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RESEARCH

Quantifying Soil Erosion and Identifying Critical Source Areas Under Current Management in the Holeta Watershed, Awash Basin, Ethiopia

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Abstract

Erosion is the most widespread form of soil degradation overall in the world. In the current study, soil erosion is quantified, and areas prone to high risk of soil erosion are identified under current management in the Holeta watershed, Awash Basin, Ethiopia, where lands are primarily cultivated. The Soil and Water Assessment Tool (SWAT) was applied to simulate the baseline hydrologic and soil erosion processes. The model used spatial (i.e., DEM, land use, and soil maps) and temporal (climate) data to simulate different biophysical processes. Moreover, streamflow and sediment data were acquired and analyzed for model calibration and validation. The performance of the model during calibration and validation with both streamflow and sediment loads was evaluated against the measured data by using statistical parameters (R^2 = 0.64, 0.81, NSE = 0.61, 0.76, PBIAS = 12.6%, 9.8%, respectively) during calibration and validation with streamflow and (R^2 = 0.78, 0.68, NSE = 0.74, 0.61, PBIAS = 16.1%, 18.2%, respectively) while calibration and validation by sediment. The annual sediment load in the Holeta watershed varies from 2 to 136.4 t/ha/year with an average of 18 t/ha/year. The annual severity of sediment load was prioritized under very low, low, moderate, high, very high, and severe. About 13.3% of the Holeta watershed's sub-basin contributed a higher sediment yield than average under current management. The significant sediment yield is generated from cultivated areas whereas; the lowest magnitude is generated from forested areas. Overall, since the generated sediment is within the tolerated range, current conservation retains soil loss for sub-basin 2, 4–15, and effective management practices can be identified by further study and established for the erosion-affected areas (sub-basins 1 and 3).

Keywords Holeta watershed · Hotspot areas · Soil erosion · SWAT model

Introduction

Background

Soil erosion is one of the consequential global environmental complications that need to be quantified regularly to provide important data for the sustainable management of watersheds [14, 25]. Poor land management is among the factors that cause soil erosion which results in damage to the soil and results in water runoff across the landscape instead of adequate infiltration [19]. Inappropriate and unsustainable land-use practices cause severe water erosion and soil loss. The severity of soil erosion has further escalated also due to other anthropogenic activities such as vegetation burning, deforestation, urban development, mining, and quarrying. These result in the loss of topsoil and the depletion of soil fertility [9]. The impact of soil erosion is not limited to the loss of fertile soil. It also causes increased contamination and siltation in reservoirs, clogging stream channels, and diminishing fish and other aquatic species. A global estimate showed that by the mid-1990s, soil degradation affected around two billion hectares of cultivated land (i.e., about one-third of total cultivated land), of which water-induced soil erosion accounted for about 56% [4, 14]. Soil is the fundamental resource for economic development and for maintaining sustainable productive landscapes and people's livelihoods, especially for countries with agrarian economies like Ethiopia [15]. However, soil degradation is a serious threat in agroecosystems and one of the global environmental problems. Globally, one-third of agricultural soils were reported as being affected by soil degradation [15]. Soil erosion is a

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serious challenge, particularly in Africa, Asia, and Latin America, where the highest number of their populations rely on agriculture for livelihood [14, 20]. Compared to Asia and Latin America, the effects of soil erosion are grave in Africa. Of the 1 billion people affected by soil erosion globally, 50% are found in Africa, which underscores the severity of the problem in the African continent [22, 24]. Soil erosion is a serious and continuous environmental problem particularly in the highlands of Ethiopia [31]. Soil erosion increased by human activities is a critical challenge affecting soil health, agricultural productivity, food security, and environmental sustainability in the highlands of Ethiopia [30]. Besides the land degradation in the highlands of Ethiopia [17], soil erosion is causing downstream sedimentation problems in water supply and hydropower-generating reservoirs [2]. Such serious soil erosion and sedimentation problems in the highlands of Ethiopia urge the implementation of agricultural BMPs that are vital to reduce soil erosion and thereby lessen the rate of land degradation and filling up of reservoirs [7, 18]. Several studies addressed the soil erosion and sediment transportation of different watersheds in the Awash River Basin [1, 11, 21, 26]. Hence, most of the studies were limited to certain watersheds with large and medium landscapes. In this paper, the Holeta watershed covers around 515 Km^2. Therefore, simulation and mitigation of sediment load in the Holeta watershed are very important for land and water management that help to improve crop yield. This study used the SWAT model to identify critical source areas in addition to the estimation of the magnitude of soil erosion. SWAT model has been chosen due to its demonstrated performance in simulating sediment yield and identifying hotspot areas across different scales of watersheds [18, 27]. The results of the study show a direction for the concerned body to formulate sound policies and give awareness to farmers thereby they set management practices in erosion-affected areas to protect productive soils and boost crop yields.

Description of the Study Area and Methodology

Description of the Study Area

The Holeta watershed of the Awash River basin, Ethiopia is located between longitudes 38°23′15″ and 38°36′18″ E and latitudes 8°56.5 and 9°13.5′ N (Fig. 1). It is a subcatchment of the upper Awash drainage basin with a total surface area of 515 square kilometers. Within the watershed, Holeta is the largest river in Walmara district [6]. The river originates at the mountain around 3500 masl about 13 km North of Holeta town and is a tributary of the larger Awash River. About 5 km north of Holeta town is the conjunction of the Holeta- and the Mintile River, which originates also in the mountains, about 12 km north of the town.

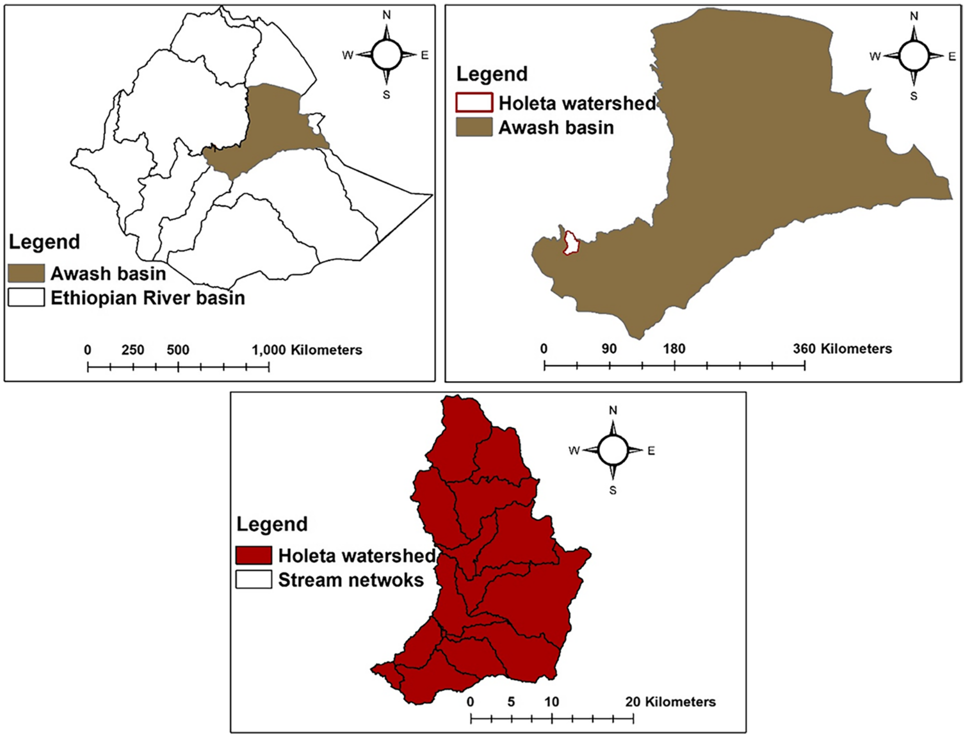

Fig. 1 Location of the study area

Methodology

Input Data

The application of the SWAT model to evaluate the spatial distribution of soil loss and quantify the effectiveness of the BMPs requires the integration of spatial and temporal data. The spatial datasets used for this study include Digital Elevation Model (DEM), land use/land cover (LULC), and soil data. Whereas the temporal data includes weather data, streamflow, and sediment data. DEM, soil, LULC, and weather data are used to develop and configure the SWAT model. DEM of 12.5m by 12.5m resolution was acquired from the website of the Alaska satellite facility (https://www.asf.alaska.edu/sar-data/palsar/). It is used to delineate the watershed and determine its characteristics. Soil data processed from the Ministry of Water, Irrigation, and Electricity with the world digital soil map and digital soil map grids were used to extract the soil physicochemical properties. LULC map of 2017 was derived from Landsat 8 OLI (Operational Land Imager) which is obtained from https://earthexplorer.usgs.gov. It was used to quantify the hydrological processes of the watershed. Daily rainfall, temperature, wind speed, relative humidity, and solar radiation of two stations (Addis Ababa and Holeta) were used to derive the hydrological balance. It was collected from National Meteorological Agency, Ethiopia (NMA) for the year 1988–2020. Streamflow and sediment data are used to calibrate and validate the model. It was collected from the Ministry of Water, Irrigation, and Electricity, Ethiopia for the year 2000–2015. The spatial maps of the Holeta watershed landscape attributes are presented in Fig. 2. Agriculture followed by forest was the dominant land use/land cover in the Holeta watershed. The dominant soil type in the Holeta watershed is Eurtic Cambisol followed by Haplic Acrisols (Fig. 2).

Soil and Water Assessment Tool Hydrological Model

SWAT is a watershed-based, continuous-time, and processed based model developed to allow the simulation of a larger and more complex watershed to predict the impact of land management practices on water quality and quantity in agricultural watersheds over long periods [3]. SWAT simulates watershed hydrology in two major phases. (1) The land phase which, controls the amount of water, sediment, nutrients, and pesticides loading to the main channel in each sub-basin and (2) the water or routing phase which, controls the movement of water, sediment, and nutrients through a channel network of the watershed to the outlet [16, 23]. The

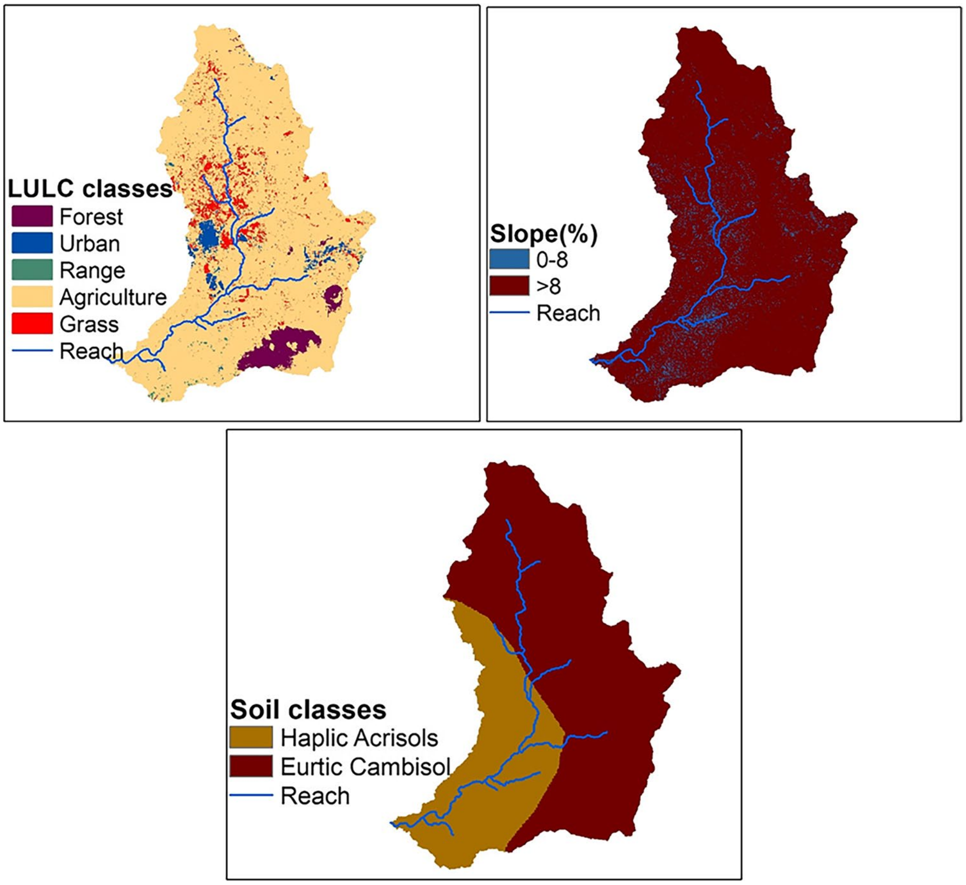

Fig. 2 The spatial data characteristics of Holeta watershed: LULC, slope, and soil classes

hydrological simulation of SWAT based on the water balance is given in Eq. (1) below:

$$SWt = SWo + \sum_{i=1}^{t}\left(R_{day-}Q_{surf-}E_{a-}W_{seep-}Q_{gw}\right) \quad (1)$$

where SW_t is the terminal soil-water capacity in mm of water, SW_0 is the first soil-water volume on the i day in mm of water, t is the duration in days, R_{day} is the quantity of rainfall on the i day in mm of water, Q_{surf} is the quantity of surface runoff on the i day in mm of water, E_a is the quantity of evapotranspiration on the i day in mm of water, W_{seep} is the quantity of flowing water penetrating the vadose zone from soil profile on the i day in mm of water, Q_{gw} is the quantity of water comes back on the i day in mm of water.

Sediment Rating Curve

Sediment concentrations with the corresponding streamflow data at Holeta gauging station collected from the Ministry of Water, Irrigation, and Electricity are available only for a few months in a year. However, the application of the SWAT hydrological model to simulate streamflow and sediment yield requires a continuous time step of streamflow and sediment data. Consequently, a sediment rating curve was used to generate sediment load data from the streamflow using the empirical relations between the sediment concentration and their corresponding streamflow. The use of estimates derived from empirical relations between sediment concentrations and the corresponding river discharge are used often when the long-term and reliable records of sediment concentrations are limited [8]. The relationship between sediment concentrations and river discharge can be written as follows:

$$Qs = a^{*}Qf^{b} \quad (2)$$

where Qs is the sediment load in ton/day, Qf is the streamflow in m^3/s, and a and b are regression constants to be determined from the suspended sediment loads and observed streamflow. The sediment concentration record was measured in mg/l and to work on Eq. (2), the sediment concentration was converted into sediment load (ton/day) using the following conversion formula (Eq. (3)).

$$Qs = 0.0864^{*}C^{*}Qf \quad (3)$$

where C is sediment concentration (mg/l), Qf is the streamflow (m3/s) and 0.0864 is the conversion factor. In the Holeta watershed, a and b are determined to be 21.229 and 1.2231, respectively. The sediment rating curve is shown in Fig. 3.

SWAT Model Setup and Uncertainty Analysis

The SWAT model setup consists of the following procedures: preparation of spatial and temporal data, watershed delineation and sub-basin discretization, HRU definition, writing weather inputs, and calibration and uncertainty analysis. A 30 by 30 m resolution DEM was used to delineate the watershed. Then, the HRU definition was held using a threshold value of 5%, 20%, and 20% for land use, soil, and slope, respectively. Holeta watershed was discretized into 15 sub-basin and 31 HRUs. Global sensitivity analysis was performed both for streamflow and sediment to identify the most influencing parameters. Then, SWAT model calibration and validation for stream flow and sediment were done using SUFI-2 algorithms in SWAT-CUP for the periods of 1990–2004 and 2005–2009 respectively. The model performance was evaluated using the coefficient of determination (R^2), Nash Sutcliff efficiency (NSE), and percent bias (PBIAS).

Results and Discussion

Sensitivity Analysis, Calibration, and Validation

The relative sensitivity analysis for streamflow and sediment was carried out on the monthly time scale at subbasin 14 where the gauging station is located. The parameter

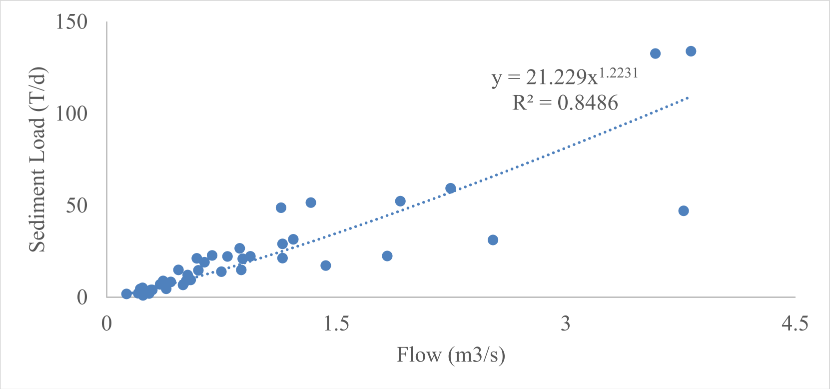

Fig. 3 Sediment Rating Curve of Holeta Watershed

sensitivity and rankings with the significance of the relative sensitivity are determined using t-stat and *p*-value. The lower *p*-stat and larger absolute t-stat value indicate the most significant parameter. Using the *p*-value and t-stat, Global sensitivity using the Latin hypercube "one-at-a-time" regression Holeta watershed is described. The three most sensitive streamflow parameters were SCS curve number (CN2), baseflow alpha factor for bank storage (ALPHA_BNK), and moist soil albedo (SOL_ALB). The most sensitive parameters for sediment parameters are a linear factor for channel sediment routing (SPCON), management support practice factor (USLE_P), and USLE equation soil erodibility (K) factor (USLE_K). The sensitive parameters were calibrated with the recommended ranges and the fitted value was used to compute the amount of sediment yield from the Holeta watershed.

Monthly streamflow and sediment datasets from 1990 to 2004 were used for model calibration and 2005 to 2009 were used for model validations. The SWAT model performance is considered to be acceptable for streamflow and sediment load simulation on the bases of R^2 and NSE > 0.5 and PBIAS ≤ ± 55% for sediment load and PBIAS ≤ ± 25% for streamflow for a monthly time step evaluation [5]. Accordingly, the estimation of streamflow and sediment load showed satisfactory performance both in calibration and validation periods. However, there are relatively lower statistical measures during the validation process. The statistical performance for streamflow and sediment load is summarized in Table 1. The lower statistical measures for sediment calibration and validation could be related to the quality and scarcity of observed data, parameters, streamflow process, and model prediction uncertainty. The negative PBIAS value during calibration and validation showed that the model slightly overestimated the predicted streamflow and the positive PBIAS during validation of sediment data showed underestimation.

Graphical analysis of streamflow simulation showed that the model predictions have shown both over-estimation and under-estimation during calibration and validation (Fig. 4). However, the general prediction of the model is good enough to simulate the streamflow except for the peak flow in most of the calibration and validation years.

The graphical analysis of observed and the predicted sediment yield indicated that the model has shown both overestimation and underestimation during calibration and underestimated sediment yield during validation (Fig. 5). SWAT model was unable to predict the peak sediment yield throughout the years of validation period and in some years of calibration period. However, the model is able to properly simulate the rising and falling limb in both cases.

Prioritizations of Holeta Watershed to Sediment Yields

Under current management and the existing land use/land cover, the sediment yield of each sub-basin was not

Table 1 Monthly streamflow and sediment calibration and validation

	Process	p-factor	r-factor	R^2	NSE	PBIAS
Streamflow	Calibration	0.10	0.04	0.64	0.61	12.6
	Validation	0.47	0.56	0.81	0.76	-2.3
Sediment	Calibration	0.40	0.80	0.78	0.74	16.1
	Validation	0.17	0.02	0.68	0.61	18.2

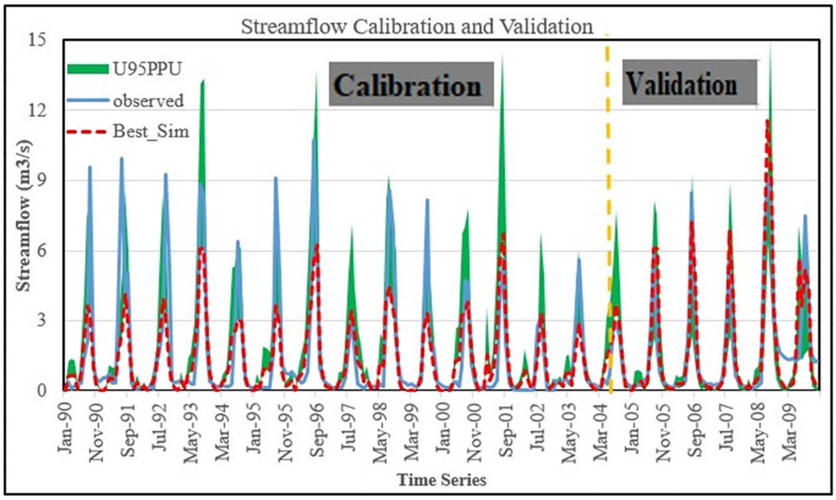

Fig. 4 Observed and simulated streamflow calibration and validation

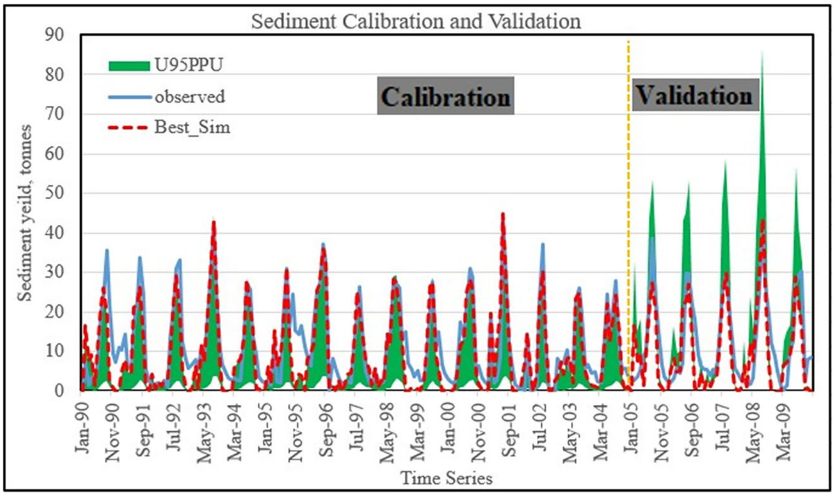

Fig. 5 Observed and simulated sediment yield calibration and validation

uniform. This was because of land use/land cover of the Holeta watershed. A previous study by [1] on modeling runoff and sediment yield of the Kesem dam watershed, Awash Basin, Ethiopia has also confirmed that good land use/land cover has positive effects on the reduction of runoff and sediment yield. The spatial distribution of the sediment sources shows that very low and low sediment yield (< 11 t ha-1 year-1) in the watershed was generated from sub-basin 2, 4–15 (Fig. 6). These sub-basins are covered by woodland followed by forestry crops. The highest contributor of sediment yield (> 40 t ha-1 year-1)) are sub-basin 1 and 3 located in the northern part of the watershed. Cultivated crops characterize these two sub-basins. Ebabu et al., [13], reported that land cover types and support practices largely control the magnitude and variability of soil erosion. The results of the study in the Lake Hawassa watershed, Ethiopia by [10] also shows, those areas covered by agroforestry, forest, and woodlands had the highest sediment retention capacity while bare land and built-up area had the lowest retention capacity. This revealed that human activities in the higher slopes were the main driving factor of sediment yield. Vanwalleghem [28] described as human-induced land use change results in much faster net erosion rates which concede with the findings of this study. In general, areas that have good vegetation cover around the middle parts of the watershed are

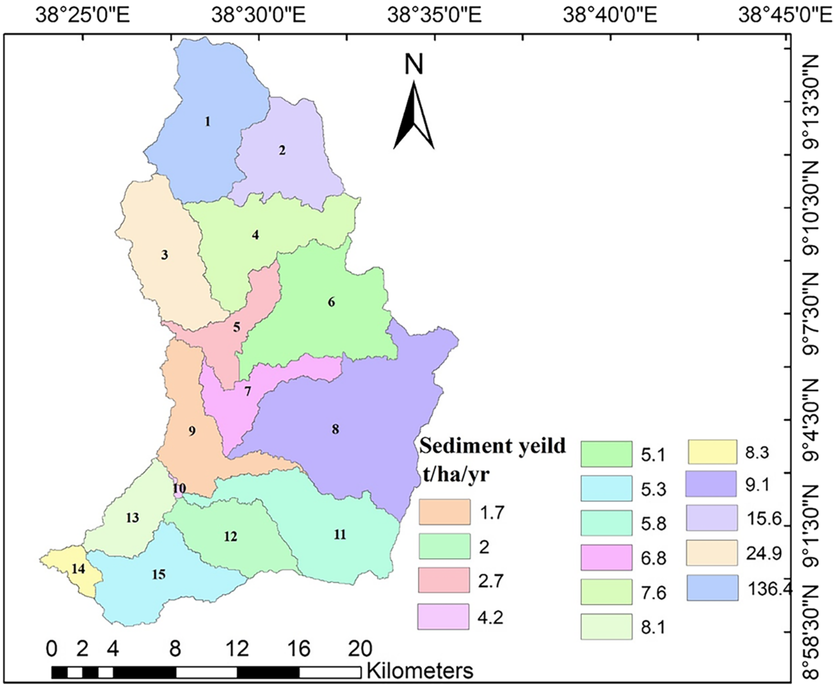

Fig. 6 Spatial distribution of sediment yields in the Holeta watershed

characterized by lower sediment yield and sloping agricultural lands are the dominant sources of higher sediment yield. This implies that agricultural lands need the application of effective management practices whereas; the existing woodlands and forest coverages are enough to retain soil loss. The study indicated that sediment yield is more sensitive to land use classes revealing areas under minimal disturbances are not a significant source of erosion and areas under extensive agriculture are the sources of high erosion. Several studies also show that land use/land cover can be controlled erosion by covering the soil surface with the canopy and reducing the mechanical action happening at the soil surface by intercepting the raindrop [1, 12, 29].

Conclusion

Soil erosion by water has become a challenge in reducing agricultural production in agricultural watersheds. The increasing risks of soil erosion and related environmental problems have driven the need for research to address sustainable land and water resources management. This study attempted to examine the soil erosion status of the Holeta watershed and identify hotspot areas. In this study, the SWAT model was applied and the results obtained indicate that the model is efficient in simulating streamflow and sediment concentration. As the statistical parameters show, the model calibration and validation results of streamflow and sediment yield were in good agreement with measured values. The estimated annual sediment yield varies from 2.0 t ha-1 year-1 to 136.4 t ha-1 year-1 with an average sediment yield of 18.0 t ha-1 year-1. The spatial distributions of the sediment yield showed sub-basin 1 and 3 have high sediment yields among the 15 sub-basins generated by the SWAT model of the Holeta watershed. The highest sediment yield was contributed by the steep farmland. These two sub-basins of the watershed area have been identified as critical areas that need management practices. This study is limited to the simulation of sediment yield and its sub-basin prioritizations under current management. Therefore, further study can include the efficiency of management practice needs to be established.

Author Contribution AWG analyzed data, reviewed and prepared related literature, simulates the model, and wrote the main manuscript text.

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Data Availability The acquired and processed data during the current study will be available upon reasonable request.

Declarations

Ethical Approval This article does not contain any studies with human participants, or animals by any of the authors.

Competing Interests The author declares no competing interests and that the findings of this paper are appropriate for Water Conservation Science and Engineering Journal.

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