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Original Research Article

Identification and prioritization of subwatersheds for land and water management in Tekeze dam watershed, Northern Ethiopia

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ABSTRACT

Sedimentation and/or soil erosion are huge problems that have threatened many reservoirs in the Northern Ethiopian highlands, particularly in the Tekeze dam watershed. This study has been conducted to identify and prioritize the most sensitive subwatersheds with the help of a semi-distributed watershed model (SWAT 2009) for improved management of reservoir sedimentation mitigating strategies at the watershed level. SWAT 2009 was chosen for this study due to its ability to produce routed sediment yield and identify principal sediment source areas at the selected point of interest. Based on a digital elevation model (DEM) the catchment was divided in to 47 subwatersheds using the dam axis as the main outlet. By overlaying land use, soil and slope of the study area, the subwatersheds were further divided in to 690 hydrological response units (HRUs). Model calibration (for the period of January 1996 to December 2002) and validation (for the period of January 2003 to December 2006) were carried out for stream flow rate and sediment yield data observed at Emba madre gage station. The results of model performance evaluation statistics for both stream flow and sediment yield shows that the model has a high potential in estimation of stream flow and sediment yield. Tekeze dam watershed has mean annual stream flow of 137.74 m^3/s and annual sediment yield of 15.17 t/ha/year. Out of the 47 subwatersheds, 13 subwatersheds (mostly located in the north eastern and north western part of the catchment) were prioritized. The maximum sediment outflow of these 13 subwatersheds, ranges from 18.49 to 32.57 t/ha/year and are characterized dominantly by cultivated land, shrub land & bare land with average land slope ranging from 7.9 to15.2% and with the dominant soil type of Eutric cambisols. These results can help to formulate and implement effective, appropriate and sustainable watershed management which in turn can help in sustaining the reservoir storage capacity of the dam.

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1. Introduction

Among serious offsite consequences of watershed responses that threaten the sustainability of dams built for various purposes throughout the world is sediment deposition in reservoirs (WCD, 2000). The amount of hydrological response of a catchment (stream flow and sediment yield) and how well the problem is addressed both during the planning stage and while the reservoir is in operation determines the length of time before the reservoir is filled with sediment. To adapt the dimensions of planned water resource developments so as to achieve the actual lifetimes of a reservoir requires the accurate estimation of sediment yield and stream flow and the location the sediment source (Nigussie et al., 2006).

In river basin management, watershed hydrological models have a vital role in simulating possible feature changes and their impact. This helps to determine improved measures of river basin management (Valentina et al., 2014). The main point of watershed development is conserving land and water. But other economic and social development of the watershed follows consequently. Any natural resource (land and water) development program must be started at the micro watershed level the primary starting point of all processes of hydrology (Dhruvanarayana, 1993). However, watershed management actions cannot be carried out at the same time over the entire area of a large watershed. Management activities useful for development have to be started with the most sensitive subwatersheds. Hence, it is mandatory to prioritize the subwatersheds lying in the main watershed (Karale, Bali, & Narula, 1977). Watershed prioritization is the process of ranking different sensitive subbasins of a larger basin, accordingly to be taken up for various interventions. The ranking of micro watersheds could be done depending on stream flow and sediment yield of subwatersheds at a specified time scale.

The Northern Ethiopian Highlands have characteristics dominated by steep slopes; intense rainfall and sparse vegetation cover. The high poverty, lack of technology and high population and livestock densities induce intense soil erosion and degradation problems in these Highlands. This not only reduces crop yields but also has various negative off-site consequences. The life expectations of many reservoirs in the area built for irrigation or water supply in the dry season are threatened by massive sedimentation (Vanmaercke et al., 2010). But still little is known about the amount and dynamics of sediment transport in the Northern Ethiopian Highlands.

The Tekeze Hydropower dam is the tallest arch dam in Africa, generating 300 MW power from a 180 m dam height. The total storage capacity of Tekeze dam is 9.2 billion m^3. According to Aforki (2006) 40% of the reservoir storage capacity (3.7 billion m^3) is provided as a volume (dead storage) for the sediment inflow through the 50 years design life time of the dam. The rate of sedimentation expected annually is about 75 million m^3 i.e. less than 1% of the total storage capacity. The sediment data in the feasibility study report of the dam is limited; hence the rate of sedimentation of the Tekeze reservoir still remains unpredicted. According to several studies carried out in the Tigray area the rate of sediment yield is almost double the above reported value.

Good watershed management is, therefore, needed to reduce the sedimentation of Tekeze dam reservoir to sustain its storage capacity at least up to its design period. Hence, in this study an attempt was made to identify and prioritize sub-watersheds according to their annual sediment yield to determine its impact on watershed management plan of Tekeze dam watershed in particular and Tekeze watershed in general. Applying a watershed hydrological model to estimate stream flow and sediment yield of each sub-watershed and the whole watershed under different land use land cover (LULC), is important in evaluating potential managements (Merritt, Letcher, & Jakeman, 2003). Even though a number of watershed models (empirical and physically based) are available (Arnold, 1998) SWAT 2009 model was used for this study.

2. Materials and methods

2.1. Location description

Tekeze River is the main tributary of the Atbara River, which is, in turn, one of the main tributaries of the Nile. Tekeze river basin is situated in the north-western part of Ethiopia and forms the most northern part of the Nile Basin within Ethiopia. Specifically the pilot study area, the Tekeze dam watershed is located south east of the basin in the range of geographical location 11° 39' 32.17" and 13° 27′ 15.96″ East longitude, and 37° 33′ 27.63″ and 39° 40′ 7.24″ North latitude (Fig. 1). The major part of the Tekeze dam watershed is in the Amhara regional state and a small part is in Tigray regional state. The watershed covers a total surface area of 29,404 km^2.

2.2. Model input data source and preparation

The main core materials used in this study were GIS software, distributed watershed model SWAT2009 and thematic layers of the study area (digital elevation model, digital soil map, digital drainage map, digital land use and land cover).

2.2.1. Meteorological and hydrological data

The climatic data required by SWAT provides moisture and energy inputs to the watershed that control the water balance and determine the relative importance of the different components of the hydrologic cycle. The climatic variables required by SWAT consist of daily minimum / maximum air temperature, solar radiation, precipitation, wind speed and relative humidity. The model allows values of these variables to be input from records of observed data. The above meteorological data was obtained from the national metrological agency of Ethiopia. The long-term records (1996-2013) meteorological data was collected from six stations (Gonder, Lalibela, Maichew, Mekele, Samre and May-Tsebri) which lie inside and on the boarder of the study watershed. Since relative humidity, wind speed and solar radiation data records were limited for all the stations except for the Lalibela station, weather generator was used to generate those data by using Lalibela station records.

Stream flow records in a daily time step for the Tekeze dam watershed at Emba Madre gauging station was obtained from the hydrology department of Ministry of Water Resource, Irrigation and Energy of Ethiopia for the period 1996–2006. The sediment concentration record is a challenge to obtain since measurements on sediment concentration taken by the Ministry of water

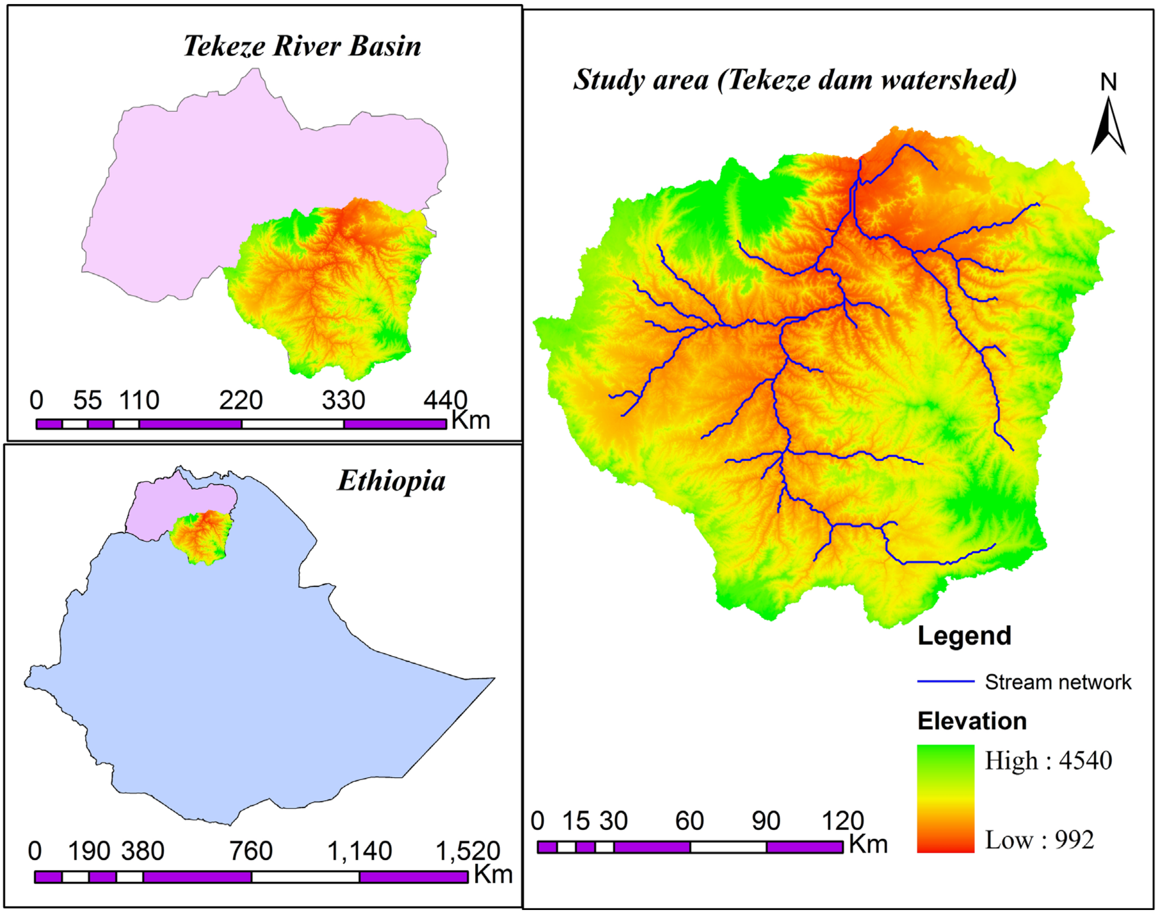

Fig. 1. Location map of Tekeze dam watershed with digital elevation model.

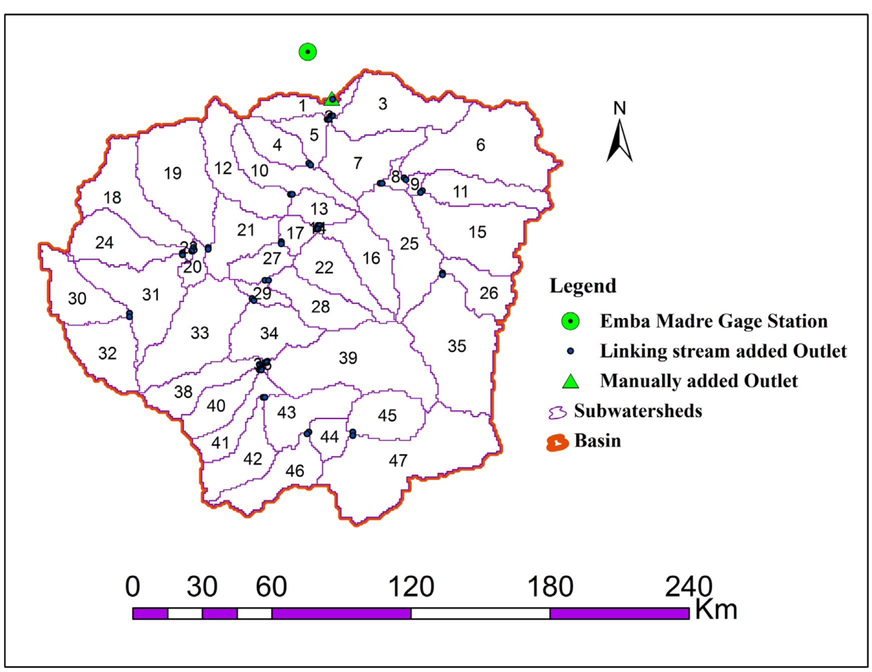

Fig. 2. Subwatersheds of Tekeze dam watershed delineated by SWAT.

resource, irrigation and energy is in a non-continuous time step. Hence the sediment data was prepared through a sediment rating curve using a series data record for 100 days in 2005 and 2006 at Tekeze dam site from the Ministry of Water Resource, Irrigation and Energy of Ethiopia.

2.2.2. Spatial data

The digital elevation model of Tekeze dam watershed was

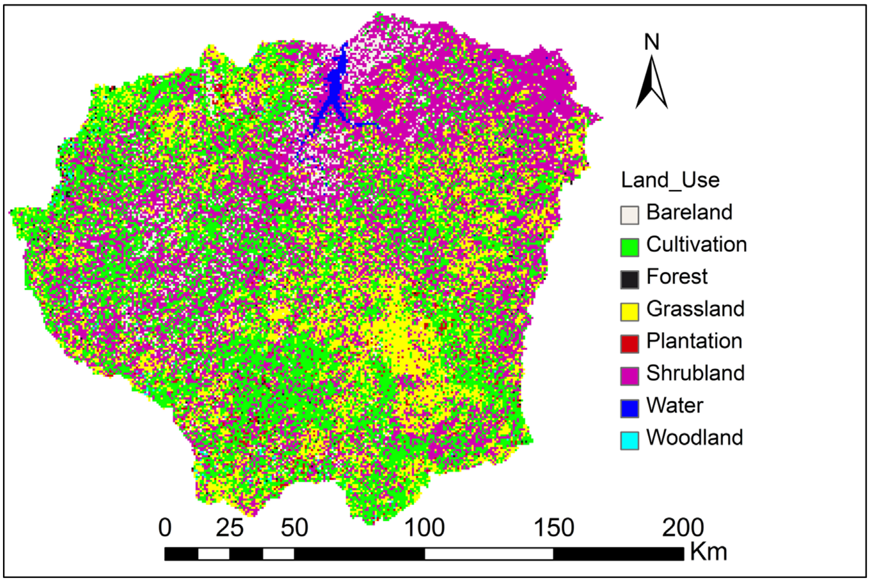

Fig. 3. Land use land of Tekeze dam watershed re-classified by SWAT.

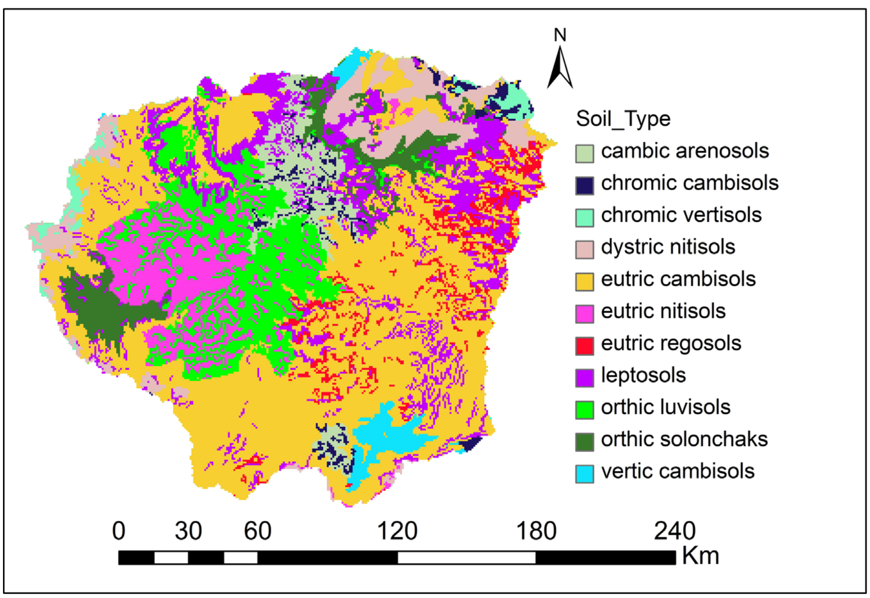

Fig. 4. Soil map of Tekeze dam watershed re-clasified by SWAT model.

obtained by downloading from the ASTER GDEM website ⟨http://gdem.ersdac.jspacesystems.or.jp/⟩. Since 30 by 30 DEM resolution of ASTER GDEM is usually stored as tiled datasets, the downloaded tiles were merged using the mosaic capabilities of Arc GIS 9.3 to form a single DEM of the study area. The digital 2008 land use/land cover map and soil map of the study area was obtained from the Ministry of agriculture in shape file format. The soil texture, hydraulic conductivity, bulk density and organic carbon content and soil depth for the different layers of soil were collected primarily from the Tekeze River basin integrated development master plan and major soils of the world (FAO, 2002).

2.3. SWAT model sensitivity analysis, calibration and validation

2.3.1. Sensitivity analysis

Performing the calibration process for all model parameters of flow and sediment yield is computationally far-reaching and complex. Hence, sensitivity analysis for parameters of the SWAT model set up is important as parameter sensitivity analysis gives the order of parameters that contribute more impact to the output variance due to input variability (Holvoet, Van Griensven, Seuntjens, & Vanrolleghem, 2005). In this study, sensitivity analysis was performed for each flow and sediment parameter within its allowable range using the relative sensitivity index equation.

$$S_r = \left(\frac{x}{y}\right)\left(\frac{y_2 - y_1}{x_2 - x_1}\right) \quad (1)$$

where S_r is the relative sensitivity index, x is the parameter and y is the predicted output. x_1, x_2 and y_1, y_2 correspond to ± 10 percent of the initial parameter and corresponding output values, respectively (James, Bruges, Haan, & Jondon, 1982).

2.3.2. Calibration and validation

After selection of sensitive input parameters, the SWAT model was calibrated for stream flow and sediment yield of the watershed at its outlet (dam axis). The model was calibrated by changing the parameters sequentially for obtaining optimum

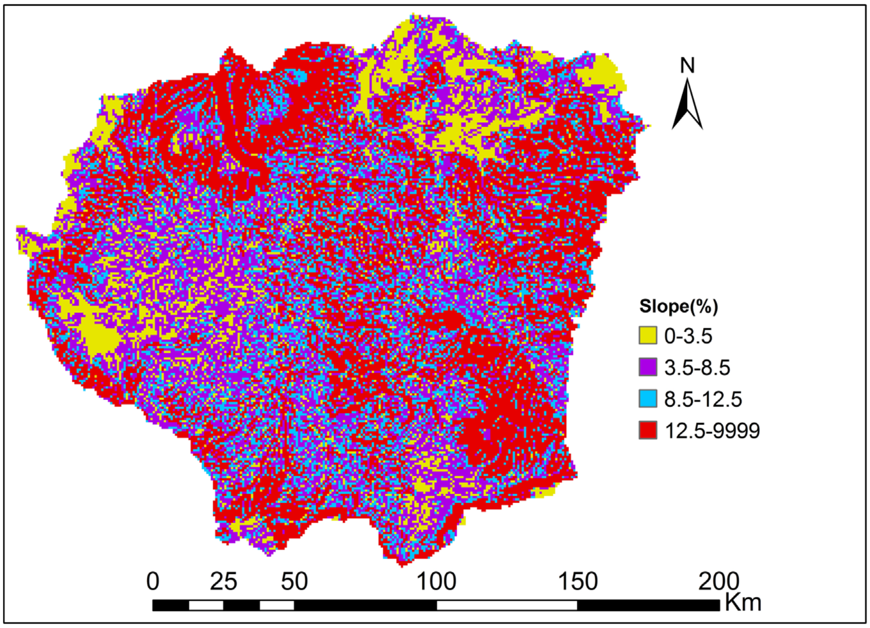

Fig. 5. Slope classification of Tekeze dam watershed by SWAT model.

Table 1
Summery LULC and soil type of Tekeze dam watershed.

LULC type	Area (km^2)	Total (%)	Soil type	Area (km^2)	Total (%)
Bare land	1458.38	4.96	Eutric cambisols	12178.18	41.42
Cultivation	10436.27	35.49	Leptosols	3822.3	13.00
Grass land	5760.72	19.59	Orthic luvisols	3580.7	12.18
Natural forest	365.54	1.24	Eutric nitisols	2433.57	8.28
Plantation	107.22	0.36	Dystric nitosols	1818.28	6.18
Shrub land	10961.72	37.28	Orthic solochaks	1543.54	5.25
Water	192.81	0.66	Cambic arenosols	1295.62	4.41
Wood land	121.82	0.41	Eutric regosols	1133.81	3.86
Total	29404.48	100	Vertic cambisols	660.95	2.25
			Chromic cambisols	554.58	1.89
			Chromic vertisols	382.95	1.30
			Total	**29404.47**	100

agreement between observed and simulated stream flow and sediment yield. The calibration was done for seven years (1996–2002). The calibrated parameters of the model were then validated using an independent data set (stream flow and sediment yield data out of the range reference year used for calibration). After observed and simulated stream flow and sediment yield of the catchment become close to each other with an allowable limit the period of 2003–2006 daily stream flow and sediment yield data were used for model validation of selected flow and sediment parameters in a monthly time scale.

2.4. Model performance evaluation

For evaluation of SWAT model results the simulated stream flow and sediment yields was evaluated by using quantitative statistics. Hence, the model performance was evaluated using three well-known statistical criteria, the coefficient of determination (R^2), the Nash–Sutcliffe efficiency (NSE) and percent bias (PBIAS) and their value were obtained using the following equations respectively.

$$R^2 = \frac{\sum_{i=1}^{n}\left(Y_{obs} - \bar{Y}_{obs}\right)\left(Y_{sim} - \bar{Y}_{sim}\right)}{\sqrt{\sum_{1}^{n}\left(Y_{obs} - \bar{Y}_{obs}\right)^2}\sqrt{\sum_{i}^{n}\left(Y_{sim} - \bar{Y}_{sim}\right)^2}} \quad (2)$$

$$\mathrm{NSE} = 1 - \left[\frac{\sum_{i=1}^{n}\left(Y_{obs} - Y_{sim}\right)^2}{\sum_{i=1}^{n}\left(Y_{obs} - \bar{Y}_{obs}\right)^2}\right] \quad (3)$$

$$\mathrm{PBIAS} = \frac{\sum_{i=1}^{n}\left(Y_{obs} - Y_{sim}\right)}{\sum_{i=1}^{n} Y_{obs}} \times 100\% \quad (4)$$

where Y_{sim} and Y_{obs} are the simulated and observed values respectively, $\bar{Y}_{obs}$ is the mean of n observed values; and $\bar{Y}_{sim}$ is the mean of n simulated values.

3. Result and discussion

3.1. Watershed delineation and HRU definition

Based on the DEM, the study area was divided into 47 sub-watersheds using the Dam axis (Latitude 9.63° N, Longitude 39.5° E) as the main outlet (Fig. 2). To define the origin of streams a threshold area (350 km^2) was set by the user and this threshold area determines the size and number of subbasins and detail of a stream network.

By defining and overlaying the land use, soil type and slope of the study area the sub-watersheds were further divided into a total of 690 hydrologic response units (HRUs). 5%, 10% and 20% of land use, soil and slope were assigned respectively for defining of the HRUs. The redefined results of land use land cover, soil and slope of the study area by SWAT model are summarized below (Figs. 3–5 and Table 1).

For simplified understanding the area coverage of the different land uses and soil types of the maps above are summarized as follows in tabulated form (Table 1).

Table 2
Flow parameter sensitivity analysis results.

SWAT code	Flow parameter description	RS	Rank	Sensitivity class
CN2	Initial SCS CN II value (%)	0.562	1	High
Alpha_Bf	Alpha base flow recession constant (days)	0.551	2	High
Gwqmn	Threshold depth of water required for return flow to occur	0.322	3	High
Esco	Soil evaporation compensation factor	0.263	4	High
Sol_Awc	Available water capacity (mm of water/mm soil	0.117	5	Medium
Sol_Z	Soil depth (mm)	0.115	6	Medium
Blai	Maximum potential leaf area index	0.0798	7	Medium
Soil_K	Soil conductivity (mm/hr)	0.0691	8	Medium
Gw_Revap	Ground water revaporation coefficient	0.0642	9	Medium
Epco	Plant evaporation compensation factor	0.0467	10	Medium
Canmx	Maximum canopy storage	0.0455	11	Medium
Revapmn	Threshold depth of water required for return revaporation to occur (mm)	0.0273	12	Small
Ch_K2	Effective channel hydraulic conductivity (mm/h)	0.0149	14	Small
Epco	Plant evaporation compensation factor	0.0138	15	Small
Ch_N2	Manning coefficient for main channel	0.0113	16	Small
Slope	Average slope steepness (m/m)	0.0042	17	Small
Gw_Delay	Ground water delay (day)	0.0033	18	Small
Sol_Alb	Soil Albedo	0.0024	19	Small

Note: RS is relative sensitivity: small to negligible $0 < RS < 0.05$, Medium $0.05 < RS < 0.2$, High $0.2 < RS < 1$, very high $RS > 1.0$

Table 3
Sediment parameter sensitivity analysis result.

SWAT_code	Sediment parameter name	RS	Rank	Class
USL_P	USLE support practice factor	0.927	1	High
Spcon	Linear factor for channel sediment routing	0.811	2	High
Slope	Average slope steepness (mm/mm)	0.557	3	High
Ch_Cov	Chanel cover factor	0.177	4	Medium
Sol_AWC	Available water capacity (mm H_2O/mm soil	0.066	5	Medium
SOL_K	Soil conductivity (mm/hr)	0.055	6	Medium
Spexp	Exponential factor for sediment routing	0.0328	7	Small
USLE_C	USLE cover factor	0.0266	8	Small
USLE_K	USLE soil erodibility	0.0215	9	Small
BLAI	Maximum potential leaf area index	0.0205	10	Small
SOL_Alb	Soil Albido	0.0182	11	small

Note: RS is relative sensitivity: small to negligible $0 < RS < 0.05$, Medium $0.05 < RS < 0.2$, High $0.2 < RS < 1$, very high $RS > 1.0$

Table 4
Calibrated stream flow and sediment yield parameters.

Rank	Stream flow parameter	Allowable range	Calibrated value	Sediment parameter	Allowable range	Calibrated value
1	CN2	0–100	−15%	USLE_P	0-1	0.65
2	Alpha_Bf	0–1	0.771	Spcon	0.0001–0.01	0.0049
3	Gwqmn	0–5000	2700	Slope	0-1	+4.5%
4	Sol_Z	0–3000	8.5%	Ch_cov	0-1	0.51
5	Esco	0.01–1	0.46	SOL_AWC	0-1	+7%
6	Sol_Awc	0–1	−2.5%	SOL_K	0-100	45.5
7	Blai	0–1	0.09	Spexp	1-2	1.25
8	Canmx	0–10	0.043	USLE_C	0-1	0.3

3.2. Model sensitivity analysis, calibration and validation

3.2.1. Sensitivity analysis

Before model calibration, sensitivity analysis for SWAT parameters was performed first to identify and rank parameters that have significant impact on specific model outputs such as stream flow and sediment yield (Saltelli, Scott, Chan, & Morians, 2000). Sensitivity analysis was done with 12 intervals within a latin hypercube for a total of 27 flow parameters. Hence, analysis was done with 324 iterations (27 flow parameter*12 iteration per parameter) for stream flow parameters and 240 iterations (12 parameters*20 iteration per parameter) for sediment yield parameters. The results of the analysis for SWAT application in the Tekeze dam watershed are described in Tables 2 and 3

Table 5
Calibration and validation statistics of model performance indicators.

Parameters	Stream flow		Sediment yield	
	Calibration (1996–2002)	Validation (1996–2002)	Calibration (1996–2002)	Validation (2003–2006)
R^2	0.85	0.83	0.87	0.83
ENS	0.84	0.79	0.86	0.82
PBIAS	−0.041	−0.098	−0.0951	−0.0785
Time step	Monthly	Monthly	Monthly	Monthly

3.2.2. Calibration and validation

The period of 1996–2002 were used for calibration. The initial/default values of flow parameters represent the groundwater, soil, runoff, evaporation and channel components of the watershed

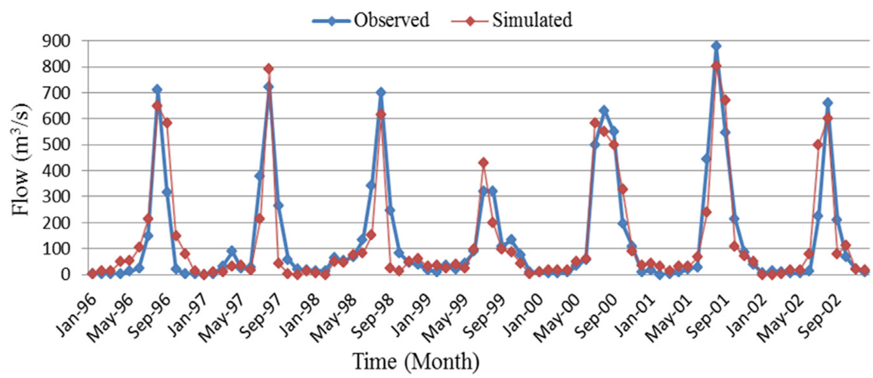

Fig. 6. Observed and simulated monthly flow hydrograph of the calibration period (1996–2002).

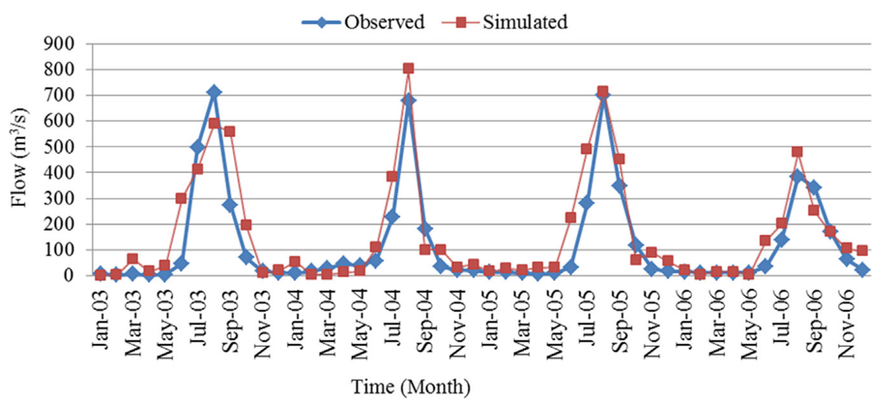

Fig. 7. Observed and simulated monthly flow hydrograph of the validation period (2003–2006).

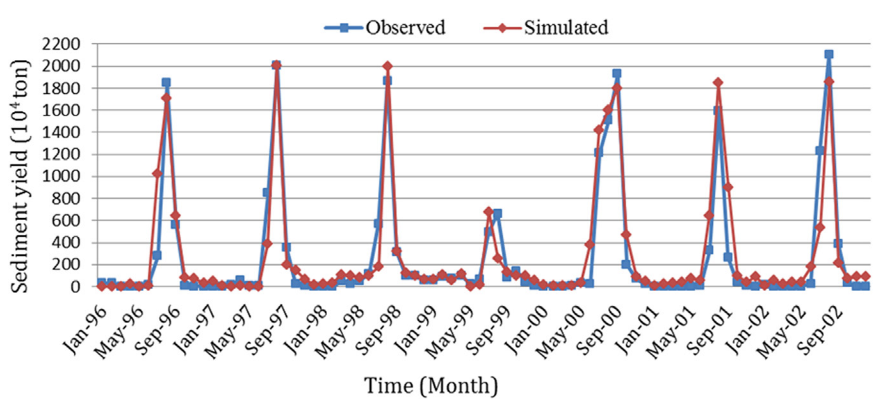

Fig. 8. Observed and simulated monthly sediment yield hydrograph of the calibration period (1996–2002).

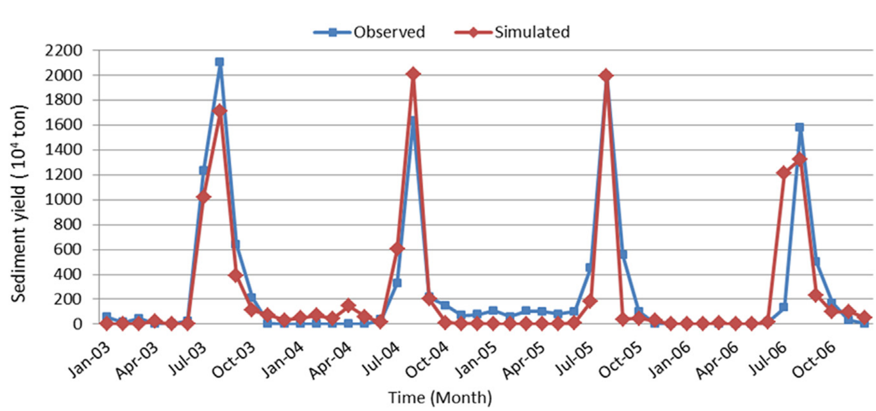

Fig. 9. Observed and simulated monthly sediment yield hydrograph of the validation period (2003–2006).

Table 6
Observed and simulated stream flow and sediment yield.

Parameters	Observed	Simulated
Mean annual stream flow (m^3/s)	135.22	136.97
Annual sediment yield (t/ha/year)	14.34	14.89

hydrological process. Their sensitivity class ranges between medium to high were calibrated and their value set as shown in Table 4. Validation of the model was carried out using the period 2003–2006 without adjusting calibrated parameters.

The model goodness fit was evaluated on a monthly basis to test the performance of the model. The model performance indicators (R^2, NSE, PBIAS) are summarized in Table 5. Monthly time set up of stream flow and sediment yield hydrograph of both calibration and validation periods are shown in Figs. 6–9.

The simulated stream flow values are slightly less than that of the measured value for peak flow months (August). But the simulated flow is slightly larger than the measured value for low flow months (January–May). Generally the model slightly over estimates for both stream flow and sediment yield of the catchment as indicated in Table 6 below.

3.3. *Prioritization of critical subcatchments for sedimentation management*

The critical subwatersheds were identified and prioritized on the basis of average annual sediment yield simulated using the SWAT model from the subwatersheds for the period 1996 to 2013 climatic conditions. Annual sediment yields were simulated for each subwatershed of the Tekeze dam watershed. 47 subwatersheds were identified during watershed delineation step. Hence, priorities among the 47 subwatersheds were fixed on the basis of ranks assigned to each critical subwatershed according to ranges of sediment yield. Identified critical subwatersheds were arranged in descending order and then priorities were fixed for their management. The spatial distribution sediment yield in the whole Tekeze dam watershed showed in Fig. 10 indicates 15.17 t/ha/year of average annual sediment yield. Hurni (1985) has conducted a research to estimate the rate of soil erosion for Ethiopia. The range of the tolerable soil loss level for various agro-ecological zones of Ethiopia was found from 2 to 18 t/ha/yr (Hurni, 1985). Accordingly, the simulated soil loss rate of some of subwatersheds in the study area (Tekeze dam watershed) exceeds the maximum tolerable soil loss rate (18 t/ha/yr). This fact shows how far soil erosion is a serious threat to the study area.

The first thirteen (13) sub watersheds which their annual sediment yield values are greater than the tolerable limit are prioritized (Table 7) for watershed management efforts.

Different subwatersheds show very high variation in their water erosion behavior as shown in the table above. Subwatershed 19 give maximum sediment outflow (32.57 t/ha/year) followed by subwatershed 12 and subwatershed 6 (31.9 and 31.03 t/ha/year) respectively. Subwatershed number 19 has about 39.1% area as cultivated land, 30.8% shrub land 23% grass land with average land slope of 15.2%. The rest of the area is covered by bare land, forest and plantation. Subwatershed 12 also contains dominantly agricultural and shrub land (35.35% and 30.56%) respectively. Considerable presence of bare land and the lack of forest cover in the high sloping land areas (average slope of 10.43%) might have contributed to the high sediment outflow from these sub watersheds beside intensive agricultural practice. The high sediment yield production rate predicted in these sub-basins may be attributed to insufficient use of the land, scanty vegetative cover, steep sloping areas, high population pressure, cultivating of the steep-lands, and other environmental problems. These 13 critical sub-basins were, hence, assigned as the top priorities and were recommended to be considered for the future conservation plans of Tekeze dam watershed.

4. Conclusion

The Tekeze dam watershed currently has an annual stream flow of 137.74 m^3/s and annual average sediment yield of 15.17 t/ha /year. The seasonal variability of sediment yield and stream flow from the individual subbasins shows maximum stream flow and sediment yield was observed during heavy rainfall seasons (July to September). This is the direct relationship of sediment yield and runoff. i.e. sediment yield is a function of runoff and other processes happening in the watershed.

Lastly, the study has shown that subwatershed runoff and sediment yields are highly variable. Hence, the critical subwatersheds were identified and prioritized on the basis of average annual sediment yield. Out of the 47 subwatersheds, 13 subwatersheds were

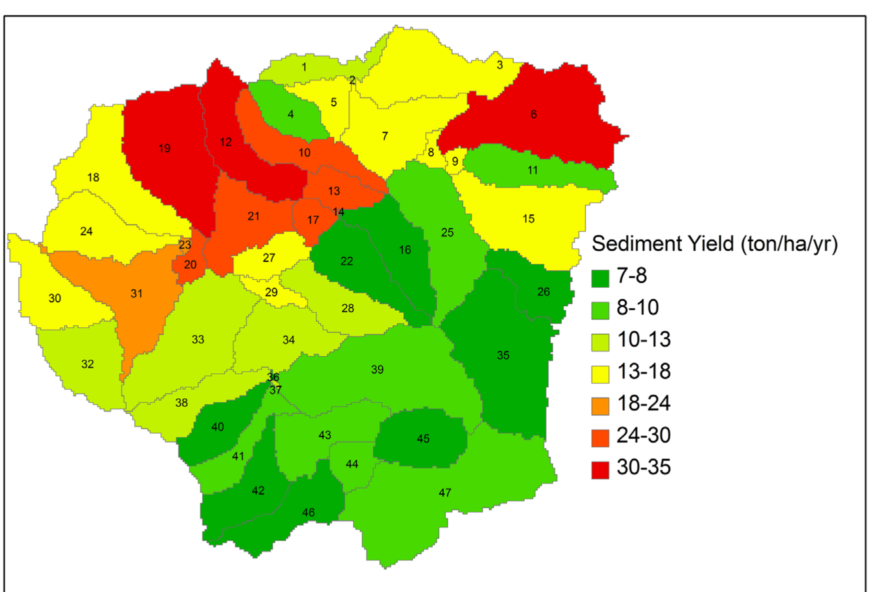

Fig. 10. : Spatial annual sediment yield distribution of Tekeze dam watershed.

Table 7
Subwatersheds showing sediment outflow and priority rank.

Catchment code	Area (km^2)	Mean slope (m/m)	Dominant soil type	Annual sediment yield (t/ha/year)	Rank
19	1281.9	0.152	Eutric cambisols	32.57	1
12	794.48	0.172	Leptosols	31.90	2
6	1539.7	0.107	Dystric nitosols	31.03	3
10	596.02	0.132	Cambic arenosols	30.22	4
14	1.8723	0.068	Chromic cambisols	29.46	5
17	187.85	0.126	Orthic luvisols	28.79	6
13	295.82	0.120	Camic arenosols	28.21	7
21	655.93	0.109	Orthic luvisols	25.18	8
20	151.03	0.068	Eutric nitosols	24.56	9
23	19.971	0.086	Eutric nitosols	22.54	10
31	1037.9	0.053	Eutric nitosols	20.53	11
30	655.3	0.084	Eutric cambisols	18.49	12
18	948.63	0.079	Eutric cambisols	17.21	13

identified as those with sediment yields above the tolerable limit. The watershed numbers 19 (32.7 t/ha/year), 12 (31.9 t/ha/year), 6 (31.03 t/ha/year) and 10 (30.22 t/ha/year) are in the higher sediment yield group which needs attention in sediment mitigating measures of the watershed for sustainable use of the Tekeze dam.

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