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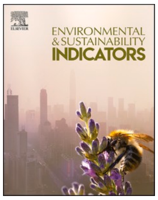

Detection of Hydrological Alteration and soil erosion in a conserved tropical sub-humid ecosystem of Ethiopia

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ABSTRACT

Soil erosion poses a significant challenge in the sub-humid Ethiopian highlands, yet research on the long-term effectiveness of soil and water conservation (SWC) practices in this region using pre- and post-conservation approaches remains limited. This study addresses this knowledge gap by evaluating the impact of SWC practices on water balance and soil erosion in the Debre Mawi watershed. The study covers two-period analyses: pre-conservation (2010–2014) and post-conservation (2015–2022) using the Soil and Water Assessment Tool (SWAT) to simulate hydrological water balance. Hydrological changes were assessed with the Indicators of Hydrological Alteration (IHA) software. Spatial and weekly sediment distribution were also computed. Results showed the SWAT effectively simulated stream flow, though sediment yield estimation was less accurate. The data demonstrated a reduction in surface runoff by 18% and a decrease in sediment yield by 75%. Conversely, evapotranspiration and groundwater storage experienced increases of 13% and 34%, respectively. The decrease in runoff and sediment can be attributed to the implementation of SWC structures with infiltration furrows, which are presently filled with sediment. Moreover, the expansion of eucalyptus tree acreage may deplete soil water during dry periods, thereby prolonging the time needed for the soil to become saturated and produce runoff, but the impact has yet to be quantified. The IHA analysis confirmed a decrease in mean annual flow from 0.06 m^3/s to 0.02 m^3/s, and sediment concentration decreased from 831.2 mg/l to 285 mg/l between the pre-and post-conservation periods. The study detected that soil erosion is higher than the allowable limits recommended for Ethiopia even after implementing SWCPs. Additionally, sediment transport reduced after the first three weeks due to improved ground cover and soil stability, although significant amounts were recorded until the end of the rainy season, primarily from gullies. The study found significant hydrological alterations in flow and sediment dynamics following the implementation of SWC practices, particularly pronounced in the early years post-conservation (2015–2018). However, the effectiveness of SWC practices diminished over time, with conditions beginning to revert to pre-conservation levels after 10 years. This suggests that these techniques (infiltration furrows) may be unsuitable for sub-humid watersheds, or that they require improved design and major maintenance beyond the third year. This study offers valuable insights into the dynamics of SWC interventions, underscoring the importance of integrating agronomic practices with SWC efforts to sustain long-term soil and water conservation in Ethiopia's sub-humid highlands. Future research should explore the hydrological effects of eucalyptus expansion and refine SWC practices suited to these unique conditions.

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1. Introduction

Soil erosion and land degradation have emerged as critical global issues over the past half-century, with an estimated 2 billion hectares of land degraded, contributing to a significant decline in agricultural productivity worldwide (Hussain et al., 2021; Tsymbarovich et al., 2020). This degradation has reduced approximately 11.9–13.4% in the global agricultural supply, with Africa experiencing some of the most severe impacts (Lal, 2015; Bekele et al., 2022; Eswaran et al., 2019). In East Africa, particularly the Ethiopian highlands, soil erosion has become a pressing concern, leading to agricultural yield losses ranging from 2 to 40%, depending on local conditions (Lal, 2015; Bekele et al., 2022; Eswaran et al., 2019).

The Ethiopian sub-humid highland ecosystem, a vital resource for agriculture, freshwater, and biodiversity (Girmay et al., 2020), faces severe land degradation due to factors such as rugged topography, intense rainfall, and unsustainable land management practices (Meseret, 2016; Mwaura et al., 2021), contributing to significant soil erosion and high annual runoff rates (Asthana et al., 2022; Fenta et al., 2021). Soil erosion reduces agricultural productivity and alters hydrological processes within the watershed (Asthana et al., 2022). Historical records suggest that the problem of soil erosion in the Ethiopian highlands began approximately 4000 years ago with the advent of agriculture, significantly reducing soil fertility and land productivity (Meseret, 2016; Wassie, 2020).

Currently, the Ethiopian highlands lose about 1.9 billion tons of soil annually, with erosion rates varying widely based on terrain, land use, and agro-ecological zones (Adem et al., 2020). The soil loss is estimated to range from negligible to 169 t ha^{-1} yr^{-1}, with an average of 32 t ha^{-1} yr^{-1} in the northwest highlands of Ethiopia (Lemma et al., 2019), equating to more than 3 mm of topsoil loss per year. This rate far exceeds the natural soil formation rate, estimated at 6–18 t ha^{-1} yr^{-1}, and allowable soil loss rates estimated for Ethiopia (1–6 t ha^{-1} yr^{-1}). This alarming rate of soil loss has profound implications for agricultural productivity, hydrological processes, and overall land sustainability highlighting the urgent need for effective soil conservation measures (Chalise et al., 2019).

Recognizing the severe implications of land degradation, Ethiopia has undertaken watershed development initiatives since the 1980s, with a particular focus on soil and water conservation practices (Chimdesa, 2016). These efforts, largely driven by government and non-government organizations implemented widely through community mobilization and food-for-work programs (Lewis et al., 2020). While SWC interventions have been shown to reduce soil loss and runoff rates, leading to improvements in soil fertility, water availability, and crop productivity, the effectiveness of these interventions remains a topic of debate (Dagnew et al., 2015a). For instance, a value of 0.1–35 g l^{-1} sediment yield and 0.5 to over 30 mm of daily storm runoff were recorded after the implementation of SWCPs in a sub-humid highlands like Debre Mawi watershed (Tilahun et al., 2015). Previous studies on SWC have produced mixed results, with their outcomes influenced by the type of measures employed and the specific agro-ecological conditions under which they were implemented.

Despite the widespread implementation of Soil and Water Conservation (SWC) practices in Ethiopia's sub-humid highlands, the soil erosion problem remains a significant concern. While SWC measures are known to reduce runoff and sediment yield, there is still a considerable lack of comprehensive scientific studies that assess these practices' long-term impacts, particularly in Ethiopia's sub-humid regions. Some studies have demonstrated the benefits of SWC measures in reducing soil loss, improving soil fertility, and enhancing crop productivity, the long-term impacts of these practices, particularly in the sub-humid highlands of Ethiopia, are not well understood. The existing research is often constrained by the use of short-term data, lamped and fragmented findings, and an absence of integrated analyses that consider the cumulative effects of SWC practices over time.

Moreover, there is a pronounced scarcity of studies that utilize long-term discharge and sediment data to evaluate the before-and-after effects of SWC interventions. Such data are crucial for a more accurate assessment of the hydrological impacts of these conservation measures. The use of time-series data, which allows for a thorough examination of changes in hydrological processes, is especially limited in the sub-humid highlands. Furthermore, there is a gap in the integrative application of models like SWAT (Soil and Water Assessment Tool) and IHA (Indicators of Hydrologic Alteration), which could provide a more comprehensive understanding of the hydrological alterations and soil erosion in these regions.

This study aims to fill these knowledge gaps by conducting a comprehensive assessment of the impacts of Soil and Water Conservation (SWC) practices on hydrological processes and soil erosion in the Debre Mawi watershed. The specific objectives are: (i) to estimate the changes in water balance components before and after the implementation of SWCP using the SWAT (Soil and Water Assessment Tool) model; (ii) to analyze alterations in sediment yield and flow using IHA (Indicators of Hydrologic Alteration) model; (iii) to assess the weekly variation in sediment yield pre- and post SWC implementation; and (iv) to identify critical source areas contributing to runoff flow and sediment yield. This study provides a detailed analysis of the long-term effects of SWC practices, offering valuable insights into the sustainability of these interventions in the Ethiopian highlands.

2. Methodology

2.1. Study area description

The study was conducted in the Debre Mawi watershed, located within the northwestern sub-humid Ethiopian highland ecosystem (Fig. 1(a–c)). The watershed covers an area of 97 ha and is geographically positioned between 11°21′18″ to 11°22′1″ North latitudes and 37°25′3″ to 37°25′37″ East longitudes. The elevation within the watershed ranges from 2195 to 2308 m above mean sea level. The terrain includes a variety of slope gradients: plain (0–5%), gentle (5–8%), moderate (8–15%), steep (15–30%), and extremely steep (>30%) accounting for 17.46%, 22.72%, 38.53%, 21.18% and 0.14% of the area, respectively (Mhiret et al., 2019).

The climate is a sub-humid, with an average annual rainfall of 1240 mm and a mean annual temperature of approximately 20 °C (Dagnew et al., 2015a, 2015b). Rainfall follows a mono-modal pattern, with most precipitation occurring between June and September (Mhiret et al., 2019). The watershed's soils consist mainly of Haplic Vertisols (32.33%), Luvic Nitisols (23.96%), Haplic Luvisols (21.58%), Vertic Cambisols (16.16%), and Haplic Leptsols (5.97%) (Tebeje et al., 2024). Nitisols, which are very deep, well-drained, permeable red clay loam soil, are found in the upper part of the watershed. The Vertisols, characterized by black cracking soil, occupy foot slopes, while Leptosols with very shallow soil depth are located at the shoulder areas.

In terms of land use land cover, agricultural land dominates the watershed. In 2022, the land cover comprised 77% cropland, 9% grass, 11% Eucalyptus, and 3% sparse vegetation. There has been a noticeable expansion of Eucalyptus and cropland at the expense of grassland and sparse vegetation. The cropping system, as described by Mhiret, Dagnew (Mhiret et al., 2019), is dominated by cereal cultivation, with *Teff*, wheat, maize, and barley being the dominant crops. Finger millet, lupine, and grass pea are also commonly grown in the area.

2.2. Identified soil and water conservation practices (SWCPs)

The Debre Mawi watershed, the focus of this study, implemented soil and water conservation practices (SWCPs) after 2012 with the new campaign by the government. However, between 2012 and 2014, farmers introduced three distinct land management practices i.e. non-conserved, soil bund, and stone bund. The SWCPs included stone bunds and soil bunds with infiltration furrows that were installed on the contour of cultivated and grazing lands, with heights ranging from 0.3 to 0.6 m (Mhiret et al., 2019). The horizontal spacing between the bunds was generally 32 m, though this was reduced on steeper land to ensure a maximum elevation difference of 1.5 m (Mhiret et al., 2019). These practices were applied to approximately 51% of the watershed area with stone bunds and 32% with soil bunds, leaving 17% un-conserved. All SWCP have targeted sheet and rill erosion, while in the watershed, there are permanent valley-bottom gully drainage networks; in particular, gully widening and head cut retreat are important erosion processes (Zegeye et al., 2016).

The study period (2010–2022) was divided into three distinct phases: pre-conservation (2010–2011), establishment (2012–2014), and post-conservation (2015–2022). For analytical purposes, the "pre-conservation" and "establishment" phases were combined into a single "before conservation" period (2010–2014) to compare with the "after conservation" period (2015–2022). This approach allows an evaluation of the effectiveness of SWCP implementation on hydrological processes and soil erosion.

2.3. Data types and sources

This study employs two key hydrological analysis tools: the Soil and Water Assessment Tool (SWAT) model and Indicators of Hydrological Alteration (IHA) software. The SWAT model utilizes a variety of spatial and climate datasets to accurately represent the watershed's characteristics. A Digital Elevation Model (DEM) provided detailed terrain information at a 12.5-m resolution (Arko et al., 2014) (Table 1). Land cover data, classified for 2022 using Sentinel 2 imagery with a 10-m spatial resolution, was another essential input (Table 1). The land cover classification followed the categories established by Ghorbanian, Kakooei (Ghorbanian et al., 2020). Soil data was compiled from existing

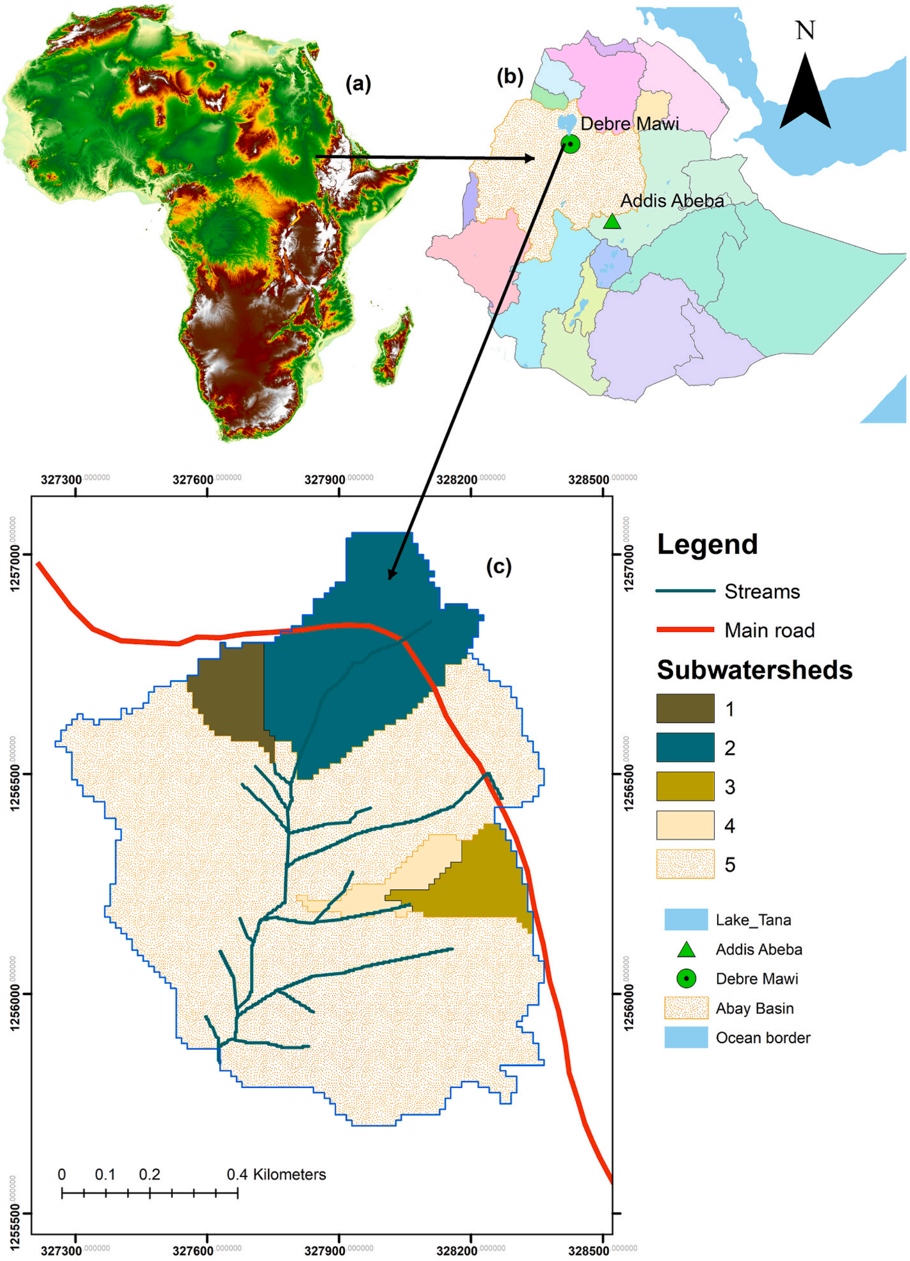

Fig. 1. Africa (a), major river basins in Ethiopia, Abay basin, Lake Tana and Debre Mawi watershed (b), and location of sub-watersheds and weir sites in Debre Mawi watershed (c).

Table 1
Summary of spatial and non-spatial data.

Data	Description	Source and description
DEM	12.5 m	https://search.asf.alaska.edu
Land cover	10 m	Sentinel image classification
Soil	~250m	https://www.isric.org/projects/africa-soil-information-service-afsis and previous survey
Precipitation	2007–2022	Present survey and CHIRPS https://climexp.knmi.nl/start.cgi) (CHIRPS 2.0 Africa 0.25° 1981-now observation
Temperature	2007–2022	https://power.larc.nasa.gov/
Relative humidity	2007–2022	https://power.larc.nasa.gov/
Wind speed	2007–2022	https://power.larc.nasa.gov/
Sunshine hours	2007–2022	https://power.larc.nasa.gov/
Discharge and sediment yield	2010–2018 and 2021–2022	Measured data

DEM, digital elevation model; and CHIRPS, Climate Hazard Group Infrared Precipitation with Station data.

soil survey reports (Mhiret et al., 2019; Tebeje et al., 2024; Tilahun et al., 2016) and further supplemented with information from the Africa Soil Information Service (AFSIS) (Hengl et al., 2015), resulting in a comprehensive soil map at a 250-m resolution.

Climate data for both the SWAT model and IHA software includes daily rainfall data for the rainy season (June–October) from 2010 to 2018 and 2021 to 2022. The primary source for this rainfall data was a micro weather station located within the watershed. Missing rainfall data for 2007–2009, 2019–2020, and the dry season (November–May) was sourced from the KNMI Climate Explorer (Xiang et al., 2021). Additionally, data on minimum and maximum air temperature, relative humidity, wind speed, and sunshine hours for the period 2007–2022 were obtained from the Power NASA data access center and were used exclusively within the SWAT model.

In addition to spatial and climate data, both the SWAT model and IHA software relied on discharge and sediment data. These data were collected at the main watershed outlet over 11 years (2010–2018 & 2021–2022) during the rainy season (June to September), with measurements taken during the rainfall event. Storm events, defined as the period between the start and end of surface runoff from precipitation (Mirus et al., 2013), were used to define measurement intervals. Flow rate data was recorded every 10 min using a water depth meter at the weir, and the depth measurements were changed into the flow using a pre-established stage-discharge rating equation (Tilahun et al., 2015; Mhiret et al., 2019).

To quantify sediment yield during runoff events, 1-L runoff water samples were collected every 10 min and filtered through 2.5 μm filters. The filtered sediments were then oven-dried at 105 °C for 24 h, after which, the samples were weighed to determine the suspended sediment weight. Daily storm runoff and sediment load were calculated by summing the 10-min data for each storm event. The daily average sediment concentration was determined by dividing the total sediment load by the total daily storm runoff volume. This 11-year record of the daily discharge and sediment data served as a valuable resource for model calibration, validation, and pre-and post-impact analysis using both the SWAT model and IHA software.

2.4. Statistical tests

Statistical analyses were performed to assess the collected data on precipitation, runoff, and sediment concentration. Rainfall variability across the study period was evaluated using the coefficient of variation (CV), which expresses the standard deviation as a proportion of the mean rainfall amount. The frequency of rainfall events that triggered runoff generation was also calculated. To compare runoff patterns throughout the wet season (June–September), a runoff coefficient was derived for each storm event, representing the ratio of runoff volume to rainfall volume for a specific storm. Monthly runoff coefficients were then obtained by averaging the storm-based coefficients within each month. Finally, cluster analysis was used to assess the impact of SWCP implementation on key parameters during the wet season months (June–September) for both pre-and post-conservation periods. These parameters included runoff volume, sediment concentration, and runoff coefficients.

2.5. Hydrological simulation

2.5.1. Soil and Water Assessment Tool (SWAT) model

2.5.1.1. Model description. This study employed the Soil and Water Assessment Tool (SWAT) model, a physically based, distributed hydrological model (version SWAT2012), to simulate hydrological processes at the watershed scale. The SWAT model is designed to account for spatial heterogeneity within a watershed by incorporating detailed information on weather, topography, land use, and soil properties. The watershed is divided into Hydrologic Response Units (HRUs), which are unique combinations of these factors, allowing for a more accurate representation of the landscape (Fig. 2).

At the core of the SWAT model is the water balance equation (Equation (1)), which tracks water movement through the watershed over time. The equation is expressed as:

$$SWt = SWo + \sum [Rday - Qsurf - ETa - Wseep - Qgw] \tag{1}$$

Where t is the time in days, SWt is the final soil water content, SWo is the initial soil water content, Rday is the amount of precipitation, Qsurf is the amount of surface runoff, ETa is the amount of evapotranspiration, Wseep is the amount of percolation, and Qgw is the amount of return flow.

Surface runoff is estimated using the Soil Conservation Service (SCS) curve number method (Lal et al., 2017), as shown in Equation (2):

$$Qsurf = \frac{(Rday - 0.2S)^2}{(Rday + 0.8S)}\ if\ Rday > 0.2S; Qsurf = 0, otherwise \tag{2}$$

Qsurf is the accumulated runoff or rainfall excess (mm), Rday is the rainfall depth for the day (mm), and S is the retention parameter (mm).

The retention parameter (S) reflects soil permeability, land use, and antecedent soil moisture conditions, and is defined by Equation (3):

$$S = 25.4\left(\frac{100}{CN} - 10\right) \tag{3}$$

To estimate soil erosion and sediment yield at the HRU level, SWAT uses the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975). The sediment yield (SY) is estimated using Equation (4):

$$SY = 11.8{*}(Qsur{*}qp{*}A)^{0.56}{*}K{*}C{*}LS{*}P{*}F \tag{4}$$

Where SY is sediment yield (t ha^{-1} yr^{-1}), qp is peak runoff (m^3s^{-1}), A is the area of HRU (ha), KCLSP is the standard USLE factor for erodibility, crop cover, slope length-gradient, and erosion control practice; and F is a factor to account for percent of stoniness (coarse fragment factor).

The peak runoff is further calculated using Equation (5):

$$qp = \frac{atc{*}Qsr{*}Area}{3.6{*}tc} \tag{5}$$

qp is peak runoff (m^3s^{-1}), atc is a fraction of daily rainfall that occurs during the time of concentration, area is a sub-basin area (km^2), and tc is the time of concentration for the basin (hr). For detailed information on the underlying equations and algorithms, refer to the SWAT theoretical documentation and user's guide (Neitsch et al., 2011; Winchell et al., 2013).

2.5.1.2. Model setup. The model delineated HRUs based on inputs from

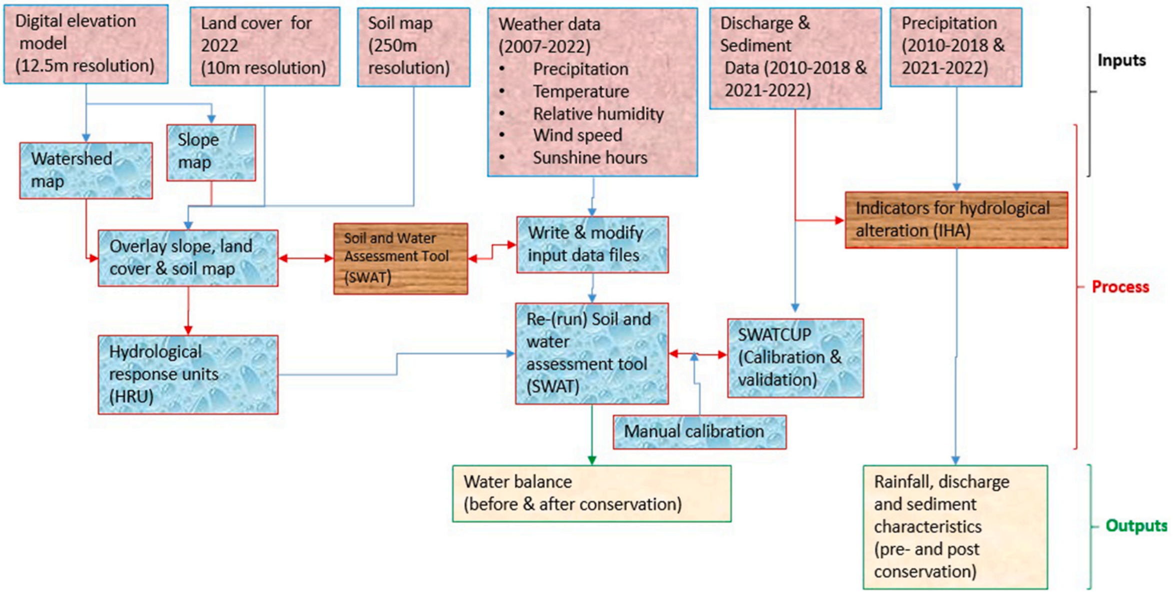

Fig. 2. Soil and water assessment tool (SWAT) model and Indicators of hydrological alterations (IHA) software inputs, process and outputs schematic diagram.

a digital elevation model (DEM), a land cover map, and a soil map. Daily climate data from 2007 to 2022, including rainfall, temperature, solar radiation, wind speed, and relative humidity, were used to drive the model simulations. The initial three years (2007–2009) served as a model warm-up period.

For comparative analysis, the observed data from 2010 to 2022 was divided into two distinct periods: pre-conservation (2010–2014) representing the period before the implementation of soil and water conservation practices (SWCP), and post-conservation (2015–2018, 2021–2022) representing the period following the introduction of these practices. This separation allowed for the visualization of model results under two scenarios: "with conservation" and "without conservation" throughout the simulation period. This approach enables an assessment of the combined influence of climate, topography, land use, soil properties, and land management practices on key water balance components within the watershed.

2.5.1.3. Model calibration and validation. To ensure model accuracy, calibration and validation were performed separately for the periods before and after the implementation of SWCPs within the watershed. Before calibration, a sensitivity analysis was conducted using SWAT-CUP (Arnold et al., 2012), to identify the parameters that most significantly influenced model performance. This analysis involved selecting based on previous studies and SWAT documentation. The sensitivity significance of each parameter was evaluated using the t-statistic test and p-value. Approximately 22 parameters were subjected to sensitivity analysis and they were categorized as sensitive, less sensitive, or insensitive based on their t-statistic and p-value, with a focus on the sensitive parameters during calibration.

The model simulation was divided into three distinct stages: warm-up, calibration, and validation. The 16-year simulation period (2007–2022) was segmented as follows: the initial three years (2007–2009) were used for model initialization (warm-up), the next five years (2010–2014) were employed for calibration and validation before conservation implementation, and the final six years (2015–2018, 2021–2022) were used for calibration and validation after conservation practices were implemented. In both pre- and post-conservation scenarios, the observed data were apportioned with 70% allocated for calibration and 30% reserved for validation.

Model performance during calibration and validation was evaluated using a combination of statistical metrics, including the coefficient of determination (R^2), Nash-Sutcliffe modeling efficiency (NSE) (Nash and Sutcliffe, 1970), and percent bias (PBIAS). The NSE was used to categorize performance as unsatisfactory ($NSE \leq 0.50$), satisfactory ($0.50 < NSE \leq 0.65$), good ($0.65 < NSE \leq 0.75$), and very good ($0.75 < NSE \leq 1.00$) (Moriasi et al., 2007). Additionally, model uncertainty was assessed using the p-factor (percentage of observations within the 95% prediction uncertainty) and the r-factor (measure of the 95% prediction uncertainty band thickness). Values closer to 1 for the p-factor and closer to 0 for the r-factor indicate superior model performance (Lemma et al., 2019; Abbaspour et al., 2004).

2.5.1.4. Water balance. SWAT model simulations were used to evaluate the impact of SWCPs on the watershed's water balance. Key water balance components, including surface runoff, lateral flow, percolation (into both shallow and deep aquifers), evapotranspiration, and sediment yield, were analyzed for both pre-and post-conservation periods. This comparative analysis allowed for the identification of changes in the watershed's hydrological processes resulting from the implementation of SWCPs. Furthermore, the water balance results were integrated with observed sediment yield data to map erosion hotspots within the watershed.

2.5.2. *Indicators of hydrological alteration (IHA)*

Following the SWAT model analysis, Indicators of Hydrological Alteration (IHA) were used to assess the hydrological changes within the watershed. The IHA framework, which utilizes a range of variability approaches (RVA) and non-parametric statistics (Richter et al., 1998), was employed to evaluate trends over the 13 years (2010–2022). This analysis focused on detecting alterations in hydrological parameters such as rainfall, sediment yield, and various flow characteristics before and after the implementation of conservation practices.

The IHA analysis considered several parameters, including maximum flow over various durations (1, 3, 7, 30, and 90 days), zero-day flow, base flow index, non-normalized mean flow, monthly median flow with flood events, and the annual coefficient of variation (CV) for rainfall, discharge, and sediment. These flow characteristics were categorized into the five environmental flow components: extreme low flows, low flows, high flow pulses, small floods, and large floods, as defined by Mathews and Richter (Mathews et al., 2007). The analysis then evaluated the magnitude, frequency, duration, timing, and rate of rise and fall for each component providing a comprehensive understanding of how conservation practices influenced the hydrological regime of the watershed.

2.6. Weekly distribution of sediment yield

The daily sediment yield was systematically measured from 2010 to 2022, and this data was analyzed weekly to understand sediment yield variation throughout the rainy season. This analysis involved compiling average daily sediment yield values, expressed in milligrams per liter (mg/l), for the first eight weeks of the rainy season. Weekly trends were monitored, with the eighth week's data representing an average of the remaining measurements for the season. This approach clarified how sediment yield progressed over the early part of the rainy season.

To assess the impact of soil and water conservation (SWC) activities on sediment yield, the data were divided into two distinct periods: before (2010–2014) and after (2015–2022) the implementation of SWC measures. Average sediment yield values for these periods were calculated and compared to evaluate how SWC practices influenced sediment dynamics. This approach highlights the effectiveness of the conservation efforts in reducing sediment yield and stabilizing the landscape.

Additionally, the analysis considered the effects of land preparation, land cover change, and crop growth on sediment yield. Changes in land cover and crop growth patterns, including variations in vegetation and soil disturbance due to land preparation, were factored into the sediment yield trends. These factors can significantly impact sediment dynamics by altering soil stability, runoff patterns, and vegetation cover, which in turn affects sediment transport and deposition.

2.7. Erosion hotspot analysis

To identify erosion hotspots within the watershed, sediment yield data derived from the SWAT model simulation integrated with observed data was utilized. This data provided a spatial representation of sediment concentration across different areas, enabling the identification of regions with particularly high erosion rates. The annual sediment yield (SY) was calculated and subsequently classified into various erosion severity categories based on established guidelines by Gelagay and Minale (Gelagay et al., 2016). These categories ranged from low to very severe, providing a nuanced understanding of erosion intensity across the landscape.

The classification was as follows: low erosion was defined as sediment yields between 0 and 7 tons per hectare per year (t ha^{-1} yr^{-1}); moderate erosion ranged from 7 to 15 t ha^{-1} yr^{-1}; high erosion was categorized as 15 to 25 t ha^{-1} yr^{-1}; very high erosion encompassed yields of 25–45 t ha^{-1} yr^{-1}; severe erosion was marked by yields of 45–60 t ha^{-1} yr^{-1}; and very severe erosion was identified in areas where sediment yields exceeded 60 t ha^{-1} yr^{-1}.

By mapping these categories across the watershed, areas particularly susceptible to erosion—referred to as erosion hotspots—were identified. These hotspots are critical areas where erosion control measures are most needed to mitigate soil loss and maintain the landscape's integrity. Understanding the spatial distribution of erosion severity allows for targeted interventions, ensuring that soil and water conservation efforts are concentrated in the most vulnerable areas. This approach not only aids in reducing overall sediment yield but also helps preserve soil fertility and prevent further land degradation within the watershed.

3. Results

3.1. General trends of hydrologic parameters

The study examined the general trends of rainfall, runoff events, sediment yield, and the impact of soil and water conservation (SWC) practices on these parameters from 2010 to 2022.

3.1.1. Rainfall-runoff relationships (2010–2022)

Rainfall data analysis from 2010 to 2022 revealed an average rainfall depth of 980 mm during the wet season (June and October), with minimum and maximum depths recorded at 750 mm (in 2014) and 1171 mm (in 2021), respectively (Fig. S2 and Table S1). The maximum daily rainfall event occurred on June 11, 2014, with a recorded depth of 152 mm. The length of the rainy season varied, ranging from 61 days in 2012 to 118 days in 2016, with more than 100 days recorded in 2010, 2014, 2015, and 2018. The start and end of the rainy season exhibited shifts of ±30 days, with 2012 marking an unusually early start and late offset. July and August were peak months for rainfall, contributing an average of 67% of the annual total rainfall (Fig. S1). The number of rainy days per year remained relatively constant, except for a significant drop to 74 days in 2019 (Fig. S1). The results of the IHA analysis demonstrated that the trend in mean annual precipitation was not statistically significant from 2010 to 2022.

The number of runoff days per year decreased from 2010 to 2013, followed by relative stability between 2014 and 2017, and an increase from 2018 to 2022. The percentage of rainy days that generated runoff mirrored this pattern, decreasing from 38% in 2010 to a low point in 2013, before increasing and stabilizing around 34% from 2017 onwards (Fig. 3). This decline in runoff generation after rainfall suggests that soil and water conservation (SWC) practices positively impact water resource management within the watershed.

Statistical analysis showed that the average daily rainfall was 2.59 mm, with a low coefficient of variation of 2.54%, indicating no significant variation in rainfall patterns during the study period. The impact of SWC practices on runoff was further evaluated using the runoff coefficient, which decreased after SWC implementation (Figs. 4 and 5). The average annual runoff coefficient before SWC implementation was approximately 0.30 (2010–2011) and dropped to 0.06 after the implementation of conservation measures.

3.1.2. Discharge trends (2010–2022)

Discharge data from 2010 to 2022 revealed a higher average value with a declining trend from 2010 to 2014, followed by a considerable drop in 2015 (Fig. S3). Discharge remained lower through 2018, then grew again from 2021 to 2022. This substantial decrease in flow during 2015 coincides with the full implementation of SWC structures in the watershed, suggesting their positive impact on reducing discharge within the first two to four years of implementation. The average annual decrease in flow due to SWC implementation was estimated to be around 18% when comparing pre-conservation data (2010–2014) with post-conservation data (2015–2022). Furthermore, the average annual decrease in flow was approximately 37.5% when comparing the pre-conservation period (2010–2014) with the immediate post-

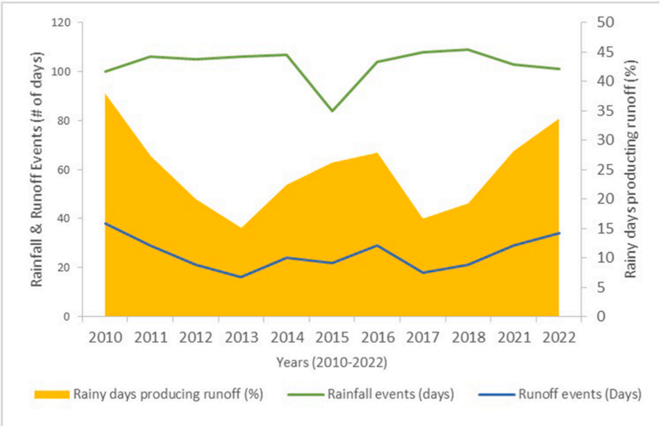

Fig. 3. Number of rainfall and runoff days and rainy days producing runoff (%) at Debre Mawi from 2010 to 2022.

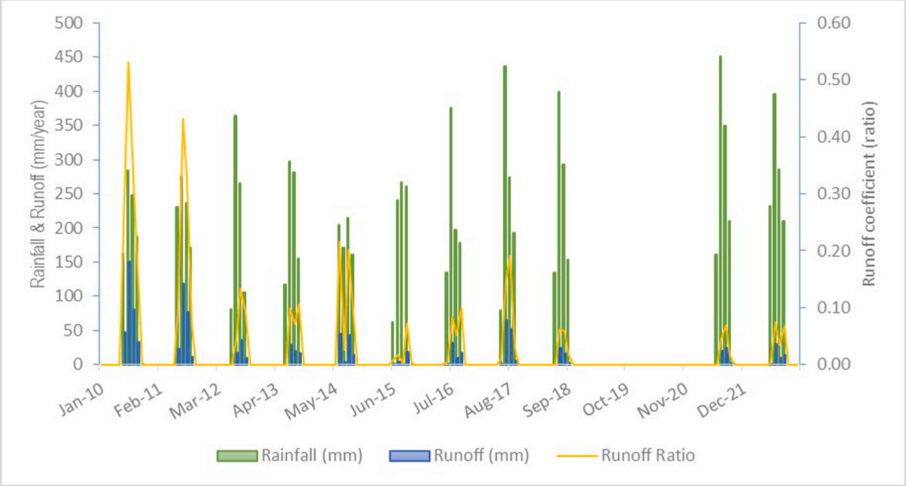

Fig. 4. The ratio of runoff to the rainfall amount derived from measured data from 2010 to 2018 and 2021 to 2022.

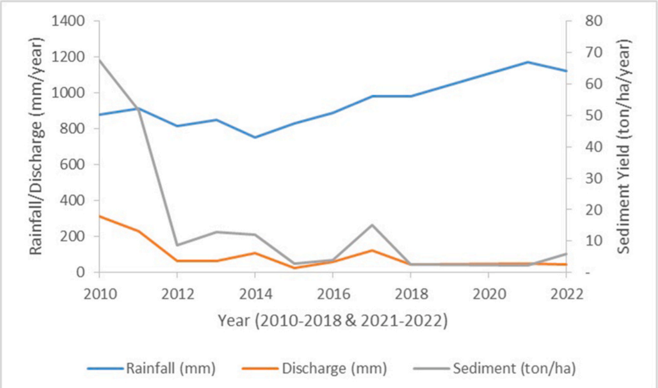

Fig. 5. Rainfall, runoff, and sediment general relationship evaluation curve (observed data).

conservation period (2015–2018).

Discharge characteristics before and after conservation revealed distinct patterns (Fig. 6, S3, and S4). Pre-conservation discharge was marked by high peak flows during rainfall events, followed by an abrupt drop after the rain stopped. In contrast, post-conservation discharge featured lower peak flows and sustained flow even after rainfall ceased, indicating more significant infiltration and reduced runoff, the decrease in runoff can be attributed to the implementation of SWC structures with infiltration furrows, which are presently filled with sediment. Moreover, the expansion of eucalyptus tree acreage may deplete soil water during dry periods, thereby prolonging the time needed for the soil to become saturated and produce runoff.

The gradual increase in discharge observed in later years suggests a decline in the efficacy of SWC structures, this suggests that these techniques (infiltration furrows) may be unsuitable for sub-humid watersheds, especially in regions similar to the Debre Mawi Watershed where runoff is produced by mechanisms related to saturated excess runoff generation, which involves landscapes that periodically reach saturation, or that they require improved design and maintenance.

3.1.3. *Sediment concentration (2010–2022)*

Daily sediment concentration analysis throughout the study period revealed a trend similar to discharge patterns (Fig. S5). The annual average decrease in sediment concentration after SWC implementation was estimated as 75% when comparing pre-conservation data (2010–2014) with post-conservation data (2015–2022). Similarly, the average annual decrease in sediment concentration was approximately 82% when comparing before conservation (2010–2014) with the data immediately after conservation (2015–2018).

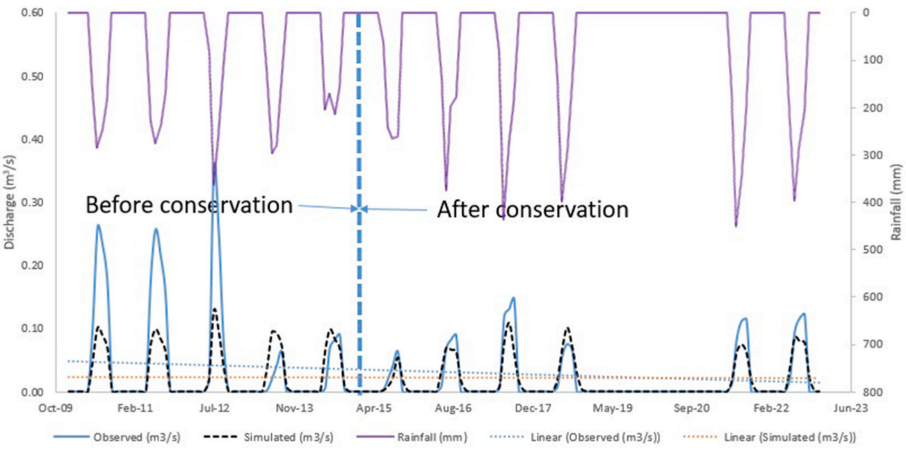

Fig. 6. Mean monthly observed and simulated discharge curve from 2010 to 2018 and 2021–2022.

3.2. SWAT model simulation results

3.2.1. Sensitivity analysis of hydrological parameters

The sensitivity analysis conducted from 2010 to 2013 identified ten key hydrological parameters that exhibited high to extreme sensitivity in the SWAT model. The most sensitive parameters included curve number (CN2), groundwater delay (GW DELAY), aquifer recharge dispersion coefficient (RCHRG DP), base flow recession constant (ALPHA BF), and minimum groundwater level (GWQMN). These parameters were prioritized for calibration to improve the model's ability to simulate stream flow, as detailed in Table 2 and Table S2.

3.2.2. Calibration and validation

Model performance was evaluated using Nash-Sutcliffe Efficiency (NSE) and coefficient of determination (R^2). During the pre-conservation period, the model achieved NSEof 0.52, and R^2 of 0.97, while for the post-conservation period, these values were NSE = 0.80 and $R^2 = 0.81$. Uncertainty analysis showed that a significant portion of measured discharge fell within the 95% prediction uncertainty (95PPU), with 80% before and 35% after conservation interventions. The r-factor, which reflects model reliability, showed values of 0.60 for the pre-conservation period and 0.15 for the post-conservation period. Although the model slightly under-predicted daily flow before conservation, the overall agreement between simulated and observed discharge was good (Fig. 6 and Table 3).

In the pre-conservation period, the validation results indicated lower model performance compared to the calibration phase. However, the evaluation indices including NSE, R^2, and PBIAS, provided satisfactory outcomes (Table 3). Hydrographs depicting observed and simulated discharge were coherent during calibration and validation periods (Fig. 6).

Before conservation, the mean daily discharge was 0.06 m^3/s (observed) and 0.03 m^3/s (simulated) during calibration (2010–2012) and 0.015 m^3/s (observed) and 0.026 m^3/s (simulated) during validation (2013–2014). After conservation, mean daily discharge values were 0.02 m^3/s (observed) and 0.019 m^3/s (simulated) during calibration (2015–2018) and 0.028 m^3/s (observed) and 0.022 m^3/s (simulated) during validation (2021–2022). The pre-conservation calibration phase underestimated simulated discharge, but other calibration and validation periods showed satisfactory agreement between observed and simulated discharge (Fig. 6 and Fig. S3).

Table 2
List of flow parameters and degree of sensitivity.

Parameter Name	Parameter description	Fitted Value	t-stat	P-value	Rank
R_CN2.mgt	SCS curve number	0.1221	44.78	0.00	1
A_GW_DELAY.gw	Delay time for aquifer recharge (days)	−25.23	−34.86	0.00	2
V_RCHRG_DP.gw	Aquifer percolation coefficient	0.121	−34.61	0.00	3
V_ALPHA_BF.gw	Base flow recession constant	0.803	6.74	0.00	4
A_GWQMN.gw	Threshold depth of water in a shallow aquifer for return flow (mm)	590	−2.52	0.01	5
V_ESCO.hru	Soil evaporation compensation factor	0.457	1.64	0.10	6
V_CH_EROD(.).rte	Channel erosivity	0.577	−1.37	0.17	7
V_CH_COV(.).rte	Channel erodability factor	0.153	1.31	0.19	8
R_SOL_Z(.).sol	Depth from the surface to the bottom of the layer (mm)	−0.0429	1.01	0.32	9
V_CH_K2.rte	Channel effective hydraulic conductivity (mm hr^{-1})	6.975	−0.78	0.44	10

SCS, Soil Conservation Service.

Table 3
Model performance statistics for discharge calibration and validation before and after conservation.

Objective function	Calibration		Validation	
	Before conservation	After conservation	Before conservation	After conservation
NSE	0.52	0.80	0.28	0.82
R^2	0.97	0.81	0.64	0.91
PBIAS	60	5	−69	20
P-factor	0.80	0.35	0.04	0.16
r-factor	0.60	0.15	0.016	0.04

NSE, Nash-Sutcliffe modeling efficiency; R2, coefficient of determination and PBIAS, percent bias.

Challenges were identified in simulating sediment yield, as very low NSE values indicated. The model's inability to accurately predict the sediment load may be attributed to its limitations in effectively representing areas with high erosion potential, especially those fields located in the periodically saturated bottomlands characterized by gullies that contribute a substantial amount of the soil loss (Zegeye et al., 2017).

As a result, sediment yield analysis for pre- and post-conservation periods relied solely on measured data.

3.2.3. Water balance analysis

The model simulations showed significant alterations in water balance components following the implementation of soil and water conservation practices (SWCP). Average annual surface runoff, sediment load, and lateral flow all decreased, while evapotranspiration and groundwater storage increased by 13% and 34%, respectively after SWCPs were implemented (Table 4). These changes are attributed to the SWCPs, which slowed water flow and increased infiltration, thus reducing overland flow and promoting deeper percolations. The rise in groundwater storage highlights the positive impacts of these conservation practices on water resource availability within the watershed.

In addition, research conducted by Mhiret et al. (2019) and Steenhuise et al. (2023) has confirmed that the reduction in runoff and sediment, along with an increase in evapotranspiration, can be partially attributed to the increase in the acreage of Eucalyptus trees in the study area. This tree removes soil water during dry periods, leading to an extended duration required for soil saturation and the subsequent generation of runoff.

3.3. Hydrological alteration analysis

3.3.1. Precipitation

Precipitation patterns, analyzed using single-period statistics (mean and variance) for the entire study period (2010–2022), showed an average daily rainfall of 2.59 mm with a low coefficient of variation (2.54%), indicating minimal variation throughout the period. Non-parametric tests further confirmed this finding, with similar mean

Table 4
Components of the water balance before and after the implementation of SWC structures.

Water Balance Components	Before Conservation (2010–2014)		After conservation (2015–2022)	
	Value	%	Value	%
Precipitation (mm)	965.5		1076.20	
Surface runoff (mm)	113.93	11.8	55.76	5.18
Lateral flow (mm)	23.74	2.45	13.13	1.22
Percolation (mm)	367.96	38.11	493.95	45.89
Evapotranspiration (mm)	459.8	47.62	520.20	48.32
Sediment (Ton/ha)	4.68		2.78	

values and coefficient of variation for pre- and post-conservation periods. The IHA assigned a low category of hydrological alteration for precipitation.

3.3.2. Discharge

The analysis of discharge metrics, including the number of zero-flow days, base flow index, non-normalized mean flow, and annual coefficient of variation (CV), revealed a decrease in mean annual flow from 0.06 m^3/s pre-conservation to 0.02 m^3/s post-conservation, with corresponding CVs of 8.82% and 6.96% respectively.

Comparing pre- and post-conservation daily maximum flow rates (Figs. 7 and 8) revealed a significant decrease during post-conservation. Pre-conservation maximum flow rates ranged from 0.24 m^3/s to 0.38 m^3/s with an average of 0.30 m^3/s, while post-conservation rates varied between 0.06 m^3/s and 0.28 m^3/s with an average of 0.18 m^3/s.

Monthly median flow patterns (Fig. 8) showed that pre-conservation flows had a higher median during the early rainy season (May to July) and a decrease from July to October. Conversely, post-conservation flows exhibited a lower median in the early rainy season but remained higher in the later months (July to November). This situation may be attributed to the saturation of the watershed occurring after mid-July.

3.3.3. Sediment concentration

Sediment concentration also exhibited a reduction, with mean sediment concentration decreased from 831.2 mg/L pre-conservation to 285 mg/L post-conservation. The coefficients of variation for sediment concentration remained relatively stable between pre- and post-conservation periods, at 4.89% and 6.08%, respectively.

3.3.4. Overall hydrological alteration

The overall hydrological alteration analysis categorized the alteration of flow and sediment concentration as high to intermediate for both pre-and post-conservation periods (Fig. 9). A high category of alteration was particularly evident between the earlier (2010–2014) and later (2015–2018) post-conservation periods, highlighting the impact of soil and water conservation practices on hydrological patterns within the Debre Mawi watershed.

3.4. Weekly sediment concentration trends

The analysis of sediment concentration distribution, resulting from sheet and rill erosion during the rainy season, indicates considerable fluctuations on a weekly basis. At the onset of the rainy season, sediment concentration was in general high both before the implementation of soil and water conservation (SWC) measures, averaging 29,650 mg/l, compared to 9833 mg/l after conservation efforts were in place (Fig. 10 and Fig. S6). This is attributed to poor surface cover and tilling practices during crop sowing, which leave the soil exposed and vulnerable to erosion. The study area typically undergoes two to three rounds of plowing, leaving the soil exposed until the first rains, which results in substantial soil loss during the first two weeks of the rainy season under both scenarios. The difference, recorded at 19,817 mg/l, reflects the reduced sediment yield due to the implementation of SWC practices.

However, even after conservation, sediment concentration gradually increases over time, approaching levels recorded before conservation. Notably, in the first week of the 2022 rainy season, the maximum sediment concentration reached 24,265 mg/l. Although this value is lower than the pre-conservation average of 29,650 mg/l, it is still higher than the concentrations recorded in the first week of 2012 (18,850 mg/l) and 2014 (21,650 mg/l) (Fig. 10).

Throughout the rainy season, sediment yield declined until the eighth week, with a more rapid decline observed before the implementation of SWC measures (Fig. S6). By the eighth week, sediment concentration levels before and after conservation had nearly equalized. This convergence is primarily due to improved land cover and enhanced soil stability over time, which contributed to reducing sediment transport across slopes and lessening severe soil loss, especially in the years following SWC implementation. Specifically, average concentrations of 3366 mg/l and 2125 mg/l were recorded before and after conservation, respectively, by the eighth week. The narrowing difference, from 19,817 mg/l at the beginning of the rainy season to 1241 mg/l at the eighth week with full crop cover, highlights the effectiveness of land cover and soil stabilization in mitigating sediment loss.

3.5. Spatial distribution of sediment yield

By integrating sediment yield data from simulated stream flow with observed sediment concentration, a comprehensive spatial mapping of sediment yield was achieved, allowing for the identification of erosion hotspots within the watershed (Fig. 11). Predicted sediment yield ranged from negligible levels up to 57.63 t $ha^{-1}yr^{-1}$, with an average annual yeild approximately 27.61 t $ha^{-1}yr^{-1}$ between 2010 and 2014.

Surface runoff was found to have a moderate positive correlation with sediment yield ($r = 0.55$). In contrast, weaker correlations were observed between sediment yield and average slope percent, with correlation coefficients ranging from 0.08 to 0.43. These findings underscore the complexity of factors influencing soil loss, which include slope, climate, land cover, and inherent soil properties. The highest predicted sediment yield (57.63 t ha^{-1} yr^{-1}) occurred on agricultural land characterized by lithic Leptosols and an average slope of 12%.

A major concern highlighted by the analysis is that very high to severe erosion classes encompass 53% of the watershed area, with an additional 25% classified as experiencing moderate to high erosion. These erosion rates exceed the estimated rate of soil formation in the Ethiopian highlands. In contrast, lower sediment production was associated with areas dominated by trees and shrubs or with flatter topography. This aligns with the experimental research conducted by Zegeye et al. (2017), which indicates that huge amount of soil loss originated

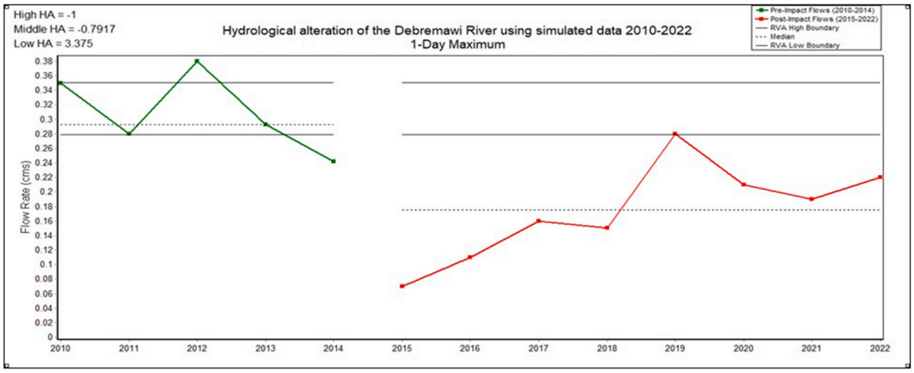

Fig. 7. A 1-day maximum flow of pre-conservation (2010–2014) and post-conservation (2015–2022) periods.

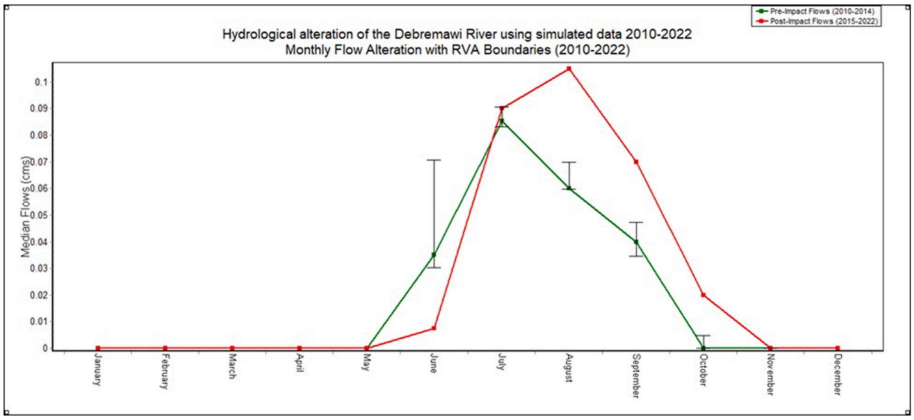

Fig. 8. Monthly flow alternations in the Debre Mawi watershed from 2010 to 2022.

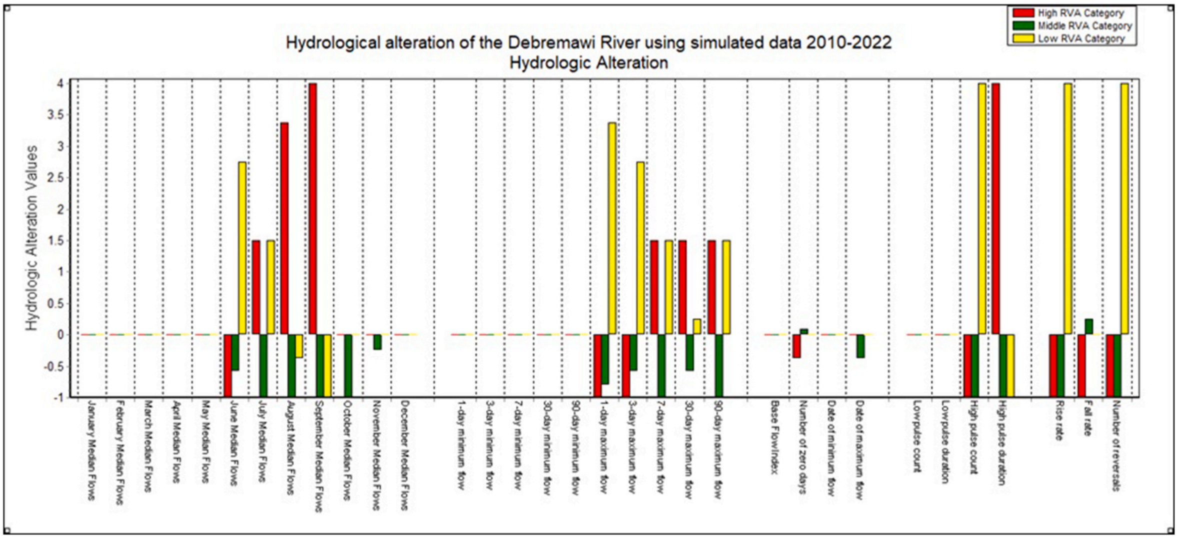

Fig. 9. Graphical representation of hydrological alternation assessments in Debre Mawi using a series of parameters.

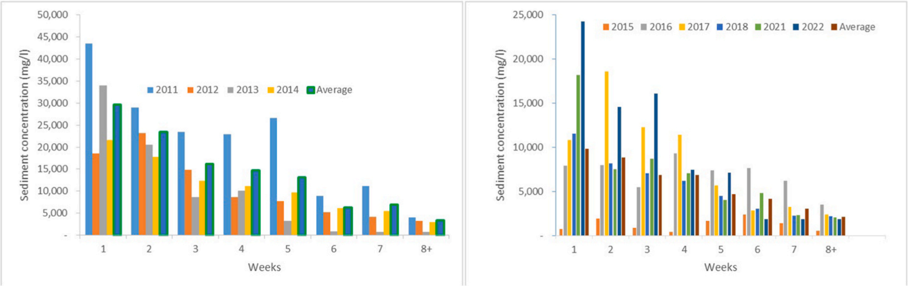

Fig. 10. Temporal distribution of sediment concentration (mg/l) in weekly perspective before (2010–2014) and after (2015–2022) soil and water conservation have been implemented.

from the gullies situated on the flatter downslopes of the Debre Mawi Watershed, an erosion process that the SWAT model was unable to capture.

The erosion severity map, derived from sediment yield data (Fig. 11), effectively identifies hotspot areas classified into moderate, high, very high, and severe erosion classes. These hotspots typically correspond to hydrological response units with minimal vegetation cover and steeper slopes. These detailed spatial maps not only pinpoint the origins and peak periods of sediment transport but also serve as essential tools for prioritizing areas for soil conservation interventions.

4. Discussion

4.1. Rainfall pattern and impacts

From 2010 to 2022, rainfall data analysis shows an average wet season depth of 980 mm, with significant variability ranging from 750 mm in 2014 to a peak of 1171 mm in 2021. These fluctuations have markedly influenced runoff and sediment dynamics, as seen in extreme events like the 152 mm rainfall recorded on June 11, 2014, which led to severe soil erosion and sediment loss. Rainfall variability, a known

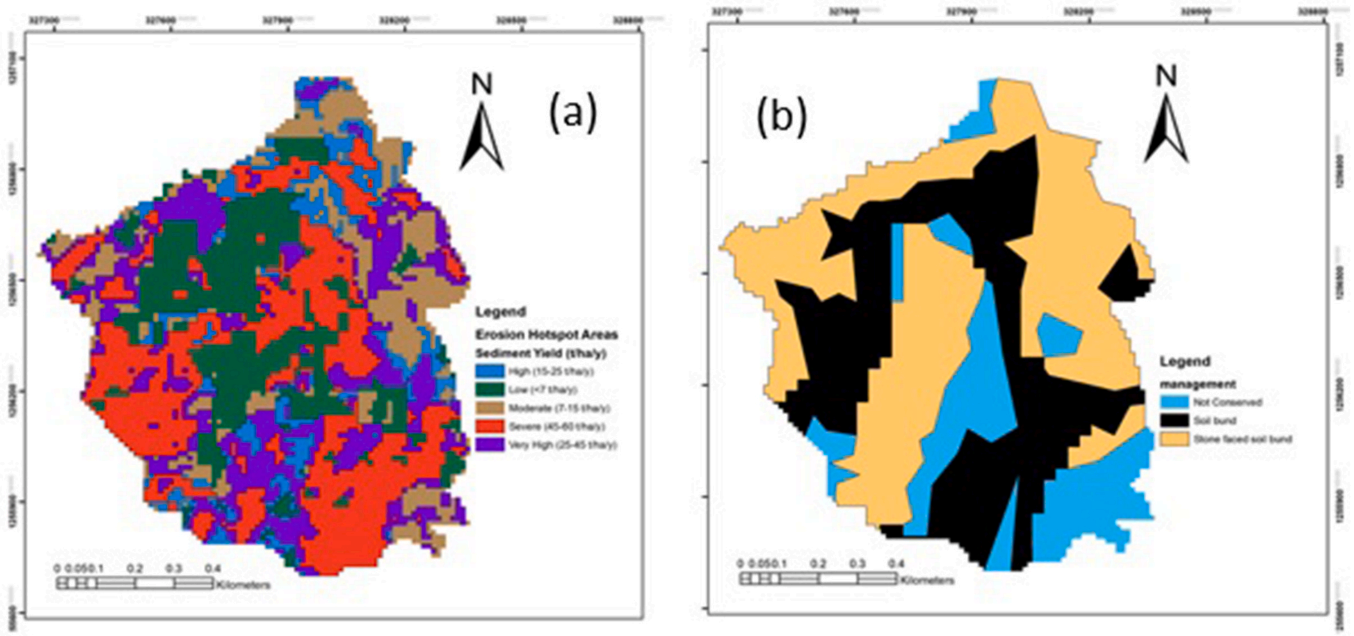

Fig. 11. Map of potential erosion hotspot areas (a) and management practices (b) in Debre Mawi watershed.

factor in the Ethiopian highlands, has been documented by Nicholson (2019) and Mhiret, Dagnew (Mhiret et al., 2019), who found that despite such fluctuations, overall rainfall trends remain relatively stable, as confirmed by both parametric and non-parametric statistical analyses. The high erosive potential of rainfall in sub-humid tropical regions, highlighted by studies like Mhiret, Dagnew (Mhiret et al., 2019) and Tilahun, Bizuneh (Tilahun et al., 2023), underscores the vulnerability of these landscapes to erosion during heavy rainfall events.

4.2. Hydrological changes from SWC measures

Implementing SWC measures led to significant changes in hydrologic parameters including discharge, sediment concentration, and overall water balance components within the watershed from 2010 to 2022. The identified patterns in rainfall-runoff interactions, discharge behaviors, and sediment levels suggest that soil and water conservation (SWC) practices have proven effective in the short term by minimizing runoff, improving infiltration, and lowering sediment yield. This finding aligns with the research conducted by Dagnew et al. (2015b). However, over the long term, the effectiveness of these measures has diminished as the infiltration furrows have become filled with sediment. Moreover, the expansion of Eucalyptus tree plantations, which deplete soil moisture during dry periods, has partly contributed to the observed reduction in both runoff and sediment (Mhiret et al., 2019; Steenhuise et al., 2023).

4.2.1. Rainfall-runoff dynamics and runoff reduction

The analysis of discharge data from 2010 to 2022 demonstrates that Soil and Water Conservation (SWC) interventions effectively reduced peak flows. Pre-conservation, rainfall events often triggered high peak flows followed by rapid declines in discharge, contributing to erosion and sediment transport. Post-conservation, these peaks were mitigated, and flow patterns became more sustained due to improvements in infiltration and reduced surface runoff from SWC measures such as terraces and increased vegetation cover mainly Eucalyptu tree. These findings align with research by Sultan, Tsunekawa (Sultan et al., 2018) and Mekonnen, Keesstra (Mekonnen et al., 2015), who noted similar impacts of SWC on runoff reduction and landscape restoration in Ethiopia.

4.2.2. Discharge trends and water retention

The shift in discharge patterns post-SWC implementation, from sharp declines to more consistent flow, supports earlier research by Kumar, Murthy (Kumar et al., 2016) and Retta, Addis (Retta et al., 2022), which highlights the role of SWC in enhancing water retention and base flow. However, the gradual increase in discharge in recent years suggests a potential decline in SWC effectiveness, due to structural degradation and filled up of the infiltration furrows with sediment. Wordofa, Okoyo (Wordofa et al., 2020) emphasized the importance of maintenance to sustain SWC benefits, suggesting that without regular maintenance, these measures may lose their efficacy over time.

4.2.3. Sediment yield

Implementing SWC practices and expansion acreage of Eucalyptus tree resulted in a significant reduction in sediment concentration, with an average decrease of 75% and a more pronounced reduction of 82% in the immediate years following conservation (2015–2018). SWCPs was effective, particularly in the initial 3 years following implementation. This is because of reduced runoff. But later, the sediment concentration elevated because of lack of maintenance and not targeting hotspot areas such as gullies in the downslope areas (Zimale et al., 2017). In the sub-humid tropics, the effectiveness of Soil and Water Conservation (SWC) practices generally diminishes without maintenance after a few years. Studies by Belayneh, Yirgu (Belayneh et al., 2019) and Tebebu, Steenhuis (Tebebu et al., 2015) suggested that, without regular maintenance, the structures and interventions can lose much of their effectiveness within 2–5 years in the Ethiopian highlands. Soil and water conservation further resulted in a significant decline in sediment yield when targeting priority gully rehabilitation points (Frankl et al., 2021). A study conducted by Mhiret et al. (2019) demonstrated that a level bund with infiltration furrows experienced a reduction of 72% in its capacity within 12 days after maintenance, returning to its original condition in the upper part of the Debre Mawi watershed.

However, the reduction in the 1st three years underscores the short term effectiveness of SWC in mitigating soil erosion and controlling sediment transport, which is critical for maintaining soil fertility and sustainable agriculture in the Ethiopian highlands. Similar reductions in sediment yield following SWC interventions have been reported by Debie (2024), and Alemu, Tolossa (Alemu et al., 2023) reinforcing the importance of these practices in erosion control.

4.2.4. Hydrologic water balance

SWC interventions have influenced the hydrological water balance, primarily through reducing surface runoff and enhancing evapotranspiration and groundwater storage. Surface runoff decreases allowing more water to infiltrate the soil, which improves groundwater recharge. This shift increases soil moisture, further driving evapotranspiration through both soil evaporation and crop transpiration. The 13% rise in evapotranspiration can be attributed to improved soil moisture and Eucalyptus tree acreage expansion. Additionally, shallow groundwater storage has seen a subtantial increase of 34%, underscoring the deeper infiltration that SWC practices promote. These changes in the hydrological cycle improve soil moisture availability, ultimately benefiting agricultural productivity. Similar results have been reported by Meaza, Abera (Meaza et al., 2022). However, the effectiveness of SWC measures is not uniform, as Masha, Yirgu (Masha et al., 2021) and Dimtsu (2018) highlight that outcomes may vary depending on site-specific factors and the quality of ongoing maintenance.

4.3. Prioritizing land management and erosion hotspots

The SWAT model identified significant erosion hotspots within the watershed, with 53% of the area categorized as very high to severe erosion zones and 25% experiencing moderate to high erosion. These hotspots typically correspond to agricultural land with minimal vegetation and steep slopes. Similar studies by Gebremedhin, Tadesse (Gebremedhin et al., 2023), Asmamaw and Mohammed (Asmamaw et al., 2019), and Mekonnen and Melesse (Mekonnen et al., 2011) followed a similar approach within the sub-humid Ethiopian highlands. While such areas are important to identify, the model lacks identifying gullies as hot spot areas in low-slope areas (Zegeye et al., 2016), which are dominant in the Debre Mawi watershed.

Moreover, field experimental research conducted by Mhiret, Dagnew (Mhiret et al., 2019) revealed higher soil loss through gully erosion from fields located in downslope than upslope in the Debre Mawi watershed (Mhiret et al., 2022). This discrepancy is due to the SWAT model's limitation and reliance on the infiltration-excess runoff generation principle, while the dominant runoff mechanism in the area is saturation-excess runoff, as identified by Tilahun, Guzman (Tilahun et al., 2015). Despite this limitation, upstream degraded areas identified by the SWAT model should still be considered for SWC development. Soil and water conservation (SWC) practices, such as graded bunds with deeper furrow depth, cutoff drains, and waterways to streams, should be properly designed and implemented in these areas to increase infiltration and minimize bottomland saturation. In addition, gullies at downslope areas should be prioritized for long-term sediment yield reduction in sub-humid areas dominated by gullies (Fenta et al., 2024). However, the parameterization of the SWAT model should be modified to take into account that downslope fields and gullies that produce more significant amounts of runoff and soil loss after the soils become saturated.

4.4. Integrated SWC and agronomic practices for sustainable agriculture

Achieving sustainable agriculture in sub-humid tropical regions like the Ethiopian highlands requires integrating SWC with innovative agronomic practices. Recent studies, such as those by Biswas, Chakraborty (Biswas et al., 2022), emphasize the benefits of combining structural conservation measures with agroforestry systems that provide multiple ecosystem services, including soil stabilization and carbon sequestration. Conservation agriculture, which minimizes soil disturbance and maintains permanent soil cover, has also been shown to improve soil health and reduce erosion (Yami et al., 2022).

Incorporating crop rotation and intercropping with leguminous species can further enhance soil fertility and reduce the need for chemical inputs, supporting sustainable agricultural systems. The integration of SWC with indigenous knowledge and farmer-led innovations has also proven effective in promoting sustainable land management in Ethiopia (Belay et al., 2015). However, as Šūmane, Kunda (Šūmane et al., 2018) noted, the success of integrated practices depends on adapting them to local conditions and ensuring farmers are trained to implement these techniques effectively. Hence, a tailored approach that combines SWC with agronomic innovations is critical to achieving long-term sustainability and reducing erosion in sub-humid tropical regions.

5. Conclusion

This study evaluated the impact of soil and water conservation (SWC) practices on hydrological dynamics and soil erosion in the Debre Mawi watershed, located in Ethiopia's sub-humid highlands. The results revealed a significant change in runoff and soil loss following the implementation of SWC measures (2015–2022), compared to the pre-conservation period of 2010–2014. Initially, the SWC practices led to substantial reductions in runoff, discharge, and sediment yield, along with improved water retention, groundwater storage, and evapotranspiration. However, these benefits diminished over time. After 10 years, sediment yield and discharge levels began to revert to pre-conservation conditions. Additionally, erosion levels after the conservation period remained above the recommended allowable soil loss for Ethiopia, underscoring the need for more robust conservation strategies and maintenance efforts beyond the third year. In the situation that Soil and Water Conservation Practices (SWCPs) are to be implemented in watersheds such as Debre Mawi, it is essential to prioritize the safe removal of surplus water. This can be achieved by strategically locating SWCPs in accordance with the specific context, ensuring effective drainage.

Weekly average sediment concentration patterns exhibited clear variations. Before SWC implementation, sediment concentration peaked during the first week of the rainy season but declined by 90% after the eighth week due to enhanced vegetation cover and soil stabilization. Following SWC implementation, initial sediment concentration during the same period dropped by 80%, illustrating the positive impact of improved land cover. However, this reduction was not sustained, highlighting the need for continuous SWC maintenance and a more comprehensive approach to erosion control.

The study suggests that a shift from the current reliance on physical SWC structures to a more integrated approach is necessary. This integrated approach should include agronomic practices such as cover cropping, mulching, zero or minimum tillage, and agroforestry etc., combined with effective soil fertility management. Furthermore, prioritizing erosion hot spots in the watershed and tailoring conservation practices to local conditions are critical for ensuring the long-term sustainability of soil and water resources in Ethiopia's highlands.

Future research should focus on the effect of the expansion of eucalyptus trees in the hydrology, parameterization of SWAT for gully-dominated watersheds, and refining agronomic practices to complement physical conservation measures. The latter is important that the benefits of SWC efforts are sustained over time and adapted to the specific needs of the sub-humid Ethiopian highlands.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

CRediT authorship contribution statement

Aschalew K. Tebeje: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Misbah A. Hussein:** Writing – review & editing, Software, Formal analysis. **Tewodros T. Assefa:** Writing – review & editing, Supervision, Methodology, Formal analysis. **Demesew A. Mhiret:** Writing – review & editing, Investigation, Conceptualization. **Fasikaw A. Zimale:** Writing – review & editing, Supervision, Formal analysis. **Wubneh B. Abebe:** Writing – review & editing, Methodology. **Anwar A. Adem:** Writing – review & editing, Software. **Seifu A. Tilahun:** Writing – review & editing. **Gizaw Desta:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mohammed A. Ahmed:** Writing – review & editing, Supervision, Investigation, Conceptualization.

Declaration of competing interest

Aschalew K. Tebeje was employed by Lihiket Design and Supervision Corporation. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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