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Assessing and mapping sediment yield response under climate projections in Songwe Watershed

Lupakisyo G. Mwalwiba[a*], Gislar E. Kifanyi[a], Edmund Mutayoba[b], Julius M. Ndambuki[c], Nyemo Chilagane[d] and Wilfred O. Molla[e]

[a]*College of Engineering and Technology, Mbeya University of Science and Technology, Mbeya, Tanzania*
[b]*Department of Water Supply and Sanitation Engineering, Water Institute, Dar es Salaam, Tanzania*
[c]*Tshwane University of Technology, Pretoria, South Africa*
[d]*Tanzania Research and Conservation Organization, P.O Box 6873 Morogoro, Tanzania*
[e]*MALK Consultants Limited, P.O Box 2839 Mbeya, Tanzania*

CHRONICLE

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ABSTRACT

Climate change creates considerable issues for watershed management, especially in areas prone to erosion and sediment production. The purpose of this study was to examine and map the sediment yield response to future climatic scenarios in the Songwe Watershed. The Soil and Water Assessment Tool (SWAT), which is integrated with Regional Climate Models (RCM) under Representative Concentration Pathways (RCPs) 8.5, was used to evaluate the possible consequences on sediment transport dynamics within the watershed. The simulated results from the four Regional Climate Models (CCLM4, HIRAM5, RACMO22T, and RCA4 RCMs) showed that sediment yields increased for future estimates from 2011 to 2100 under RCP 8.5, owing mostly to increased rainfall and altered hydrological cycles. The results reveal that the average annual sediment yield could increase by 30-50% under RCP 8.5. scenario. Sediment yield mapping highlights crucial hotspots, notably in steep terrain and places with minimal vegetation cover, that are extremely susceptible to erosion, providing useful insights for focused intervention measures. The study emphasized the need for adaptive watershed management methods to counteract the negative effects of climate change on soil erosion and sediment crusade.

1. Introduction

Sediment yield is a critical factor in river basin management, influencing water quality and the longevity of hydraulic structures such as dams and reservoirs. Various factors, including climate, land use, topography, and soil type, affect sediment transport in rivers (Mwalwiba et al., 2023; Ranjan & Mishra, 2023; Santos et al., 2021).With changing climate patterns, it's vital to assess how future conditions might alter sediment yield, particularly in regions prone to soil erosion and sedimentation (Neverman et al., 2023). Numerous studies have explored sediment yield in different watersheds using models like the Soil and Water Assessment Tool (SWAT) to predict future scenarios (Zhang, & Yang, 2021; Tadesse et al., 2024; Zhang et al., 2019). Tanzania and other African countries have experienced significant shifts in precipitation and temperature due to climate change, impacting river flow, soil erosion, sediment movement, and watershed hydrology (Luhunga et al., 2018; Tibangayuka et al., 2022).Tanzania's diverse topography, soil composition, climate changes, and land use dynamics result in significant river flows and sediment discharges (Chilagane et al., 2021; Mfwango et al., 2022; Nilawar & Waikar, 2019). Human activities, such as deforestation and fossil fuel use, contribute to global warming and increasing greenhouse gas levels (Kassian et al., 2017; Ndulue & Mbajiorgu, 2018). The Intergovernmental Panel on Climate Change predicts global warming will reach 1.5 degrees Celsius between 2030 and 2052, with East African temperatures expected to rise by 1-4 degrees Celsius by the 2090s, potentially increasing rainfall by 48% (Guilyardi et al., 2018).

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* Corresponding author.
E-mail address: lupakisyog@yahoo.co.uk (L. G. Mwalwiba)

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The Songwe Watershed in Tanzania faces pressures from environmental changes and human activities like mining, deforestation, and agriculture(Mwalwiba et al., 2023). Understanding sediment yield response in this watershed is crucial for effective water resource management and sustainable development. Using hydrological models and QGIS, this study assessed and mapped sediment yield under projected climate scenarios for the Songwe Watershed. The research used Regional Climate Models under RCP 8.5 and the SWAT hydrological model to assess sediment yield over three time periods: 2041-2040, 2041-2070, and 2071-2100. Based on simulations of the 2020 land use land cover map and future climatic forecasts, the study found substantial sub-basins prone to soil erosion and sediment yield. The results provide insights into climate change's impact on sediment processes, informing local and global efforts to manage and mitigate these effects on riverine systems. This study highlights the importance of incorporating climate projections into watershed management strategies to address future sediment yield challenges. The detailed maps and data generated provide valuable insights for designing targeted intervention measures, such as reforestation, terracing, and improved agricultural practices, to mitigate erosion and enhance watershed resilience. The research highlighted the necessity for adaptive watershed management practices to preserve the ecological integrity and sustainability of the Songwe Watershed in the face of a changing climate. By combining robust climate projections with sediment yield modeling, this research contributes to a deeper understanding of hydrological responses to climate change and offers a basis for developing resilient watershed management plans.

2. Materials and methods

2.1 Study area

Fig. 1 shows the 10,800-square-kilometer Songwe watershed in eastern Lake Rukwa Basin, southern-western Tanzania. The position is between 07^{0}40'S and 09^{0}20'S and 33^{0}00'E and 33^{0}50'E(Mwalwiba et al., 2023). The region has many hills that cross fertile valleys at 600–2400 meters above sea level. The watershed has good soils, ample precipitation, temperate temperatures, and excellent agricultural potential. The Songwe watershed is one of Tanzania's most productive. The watershed includes Mbeya City, a major commercial and industrial hub. The watershed has a tropical climate with a protracted rainy season from October to May. A dry season occurs between June and September. The highlands receive 2600mm of yearly precipitation, while the lowlands receive 650mm. Height affects average temperature, which ranges from 16°C to 30°C. The Lupa, Songwe, and Zira rivers drain the Songwe watershed. These rivers divide the watershed into north, middle, and south. In the gold mining zone, rivers converge and discharge into Lake Rukwa after crossing vast, flat plains. All watershed rivers have strong seasonality, with high flows in the rainy season and low flows otherwise. River flows peak in February and March and drop between July and November, with September being the driest.

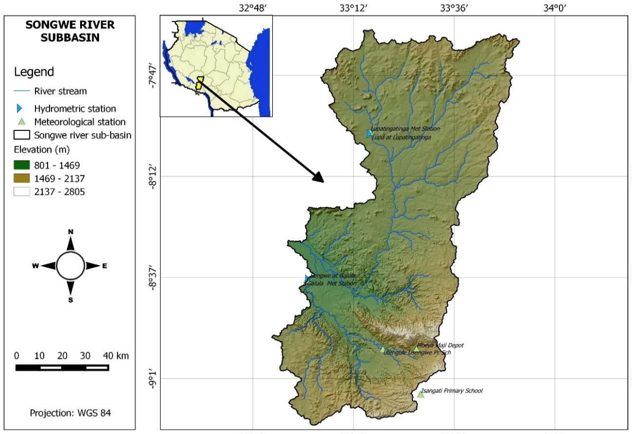

Fig. 1. Map of the study area

2.2 Data used

The Ministry of Water Tanzania's Lake Rukwa Water Basin, office provided the daily streamflow information for the Songwe watershed at Galula station. In this study, a Digital Elevation Model (DEM) with a 30-meter spatial resolution was acquired from the Advanced Land Observing Satellite Phased Array L-band Synthetic Aperture Radar (ALOS PALSAR) (Mwalwiba et al., 2023). This data, available from the Alaska Satellite Facility (ASF) at http://www.asf.alaska.edu, was used to delineate the watershed and analyze its topographic features. Land use and land cover (LULC) LULC data for the year 2020 were downloaded from the United States Geological Survey (USGS) Earth Explorer platform at https://earthexplorer.usgs.gov (Mwalwiba et al., 2023). The data were categorized to match the input requirements of the

SWAT model, providing an accurate representation of the watershed's surface characteristics. Soil information was extracted from the FAO-UNESCO Soil Map of the World, Volume VI, available online at https://swat.tamu.edu/data/. This data was essential for defining soil properties and distribution within the SWAT model.

Data on the everyday rainfall were collected from Lake Rukwa Water Basin office. Additional meteorological parameters, including minimum and maximum temperatures, solar radiation, wind speed, relative humidity, and wind direction, were obtained from the updated Global Weather Database for SWAT (Mwalwiba et al., 2023). Daily streamflow information for the baseline scenario (1981-2005) was provided by the Lake Rukwa Water Basin office for the Lupa tinga tinga and Galula stations (Mwalwiba et al., 2023). This data was crucial for model calibration and validation.

There are eight dominant land use and land cover types in the Songwe watershed as shown in Figure 2. The large area of the watershed is covered by cultivated land 39.35%, bushland 33.42%, and woodland 13.37%. The mountainous area of the sub-basin is covered by woodland, cultivated land, and built-up areas. The land downstream of the sub-basin is cultivated land, bushland, and grassland. The soil type used in this study was extracted from the FAO-UNESCO Soil Map of the World soil database (Mwalwiba et al., 2023). The Songwe watershed contains nine major soil types, Eutric Fluvisol, Chromic Cambisols, Mollic Andosols, Vitric Andosols, Haplic lixisols, Eutric leptosols, Haplic solonetz, Ferralic Cambisol, and Umbric Nitisol.

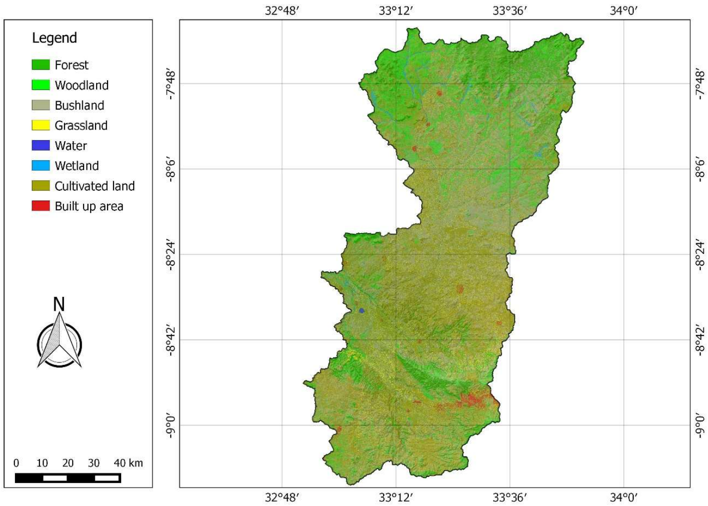

Fig. 2. Land use/cover of Songwe watershed

2.3 SWAT Model

The SWAT Model was used to accomplish this objective. SWAT model is a continuous, long-term, physical-based distributed model developed by Agricultural Research Services of the United States Department of Agriculture to predict the impact of land management practices on water, sediment, and agriculture chemical yields in large and complex watersheds with varying soil, land use, and management conditions over long periods (Akoko et al., 2021). The SWAT model includes a weather engine capable of generating precipitation and other weather parameters for un-gauged watersheds using stochastic (randomly determined) and probabilistic methods (Chilagane et al., 2021). This weather generation relies on global data sets like the CFSR (Climate Forecast System Reanalysis) to ensure accurate weather simulations.

The SWAT model developed by (Mwalwiba et al., 2023) was used to accomplish this study. The model was built on the QGIS 2.6.1 interface, which is an open-source geographic information system. The model incorporates relative humidity, solar radiation, wind speed, and temperature data (both minimum and maximum) from the CFSR Global Weather Data for SWAT (https://swat.tamu.edu/data/cfsr), Rainfall data obtained from the Tanzania Meteorological Agency (TMA), water discharge data from the Songwe sub-basin, specifically at the Galula and Lupa gauging stations, provided by the Lake Ruka Basin Water Office (Mwalwiba et al., 2023).

Modified Universal Soil Loss Equation (MUSLE) was employed to model soil erosion processes. whereas the Bagnold equation was utilized to characterize channel transport(Srinivasan, 2009). Unlike the Universal Soil Loss Equation (USLE), which predicts long-term average annual soil loss, MUSLE can predict sediment yield from individual storm events, making it more suitable for dynamic watershed modeling. The MUSLE sediment model is as follows:

$$Sed = 11.811.8b(Q_{surf}\ x\ q_{peak}\ x\ Area_{HRU})^2\ x\ K_{USLE}\ x\ C_{USLE}\ x\ P_{USLE}\ xLS_{USLE}\ x\ CFRG2$$

where Sed is the sediment yield (metric ton day^{-1}), Qsurf is the surface runoff volume (mm ha^{-1}), peak is the peak runoff rate in m^3 s^{-1}, Area HRU is the area of HRU in ha, KUSLE is the soil erodibility factor, CUSLE is the cover and management factor, PUSLE is the support practice factor, LS is a topographic factor, and CFRG is the course fragment factor, in the universal soil loss equation (USLE).

2.4 Model calibration and simulation analysis

Model calibration and validation to reduce prediction uncertainty were conducted using the Sequential Uncertainty Fitting (SUFI-2) algorithm within the SWAT-CUP framework (Abbaspour et al., 2007). The calibration and validation processes utilized monthly flow data spanning from 1981 to 1992. A five-year warm-up period prior to 1981 was implemented to achieve steady-state conditions and mitigate the impact of unknown initial conditions on the model.

Four objective functions were employed to evaluate the model's performance: Nash-Sutcliffe Efficiency (NSE), Coefficient of Determination (R^2), Probability Bias (PBIAS), and Root Mean Square Error (RSR) (Chilagane et al., 2021; Mazengo et al., 2022). The general performance rating statistics for these objective functions, as suggested by Gyamfi et al., (2016), were used to determine the model's performance. The results of this calibration and validation indicate how well the model simulates the observed data, providing confidence in its predictive capabilities and helping to reduce the uncertainties associated with the model's predictions.

2.5 Scenario analysis

The study utilized climate projections for the Songwe watershed developed by Mwalwiba (2023). The climate projection scenario was created using simulations from four high-resolution regional climate models (RCMs) driven by general circulation models (GCMs) from the Coordinated Regional Climate Downscaling Experiment (CORDEX). These were assessed under two Representative Concentration Pathways (RCP): RCP 4.5 and RCP 8.5. Table 1 lists the RCMs and their respective driving GCMs used in this study. The selected models were previously employed to simulate climate conditions over the southern highlands of Tanzania with relatively minimal errors (Luhunga et al., 2018; Mwalwiba et al., 2023).

A fixed change scenario was employed to assess the influence of climate projections from different regional climate models on soil erosion and sediment yield. In this scenario, the calibrated and validated Soil and Water Assessment Tool (SWAT) model was run with modified climate projection data while maintaining constant physical variables. The impact of the climate projection on soil erosion, sediment yield, and other hydrological components was quantified by comparing SWAT outputs for the four different RCM scenarios: CLM4, HIRAM5, RACMO2T, and RCA4. The simulated sediment yield results for these four RCM scenarios were then compared to determine the sediment yield response under varying climate projections. The study evaluated the impacts of climate change on sediment production in the Songwe watershed by comparing sediment yields between historical (1981–2005) and future periods under the RCP 8.5 scenario (Nilawar & Waikar, 2019; Srinivasan et al, 2023)). The SWAT model's simulations under current subbasin management systems projected sediment yields in response to climate change scenarios.

Table 1
The CORDEX RCMs and their driving GCMs

S/N	RCM	Mode Center	Short name	GCMs
1	DMI HIRHAM5	Denmarks Meteoroliske Institute (DMI), Denmark	HIRHAMS	ICHEC
2	CLMcom COSMO-CLM (CCLM4)	Climate Limited-Area Modelling (CLM) Community	CCLM4	MPI ICHEC CNRM
3	KNMI Regional Atmospheric Climate Model, Version (RACMO2.2T)	Kininklijk Nederlands Meteorologisch Institute (SMHI), Swiden	RACMO99T	ICHEC
4	SMHIRossby Center Regional Atmospheric Model (RCA4)	Sweriges Meteorologiska OchHydrologiska Institut (SMHI), Sweden	RCA4	MPI ICHEC CNRM

3. Results

3.1 Model calibration and validation results

The model calibration and validation results were presented by Mwalwiba (2023). The model showed the goodness of fit with NSE 0.45, R2 0.59, and RSR 0.73 for the calibration period and NSE 0.59, R2 0.59, and RSR 0.64 for the validation period. The curve number (CN2) which indicates the runoff response of a catchment was found to be the most sensitive parameter followed by the Available water capacity of the soil layer (SOL_AWC), the Threshold depth of water in the shallow aquifer required for return flow to occur (GWQMN), Groundwater delay (GW_DELAY) and Groundwater "revap" coefficient (GW_REVAP).

3.2 The influence of different variables on sediment yield generation under the baseline scenario

The sediment output in subbasins covered with bushland and cultivated land is significant, as highlighted by the SWAT model and QGIS analysis. The erosion of farmed land leads to faster depletion of topsoil. Cultivated land contributes 54.94 tons/ha of sediment annually, while bushland contributes 40.6 tons/ha, and grassland on steep slopes contributes 22.91 tons/ha (Tables 2 and 3). In the subbasin, these land uses resulted in an average annual sediment output of 125.61 tons/ha. In the Songwe watershed, historical data indicates that average monthly sediment production peaks in January, February, and March, with estimates of 171.84 tons/ha, 109.4 tons/ha, and 129.04 tons/ha, respectively (Figure 6). Agricultural fields and bushland in the southern, middle, and lower regions of the Songwe subbasin, with soils such as eutric leptosols, eutric fluvisols, vitric andosols, haplic lixisols, and umbric nitisols on steep slopes, are estimated to yield higher sediment (Table 3). Eutric leptosols, being extremely shallow and found on hard rock or unconsolidated, very gravelly materials, are particularly prone to erosion (Tadesse et al., 2024).

The agricultural land and bushland in the Songwe watershed contribute approximately 76.1% of the sediment output. Forest and woodland regions, due to their heavy vegetation cover, do not significantly contribute to sediment output (Table 2)

Table 2

LULC classes contribution to mean annual surface runoff and sediment yield

Land use/cover	Surface runoff (mm)	Sediment yield (t/ha)
Cultivated land	290.43	54.94
Built-up are	179.32	0.29
Woodland	173.97	1.34
Forest	110.54	5.53
Grassland	156.14	22.91
Bushland	145.29	40.60

Table 3

Influence of different variables on sediment yield at sub-basin level

Sub-basin	Coverage (Km2)	Dominant land use	Dominant soil	Slope	Annual mean SYLD (t/ha)
1	389	FRSD	Af3-1-2a-407	3.0-9.0	3.07
2	929	FRST	Ao66-2ab-429	3.0-9.0	5.12
3	359	RNGB	Af3-1-2a-407	3.0-9.0	5.10
4	316	FRST	Ao66-2ab-429	3.0-9.0	5.52
5	349	RNGB	Ao66-2ab-429	3.0-9.0	4.32
6	278	AGRR	Af3-1-2a-407	3.0-9.0	4.13
7	405	RNGB	Ao66-2ab-429	3.0-9.0	3.98
8	503	RNGB	Af3-1-2a-407	3.0-9.0	3.95
9	396	RNGB	Af3-1-2a-407	3.0-9.0	6.62
10	328	AGRR	Nd34-2bc-803	3.0-9.0	19.88
11	207	AGRR	Rd20-2c-932	3.0-9.0	43.43
12	527	AGRR	Tm13-2-3c-945	9.0-25.0	6.97
13	234	RNGB	Rd20-2c-932	3.0-9.0	12.09
14	197	AGRR	Gp6-2-3a-633	3.0-9.0	7.78
15	263	AGRR	Ne43-2-3a-839	3.0-9.0	5.74
16	527	AGRR	Tm13-2-3c-945	9.0-25.0	18.84
17	132	AGRR	Rd20-2c-932	9.0-25.0	97.10
18	196	AGRR	Rd20-2c-932	9.0-25.0	29.96
19	76	AGRR	Af3-1-2a-407	3.0-9.0	7.66
20	208	RNGB	Af3-1-2a-407	0-3.0	2.66
21	407	RNGB	Af3-1-2a-407	0-3.0	3.52
22	101	RNGB	Ao66-2ab-429	3.0-9.0	4.26
23	185	AGRR	Rd20-2c-932	9.0-25.0	94.46
24	31	RNGB	Af3-1-2a-407	0-3.0	3.30
25	5	AGRR	Rd20-2c-932	0-3.0	35.01
26	100	AGRR	Rd20-2c-932	9.0-25.0	41.19
27	141	RNGB	Af3-1-2a-407	0-3.0	3.96
28	137	RNGB	Af3-1-2a-407	3.0-9.0	4.46
29	82	RNGB	Af3-1-2a-407	3.0-9.0	8.38
30	86	AGRR	Af3-1-2a-407	3.0-9.0	17.91

3.3 Spatial distribution of sediment yield under different RCM scenarios

To assess future sediment yields in the watershed, the SWAT model was employed using bias-corrected data from four regional climate models (RCMs): CCLM4, HIRAM5, RACMO22T, and RCA4. These models were used to project sediment yields for the period 2011–2100 under the RCP8.5 scenario, which assumes a high greenhouse gas concentration pathway. The RCP 8.5 scenario reflects the socioeconomic activities within the subbasin, such as intensive agriculture and land use changes, which influence erosion rates (Mwalwiba et al., 2023). Historically, the mean annual sediment output in the Songwe watershed was estimated at 514.58 tons/ha for CCLM4, 411.012 tons/ha for HIRAM5, 203.514 tons/ha for RACMO22T, and 219.3 tons/ha for RCA4 RCMs (Figure 6). The analysis further showed that the months of January, February, and March exhibited the highest average monthly sediment outputs historically. For the CCLM4 model, these outputs were 171.84 tons/ha, 109.4 tons/ha, and 129.04 tons/ha, respectively. For the HIRAM5 model, the outputs were 122.10 tons/ha, 102.92 tons/ha, and 123.9 tons/ha, respectively. The RACMO22T model indicated outputs of 37.27 tons/ha, 28.76 tons/ha, and 87.78 tons/ha, respectively, while the RCA4 RCMs projected 73.37 tons/ha, 49.96 tons/ha, and 60.97 tons/ha, respectively (Table 4).

The highest increase in future average monthly sediment yield in the 2011 – 2040 period was 32% in February for the HIRAM5, 79.49%,68.96% and 221.85% in April for the CCLM4, RACMO22T, andRCA4 RCMs respectively. For the mid period the future sediment yield increased by 190.51, and 91.84% in February for the CCLM4, and HIRAM5 respectively, 82.37%, and 144.6% in April for the RACMO22T, andRCA4 RCMs respectively. For the last period the future sediment yield increased by 192.57, and 81.47% in February for the CCLM4, and HIRAM5 respectively, 150.74%, and 155.8% in April for the RACMO22T, andRCA4 RCMs respectively (Table 4). According to the results of the SWAT model running under the RCP 8.5 scenario, the Songwe watershed's sediment yields will rise in the future during the rainy season (Figures 6, 7, 8, and 9). The model findings show that, for all future projection periods, the maximum sediment yields were observed in January, February, March, and April (Figs. 7,8 and Fig. 9).

Table 4
Future Sediment yield results under four regional climate models at watershed level

Range	Date	CCLM4	Increase/ Decrease	% + -	HIRAM5	Increase/ Decrease	% + -	RACMO 22T	Increase/ Decrease	% + -	RCA4	Increase/ Decrease	% + -
2011 - 2040	January	138.9	-32.94	-19.17	143.87	+21.77	+17.83	36.24	-1.01	-2.71	107.53	+34.16	+46.56
	February	184.77	+75.37	+68.9	135.9	+32.98	+32	41.92	+13.17	+45.78	98.57	+48.61	+97.3
	March	113.34	-15.7	-12.17	115.56	-8.34	-6.73	37.95	-49.84	-56.77	90.40	+29.43	+48.27
	April	118.95	+52.68	+79.49	47.244	+4.244	+9.87	77.72	+31.72	+68.96	83.17	+57.33	+221.85
2041 - 2070	January	101.45	-70.39	-40.96	166.8	+44.70	+36.61	37.63	+6.4	+1.1	69.29	-4.08	-5.56
	February	317.82	+208.42	+192.57	197.44	+94.52	+91.84	51.61	+22.85	+79.46	97.89	+55.07	+95.94
	March	135.69	+6.65	+5.15	173.93	+50	+40.35	45.22	-42.57	-48.37	55.68	-5.29	-8.68
	April	21.70	-44.57	-67.26	45.81	+2.81	+6.54	83.89	+37.89	+82.37	63.21	+37.37	+144.6
2071 - 2100	January	124.78	-47.06	-27.39	210.97	+88.874	+72.79	44.287	+7.037	+18.89	71.289	-2.08	-2.84
	February	320.07	+210.67	+192.57	186.76	+83.84	+81.47	48.88	+20.13	+68	105.03	+55.07	110.23
	March	59.69	-69.35	-53.74	177.22	+53.32	+43	46.65	-41.14	-46.86	73.77	12.8	21
	April	153.41	+87.13	+131.48	34.86	-8.138	-18.93	115.34	+69.34	+150.74	66.095	40.26	+155.8

The sediment output for the Songwe watershed is highly concentrated in four months, accounting for approximately 78.88% of the annual total. Climate change has significantly impacted the region, leading to high rates of soil erosion and sediment output. The Songwe watershed's sub-basins have been analyzed for future soil erosion hotspots based on predicted average yearly sediment outputs.

From 2011 to 2040, sub-basins 17, 18, and 23 exhibited the highest simulated sediment yield. For 2041 to 2070, the highest yields were found in sub-basins 16, 17, and 23. For 2071 to 2100, sub-basins 16, 17, 18, and 23 showed the highest yields across all four regional climate models (RCMs) (Figure 3, 4 and 5). The highest simulated average sediment yield ranged from 3.7 tons/ha to 12.9 tons/ha in these sub-basins. Moderate sediment yields were observed in sub-basins 11, 12, 13, 14, 15, and 26, located in the upstream southern parts and lowlands of the watershed, areas characterized by agricultural activities, mining, urbanization, and bushlands. Sub-basins in the upstream northern regions, covered by dense forests, showed the lowest sediment yields. Low sediment outputs were strongly correlated with excellent plant cover in these areas. The study on the Songwe watershed using the SWAT Model under the RCP 8.5 scenario reveals significant insights into sediment yields over the 21st century. The predictions are based on four regional climate models (RCMs): CCLM4, HIRAM5, RACMO22T, and RCA4.

The total average annual sediment yields predicted by the SWAT Model under RCP 8.5 were anticipated to be 749.65 tons/ha, 555.85 tons/ha, 210.63 tons/ha, 404.91 for CCLM4, HIRAM5, RACMO22T, and RCA4 RCMs respectively for the years 2011 to 2040, 689.44 tons/ha, 760.87 tons/ha, 235.12 tons/ha, 311.23 tons/ha for CCLM4, HIRAM5, RACMO22T, and RCA4 RCMs respectively for the years 2041 to 2070, and 831.44 tons/ha, 782.17 tons/ha, 286.92 tons/ha, 341.56 tons/ha for CCLM4, HIRAM5, RACMO22T, and RCA4 RCMs respectively for the years 2071 to 2100 (Figure 7, 8 and 9). All four RCMs predict that the greatest sediment yields will occur in January, February, March, and April across all future periods. In contrast, sediment yields during the dry season are predicted to be minimal or nonexistent. According to the findings, sediment yields increased by 45.68%, 35.24%, 3.5%, 84.64% for CCLM4, HIRAM5, RACMO22T, and RCA4 RCMs respectively between 2011 and 2040, 34%, 85.12%, 15.53%, 41.92% for CCLM4, HIRAM5, RACMO22T, and RCA4 RCMs respectively between 2041 and 2070, and 61.58%, 112.2%, 40.99%, 51.19% between 2071 and 2100 under RCP 8.5. These predictions indicate a notable increase in sediment yields under the RCP 8.5 scenario, particularly during the wet season months. The data show significant variability among the different RCMs, underscoring the potential impacts of climate change on sediment transport in the Songwe watershed.

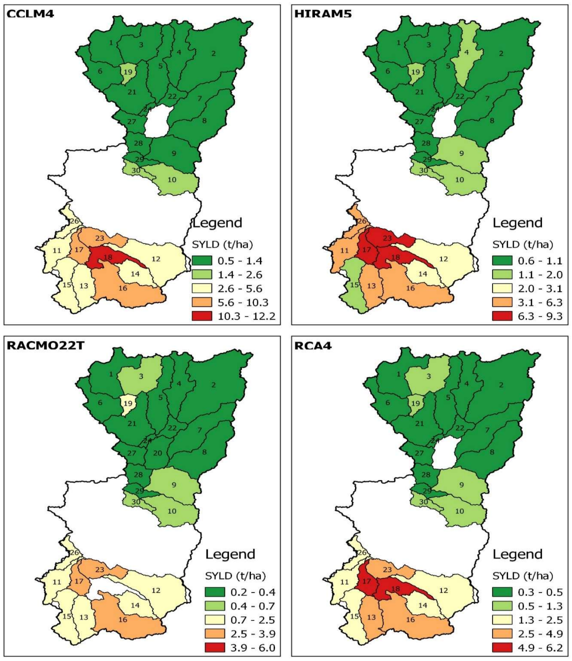

Fig. 3. Spatial distribution of sediment yield map under RCM – RCP8.5 scenario (2011 – 2040)

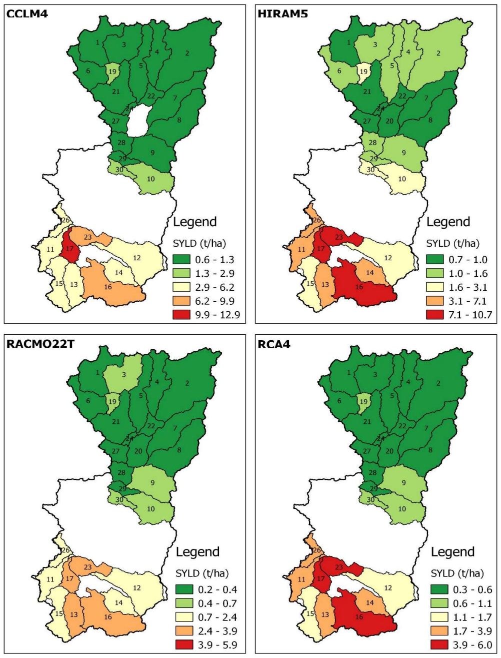

Fig. 4. Spatial distribution of sediment yield under RCM – RCP 8.5 scenario (2041 – 2070)

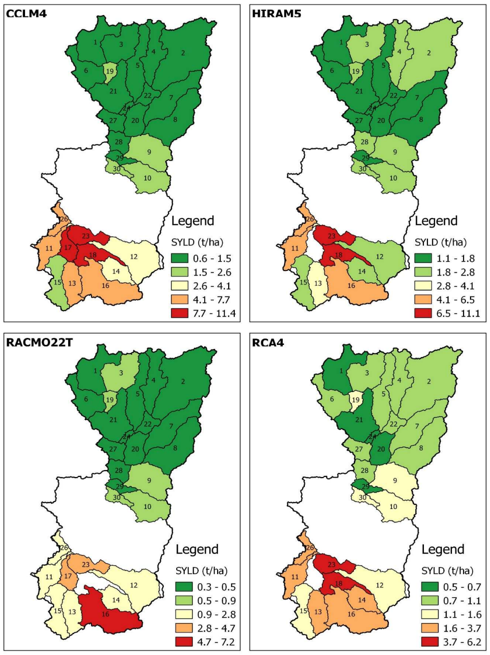

Fig. 5. Spatial distribution of sediment yield under RCM – RCP 8.5 scenario (2071 – 2100)

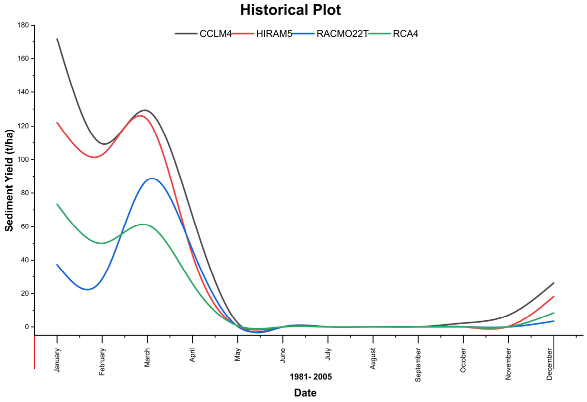

Fig. 6. Spatial distribution of monthly sediment yield under RCM scenario (1981 – 2005)

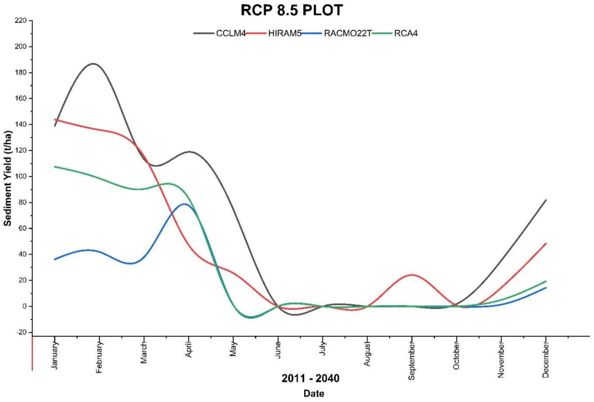

Fig. 7. Spatial distribution of monthly sediment yield under RCM – RCP 8.5 scenario (2011– 2040)

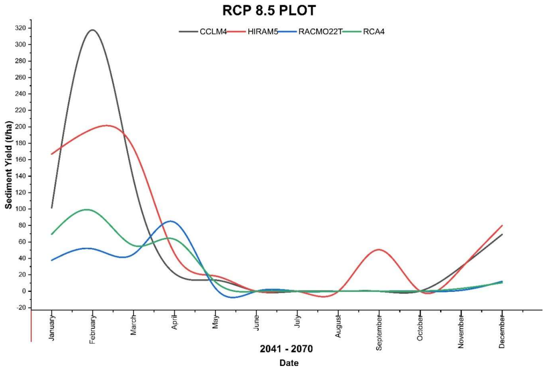

Fig. 8. Spatial distribution of monthly sediment yield under RCM – RCP 8.5 scenario (2041 – 2070)

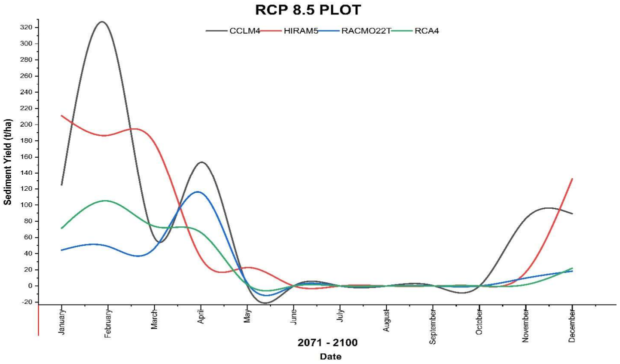

Fig. 9. Spatial distribution of monthly sediment yield under RCM – RCP 8.5 scenario (2071 – 2100)

4. Discussion

Mwalwiba's (2023) study provides a thorough examination of the calibration and validation of hydrological models, with particular attention paid to important performance indicators like the Ratio of the Root Mean Square Error to the Standard Deviation of the Measured Data (RSR), the Coefficient of Determination (R^2), and the Nash-Sutcliffe Efficiency (NSE). The findings show a reasonable degree of predictive performance, which offers important information about how well the model can replicate the hydrological processes in catchments. The prediction accuracy and dependability of the model are revealed by the performance metrics during both the calibration and validation phases. The model appears to have a moderate capacity for prediction during the calibration phase, based on the NSE value of 0.45. During the calibration phase, the model explains around 59% of the variance in the observed runoff data, according to an R2 value of 0.59. This points to the possible need for further improvement while also indicating a reasonable correlation between the simulated and observed values. With an RSR value of 0.73, the observed data's standard deviation is 73% of the RMSE, indicating a significant degree of error in the model's predictions. A large variance is indicated by an RSR value near 0.7, but it is within tolerable bounds for early modeling attempts. During the validation period, the NSE improved to 0.59, indicating improved predicted accuracy and model reliability. This improvement suggests that the post-calibration model tweaks were successful in improving the model's representation of the watershed area's hydrological processes. The R2 value of 0.59 during validation shows a persistent degree of correlation between observed and predicted values, which is consistent with the calibration period. This consistency highlights the applicability and dependability of the model. The parameters that have a substantial impact on the model's performance are identified by the sensitivity analysis carried out as part of Mwalwiba's study. It is essential to comprehend how these factors affect the model's output in order to improve and optimize the model for use in the future. The most sensitive metric was shown to be the CN2, which represents a catchment's runoff reaction. This sensitivity emphasizes how crucial a role it plays in affecting the formation of surface runoff and emphasizes how crucial precise CN2 estimation is for model calibration. River flow and sediment output forecasts are greatly impacted by antecedent moisture conditions, soil types, and changes in land use, according to the CN2. As a result, increasing the accuracy of data pertaining to these variables might enhance model performance. Its effect on the model's capacity to replicate soil moisture dynamics and water availability for plant uptake is shown by the SOL_AWC. Predictions of river flow, sediment production, and groundwater recharge depend on the accurate modeling of soil qualities and water retention traits, which are essential for evapotranspiration and infiltration processes.

Based on the SWAT model and QGIS analysis, the sediment yield in the Songwe watershed provides important insights into the dynamics of soil erosion and sedimentation under various land cover types. With an annual input of 54.94 tons/ha, farmed land is the largest contributor to sediment yield. The amount of time that rain and wind may erode soil is increased by frequent tilling and insufficient cover crops. Fertilizer and pesticide applications in the watershed erode the structure of the soil and increase its susceptibility to erosion. Soil loss is also exacerbated by the absence of cover crops, contour farming, or terracing. Bushland is a major source of sediment, contributing 40.6 tons/ha yearly. Although there is some plant cover in bushland, it is not dense enough to completely protect the soil. Slope-facing grassland adds 22.91 tons of silt per hectare each year. The possibility for erosion is increased by the slope angle, which also speeds up water flow. Grass roots are not strong or deep enough to keep the soil in place when water moves quickly. Because of their lush vegetation, forest and woodland regions contribute the least amount of silt. Rainfall is captured, lessening its immediate effect on soil erosion. The historical average monthly sediment production of the Songwe watershed was estimated to be higher in January, February, and March (171.84 tons/ha, 109.4 tons/ha, and 129.04 tons/ha, respectively). The peak months line up with the rainy season, which raises sediment output in watersheds, soil erosion, and river flow. Planting and farming at certain times of the year may expose more soil to erosion. Higher sediment yields are found in the watershed's Southern, Middle, and Lower Regions as a result of a mix of steep slopes, intensive farming methods, and soil types such eutric leptosols that are prone to erosion. Extremely shallow and prone to soil erosion, eutric leptosol soils can be found in unconsolidated, highly gravelly materials or scattered over hard rocks (Tadesse et al.,2023). High sediment production is most often due to a lack of vegetation, poor land management, and intensive agriculture activities. The study indicates sub-basins 16, 17, 18, and 23 as potential soil erosion hotspots, with the largest sediment production. Intensive agriculture, mining, urbanization, and wildland areas are more prone to erosion due to diminished vegetation cover and increased surface runoff. In contrast, subbasins with extensive forest

The results of this work, which used the SWAT model with bias-corrected data from four RCMs (CCLM4, HIRAM5, RACMO22T, and RCA4) under the RCP8.5 scenario, provide a detailed knowledge of sediment yield dynamics in the Songwe watershed from 2011 to 2100. Our findings show considerable differences in sediment yield forecasts between RCMs, emphasizing the relevance of model selection and bias correction in hydrological investigations. The study's forecasts show a large rise in sediment yields throughout the twenty-first century, particularly during the wet season months of January, February, March, and April. This is constant across all RCMs, demonstrating the impact of increased rainfall and land use changes on erosion processes. The larger sediment yields during the wet season are most likely due to increased rainfall intensity, which causes more surface runoff and erosion. Because sediment transport is so closely tied to precipitation patterns, soil conservation activities should be concentrated during these months. This emphasizes the significance of including climate change scenarios in hydrological models to better anticipate future erosion dynamics. The sediment yield forecasts for the Songwe watershed show a significant rise over three future periods: 2011-2040, 2041-2070, and 2071-2100. Sediment yields are much larger under the RCP 8.5 scenario than they are today, demonstrating a direct association with the expected climate changes. These patterns indicate a large rise in sediment production, particularly during the rainy season, emphasizing the importance of adaptive management measures to limit the effects on the watershed. The seasonal patterns in sediment output show that the majority of sediment transport takes place during the wet months of January, February, March, and April. This is constant across all RCMs and time periods, implying that heavy rainfall and runoff during these months contribute significantly to sediment displacement. During the dry season, however, sediment outputs are small or nonexistent, reflecting the lower precipitation and runoff that are typical of these months. This seasonal trend implies that peak sediment yields occur during the wettest months, underscoring the importance of precipitation in driving erosion processes in the region. The disparities between models may also be due to variances in the geographical and temporal resolution of climatic data, soil properties, and land use changes reflected by each model.

The examination of sediment yield from 2011 to 2100 demonstrates considerable temporal variations throughout the watershed. Initially, from 2011 to 2040, subbasins 17, 18, and 23 had the highest sediment yields. This pattern shifted slightly in the mid-century era (2041–2070), with sub-basins 16, 17, and 23 showing elevated yields, and then expanded to encompass sub-basin 18 by the end of the century (2071–2100). These patterns indicate that sediment yield hotspots are changing, possibly due to climate-induced changes in rainfall intensity and distribution, which are known to have a direct impact on erosion and sediment transport mechanisms. High sediment production is concentrated in various subbasins, most notably 16, 17, 18, and 23. These places appear to be particularly prone to erosion, potentially due to a combination of steep slopes, soil type, and land use practices that increase sediment mobilization. The highest sediment yields, which ranged from 3.7 to 12.9 tons/ha, show the importance of tailored erosion control strategies in these sensitive sites. Moderate sediment production in subbasins 11, 12, 13, 14, 15, and 26 are associated with agricultural activities, mining, urbanization, and bushlands. These land activities often disrupt the soil and reduce plant cover, resulting in increased sediment runoff. Agricultural operations, in example, can considerably increase sediment outputs through soil tillage, deforestation for farmland expansion, and poor land management. Mining activities disturb the soil structure and contribute to increased silt flow into waterways. The upstream northern subbasins with thick forest cover had the lowest sediment production. The substantial association between low sediment discharges and high plant cover highlights trees' importance in soil stabilization and erosion reduction. Simulated sediment yield patterns have significant consequences for watershed management. High-yield areas, notably sub-basins 16, 17, 18, and 23, should be prioritized for erosion control measures such as reforestation, terracing, and the adoption of sustainable agriculture methods. These techniques can help reduce sediment production, preserve soil fertility, and safeguard downstream water quality. Our findings are consistent with prior research that has emphasized the impact of climate change and land use practices on sediment dynamics in tropical watersheds. Similar studies in other African basins have found similar results, with greater precipitation and warmth under high emission scenarios leading to higher sediment production (Gyamfi et al., 2021; Leta et al., 2023).

5. Conclusions and Recommendations

The study of sediment yield in the Songwe Watershed under various climate forecasts demonstrates a strong relationship between climate change and sediment yield. The expected increases in temperature and precipitation variability contribute to higher erosion rates, which leads to increased sediment production. The sensitivity of sediment output to climate projections emphasizes the necessity of knowing regional hydrological systems and how they interact with climate change. The use of several climate models and scenarios emphasizes the uncertainty involved in estimating sediment output under future climate circumstances. However, models consistently forecast an increase in extreme weather events, such as heavy rainfall, which worsens soil erosion and sediment transport. The study stresses the need of region-specific climate models in effectively representing local climatic fluctuations and their effects on sediment movements. Land use and cover changes in the Songwe Watershed have a substantial impact on sediment output. Deforestation, agricultural development, and urbanization make soil more susceptible to erosion. The interaction between land use changes and climate forecasts increases sediment yield, emphasizing the importance of sustainable land management techniques in sediment mitigation. The Songwe Watershed's hydrological response to climate forecasts implies changing flow regimes, which may have implications for water resource management. Increased sedimentation has an impact on water quality, reservoir capacity, and aquatic ecosystems, providing issues for downstream communities who rely on these resources.

Understanding sediment yield response under climate change scenarios is critical for sustainable water resource management in the Songwe Watershed. According to the findings, sedimentation will continue to affect water infrastructure, agricultural output, and ecosystem health unless adequate actions are implemented. To counteract the effects of increased sediment output, it is critical to undertake soil conservation methods such as contour farming, terracing, and reforestation. These methods help to stabilize the soil, prevent erosion, and improve water infiltration, hence limiting sediment transport. Promoting climate-resilient agriculture methods like agroforestry and conservation tillage can help prevent soil erosion and increase soil health. Encouraging farmers to implement these methods through education and incentives will be critical to lowering sediment yield.

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