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A Data-Constrained Mixed-Methods Assessment and Proposed Socio-Hydrological Feedback Framework for Sedimentation in the Middle Shire River Basin, Malawi

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Abstract
Sedimentation processes in the Middle Shire River Basin of Malawi can be attributed to differences in the hydroclimatic parameters and the interaction between the landscape characteristics and land management. An analysis of the available quantitative and qualitative data was undertaken, and a socio-hydrological feedback loop has been suggested in this study. Statistical methods have been used in Python for analysing precipitation and temperature (2010-2024), discharge at three gauging stations, SSC, turbidity, vegetation indices, land cover composition, and correlations between sediment indicators. The results demonstrated the seasonality of rainfall and vegetation, greater discharge at G-03 in comparison with G-02 and G-01, as well as a positive relationship between discharge and SSC. An increase in cropland and a reduction in woodland area were revealed. Annual driver analysis demonstrated positive correlations between specific sediment yield and soil erodibility and mean slope. Qualitative information includes Q-sort data and interviews and focus groups coding results; nevertheless, verification by documentary sources of the recruitment process, ethics approval, and factor meaning is required. Flow predictions and scenario rankings can be considered exploratory since independent verification has not been performed. This suggested framework incorporates various indicators for the environment, stakeholder viewpoints, and possible managerial actions toward achieving an understanding of the sediment dynamics in the Middle Shire River Basin.

Keywords: socio-hydrology, sediment yield, suspended sediment, sediment connectivity, Middle Shire River Basin, land-use change, adaptive catchment management.

1. Introduction

Sediment transportation is a natural process in rivers; nonetheless, too much sediment delivery may lower storage capacity, destroy hydroelectric plants, incur more costs for water purification, and transform aquatic environments. Rainfall intensity, production of runoff, soil characteristics, vegetation cover, slope, and connectivity of sediment with the river network are all factors that affect sediment delivery. The factors mentioned vary in space and time, and may mask the locations and time periods of the most likely sediment mobilization and sediment transportation processes. Climate change and land cover change could occur simultaneously, and the impacts of both may vary in space and time (Kayitesi et al., 2022).

In Malawi, the Middle Shire is used for water supply, irrigation, and to generate hydropower. The Liwonde Barrage and downstream regulated reaches link sediment transport to water allocation and downstream ecosystems. Therefore, sediment management is a hydrological challenge and a challenge to competing land and water resource demands. Basin-specific investigations have combined field evidence, erosion modelling, geomorphology, and sediment budgets, and this has shown the value of these combined approaches, as well as the uncertainty of the measurements available (Roca et al., 2024). This reflects a need to consider sedimentation sources and pathways along with decisions that affect land management rather than sedimentation as a problem that only occurs downstream.

Rainfall variability influences soil detachment and transport, whereas land cover affects interception and soil protection. The hydrological response is also affected by antecedent moisture, terrain, and connectivity of hillslopes with channels. On a hillslope, sediment generated can either be deposited, stored, remobilized, and disconnected from the transport pathway or not reach an outlet at the end of the pathway. Thus, the measured suspended sediment concentration and discharge at a gauge is not a direct measurement of gross hillslope erosion, but rather sediment delivered to that site at that time. Research at the tropical catchment scale reveals a local-scale variation in the impact of climate and land cover on river hydrology and geomorphology (Kayitesi et al., 2022), and at the basin scale, changing relative importance of land use and climate change over time suggests that climate change exerts different influences on the hydrology of a basin depending on the land use and land cover (LULC) along the basin boundary (Bian et al., 2023).

These involve physical factors, which are linked to livelihood and institutional factors. Agricultural production, land tenure, availability of agricultural inputs, local knowledge, and conservation incentives and enforcement can impact cultivation, retention of vegetation, and soil protection. Erosion and sediment delivery changes, in turn, may impact on the irrigation system operation and hydropower generation, water treatment, and the perception of environmental hazards. The socio-hydrological approach considers these human choices and water processes to not be distinct parts of a changing system, but rather different components of a coupled human–water system (Sivapalan et al., 2012). The environmental record, however, can only be "empirically supported" when accompanied by evidence of the environmental decisions made that are temporally and geographically compatible with the environmental record. Without such evidence, the pathway remains a hypothesis.

The research gap is the limited subbasin-level integration of environmental indicators with structured stakeholder accounts and documented management decisions in the Middle Shire. The existing sediment assessments can differentiate between hydrological and/or erosion processes without identifying local management priorities, whereas participatory studies can identify local preferences without linking them to the measured conditions of sediment. Compared with existing Shire sediment-budget studies, this analysis links meteorological, land-cover, soil, and sediment indicators to Q-sorts, interview themes, and focus-group records using explicit subbasin identifiers; the reciprocal feedback model remains proposed. Its role is to provide a framework with evidence-tracing to compare what is happening in the environment with what stakeholders worry about and to determine which proposed environmental feedback paths are supported, contradicted, or not yet testable. The analysis is organised in terms of three questions: (1) What changes are observed in the study area and time in relation to the environmental indicators (rainfall, vegetation, land cover, terrain, and soil conditions)? (2) What associations are displayed between the environmental indicators and the discharge and the suspended-sediment measures? (3) How do the stakeholder perspectives and the qualitative themes relate to the observed patterns in the environment, and how do they overlap and diverge? The quantitative and qualitative records were assessed against these questions, with unmatched or temporally untested links identified explicitly. It is not assumed that correlation has any causal link, nor that a conceptual feedback pathway has any measured behavioral effect.

2. Materials and Methods

2.1 Study area and research design

The study covered the Middle Shire reach between Liwonde Barrage and the M1 crossing in Chikwawa. Subbasin-, monitoring-station-, flow-gauge-, and sediment-site-level analyses are presented, enabling comparisons of the environmental conditions to hydrological and sediment observations at each of the spatial units recorded. There are 24 subbasin records, eight meteorological-station records, three flow-gauge records, and four sediment-site records contained in the quantitative dataset. Subbasin identifiers are a spatial key that connects the datasets of the environment and stakeholders. The data are used to interpret spatial data summaries, not at the resolution of a single point of data but based on the resolution represented by the data for the study geography and monitoring locations. The 24 tabulated subbasin areas sum to 3,500.0 km². The recorded gauge locations (latitude, longitude) were G-01 (−14.63°, 34.74°), G-02 (−15.05°, 34.92°), and G-03 (−15.58°, 34.80°). The subbasin table provides centroids, not boundary polygons; no independently verified projected CRS/EPSG was specified.

A convergent mixed-methods design was employed. Quantitative environmental and hydrological records were analysed separately, and the qualitative evidence from stakeholders was analysed separately and then combined using the subbasin and stakeholder-group identifiers within the data. The quantitative strand reports on the measurements of rainfall and temperature, streamflow, land-cover composition and transitions, soil properties, vegetation indices, and suspended-sediment observations. The qualitative strand includes Q-sort records, key-informant interviews, and focus-group records. Stakeholder themes and Q-sort records were matched to available subbasin identifiers for comparison but were not treated as quantitative predictors or evidence of causation.

2.2 Quantitative data sources and preparation

The quantitative workbook includes an array of daily meteorological data (5,479 records), daily streamflow data (16,437 records), land-use epoch data (96 records), land-use transition data (3,528 records), soil-sample data (60 records), monthly vegetation data (4,320 records), sediment-sample data (408 records), monthly suspended-sediment data derived from satellite measurements (576 records), an annual driver panel (360 records), and annual model-output data (360 records). It also includes model parameters, scenario design, scenario output, source-area priority, and flow-model comparison, and model-performance tables. These records did not contain derived indices, model outputs, or scenario results; they were already treated as separate data products with their own meaning. Measured or remotely sensed observations were not mixed with the output of models or with scenarios. CHIRPS version 3 was referred to as the source for precipitation (Funk et al., 2026). ERA5-Land was referred to for meteorological variables (Muñoz-Sabater et al., 2021). Product citations are intended to give references to the sources, but not to the independently verified origin of individual workbook values. The land-cover epochs were 2010, 2015, 2020, and 2023. The monthly vegetation records were taken from three datasets (Landsat 5/7, Landsat 8, and Landsat 8/9 with Sentinel-2) – no acquisition-day scene IDs were recorded. Terrain and soil-property inputs (Poggio et al., 2021) came from SRTM elevation and Soil Grids soil information. The streamflow, sediment sample, and satellite-SSC tables contained hydrological and sediment information. The dataset also included data on the three flow gauges and four sediment sites. Table-specific date fields and temporal resolutions were retained. Daily, monthly, mapping-epoch, and annual records were not assumed to share one sampling interval.

Input/fields	Period and unit	Records/provenance status
Rainfall; temperature	2010–2024; daily; mm, °C	5,479 dates; CHIRPS v3 / ERA5-Land cited; values not portal-audited
Discharge	2010–2024; daily; m³/s	16,437 gauge-date rows; 3 gauges
Land cover; vegetation	2010, 2015, 2020, 2023 (%); 2010–2024 monthly (NDVI/SAVI)	96 epoch rows; 4,320 monthly records; exact scene IDs not stored
Sediment / SSC proxy	2023–2024 samples (mg/L); 2013–2024 monthly proxy (mg/L)	408 field-labelled entries; 576 satellite proxy rows
Soil, terrain, annual drivers	60 soil samples (%; K-factor); 2010–2024 annual	24 subbasins; 360 annual records; full lineage requires source files

Records were supplied with linked records using the supplied date, station, gauge, sediment-site, and subbasin identifiers before analysis. The date fields were properly parsed, duplicate keys checked, units and variable definitions were read from a field dictionary, and missing dates were left as missing. Daily and monthly measurements were not considered to be the same, and comparisons were made with compatible temporal units. Using the provided identifier keys, the join of the polygons was verified; no reprojection of the polygons was asserted without the GIS boundary and CRS metadata. The data register, field dictionary, and quality-assurance rules in the workbook were used to define the rules used to make these checks. Rechecking the supplied workbook found zero duplicate keys in six principal tables; 93 of 16,437 streamflow rows were flagged missing, 40 of 576 satellite-SSC proxy rows were cloud-obscured, and 342 of 87,664 meteorological station-variable cells were blank. These entries were not silently imputed.

2.3 Python-based sediment driver analysis

Land-cover classes were used in the quantitative dataset, and the mapping epochs and transition records for the data were analysed. There are 96 records on the epoch table, and 3,528 records in the transition table. The spatial unit (SU) and epoch (E) of land-cover composition and transitions were summarised. The interpretation assumes that the class does not change, but the transitions are made from one class to another: The number of a class can change, but the conversion pixel cannot come from or go to the class that corresponds to the number. Soil sampling, attributes of the terrain, monthly vegetation indices (MVI), and meteorological summaries were used as complementary environmental indicators. The provided land cover tables contained no independent reference point labels, mapping-year confusion matrices, or class-specific accuracy values, so the accuracy of the classifications could not be verified. Other transition area values were higher than their subbasin areas and were not counted as separately reconciled hectares.

In order to examine sediment yield, the annual driver panel for each year was recalculated for each subbasin, linked to the modelled specific sediment yield table, and tested for each subbasin in each year (360 complete paired records across 24 subbasins). The variables were interpreted as defined in the workbook and between the measured and derived/modelled sediment yield indicators. The correlations were not interpreted as causal effects. To address repeated annual observations, 95% uncertainty intervals were calculated using 500 subbasin-cluster bootstrap resamples (fixed seed = 42). If the dataset did not have a basis for a formal adjustment or uncertainty interval, the result was not formally reported, but this did not mean that there was no spatial or temporal dependence. The Spearman ρ for the modelled specific yield was 0.564 for soil erodibility (cluster-bootstrap 95% CI 0.284–0.738), 0.501 for slope (0.160–0.724), and 0.206 for cropland (−0.132–0.602). These estimates concern the modelled yield, not the independently observed sediment loads.

2.4 Hydrological and sediment modelling

The hydrological and sediment model information was viewed in the model parameter, annual output, flow model comparison and model performance tables of the quantitative workbook. There are 24 model parameter records, 360 model output records per year, 540 flow model comparison records and there are 6 model performance records. Discharge and sediment sample columns were not mixed with predicted discharge and modelled sediment yield fields. The curve number, soil storage (mm), concentration time (h), storage coefficient (h), Manning roughness, erosion scale, and baseflow recession are listed in the parameter table. No executable HEC-HMS project, Python routing script, or sediment governing equation was provided; thus, the predictions in the workbook were reviewed, but a new simulation was not claimed.

The model evaluation was treated separately from model fitting and/or visual agreement. The six performance rows labelled 2010–2019 (120 paired records per gauge) and 2020–2024 (60 per gauge) reported NSE 0.980–0.991 and KGE 0.959–0.990; the 2020–2024 label alone did not demonstrate an independent holdout or establish sediment-prediction validity. Performance was not used as a measure of the validity of sediment-yield estimates for a discharge model. Predictions of sediment should be accompanied by independent observations of sediment. The results of the scenarios were read as results from the model under the set assumptions, not as direct measurements or as a forecast outside of the set assumptions.

2.5 Qualitative sampling and Q-methodology

The Q methodology workbook included 40 participant sets of records, 40 wide-format Q-sorts, 1,680 long-format statement rankings, and 42 Q-set statements. The participant records contained the following information: stakeholder group, subbasin identifier, analysis group, age band, consent status, and consent date. The stakeholder groups present in the dataset were smallholder farmers, commercial agriculture, catchment authorities, district officers, and non-governmental or civil society. The Q-sort data were arranged by participant and statement to enable the ranking of the statements according to the participants' responses and to review the ranking considering the other participants' responses. The 42 statements make up the concourse used for the structured ranking exercise. Participant records list purposive diversity-grid selection, dates from 1 January to 24 December 2024, and consent marked “Yes” for all 40 entries. The Q-set table contains 42 statements, with wording/review-status fields; the field-approved instrument and recruitment audit were not separately attached.

The analysis used a Q-sort, which was conducted as a by-person analysis to find commonalities and differences in the participants' views rather than to determine the percentage of the population holding similar views. Statement ranking and the defining sorts were used in conjunction with the correlation matrix and factor solution of the participants' responses. The by-person correlation matrix was eigen decomposed, and an exploratory three-component solution was subjected to orthogonal varimax rotation (initial eigenvalues 3.95, 3.26, and 3.06). Under an exploratory defining-sort rule (absolute loading ≥0.40 and ≥0.10 above the next component), the factors had 7, 5, and 4 defining sorts, respectively. Because the scree pattern lacked a decisive break and participant-confirmed factor arrays were unavailable, final interpretive factor labels were not asserted.

Exploratory Q component	Initial eigenvalue	Defining sorts	Illustrative high-ranked statements
Component 1	3.95	7	Q06, Q31, Q28
Component 2	3.26	5	Q17, Q33, Q25
Component 3	3.06	4	Q18, Q36, Q19

2.6 Interviews, focus groups and thematic analysis

Qualitative data consists of 25 key informant interview records (1 January–24 December 2024) and five focus-group records (5 January–21 May 2024; 46 participants in total). Interview records contain date, stakeholder group, subbasin ID, length of interview, interview format, and consent of interviewees. The group table includes membership counts (8–12), discussion dates, duration, focus-group type, and group-consent fields. There are an additional 60 coded qualitative records and a ten-entry theme codebook. These records were sorted by their identifier and associated with a stakeholder group and subbasin (when available). Interview and focus group data were analysed thematically, looking for patterned meanings as well as points of difference between stakeholder groups and alternative accounts to the dominant interpretation. The workbook records de-identified discussion notes and coded summaries but does not contain interview audio or verbatim transcripts; verbatim quotations were therefore not attributed.

Reflexive thematic analysis (Braun and Clarke, 2021) guided the thematic interpretation, which means that the theme frequency is not a measure of the importance of the themes, but rather the process of interpretation is explicit and auditable. Coded record counts were then used to describe the distribution of coded material in the supplied dataset. They did not have connotations of population prevalence or ranking of stakeholder priorities. Quotations/claims relating to participant experiences should be attributed only if there is an underlying anonymised source record to support them.

2.7 Mixed-methods integration and feedback framework

The links table was used as a bridge to connect the subbasins, stakeholder groups, and themes identified in the quantitative and qualitative datasets during integration. A joint display compared the 2023 subbasin cropland proportions with the linked 2024 interview/focus-group themes and Q-sort coverage; factor labels were not assigned where extraction remained exploratory. Links were classified as spatially matched or unmatched, followed by convergence/divergence assessment only when temporal and directional evidence supported it. For the tabulated cases, directional convergence and contradiction both remained unconfirmed. There was no privilege of one strand of evidence, but divergent evidence was retained and investigated. This method is carried out based on the guidance of mixed methods to make the relationship between the datasets explicit in joint displays (Fetters and Tajima, 2022). Eight subbasins had both Q-sort and interview records; only SB11 also had a focus-group record. Other subbasins lacked one or more stakeholder strands. Neither a directional contradiction nor a causal feedback loop was established from these cross-sectional matches.

Subbasin; 2023 cropland	Linked qualitative evidence	Q records
SB02; 41.58%	Interview: farming pressure; local knowledge	Q-sort present
SB11; 39.45%	Interview + focus group: livelihood/local knowledge	Q-sort present
SB17; 46.28%	Interview: adaptive rules; livelihood security	Q-sort present
SB07; 51.31%	Interview + focus group: livelihoods/knowledge	No matching Q-sort

The feedback framework identifies three types of evidence: measured associations with the environment and hydrology; (non-measured) stakeholder-reported explanations of decisions and experiences; and hypothesised feedback pathways between the two. Rainfall –vegetation – land cover – runoff – discharge, and sediment indicators can be correlated if there is an overlap in dates and spatial units. The connections between sediment conditions and livelihood choices, as well as between livelihood choices and subsequent land cover or sediment changes, are hypotheses that are only substantiated with a temporal sequence of evidence and cannot be confirmed without temporal evidence. Candidate feedback were expressed as testable directions: increased erosion/SSC → reduced irrigation reliability → possible conservation response → subsequent cover change → later sediment change. Decision and vegetation responses require assessment across one or more agricultural seasons; a cross-sectional correlation cannot determine their sign or lag.

2.8 Quality assurance, validation and ethics

The data register in the workbook, field dictionary and data quality rules, as well as the checks of record identifiers, date consistency, duplicate records, variable units, missingness, and compatibility of temporal and spatial units were used for quality assurance. Derived summaries were validated with the original tables from which they were derived, and observed measurements were differentiated from remotely sensed products, built indices, and model results. Dependencies, if present, on a classification or aggregation were identified as analytical limitations and not hidden in a single value. The processing should be reproducible (source table, variable definition, and setting of the transformation and analysis should be traceable).

There are fields included with qualitative records for participants and interviews to document the consent status. The manuscript should contain the appropriate ethics approval authority, approval number, and date (or the formal exempt decision) for the study as per approved documentation. Consent that has been given in the dataset is not a substitute for institutional ethics approval. Data should be analysed and reported anonymised, and personal identifiers should not be present in analysis or publication; participant IDs are only for data management purposes. Permission to access restricted source records must be based on the permission of the source records.

3. Results: Descriptive Findings and Exploratory Conceptual Synthesis

3.1 Identified physical and anthropogenic sediment drivers

For the figures depicting climate and vegetation trends, there is seasonality that recurs within the time interval of 2010-2024. Data on daily precipitation are characterized by peaks above 100 mm/day (Figure 1), monthly precipitation has very high seasonal peaks (Figure 2), and NDVI and SAVI have annual trends (Figure 3). The weighted means of land cover proportion in the 24 sub-basins indicate a rise in the percentage of agricultural cover from around 38% in 2010 to 46% in 2023, while that of woodlands decreased from around 32% to 22% within the same period (Figure 4). This illustrates the trend of land cover mapping related to agriculture and woodland in the study area. For the figure shown in Figure 5, persistence occurs along the diagonal, and transition occurs off-diagonal, but transition-area values have not been independently reconciled with respect to the basin area.

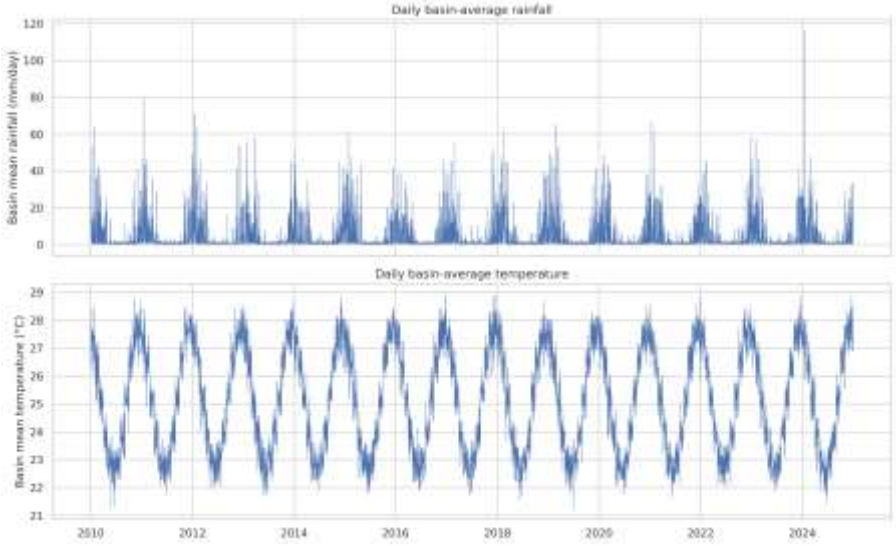


Figure 1. Average daily rainfall (mm/day) and temperature (°C) of the Middle Shire River Basin for the years 2010-2024. The dataset of the daily observations includes observations made at eight different meteorological stations, the daily average of which provides the rainfall and temperature averages over the basin. The number of stations providing the information on each day is recorded to capture the difference in reporting frequency of the stations.

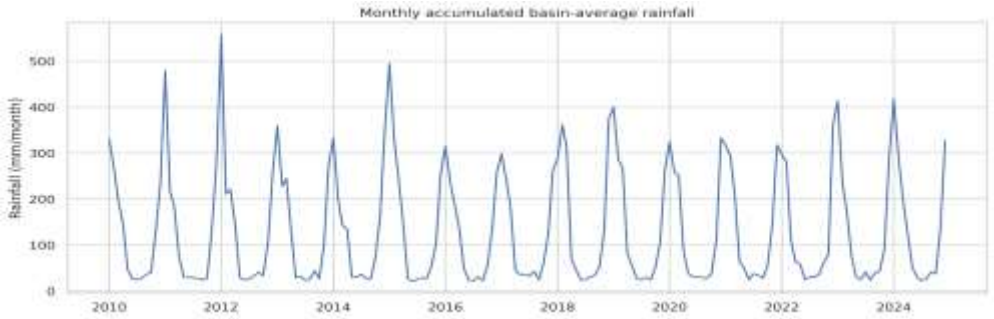


Figure 2. Monthly accumulated basin-average rainfall, 2010–2024.

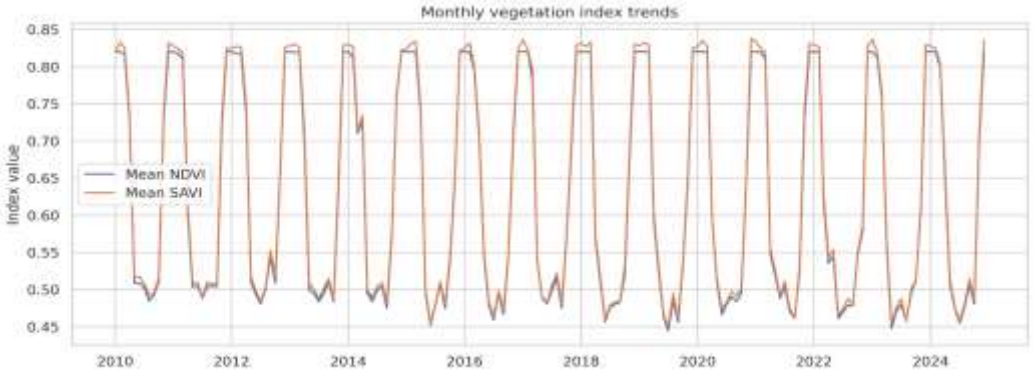


Figure 3. Monthly NDVI and SAVI trends, 2010–2024.

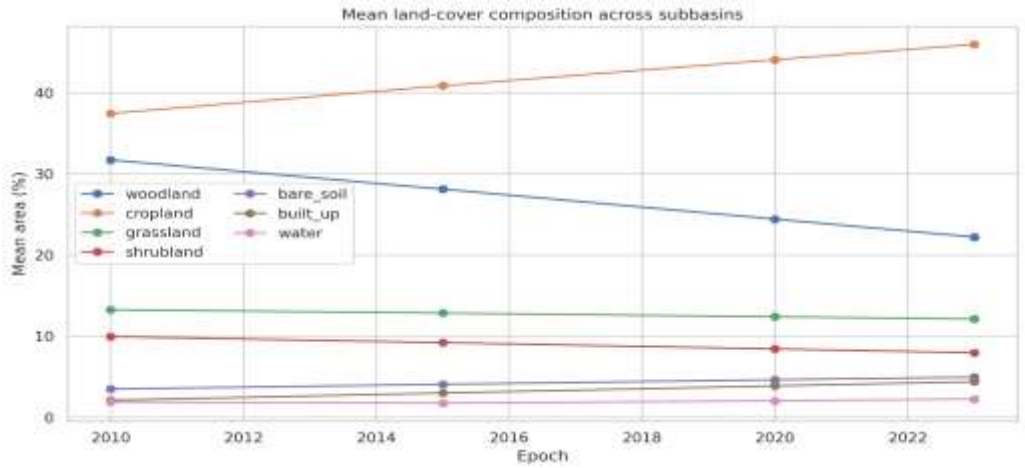


Figure 4. Percentage distribution of mean land cover types (%) over the 24 sub-basins in the years 2010, 2015, 2020 and 2023. This is the un-weighted arithmetic mean of percentages of land cover types per sub-basin.

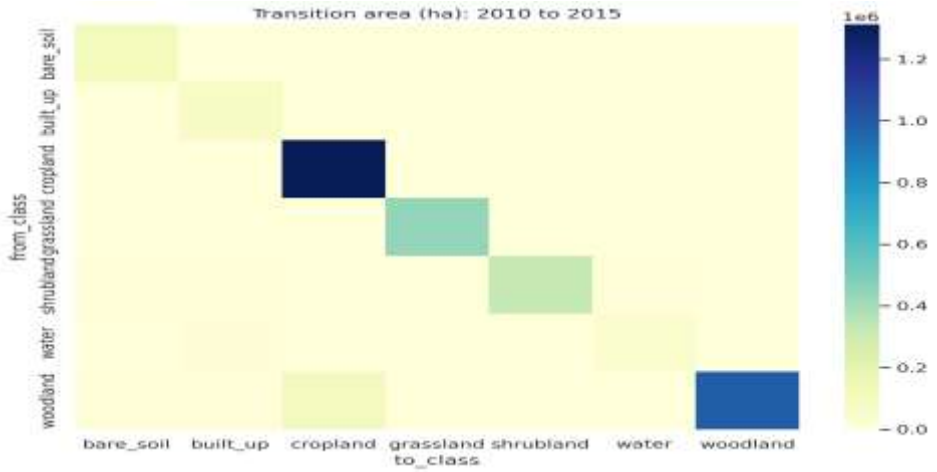


Figure 5. Heatmap of the land-cover transition in the 24 subbasins from 2010 to 2015. Row represents the land-cover classes in 2010 whereas the column represents the land-cover classes in 2015. Values in cells represent the area of the transition in hectares. The land-cover classes remain the same in rows and columns: bare soil, built-up, cropland, grassland, shrubland, water and woodland.

Table 1. Heatmap of the land-cover transition

From / To	Bare soil	Built-up	Cropland	Grassland	Shrubland	Water	Woodland
Bare soil	12,209.4	0	0	0	0	0	0
Built-up	0	7,279.8	0	0	0	0	0
Cropland	0	0	131,309.0	0	0	0	0
Grassland	376.7	304.7	492.2	44,450.1	0	344.5	0
Shrubland	714.0	676.6	392.4	0	33,208.3	851.1	0
Water	295.1	1,597.9	37.3	0	0	4,804.0	0
Woodland	631.0	626.6	11,128.7	0	0	244.3	98,026.0

Class-by-class transition matrix analysis revealed that most of the mapped land cover area did not change from 2010 to 2015. The major transition off-diagonal entry was transition from woodland to cropland, which covered an area of about 11,128.7 ha. Some of the other transitions off-diagonal entries were transition from shrubland to water (851.1 ha), shrubland to bare soil (714.0 ha), and grassland to cropland (492.2 ha). The sum of the subbasins listed in the table is 350,000 ha.

3.2 Relationships between land-use decisions and sediment processes

The graphs in Figures 6 and 7 illustrate the increase in the amount of discharge from G-01 to G-02 and G-03 but do not provide any reasons that could explain this phenomenon for each gauge. The discharge data contains 16,437 records per day for three gauges, with counts of 5,449, 5,448, and 5,447, respectively (Figure 6). Figure 8 illustrates right-skew SSC and turbidity, and Figure 9 hints at a positive paired discharge and SSC correlation along with site variability. The number of sediment samples recorded in the table is 408. For the annual drivers, 360 catchment-year records were compiled between 2010 and 2024 for 24 subbasins, with 15 annual observations per subbasin. The environmental factors were then compared with the annual model results based on their years and subbasin ID numbers. The Spearman rank correlation coefficients for annual precipitation, mean NDVI, crop/woodland ratio, soil erodibility (K-factor), mean slope, cover management factor (C-factor), and the runoff driver index are given in Figure 10 below. Also, the total sediment yield (tons) and the specific sediment yield (tons km^{-2}) from the model results were seen to be different from the suspended sediment concentration (SSC) measurements and satellite SSC estimates. The specific sediment yield was found to be positively correlated with soil erodibility ($\rho = 0.564$; 95% CI: 0.284–0.738) and mean slope ($\rho = 0.501$; 95% CI: 0.160–0.724), but less pronounced with cropland ratio ($\rho = 0.206$; 95% CI: −0.132–0.602). Since the annual observations were made in the same 24 subbasins, they should not be considered as 360 statistically independent catchments. Uncertainty intervals were calculated via subbasin cluster bootstrap with 500 resamples and fixed seed of 42. In Figure 10, sediment yield and specific yield are modelled rather than independent sediment loads. Positive correlation with soil erodibility and slope is exploratory; multicollinearity may result from strongly correlated land-cover predictors (Ren et al., 2024; Jing et al., 2025).

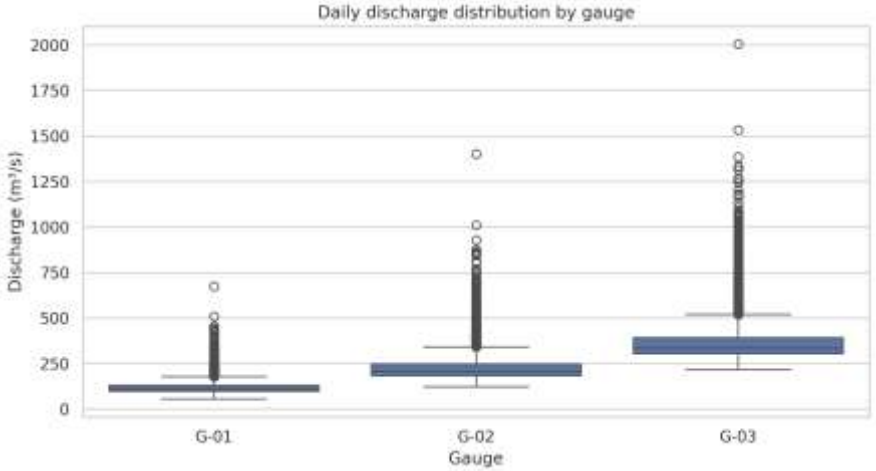


Figure 6. Daily discharge values from G-01, G-02, and G-03 for the period of 1 January 2010 to 31 December 2024 based on 5,449, 5,448, and 5,447 daily observations respectively. Metadata of gauge shows that it is a staff gauge/ADCP gauge with Malawi Water Authority as the agency.

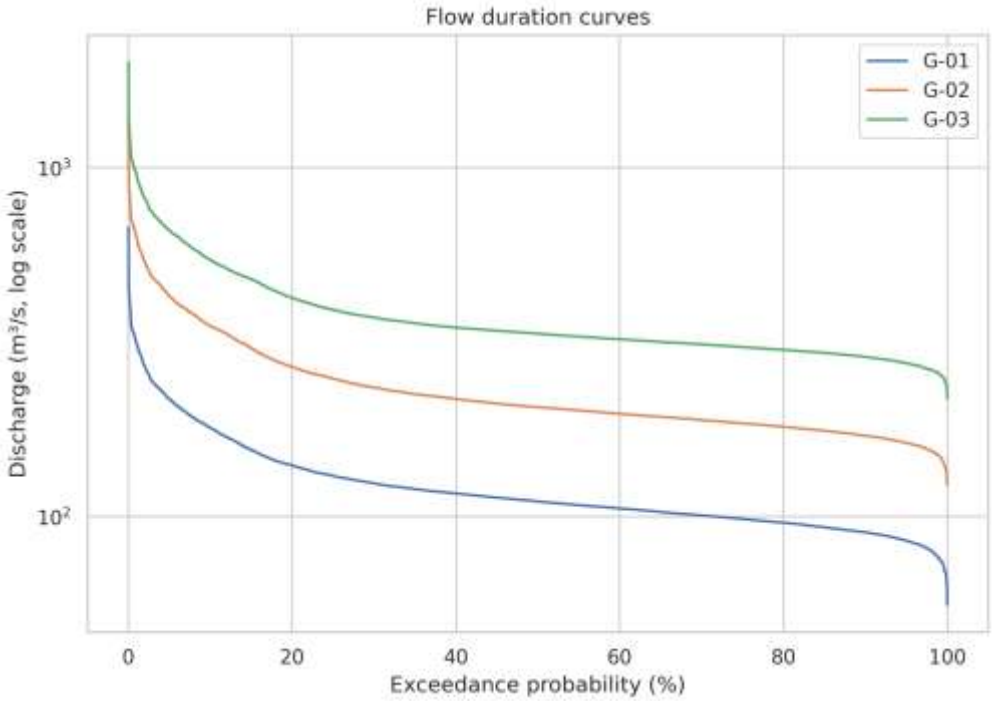


Figure 7. Flow-duration curves for gauges G-01, G-02 and G-03.

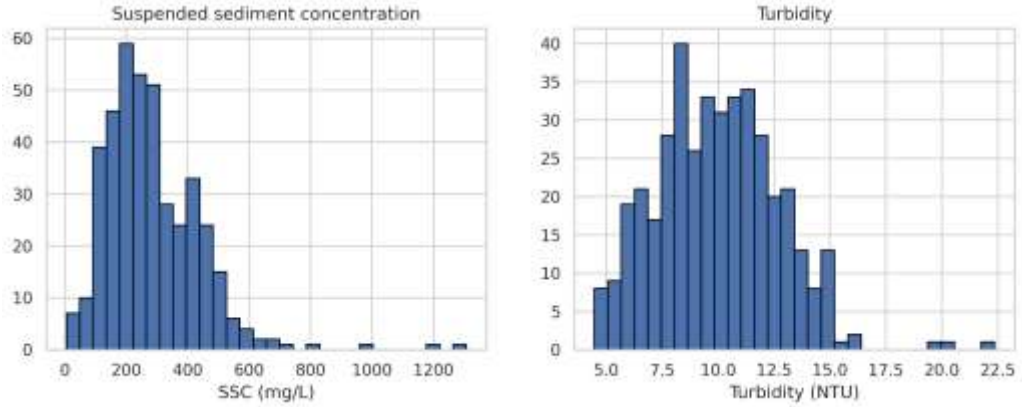


Figure 8. Distributions of suspended sediment concentration (SSC) and turbidity.

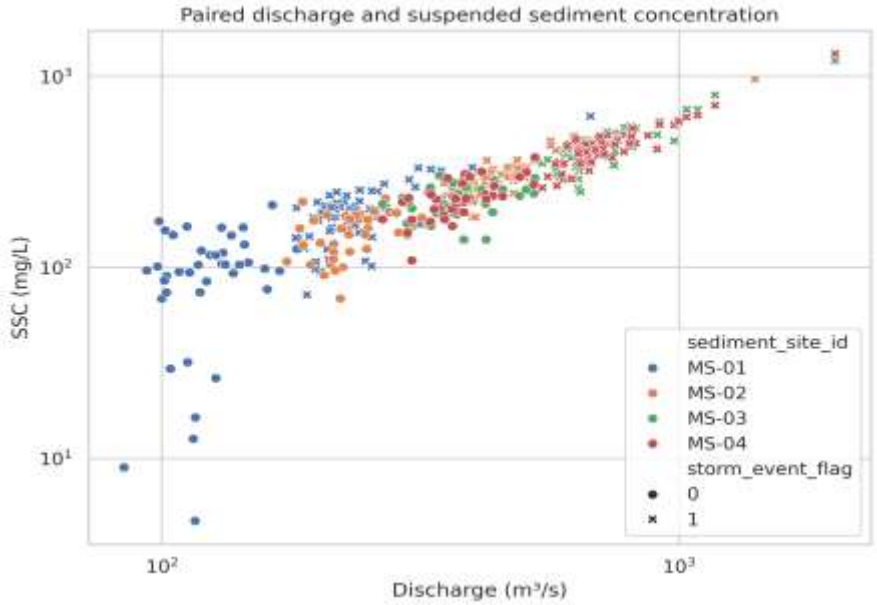


Figure 9. Discharge and Suspended Sediment Concentration for Sites MS-01 to MS-04 from 2 January 2023 to 28 December 2024. This data consists of 408 sediment samples (102 for each site), in which both discharge and SSC are fully recorded; 406 of those sediment samples have the same number of entries for the daily gauge reading. Events are defined by 0 (non-storm) and 1 (storm).

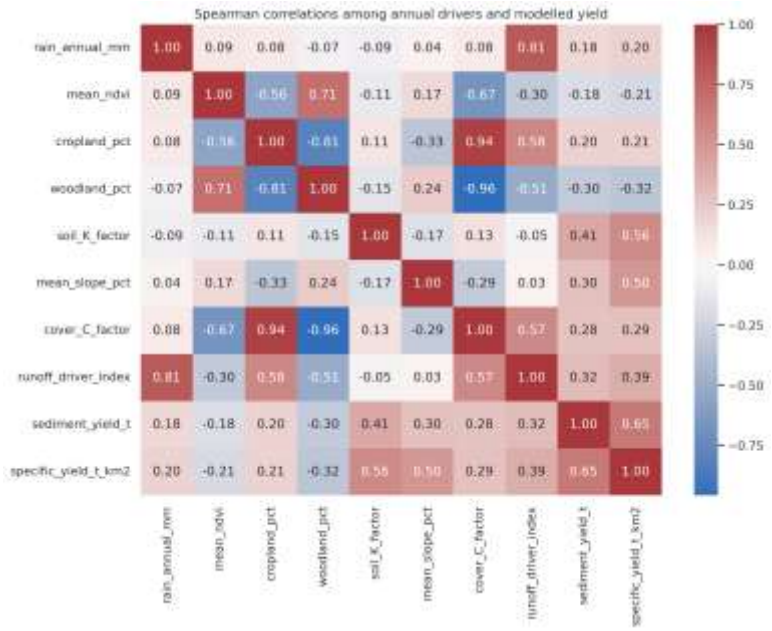


Figure 10. Spearman rank correlation analysis of annual environmental drivers and modelled sediment-yield indicators across 24 subbasins (2010–2024). The analysis uses annual subbasin-level observations, with sediment yield and specific sediment yield identified as modelled outputs rather than independently measured sediment loads.

Spearman Correlations of Environmental Variables with Modelled Sediment Yield

Table 2. Correlation coefficients (ρ)

Environmental variable	Modelled total yield ρ	Modelled specific yield ρ
Annual rainfall	0.179	0.200
Mean NDVI	−0.179	−0.206
Cropland (%)	0.197	0.206
Woodland (%)	−0.300	−0.325
Soil K-factor	0.409	0.564
Mean slope (%)	0.295	0.501
Cover C-factor	0.276	0.287
Runoff-driver index	0.319	0.388

Table 3. 95% confidence intervals

Variable	Total yield	Specific yield
Rainfall	−0.013 to 0.374	0.040 to 0.371
NDVI	−0.360 to 0.000	−0.368 to −0.067
Cropland	−0.128 to 0.518	−0.084 to 0.551
Woodland	−0.564 to −0.045	−0.575 to −0.108
Soil K-factor	0.032 to 0.668	0.264 to 0.753
Mean slope	−0.133 to 0.620	0.236 to 0.716
Cover C-factor	−0.013 to 0.558	0.037 to 0.574
Runoff-driver index	0.121 to 0.536	0.164 to 0.626

Sample information: n = 360 for every pair; pairwise missing observations = 0

3.3 Proposed two-way feedback framework and its components

The proposed socio-hydrological conceptual framework illustrates the relationships among environmental strategies and institutional responses in the Middle Shire River Basin. The framework distinguishes empirical environmental associations, stakeholder-mentioned relationships, and hypothetical feedback pathways. The framework distinguishes observed environmental patterns from stakeholder perspectives and proposed reciprocal interactions. The effects of livelihood security, conservation benefits, and institutional actions on further land cover change require empirical confirmation of stakeholder narratives and time-series data. On the other hand, environmental influences on livelihood and management behaviour are possible mechanisms, but not actual feedback loops (Mijic et al., 2024; Bian et al., 2023).

The correlations observed from the Q-sort analysis of 40 participant Q-sorts were inconsistent among the provided sorts (Figure 11). A three-factor solution was investigated using eigendecomposition and orthogonal varimax rotation with initial eigenvalues of 3.95, 3.26, and 3.06. Nevertheless, there was no distinct factor solution based on the scree plot (Figure 12). No factor interpretation was performed. The coding table included 60 coded records across ten themes, where livelihood security (11 codes) and local knowledge (10 codes) had the highest number

of codes (Figure 13). Frequencies are indicative of the number of codes for each topic within the dataset and not the priority of these topics. Livelihood security and local knowledge emerged as important themes in the qualitative analysis (Lovett et al., 2021; Braun and Clarke, 2021).

Operationally, there are four phases in the framework: (1) measuring environmental pressures and sediment response, (2) determining land use and institutional decisions that go with them, (3) checking the plausibility of suggested pathways against spatial and temporal data, and (4) evaluating the interventions available through consultations with those involved. Climate alone, land use alone, and both climate and land use together need to be considered instead of making assumptions about the effect of one pressure. The effects of delayed feedback, catchment differences, and differential ability to undertake conservation practices need to be accounted for explicitly. A relationship is still an assumption until the environmental and stakeholder data confirm the same pathway.

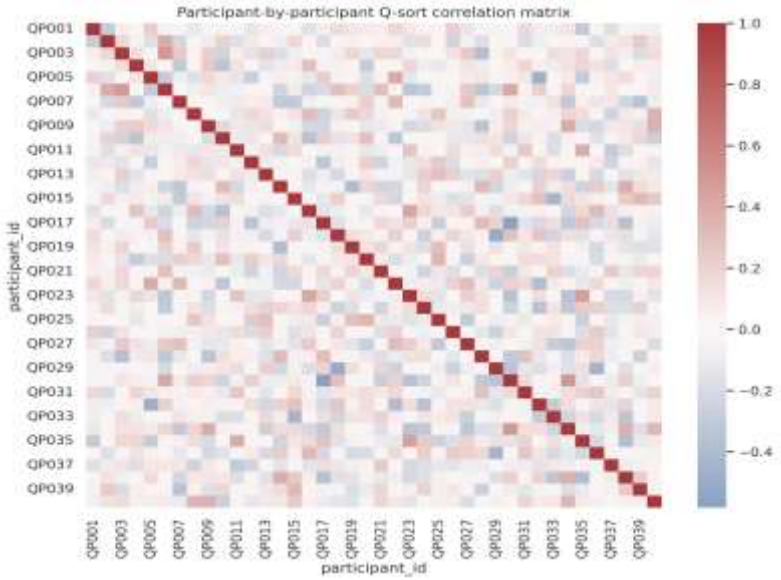


Figure 11. Pairwise correlations for 40 supplied participant Q-sorts (42 statements per sort).

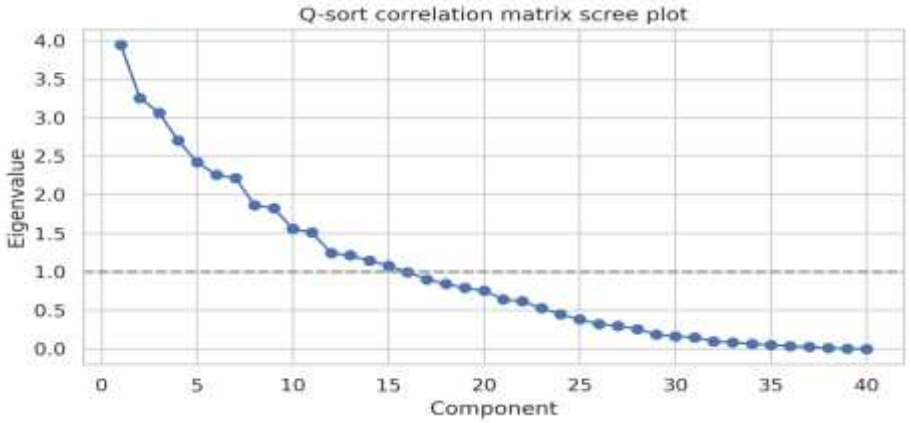


Figure 12. Q-sort correlation-matrix scree plot.

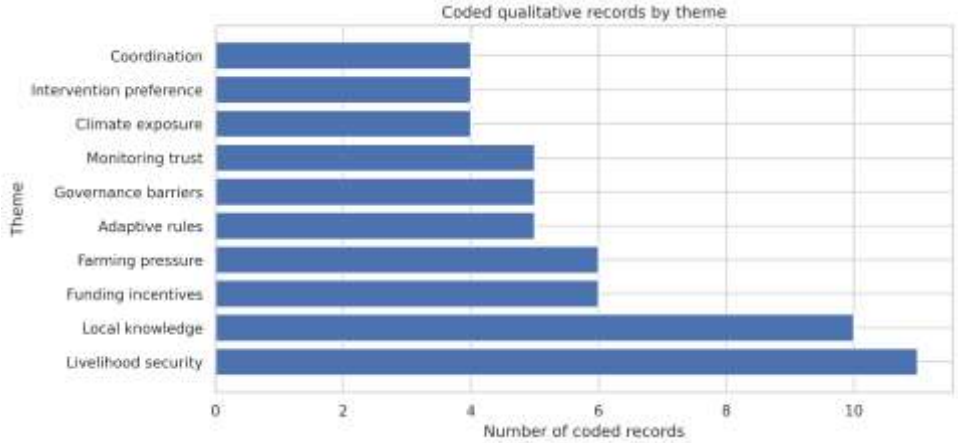


Figure 13. Frequency of coded theme assignments across ten qualitative themes (60 entries), comprising 50 interview-linked and 10 focus-group-linked records.

The qualitative coding consisted of 60 coded records within ten themes, with 50 coded records from interviews and 10 coded records from focus groups. One coded record corresponded to one thematic 319ategorization of each source record with a record identifier, sub-basin identifier, theme code, and coded record context and information. Livelihood security was the most common theme (11 coded records), which relates to the cost of adopting erosion control methods. Local knowledge was another common theme (10 coded records), which relates to the experience of the community regarding erosion and floods (see Figure 13). Another recurring theme included farming pressure and funding incentives (six coded records each), which relate to the expansion of croplands and funding support for conservation practices, respectively.

3.4 Proposed model outputs and evaluation criteria

Observations and discharge simulations for G-01, G-02, and G-03 are presented in Figures 14–16. In each figure, data points are shown relative to the 1:1 line indicating the correlation between simulated and observed flows for the three gauge sites. The performance summary table provides information about the gauges for six periods: 2010–2019 (120 pairs per gauge) and 2020–2024 (60 pairs per gauge). The NSE in all six summaries is in the range from 0.980 to 0.991, while the KGE is from 0.959 to 0.990. These are the values of the statistics used to assess the performance of the discharge simulation model. Yet, Cinkus et al. (2023) highlighted that visual hydrological indicators to measure the performance of the model in terms of prediction, systematic bias, and flow variability should support correlation. This point is important to make while discussing the Middle Shire River Basin, as Roca et al. (2024) noted the presence of uncertainties in the observations of sediments and the necessity of combining hydrological modelling with sediment budget evaluation in the river basin. Moreover, Figure 17 presents the 20 highest outputs of sediment yield simulations and reveals how different outputs may be influenced by climatic and land use changes. Thus, the results obtained in this study serve as a good starting point for analysing the hydrological processes and comparing different scenarios of sediment yield in the Middle Shire River Basin.

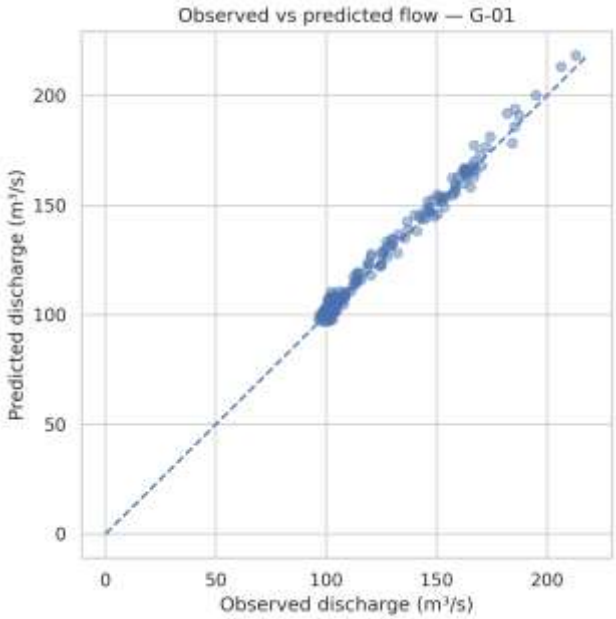


Figure 14. Observed vs. simulated flow at station G-01 using 180 months of observations from 1 January 2010 to 1 December 2024. In total, 120 monthly observations were made in 2010-2019, while 60 observations were made in 2020-2024. Performance measures for both periods are shown in Table 4 (NSE, KGE, RMSE, and percentage bias [PBIAS]).

Table 4. Performance table for all three gauges

Gauge	Period	n	NSE	KGE	RMSE (m³/s)	PBIAS (%)
G-01	2010–19	120	0.9825	0.9709	3.725	1.221
G-01	2020–24	60	0.9886	0.9829	2.914	1.404
G-02	2010–19	120	0.9866	0.9842	6.793	1.217
G-02	2020–24	60	0.9910	0.9902	5.470	0.851
G-03	2010–19	120	0.9845	0.9837	10.550	1.286

G-03	2020–24	60	0.9801	0.9588	11.559	1.077

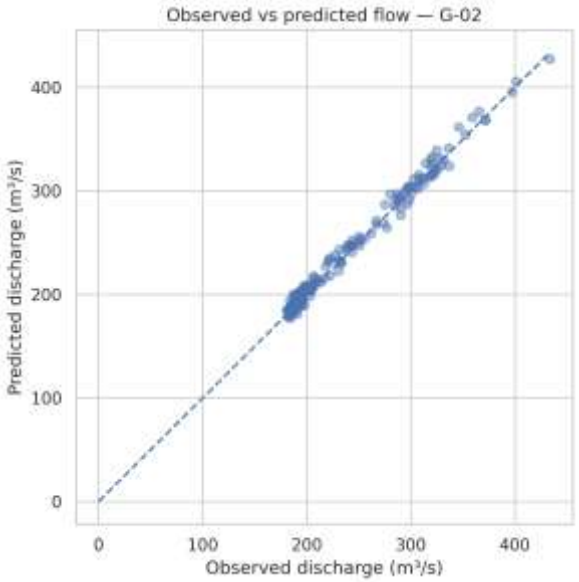


Figure 15. Observed-versus-predicted discharge at G-02

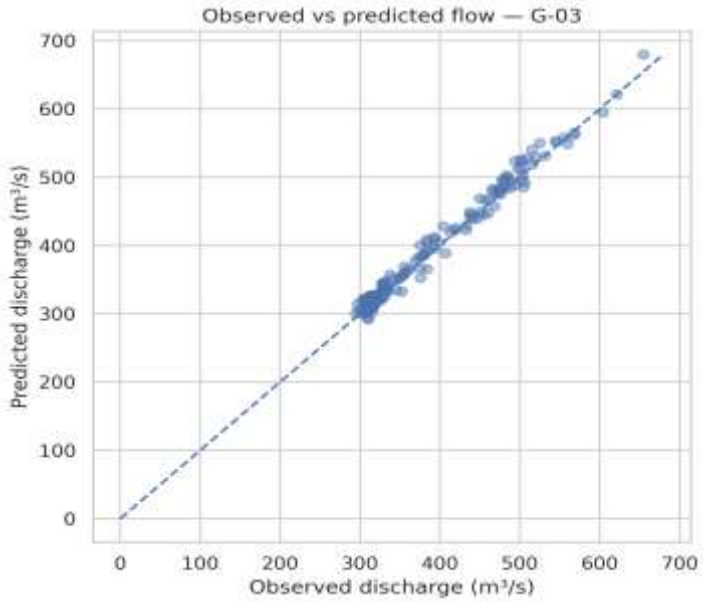


Figure 16. Observed-versus-predicted discharge at G-03

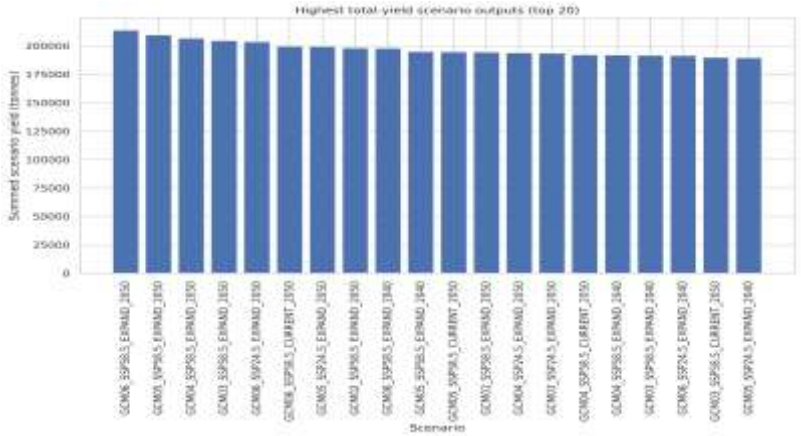


Figure 17. Top 20 illustrative total sediment-yield scenario combinations across 24 subbasins for 2030, 2040 and 2050. Total yield is expressed in tonnes and represents the sum of subbasin-level model outputs. Scenarios combine six climate-model members, two SSP pathways and four land-use pathways.

The scenario generation process involved 144 permutations of six climate model members, two emission scenarios (SSP2-4.5 and SSP5-8.5), four land use scenarios (current land management, agricultural expansion, riparian and woodland restoration, and co-management activities), and three projection years (2030, 2040, and 2050). Scenario variables involved variation in rainfall (-1.0% to 23.5%), temperature (0.214–2.436°C), cropland area (-5 to +7 percentage points), and the relative cover management factor (-0.13 to +0.12). Sediment yield under each scenario was derived by adding up sediment yields of subbasins using 24 subbasin-level data. The 2024 baseline figure in the annual output table of the model was 173,025.16 tonnes. Output minimums and maximums were generated too but their computational methodology was not indicated. Hence, the scenario ranking is presented as a hypothetical comparison and not a predictive one (Figure 17).

4. Discussion

4.1 Integration of physical and human systems in sediment management

The differences in precipitation, vegetation indices, and land cover components can be observed from Figures 1-5. The differences in discharge at all three gauging stations, suspended sediment concentration, and turbidity, as well as correlations between environmental parameters and simulated sediment yield are provided in Figures 6-10. The patterns mentioned above represent a description of the environment and hydrology, while the correlations show only the presence of the relationship between the variables. The conclusions made above mean that the process of sediment transportation in the Middle Shire Basin area depends on the interaction of several climatic and landscape characteristics. Such findings are confirmed by the study conducted by Kayitesi et al. (2022), which has proven that the influence of the land cover and climate of tropical rivers depends on soil and topography. In addition, Bian et al. (2023) revealed that the impact of land use and extreme precipitation on the sediment yield may vary with time. According to Jing et al. (2025), the sediment availability and timing of runoff events may influence the discharge–sediment relation. Nevertheless, the obtained correlations do not distinguish the influence of cropland expansion from rainfall and other common factors. Therefore, the feedbacks in human institutions illustrated in Figure 14 provide an empirical basis for future research.

In socio-hydrology, determinants of exposure and responses involve the socio-hydrological system. Households rely on agricultural production as a means of sustenance and economic gains, whereas the governance system considers the balance between soil conservation, irrigation, water supply, and hydroelectric power generation. The delivery of sediments may influence livelihood and service delivery activities, thus affecting land-use decision-making processes. This is congruent with ongoing research that focuses on feedback and unexpected consequences that may result from water resources intervention that does not consider the socio-aspect (Mijic et al., 2024). In the case of the Middle Shire River, the intervention should focus on the interconnected sources-paths-receptors system: erodible areas, tributaries, and rivers, and controlled and uncontrolled sections of the downstream portion. The management of sediments should involve addressing the issue of source reduction, connectivity, and deposition, and not just data collection at the downstream areas (Roca et al., 2024; Abeysingha and Ray, 2025). The intervention may shift the exposure risk to other stakeholders.

Cross-country evidence for BRICS+ associates renewable-energy consumption with better environmental performance, but it does not establish sediment or hydropower effects at the Middle Shire scale (Pata et al., 2025).

4.2 Comparison with existing socio-hydrological and sediment modelling approaches

In this study, Kayitesi et al. (2022) 321tabilizat 60 tropical catchment studies conducted from 2010 to 2021 based on evidence from GIS, remote sensing, statistical, and hydrological modelling. According to their review, 45 papers focused on land cover and hydrological responses over decades, whereas 12% of the papers focused on morphological responses related to sediment transport and riverbank erosion. Expansion of agricultural activities and deforestation were frequently observed as factors that cause stream flow, surface runoff, and sediment transport. In contrast to this review, the present study analysed the associations of environmental drivers on an annual basis in the 24 sub-basins of Middle Shire for 2010–2024, together with sediment measurements from 2023–2024. Unlike the general review, the present study related the indicators of land cover, soil, and topography with sediment yield. Likewise, the Middle Shire study revealed connections between land-cover parameters and sediment parameters (Figure 10), even though correlated parameters do not allow identifying independent factors. However, unlike this description of the relationships, Luo et al. (2024) quantified changes in soil erosion using InVEST in China's Anning River Basin, where most changes were attributed to climate. Ren et al. (2024) used a combination of SWAT and hydrological monitoring to differentiate the effects of climate, land use, and engineering factors in the Yellow River Basin. The scenario ranking of Middle Shire (Figure 18) shows opposing results.

A comparison between the observed and predicted discharge is illustrated in Figures 14-16, whereas Figure 17 shows the ranking of the scenarios. The analysis results offer an exploratory comparison of the discharges and evaluation of the model performance (NSE, KGE, RMSE, and PBIAS). In case of the random forest method applied to groups hold-out, the estimation of the modelled specific sediment yield produced R^2=-6.91 (270 training cases and 90 test cases), suggesting low prediction accuracy. According to Cinkus et al., (2023), each performance measure might conceal compensating errors. Any negative random-forest holdout R^2 should be compared to the stored results; if verified, it would indicate that the model performs worse than the test set mean. Hence, the algorithm used, time period of validation, NSE, KGE, bias, and sediment-specific performance need to be considered separately.

4.3 Implications for sustainable river basin management in Malawi

Sediment management intervention priorities for the Middle Shire River Basin could be developed through the assessment of the source of sediments, connectivity, and feasibility at the field level. The interventions may include maintaining soil cover, contouring, riparian protection, gully 322tabilization, and event-based sediment sampling. Interventions will be developed based on the degree of erosion sensitivity, sediment transport pathways, costs of implementation, and livelihood needs. According to Roca et al. (2024), scientific assessment of the source of sediments, geomorphological assessment, erosion modelling, and sediment budget analysis are crucial in understanding the nature of sediment dynamics in the Shire River. In a similar vein, de Waal et al. (2024) used distributed hydrological modelling to demonstrate the spatial differences in response to erosion in different scenarios of land cover types in catchments with sparse data. Therefore, it is necessary to integrate scientific analysis with stakeholder analysis to develop suitable sediment management intervention priorities.

Research on genetic and biotechnological approaches also frames crop resilience as a response to climate stress; however, those crop-level approaches do not demonstrate sediment-control effects in this basin (Amin and Simran, 2025).

Third, the management process needs to incorporate traditional knowledge and livelihood security along with scientific data. The provided coding summary reveals that these topics have been among the top coded topics; however, this is an invitation to engage and not necessarily to reach a consensus. Research on Q-methodology in Zambia indicates that stakeholder groups (Siangulube, 2024) could understand the environmental governance framework and institutions differently. Interpretation of the data needs to take into account the priorities of different groups of actors, such as farmers, traditional authorities, irrigation farmers, environmental officials, and hydropower stakeholders, including the less influential ones. Scenario planning should come up with strategies to use in different rainfall and land use scenarios in the future.

Broader policy research associates government ecological concern with coordinated pollution and carbon-reduction governance; this supports institutional coordination, but does not demonstrate sediment-specific outcomes in Malawi (Wang et al., 2025).

4.4 Theoretical and methodological contributions

This study offers a basin-level analysis of environmental indicators in 24 sub-basins of the Middle Shire River Basin and discusses the identified patterns in the context of the provided qualitative themes. The analytical contribution is a descriptive comparison of indicators for rainfall, vegetation, land cover, discharge, and sedimentation and the relationship between the identified environmental factors and sediment yield modelling. This research offers a socio-hydrological framework for the identification of possible convergences, divergences, and gaps between the identified patterns and qualitative themes on the basis of the principles of joint-display (Fetters and Tajima, 2022) and socio-hydrological modelling (Mijic et al., 2024). The proposed framework is conceptual in nature, and feedback mechanisms do not imply causal relationships (Braun and Clarke, 2021).

4.5 Limitations and future validation requirements

There are six performance records for the observed and simulated monthly discharge for gauges G-01, G-02, and G-03 within the quantitative workbook. Each gauge has 120 pairs of observations for the period from 2010 to 2019 and 60 pairs of observations for the period from 2020 to 2024. The performance measures used in this study include NSE, KGE, RMSE, and PBIAS. The same performance records are presented in Table 5.

Table 5. Existing model-performance records

Gauge	Evaluation period	n	NSE	KGE	RMSE	PBIAS (%)
G-01	2010–2019	120	0.9825	0.9709	3.725	1.221
G-01	2020–2024	60	0.9886	0.9829	2.914	1.404
G-02	2010–2019	120	0.9866	0.9842	6.793	1.217
G-02	2020–2024	60	0.9910	0.9902	5.470	0.851
G-03	2010–2019	120	0.9845	0.9837	10.550	1.286
G-03	2020–2024	60	0.9801	0.9588	11.559	1.077

Diagnostic hydrology should be presented independent of the accuracy of sediment predictions; NSE, KGE, bias and residuals need to be considered together (Cinkus et al., 2023). Accuracy of land cover classifications, transition matrix units and scenarios needs to be specified. It would be useful if the sample size and uncertainties were presented to better understand the findings. Q-sort factor matrices, interviews and ethical considerations will help present qualitative evidence.

5. Conclusion

This study presents a mixed-method approach in synthesizing the environmental indicators in relation to sediments and documents from stakeholders in the Middle Shire River Basin of Malawi. As shown in the provided graphs

below, there are variations in precipitation and vegetation in the seasons, variations in the water flow from the three gauges, positive relationship between flow and suspended sediment concentration, and variation in woodland and cropland mapping percentages. For the annual driver analysis, 360 full sub-basin year pairs were used in reporting the Spearman correlation. The relationships show the possible regulators of sediments and not the effects of land use changes and long term sediment outputs. This point of view is supported by Kayitesi et al. (2022) and Bian et al. (2023).

The methodological contribution of this study is an evidence-labelled socio-hydrological framework that connects observations, stakeholders' views, and future decisions. The management of land and its institutional capacity may affect vegetation protection and sediment discharge, which, in turn, can affect livelihoods and governance. Both directions are propositions for further research because there is no evidence that such feedback exists (Mijic et al., 2024). Even though there are Q-sorts, interviews, focus groups, and codes presented in the tables provided, the understanding of this information is conditional on proving recruitment, ethics approval, rotated factors, and traceable anonymity (Siangulube, 2024).

With regard to catchment management, there is evidence from the results that an investigation into storm based sediment sampling, riparian protection, and soil conservation needs to be undertaken. The decision should be made depending on field proven sources of sediment, connectivity of sediment transport, independent verification of flow and sediment modeling, and feasibility study conducted by stakeholders. More attention should be paid towards correlation analysis, verification of the land cover classification, numerical transition area reconstruction, model performance verification on withheld observations, and scenario testing with stakeholder participation through monitoring. This will allow transforming a transparent concept into the base of sediment management (Roca et al., 2024; Cinkus et al., 2023).

Declarations

Ethical Approval: [AUTHOR CONFIRMATION REQUIRED: provide the approving ethics committee/institution, approval number and date, or the formal exemption decision.]

Informed Consent: [AUTHOR CONFIRMATION REQUIRED: confirm informed consent for the interview and focus-group participants, including its form. The manuscript reports consent fields but does not provide this confirmation.]

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Conflicts of interest: The authors declare no competing interests.

Author contributions: Emmanuel Chiundira: conceptualisation, methodology, data curation, formal analysis, investigation and original draft preparation. Geofrey Chavula: methodology, validation, supervision and review and editing. Vincent Cheyo Msadala: resources, validation, supervision and review and editing. All authors should confirm these contributions and their approval of the final manuscript.

Use of generative AI: The authors used ChatGPT to assist with manuscript formatting. All intellectual content is original and the authors take full responsibility.

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