increased from time to time, leading to an increase in the cost of drinking water treatment in both watersheds. An increase in sediment yield and transport in the study watersheds can be used as a proxy for an increase in nutrients and other chemicals with the potential to deteriorate water quality. In addition, an increase in soil loss suggests a reduction in soil fertility and agricultural productivity, with significant negative implications for food security. Future studies should verify the simulated sediment inflow to the reservoirs with observed data to gain a better understanding of the current reservoir capacities and lifespan. This verification is essential and can be considered as the limitation of the current study due to the lack of available observed data.

3.3. *Impact of climate change*

The future climate change scenarios depict changes in precipitation and temperature in the near-term, as demonstrated by the 5th and 95th percentile values derived from the 30 + RCMs. The 5th percentile represents the lower tail to capture lower values associated with dry and cooler conditions because of lower precipitation and temperature, respectively. The 95th percentile describes the upper tail to capture the extremely high values of wet and hot conditions corresponding to high rainfall and temperature, respectively. In the

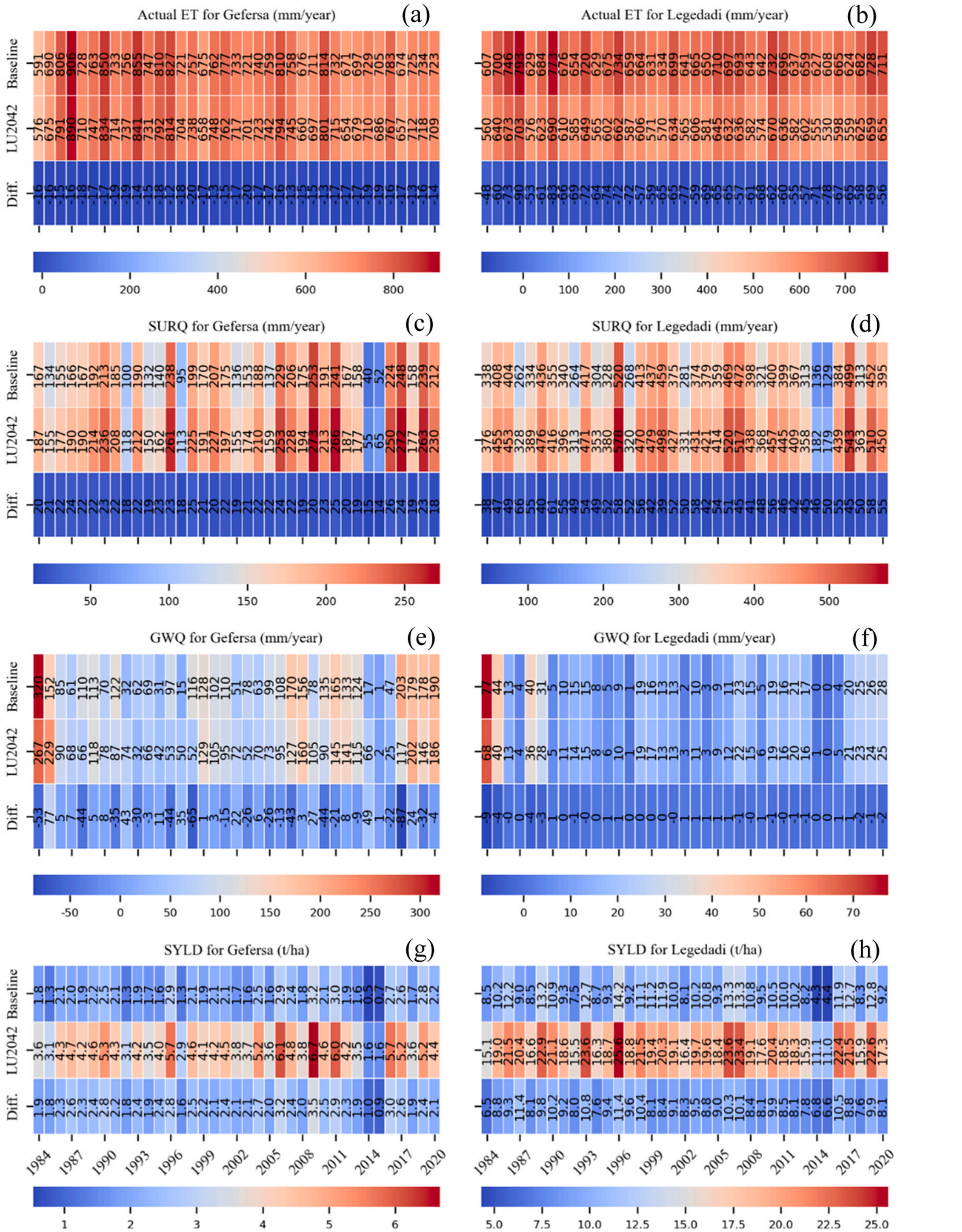

Fig. 4. Comparison of selected water balance components (i.e., actual ET, surface runoff (SURQ), groundwater (GWQ) and sediment yield (SYLD)) simulated in the baseline and future land use predictions for the Gefersa (a, c, e and g) and Legedadi (b, d, f and h) watersheds.

study region, precipitation is expected to decrease with an average value of up to 16 %, and to increase by up to 43 % for extremely dry and wet scenarios, respectively. Conversely, the temperature is expected to increase by 1.2°C, which highlights the occurrence of hotter conditions in the future. These findings indicate that drier seasons will become drier because of an increased chance of occurrence of drought events that instigate potential water supply shortages during the season when water demand peaks. On the other hand, the increase in precipitation during the wet season may increase the number of flash flood events, exacerbating potential property damage and losses.

3.3.1. Wet-cold scenario

The result and discussion section of the ensemble mean and Dry-Hot scenarios are provided as supplementary material (supplementary 4) to avoid redundancy. The result obtained for the wet-cold scenario is discussed in this section. In this scenario, there is a high chance of increases in flow and sediment under SSP2–4.5 and SSP5–8.5 in both watersheds. The long-term average values depict significant increases in flow (Fig. 5a) and sediment (Fig. 5c) of 27 % and 26 %, respectively, for SSP2–4.5 in the Gefersa watershed. Both flow and sediment increased by 43 % under the SSP5–8.5 climate scenario in this watershed. Relatively pronounced changes were observed in the Legedadi watershed for both climate pathways. Flow and sediment (Fig. 5b and d) are expected to increase up to 67 % and 92 %, respectively. The significant increase in flow and sediment under these climate pathways suggests potential challenges in maintaining water quality and managing flood risks. The substantial rise in sediment levels could lead to increased siltation in reservoirs and water channels, reducing their capacity and efficiency. Additionally, increased flow rates might exacerbate erosion processes, threatening infrastructure and agricultural lands. The findings of the previous studies in Ethiopia and elsewhere align with the finding of this study (Taye, et al., 2018; Chanie, 2024; 2018). In the region, rain-fed agriculture is a predominant practice and highly sensitive to changes in weather patterns. Future improvements in this research could involve integrating more localized climate models to better capture regional variations to enhance the precision of predictions. Additionally, exploring the impacts of climate change on water quality parameters, such as nutrient levels and pollutant concentrations, would provide a more comprehensive understanding of the overall effects on water resource management. Developing and testing adaptive management strategies under various scenarios could also be essential in guiding policymakers and stakeholders toward sustainable water resource management in the face of an uncertain climate future.

3.4. Benefits of NbS in improving water balance components

Table 5 also presents the area coverage (%) of the land suitability of each intervention in the Gefersa and Legedadi watersheds. The description and land suitability analysis maps for the NbS interventions are provided in the supplementary material (supplementary 4

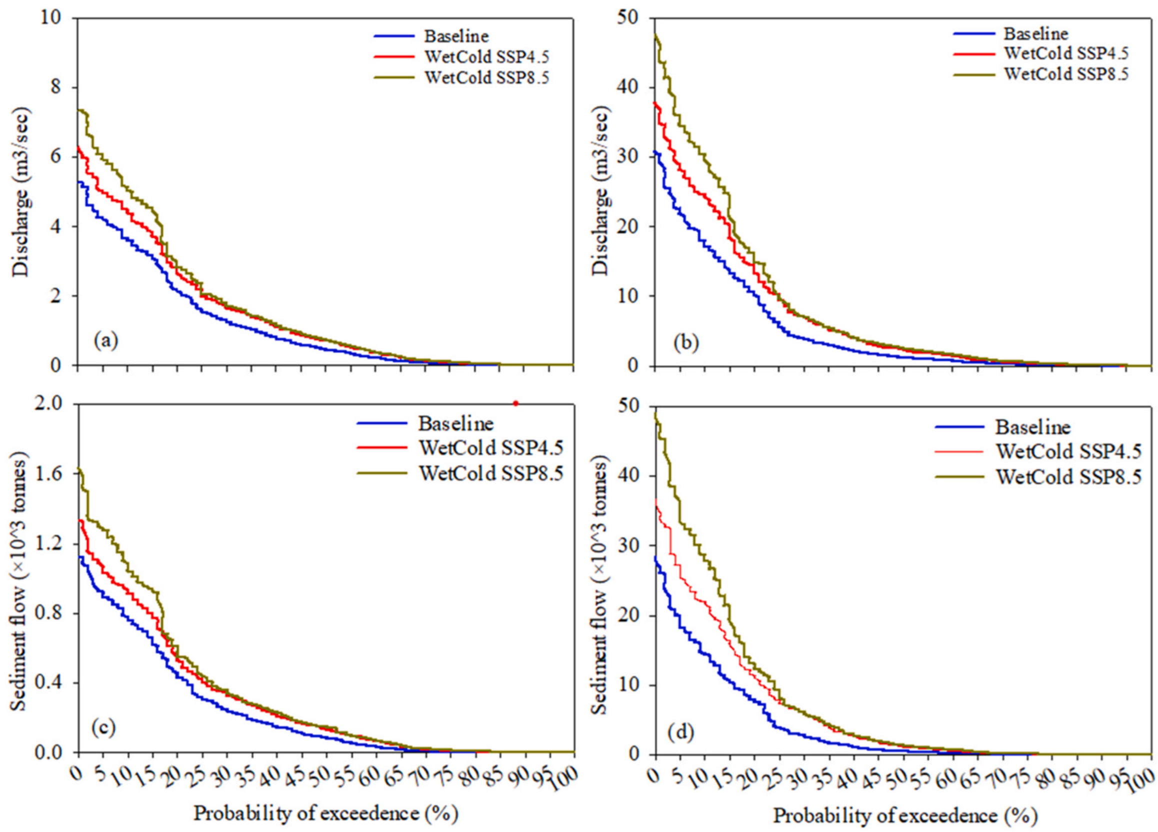

Fig. 5. Wet-cold climate change scenario-based flow duration curves for the Gefersa (a) and Legedadi (b) watersheds. The sediment rating curves for the wet—cold scenario is also presented for the Gefersa (c) and Legedadi (d) watersheds.

and 5). Most areas in both watersheds are highly or moderately suitable for all interventions except check dams and detention basins. A relatively high weight was assigned to the slope when identifying suitable land for checkdams. As the watersheds are dominated by low gradients (<15 %), most areas are suitable for checkdams based solely on this metric. However, check dams are generally recommended in areas where gully erosion has formed, and field surveys are needed to identify more suitable locations in the watershed. Approximately 36 % of the areas in the Legedadi watershed are marginally suitable for detention basins possibly because of land in the watershed is primarily agricultural land, with relatively less urban development. Only 12 % of the area, mainly near urban areas, is highly suitable for this intervention.

Fig. 6 shows the suitability of land for each NbS at the subbasin scale within the Gefersa and Legedadi watersheds. A detailed summary of the area suitable for interventions in each subbasin is provided in supplementary material 5. Overall, the majority of subbasins in the northwest region of the Gefersa watershed and the central to northern regions of the Legedadi watershed are identified as suitable for soil bunds (Fig. 6a and b). Similarly, subbasins located in the highlands in the eastern part of the Gefersa watershed and the northwestern region of the Legedadi watershed are more suitable for terraces. Urban-dominated subbasins in the south and southwest parts in both watersheds are identified as suitable for retention and detention basins. The implementation of NbS was carried out at the HRU level within each subbasin, representing the finest spatial resolution in SWAT modeling. Because of the irregular shapes of the HRUs, approximate areas were used to integrate the NbS. However, future improvements are needed to achieve a more accurate representation in terms of both area and location.

The subbasin-scale model outputs of the four water balance components simulated under baseline conditions and with the integration of different NbS are presented for the Gefersa (Fig. 7) and Legedadi (Fig. 8) watersheds. The difference maps for each water balance component were derived by comparing model simulations after interventions with baseline simulations. The interventions were implemented at the HRU level only in optimally suitable areas, as determined using factors such as slope, land use and soil characteristics. Overall, the results demonstrate several positive impacts of the interventions, primarily reductions in soil erosion and surface runoff, as well as improvements in water storage in the form of groundwater within the watersheds. The interventions increased infiltration through groundwater recharge and reduced surface runoff by slowing flow. Compared with the other subbasins, the groundwater recharge in the northwestern and western parts of both watersheds has increased. In these subbasins, bunds and terraces are dominantly implemented, which likely illustrates the effectiveness of these interventions.

The implementation of bunds and bench terraces, primarily in the northwestern part of the subbasins of the Gefersa watershed, where agricultural practices and gentle slope gradients of less than 5 % are predominant, led to a relative increase in actual evapotranspiration, with subbasin average values reaching 10 mm/month. However, no significant changes in actual ET were observed in subbasins without these interventions in the central and northern parts. Similarly, subbasins with high slope gradients and forestland-dominated land use in the eastern part showed no significant changes due to the implementation of hillside terraces. This occurred because the intervention was implemented only on agricultural land, which covers a relatively small area in these subbasins. A similar result was obtained for the Legedadi watershed, with increased actual ET in subbasins dominated by the optimally suitable class.

Furthermore, the interventions contributed to a reduction in soil erosion and sediment yield of up to 18 % in most subbasins located in the northern, northwestern, and northeastern in the Gefersa watershed and up to 10 % in the central parts extending from south to north in the Legedadi watershed. Reductions in sediment yields help to maintain soil fertility and ensure sustained agricultural productivity. In addition, reductions in sediment transport minimize siltation in reservoirs and thus increase the effective water storage capacity and lifetime of reservoirs. The positive effects of these interventions on the baseline simulation suggest potential mitigation strategies to counteract changes in water balance indicators caused by future land use and climate changes.

In subbasins with high surface runoff, ponds were implemented as NbS to store portions of the runoff to trap sediment yield. The retention of surface runoff enhanced water infiltration to the ground, which eventually increased the soil moisture content and groundwater availability in most subbasins. This could increase water availability during the dry season due to groundwater contributions in baseflow, improving the drinking water supply during the peak demand period. Adequate groundwater storage in subbasins dominated by agricultural land could promote supplemental irrigation for dry season farming, increasing crop productivity and

Table 5
Area coverage (%) of the land suitability for different interventions across the different suitability classes for the Gefersa and Legedadi watersheds.

Type of intervention	Watershed	Land suitability classes and area coverage (%)					
		Optimally suitable	Highly suitable	Moderately suitable	Marginally suitable	Not suitable	Total area (sq km)
Bunds	Gefersa	28	49	19	3	1	55
	Legedadi	14	46	25	14	1	394
Terraces	Gefersa	3	38	44	12	3	55
	Legedadi	10	29	48	12	1	394
Ponds	Gefersa	15	22	52	8	3	55
	Legedadi	16	40	31	13	0	394
Detention basins	Gefersa	5	56	23	11	5	55
	Legedadi	2	11	16	35	36	394
Retention basins	Gefersa	6	54	24	13	3	55
	Legedadi	6	10	16	34	34	394
Check dams	Gefersa	90	5	2	1	1	55
	Legedadi	71	7	8	14	0	394

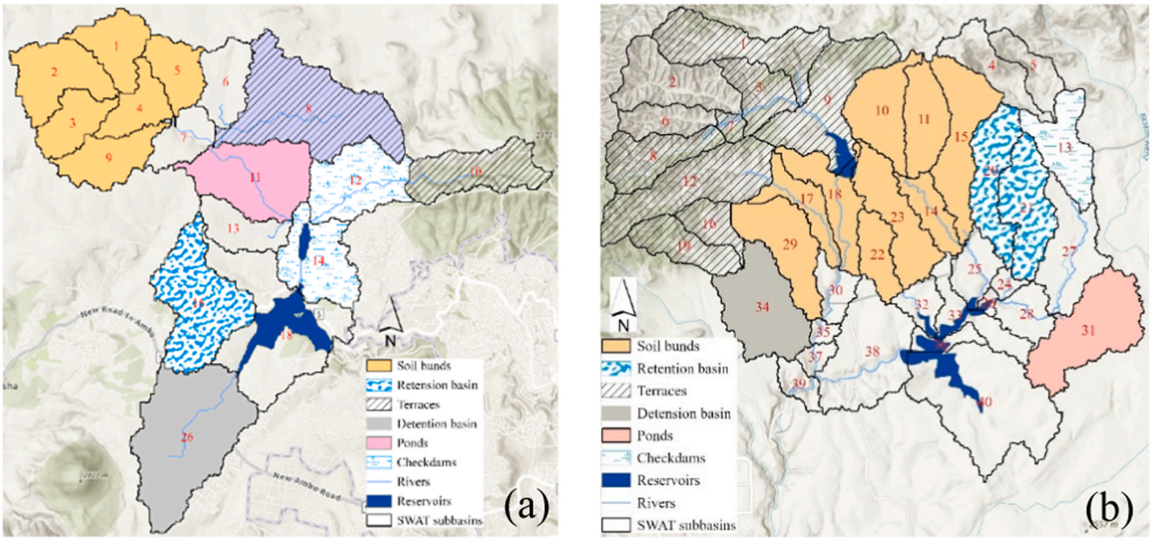

Fig. 6. Subbasins suitable for the implementation of NbS in Gefersa (a) and Legedadi (b) watersheds. The NbS were implemented in portion of each subbasin as summarized in supplementary 5.

income for smallholder farmers and environmental sustainability. Groundwater storage provides a resilient water source during droughts, helping farmers withstand climate-related shocks and maintaining agricultural production even under adverse conditions. Tefera et al. (2023) reported the positive impacts of interventions on increasing water availability, reducing reservoir sedimentation and enhancing dry season flow in the Akaki watershed. Other studies also support the positive impacts of these interventions (Zeberie, 2020; Asnake et al., 2021).

3.4.1. Limitations and recommendations

The model performance can be further improved by conducting seasonality in model verification using recent streamflow and more localized climate data (when available). To address data gaps, incorporating citizen science data could be a valuable approach for future studies. Addressing the limitations of the SWAT model in defining HRUs under land use change scenarios, as highlighted by Meng et al. (2018), can present an opportunity for improving model performance.

Downscaling and bias correction of GCMs are essential for reasonably capturing the climatic variability in such local and heterogeneous topographic watersheds. These approaches may improve the accuracy of climate change analyses and the reliability of the findings in future studies.

The machine learning models to predict land use assume that historical trends and relationships between land cover and other independent variables including human activities will continue. However, uncertainties arise from factors such as sensor errors, incomplete input data, and changes in socioeconomic drivers that are not captured in the model. Additionally, misclassification errors and the simplification of complex ecological processes introduce variability in predictions. Verifying land use with field observation data can further improve the accuracy of land use predictions, beyond Google Earth comparison. This can be considered as some of the limitations of the land use prediction that needs improvement in future studies.

The accuracy of the integration of the NbS in the SWAT depends on the accuracy of HRUs discretization to accommodate the exact extents of the interventions. However, achieving this level of accuracy is somehow difficult and unmanageable in SWAT and can be considered as a limitation in this study.

4. Summary and conclusion

Land use and climate changes have induced another layer of stress on water availability for water supply, agricultural and other uses, and environmental sustainability. The available records from the AAWSA indicate that water demand, which is proportional to population growth, has increased over time in Addis Ababa. On the other hand, the water supply from both the surface water and groundwater remains under stress due to many complex factors, such as climate, biophysical variables, poor watershed management and other anthropogenic activities. As a result, the gap between the city's water supply and demand has widened in recent years. Thus, this study attempts to assess not only the impacts of land use and climate changes but also the potential benefits of NbS in enhancing water availability and reducing sediment yield.

The impact assessment of land use and climate change in the Gefersa and Legedadi watersheds have significant implications on water availability and sediment yield. The expansion of urbanization in the watershed has resulted in decreased agricultural land and vegetation cover and increased runoff. Furthermore, climate change scenarios predict more frequent extreme events such as flash floods and droughts due to potential wet and dry conditions in the future. These findings highlight the need for the implementation of

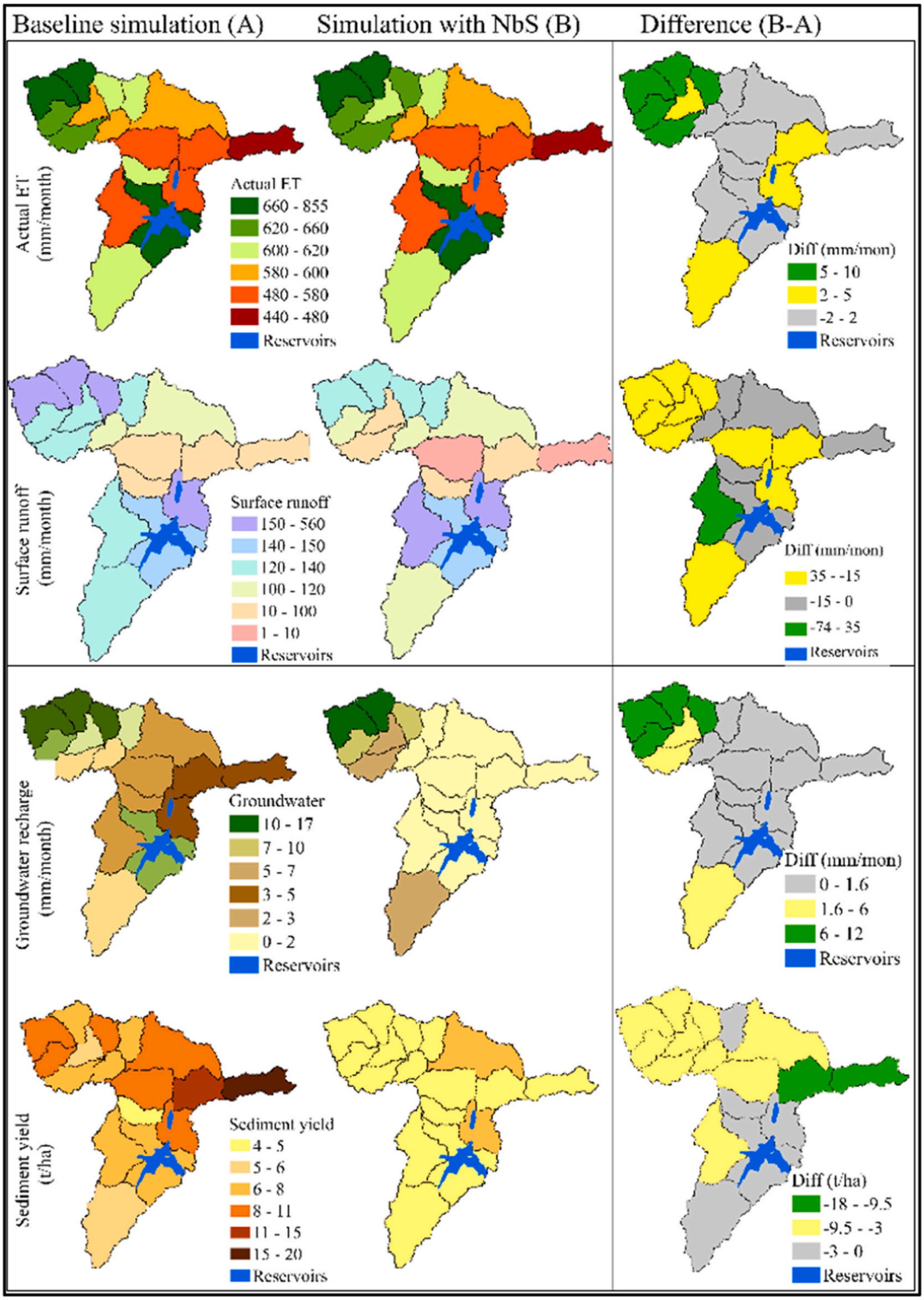

Fig. 7. Maps of the Gefersa watershed illustrate water balance model simulations for the baseline scenario (left) and with NbS (middle), as well as the difference between the two (right).

proper watershed management practices to protect and control land use change, which is due mainly to human interventions.

Furthermore, model simulation results with the integration of NbS illustrated the positive impacts of interventions in improving groundwater recharge and reducing sediment yield in both watersheds. This demonstrates the benefits of NbS in enhancing the water

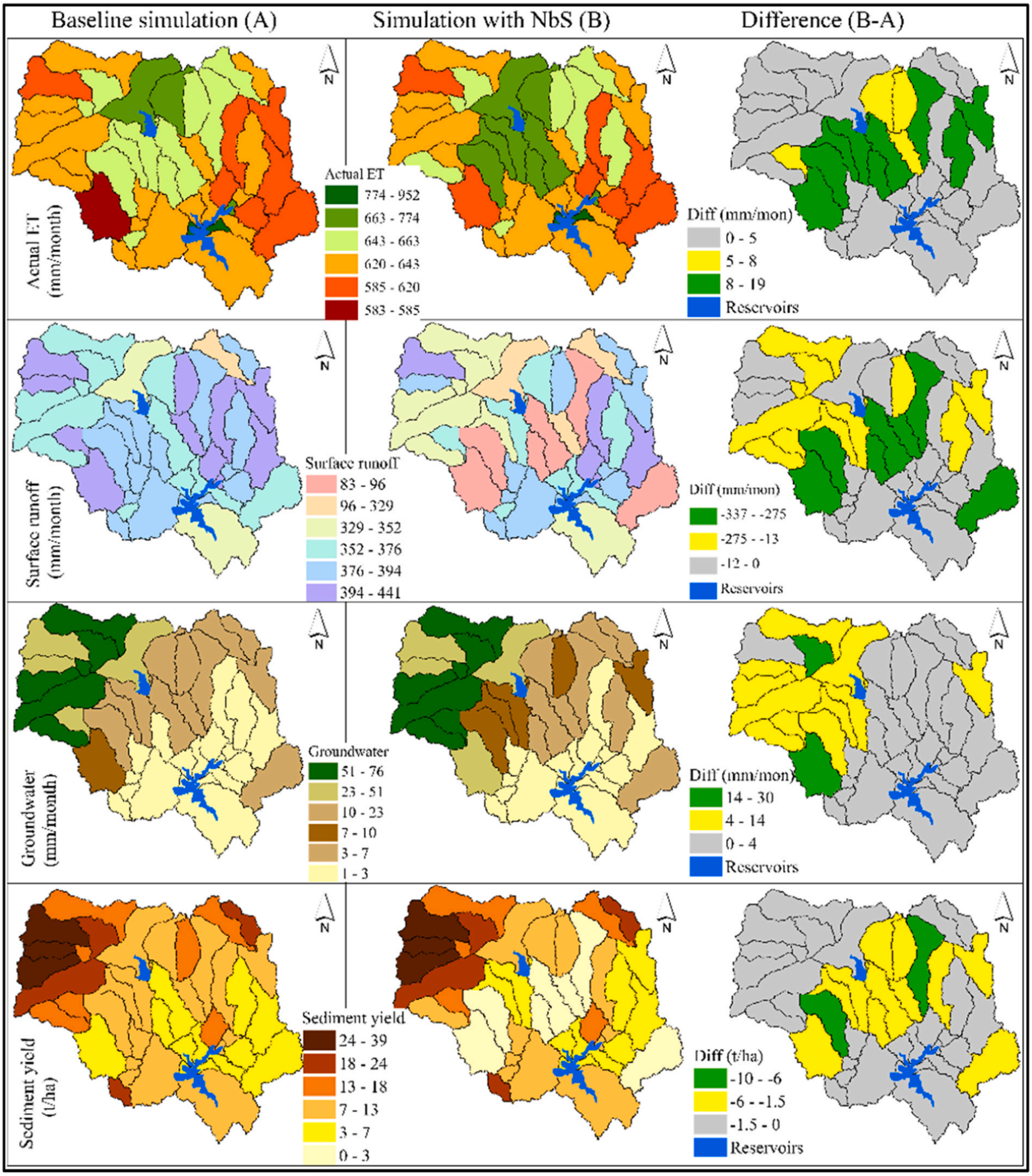

Fig. 8. Maps of the Legedadi watershed illustrate water balance model simulations for the baseline scenario (left) and with NbS (middle), as well as the difference between the two (right).

storage capacity and extending the lifespan of the water supply reservoirs. Additionally, the implementation of the NbS would help to maintain soil fertility and water availability primarily during the dry season to promote dry season farming and enhance agricultural productivity and environmental sustainability in the watersheds. The findings of this study can be upscaled to larger spatial scales such as the basin and national levels. By prioritizing sustainable land and water management practices, these watersheds can be used as a model for integrated water resource management in Ethiopia and beyond to increase the life expectancy of water supply reservoirs through an increase in water availability and reduction in siltation.

Addressing the challenges identified in this study requires policy actions to improve sustainable water management. First, enforcing land use regulations that promote sustainable watershed management is essential. Second, integrating NbS into national and regional water policies can enhance climate resilience and reduce sedimentation in key reservoirs. Third, building climate-resilient infrastructure, such as rainwater harvesting systems and managed aquifer recharge zones, will help secure water availability during dry seasons. Finally, community-based early warning systems and climate-smart agriculture are vital for mitigating extreme weather impacts. Scaling up successful interventions from Gefersa and Legedadi can serve as a model for integrated water resource management across Ethiopia and other vulnerable regions.

The approach followed in this study can be adapted to other watersheds with access to better quality, representative and recent input datasets for future research. Moreover, the findings of this study could be further refined with the availability of updated, high-quality datasets for the study watersheds. This would also require additional efforts in future research to address uncertainties attributed to model structure, parameter estimation, and projections of climate and land use changes.

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CRediT authorship contribution statement

Douglas Nyolei: Writing – review & editing, Methodology. **Johannes Hunink:** Writing – review & editing, Methodology. **David de Andrade Costa:** Writing – review & editing. **Semu Moges:** Writing – review & editing, Data curation. **Assefa Melesse:** Writing – review & editing. **Dereje Tadesse:** Data curation. **Seifu Tilahun:** Writing – review & editing. **Yared Bayissa:** Writing – original draft, Methodology, Data curation, Conceptualization. **Raghavan Srinivasan:** Writing – review & editing, Methodology, Conceptualization.

Declaration of Competing Interest

We have no conflicts of interest to disclose. The material presented is solely the work of the authors, with no duplication. We also confirm that the research adheres to established scientific standards and integrates knowledge within the recognized norms of the field.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2024.102130.

Data availability

Data will be made available on request.

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