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Effects of Catchment Soil Erosion on Rice Production: A Rusle-Gis Based Case Study of Nyiramageni Marshland, Gisagara District, Rwanda

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Authors' contributions

This work was carried out in collaboration among all authors. Author BA conceptualized the study, collected the data, conducted the formal analysis, and wrote the original draft; Author JN collected the field data; Author PN supervised the study, reviewed the methodology, and critically reviewed and edited the manuscript. All authors read and approved the final manuscript.

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Abstract

Aims: This study aimed to quantify catchment soil erosion, assess sediment transport pathways, and determine their effects on rice production in Nyiramageni Marshland, Gisagara District, Rwanda.
Study Design: A mixed-methods research design integrating geospatial modelling and statistical analysis was adopted.
Place and Duration of Study: The study was conducted in Nyiramageni Marshland and its contributing catchments in Gisagara District, Southern Province, Rwanda. Spatial and rice production data covering the period 2020–2025 were analysed.
Methodology: Soil erosion was estimated using the Revised Universal Soil Loss Equation (RUSLE) integrated with a Geographic Information System (GIS). The five RUSLE factors (rainfall erosivity, soil erodibility, slope length and steepness, cover management, and conservation practices) were derived from rainfall records, soil data, Sentinel-2 satellite imagery, SRTM Digital Elevation Model data, and field observations. Sediment transport pathways were evaluated using the Sediment Transport

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Index (STI). Rice production data from COOPRORIZ Nyiramageni Cooperative were analysed using descriptive statistics, one-way analysis of variance (ANOVA), and Tukey HSD post-hoc tests.

Results: The estimated annual soil loss ranged from 0 to 1,462.54 t ha^{-1} yr^{-1}, with a mean value of 326.35 t ha^{-1} yr^{-1}, indicating severe erosion conditions in the catchment. The highest erosion rates were associated with steep slopes, inadequate vegetation cover, and limited conservation practices. STI analysis revealed strong sediment connectivity between upland erosion hotspots and marshland deposition zones. Rice productivity differed significantly among marshland zones, particularly during Season B ($F (2,15) = 15.17$, $p = 0.000249$, $\eta^2 = 0.669$), with the Middle Zone recording significantly lower production than the Upper Zone.

Conclusion: The study demonstrates that upstream catchment soil erosion significantly influences spatial variability in rice productivity through sediment transport and deposition processes. Topographic amplification (LS-factor) and the near-total absence of structural conservation practices (P-factor) were identified as the principal controllable drivers of erosion, while rainfall erosivity (R) and soil erodibility (K) act as comparatively fixed background conditions. Integrated watershed management interventions, including bench terracing, cover-management improvement, and targeted erosion control on slopes draining into the Middle Zone's second-order channels, are recommended to sustain rice production in Nyiramageni Marshland. The findings are based on a six-year secondary production record and a zone-stratified statistical design; the limitations of this approach are discussed, and results should therefore be interpreted as indicative of a robust catchment-scale pattern rather than a fully generalisable predictive model.

Keywords: Soil erosion; geographic information system; sediment transport; sediment transport index; rice production; marshland agriculture; watershed management.

1. Introduction

Soil erosion by rainwater is globally recognised as the most critical form of land degradation threatening agricultural sustainability and food security. Borrelli et al. (2022) estimated that approximately 35.9 billion tonnes of soil are displaced by rainwater erosion annually across the world's croplands and rangelands, with Sub-Saharan Africa, South America, and Southeast Asia identified as regions of greatest concern. The economic consequences are severe: the European Commission Joint Research Centre (2024) projected that soil erosion by rainwater could generate total global GDP losses ranging from USD 216 billion to USD 625 billion between 2015 and 2070. Sub-Saharan Africa (SSA) faces particularly acute soil erosion challenges. Approximately 70% of SSA's soil resources are affected by erosion and nutrient depletion, directly threatening the livelihoods of over 83% of the population who depend on land for survival (Mesele et al., 2025). Borrelli et al. (2022) documented Africa's average erosion rate at 17.1 t ha^{-1} yr^{-1}, considerably higher than Europe's 2.6 t ha^{-1} yr^{-1}. In the East African highlands, GIS integration with RUSLE and remote sensing has emerged as the standard approach for spatially identifying erosion hotspots, quantifying sediment production, and designing evidence-based conservation interventions. Rwanda, the 'land of a thousand hills,' presents one of the most extreme national contexts for soil erosion in sub-Saharan Africa. Using RUSLE-GIS at 30-metre resolution, Karamage et al. (2016) estimated a mean national soil erosion rate of 250 t ha^{-1} yr^{-1}, among the highest recorded globally, with croplands generating approximately 95% of total national soil loss. A comprehensive national assessment by the Rwanda Water Resources Board (RWB) and the International Union for Conservation of Nature (IUCN) (2022) found that approximately 1,080,168 hectares (45% of the assessed national land area) are at erosion risk, costing Rwanda approximately 37.9 billion Rwandan francs annually in agricultural production losses.

Recent watershed-scale studies also indicate that RUSLE integrated with GIS and remote sensing can delineate erosion-prone areas and support conservation prioritisation in data-limited agricultural landscapes (Desalegn et al., 2022; Chasia et al., 2024; Uwamahoro et al., 2024; Handique et al., 2025). Recent sediment-connectivity research further supports complementing spatial soil-loss estimates with connectivity metrics to identify likely pathways linking erosion sources to downstream deposition zones (Räsänen et al., 2024).

Gisagara District's landscape is characterised by steeply dissected hills with slopes commonly exceeding 20–40% gradient, surrounding broad valley-bottom marshlands critical for local food security. Marshlands in Rwanda cover approximately 92,000 hectares used for agriculture, predominantly for rice production (Nabahungu & Visser, 2011). Rice yields across sub-Saharan Africa remain constrained by soil-related and water-management limitations even where production area has expanded, underscoring the importance of catchment-level erosion and sediment management, alongside agronomic interventions, for closing regional yield gaps (Saito et al., 2023). Sediment loads from upstream agricultural lands accumulate in low-lying marshlands, adversely affecting soil fertility, water retention, and crop productivity (Nambajimana et al., 2020). Despite this recognised threat, no comprehensive study had applied RUSLE to quantify soil erosion patterns in the upstream catchments of Nyiramageni marshland, modelled sediment transport pathways using the STI, or empirically evaluated the relationship between sedimentation intensity and agricultural production variability. This study therefore aimed to: (i) quantify the spatial distribution and severity of soil loss in the contributing catchments of Nyiramageni marshland using the full five-factor RUSLE model integrated with GIS; (ii) model sediment transport pathways using the Sediment Transport Index (STI) derived from DEM-based terrain analysis; and (iii) quantitatively assess the relationship between soil erosion exposure across marshland zones and rice production variability over the period 2020–2025.

2. Materials and Methods

2.1 Study Area

The study was conducted in the Nyiramageni marshland and its directly contributing upstream catchments, located within Gisagara District, Southern Province, Rwanda. Gisagara District lies approximately between 2°20′ and 2°45′ South latitude and 29°40′ and

29°58′ East longitude, at elevations ranging from approximately 1,346 m to over 1,800 m above sea level. The climate is tropical highland, with mean annual temperatures of approximately 20°C and annual rainfall ranging between 1,100 and 1,400 mm, concentrated in two rainy seasons: September–December and February–May. Nyiramageni marshland is a valley-bottom wetland system of approximately 160 ha gross area (130 ha net planted area) used for irrigated paddy rice cultivation as the dominant crop.

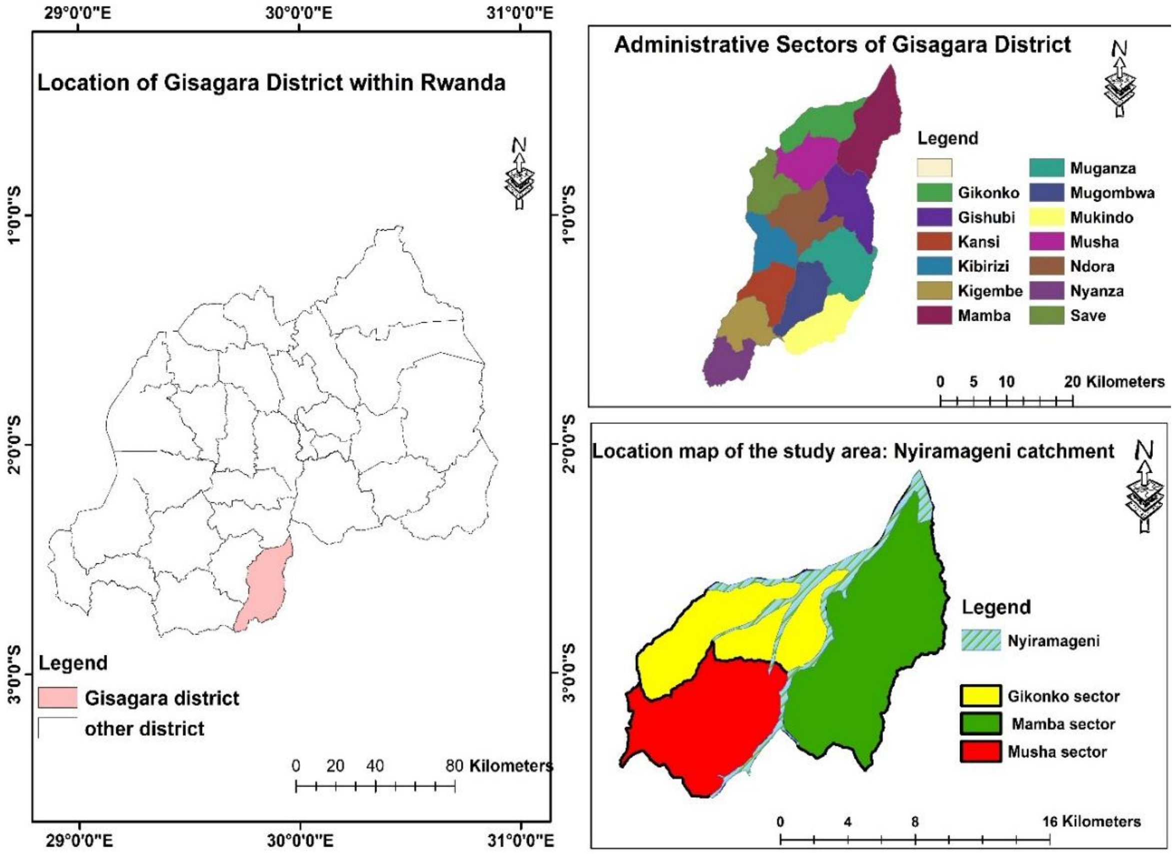

Fig. 1. Location map of the study area

2.2 Research Design and Approach

The study adopted a mixed-methods cross-sectional research design incorporating descriptive, analytical, and field-based quantitative approaches. The quantitative spatial modelling component generated spatially explicit outputs on RUSLE-based soil erosion intensity, land use and land cover (LULC) classification, sediment transport pathways, and sediment deposition patterns. The research design was descriptive because it characterised the spatial distribution and magnitude of RUSLE-estimated soil erosion, and correlational because it examined the statistical relationship between sedimentation intensity and rice production variations across three marshland zones.

2.3 Rusle Factor Derivation

All spatial data were processed in ArcGIS at 30-metre raster resolution consistent with the SRTM DEM, and all raster datasets were re-projected to WGS 1984 UTM Zone 36S before raster computation. The five RUSLE factors were derived as follows.

2.3.1 Rainfall Erosivity (R-Factor)

Monthly and annual rainfall records (2015–2025) were obtained from Meteo Rwanda, Gikonko meteorological station. The R-factor was derived using the regression equation validated by Karamage et al. (2016) for Rwandan conditions: $R = 1.03 \times P$, where P is mean annual precipitation (mm). The resulting R-factor value (MJ mm ha^{-1} h^{-1} yr^{-1}) was applied as a spatially interpolated value across the study catchments.

2.3.2 Soil Erodibility (K-Factor)

K-factor values were derived from National Land Authority (NLA) national soil maps at 1:50,000 scale and field-collected soil samples analysed for texture, organic matter (Walkley-Black method), and soil structure. Laboratory K-values were computed using the USDA monograph approach (Abdu, 2019; Byizigiro et al., 2020).

2.3.3 Slope Length and Steepness (LS-Factor)

The LS-factor was derived from the 30-metre SRTM DEM using ArcGIS Spatial Analyst. The DEM was hydrologically conditioned through sink filling, after which the LS-factor was computed as:

LS = (Flow Accumulation × cell size / 22.13) ^{0w4} × (sin(slope) / 0.0896) ^{1w3} (Moore & Burch, 1986), where flow direction was computed using the D8 algorithm.

2.3.4 Cover Management (C-Factor)

The C-factor was derived through supervised maximum likelihood classification of Sentinel-2 MSI imagery using Google Earth Engine and ArcGIS. Seven land cover classes were mapped. Classification accuracy was evaluated using a confusion matrix and Kappa coefficient, with a minimum overall accuracy threshold of 85% required. C-values were assigned per class following Karamage et al. (2016) and Maniraho et al. (2023).

2.3.5 Support Practice (P-Factor)

The P-factor was assigned based on GPS-referenced field surveys mapping the type and spatial extent of soil and water conservation measures. P-values followed the classification applied by Jothimani et al. (2022): no conservation practice = 1.0; contour cultivation = 0.75; contour strip cropping = 0.5; progressive terraces = 0.25; bench terraces = 0.1.

2.3.6 Annual Soil Loss (A)

The five RUSLE factor rasters were multiplied cell-by-cell in ArcGIS Raster Calculator: A = R × K × LS × C × P. The output A-raster (t ha^{-1} yr^{-1}) was classified into five erosion severity classes following Karamage et al. (2016), Rizinjirabake et al. (2023), and Maniraho et al. (2023).

2.4 Sediment Transport Analysis

The Sediment Transport Index (STI) was computed as:

STI = (As / 22.13) ^{0w6} × (sinβ / 0.0896) ^{1w3} (Moore & Burch, 1986), whereas is the upslope contributing area and β is the local slope angle. D8 flow direction and flow accumulation analyses were performed to derive the overland runoff pathway network, classified using Strahler stream ordering.

2.5 Rice Production Analysis

Paddy rice harvest records from COOPRORIZ Nyiramageni Rice Cooperative (2020–2025; N = 6 years × 2 seasons = 12 seasonal observations per zone) were obtained for the Upper, Middle, and Lower marshland zones. Descriptive statistics, including the mean production, standard deviation, and coefficient of variation (CV), were computed per zone and season using SPSS. A one-way analysis of variance (ANOVA) was applied to test whether statistically significant differences in mean rice production existed across the three zones (Season B and Season A separately), with Tukey HSD post-hoc tests applied to identify significantly differing zone pairs ($\alpha = 0.05$). Effect sizes were computed using eta squared (η^2) and Hedges' g.

3. Results and Discussion

3.1 RUSLE-Based Quantification of Soil Erosion Drivers

3.1.1 Results

The five RUSLE input factors were quantified across the Nyiramageni catchment to isolate the relative contribution of rainfall, soil, topography, cover, and management practice to spatial erosion patterns.

3.1.1.1 Rainfall Erosivity (R-factor)

The R-factor ranged from 265.63 to 751.40 $MJ \cdot mm \cdot ha^{-1} \cdot h^{-1} \cdot yr^{-1}$ (mean = 508.52; SD = 121.67), with a coefficient of variation (CV) of 23.9%, indicating a moderate orographic gradient in rainfall erosivity from the valley floor towards the northern and north-eastern ridges. A simple linear regression of mean annual R against total paddy production (2020–2025) returned Y = 1,550.6 + 2.14R ($R^2 = 1.00$), reflecting a positive aggregate, catchment-wide water-supply effect of wetter years on total production.

3.1.1.2 Soil Erodibility (K-factor)

The K-factor was spatially uniform across the catchment at 0.015 $t \cdot ha \cdot h \cdot ha^{-1} \cdot MJ^{-1} \cdot mm^{-1}$ (CV = 0%), consistent with the homogeneous dominance of Ferralsols and Cambisols. Because K showed zero spatial variability, it was effectively eliminated as a driver of differential erosion within the catchment; all spatial variation in soil loss is therefore attributable to R, LS, C, and P.

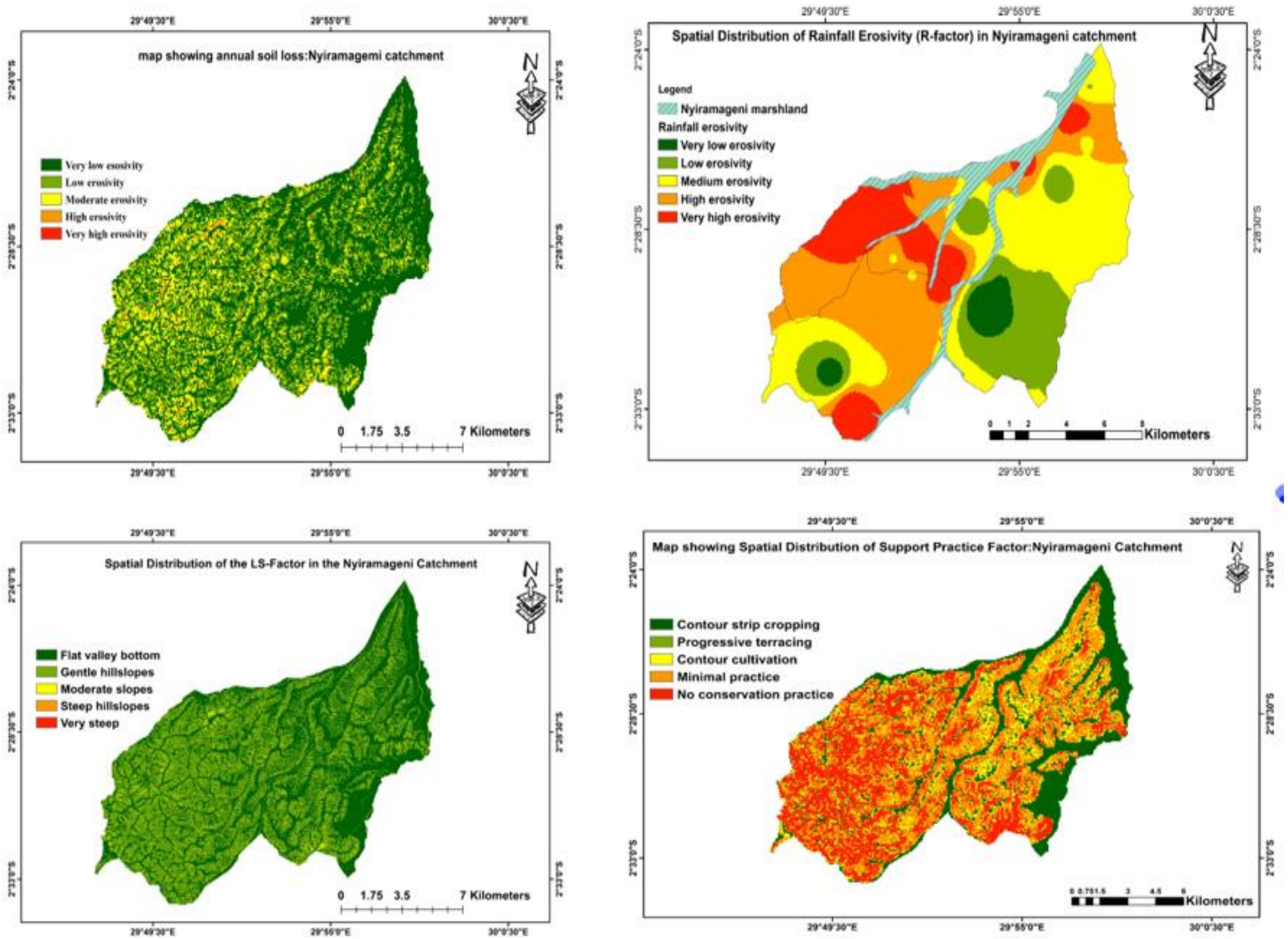

Fig. 2. Spatial distribution of key RUSLE erosion factors across the Nyiramageni contributing catchment: (a) annual soil loss (A) severity class; (b) rainfall erosivity (R-factor); (c) slope length–steepness (LS-factor); (d) support/conservation practice (P-factor). Class breaks follow Karamage et al. (2016) and Jothimani et al. (2022) (see Section 2.3)

3.1.1.3 Topographic Factor (LS-factor)

LS ranged from 0 in the flat valley-bottom marshland to 823.42 on the steepest ridge positions (mean = 89.6; SD = 148.3; CV = 128.8%), a more than 290-fold range reflecting the steeply dissected relief in which marshland and near-vertical ridge scarps coexist within one watershed. Regression of zone-mean LS against six-year mean paddy yield yielded: $Y = 484.8 - 0.253 \times LS$ ($R^2 = 0.817$), making LS the single strongest predictor of inter-zone rice yield variation in this study.

3.1.1.4 Cover-management Factor (C-factor)

C ranged from 0.527 to 1.0 (mean = 0.782; SD = 0.124; CV = 15.9%). No pixels approached the 0.001–0.01 range characteristic of dense undisturbed forest, confirming the absence of meaningful natural protective cover. Even the best-managed cropland ($C \approx 0.527$, contour-cultivated) remains highly erosion-prone relative to a forested benchmark. A marginal scenario reducing mean C from 0.782 to 0.527 through widespread contour cultivation predicted an approximate 33% reduction in mean annual soil loss.

3.1.1.5 Support-practice Factor (P-factor)

P ranged from 0.55 to 1.0 (mean = 0.868; SD = 0.076; CV = 8.8%), confirming the near-total absence of high-standard bench terracing (P = 0.1) across the contributing catchments. A simulation replacing the observed mean P (0.868) with bench-terrace P (0.10) on slopes exceeding 20°, holding R, K, LS, and C constant, predicted an 88.5% reduction in catchment-wide soil loss.

Table 1. Summary statistics of the five RUSLE input factors across the Nyiramageni contributing catchments

RUSLE Factor	Unit	Minimum	Maximum	Mean	SD	CV (%)
Rainfall erosivity (R)	$MJ \cdot mm \cdot ha^{-1} \cdot h^{-1} \cdot yr^{-1}$	265.63	751.40	508.52	121.67	23.9
Soil erodibility (K)	$t \cdot ha \cdot h \cdot ha^{-1} \cdot MJ^{-1} \cdot mm^{-1}$	0.015	0.015	0.015	0.000	0.0
Slope length-steepness (LS)	dimensionless	0	823.42	89.6	148.3	128.8
Cover management (C)	dimensionless	0.527	1.0	0.782	0.124	15.9
Support practice (P)	dimensionless	0.55	1.0	0.868	0.076	8.8
Annual soil loss (A)	$t \cdot ha^{-1} \cdot yr^{-1}$	0	1,462.54	326.35	426.28	130.6

Note: $A = R \times K \times LS \times C \times P$. Because K was spatially uniform (CV = 0%), all spatial variability in A is attributable to R, LS, C, and P (Section 3.1.2)

3.1.2 Discussion

These five-factor results directly address the study's objective of identifying which erosion drivers are responsible for the catchment's soil-loss problem, rather than simply confirming that erosion occurs. The uniform K-factor (0.015) places this catchment towards the lower-to-middle portion of Rwanda's national K range; comparable Ferralsol- and Cambisol-dominated catchments elsewhere in the country have reported K values of roughly 0.010–0.030 (Karamage et al., 2016; Li et al., 2023). Because K does not vary spatially here, the study's central diagnostic finding that differential erosion across zones is driven entirely by topography, cover, and management rather than inherent soil susceptibility is consistent with the broader national pattern in which steep relief and inadequate conservation practice, rather than soil type, are repeatedly identified as the principal erosion drivers in Rwanda's highland catchments (Karamage et al., 2016; Nyesheja et al., 2019).

The P-factor result is the most diagnostically important of the five. A mean P of 0.868 with a minimum of only 0.55 indicates that almost none of the catchment benefits from effective structural conservation. This finding gain weight when set against field-based evidence from elsewhere in Rwanda: Rutebuka et al. (2021), working in two contrasting agro-ecological zones, measured P-factor values of 0.001–0.02 under well-installed bench terraces and demonstrated soil-loss reductions of 93–98% relative to traditional slope farming, while farmer-built progressive terraces achieved smaller but still substantial reductions where installation quality was adequate.

The 88.5% reduction simulated for Nyiramageni under a bench-terrace scenario sits within the range Rutebuka et al. (2021) observed empirically, lending external support to the model's P-factor sensitivity result and reinforcing that the gap between current practice and best practice—not an intractable physical constraint—is the catchment's primary erosion-control opportunity. This is consistent with wider evidence that terracing is one of the most effective single interventions available in Rwanda's highland agro-ecosystems (Byizigiro et al., 2020).

The C-factor results similarly indicate that the problem is one of absent protective cover rather than unsuitable land use per se: no land cover class approached forest-equivalent values, meaning even compliant farmers practising contour cultivation remain exposed to erosion several orders of magnitude above forested conditions. Taken together, the R, LS, C, and P results converge on a single interpretation directly relevant to the study's problem statement: erosion risk in Nyiramageni is structurally driven by steep, highly dissected topography (LS) interacting with the near-complete absence of terracing and adequate cover management (P and C), while rainfall (R) and soil type (K) act as comparatively fixed background conditions that intervention cannot alter. This reframes the policy-relevant conclusion away from rainfall variability, which cannot be managed, and towards conservation practice, which can.

3.2 Annual Soil Loss and Spatial Severity

Combining the five RUSLE factors ($A = R \times K \times LS \times C \times P$) produced an annual soil-loss surface ranging from 0 t ha⁻¹ yr⁻¹ in the flat valley-bottom marshland to 1,462.54 t ha^{-1} yr^{-1} on the steepest ridge positions (mean = 326.35; SD = 426.28; CV = 130.6%). Regression of zone-level mean annual soil loss against Season B paddy yield yielded $Y = 618.47 - 5.89A$ ($R^2 = 0.880$), indicating that 88.0% of inter-zone variance in paddy yield is statistically explained by upstream annual soil loss.

The catchment means of 326.35 t ha^{-1} yr^{-1} is approximately 33 times the tolerable tropical soil-loss threshold of 5–10 t ha^{-1} yr^{-1} (Alewell et al., 2019), confirming that erosion in Nyiramageni is not a marginal management concern but a severe, catchment-defining process. Placed in national context, RUSLE-based assessments elsewhere in Rwanda have reported mean annual soil losses in the order of 39–49 t ha^{-1} yr^{-1} at the national scale (Karamage et al., 2016), with cropland-specific rates considerably higher in steep, intensively cultivated districts of the Southern and Western Provinces. The Nyiramageni mean substantially exceeds these national averages, which is consistent with the catchment's combination of extreme LS variability (CV = 128.8%) and a near-complete absence of effective P-factor mitigation—the same structural drivers identified in Section 4.1. The maximum value of 1,462.54 t ha^{-1} yr^{-1}, while severe, remains below the most extreme cropland maxima reported nationally (on the order of several thousand-t ha^{-1} yr^{-1} on the steepest unconserved slopes; Karamage et al., 2016), situating Nyiramageni as a severely rather than uniquely eroding catchment within the national erosion landscape. This addresses the study's underlying problem statement directly: the erosion identified is not only present but quantitatively severe enough to plausibly explain a meaningful share of observed agricultural underperformance downstream. The $R^2 = 0.880$ result linking annual soil loss to Season B yield is unusually strong for a field-scale agro-environmental relationship and should be interpreted with appropriate caution given the small number of zone-level observations underlying it; nonetheless, its direction and magnitude are consistent with the erosion–sedimentation–yield pathway documented in comparable valley-bottom and terraced rice systems elsewhere.

3.3 Sediment Transport and Connectivity

Catchment slope ranged from 0° in the valley floor to over 35° on incised channel walls and ridge crests (mean = 18.4°; SD = 12.7°; CV = 69.0%), confirming high terrain heterogeneity. Flow accumulation analysis showed that more than 90% of catchment pixels exhibited diffuse sheet flow (Class 1), with transport capacity rapidly concentrating within a well-integrated dendritic channel network as confirmed by hierarchical Strahler ordering. The 3rd-order trunk channel functions as the primary sediment-delivery corridor to the Upper Zone, while 2nd-order channels supply the Middle Zone. The Sediment Transport Index (STI) ranged from 0 to 846.68 (mean = 120.5; SD = 85.3; CV = 70.8%); the maximum value is 7.03 times the catchment mean, identifying the trunk channel corridor as an extreme sediment conveyor. A moderate STI band (69.73–202.54), corresponding to 2nd-order channel corridors, was identified as the mechanistic pathway delivering chronic, intermediate sediment loads specifically to the Middle Zone.

This is the result that connects upstream erosion to the downstream productivity pattern reported, and it is therefore central to answering the study's core question of how catchment-scale erosion translates into within-system rice-yield variation. The identified mechanism—in which intermediate, second-order sediment corridors deliver chronic, moderate sediment loads that physically degrade receiving soils without the compensatory nutrient input associated with larger, episodic trunk-channel deposits—mirrors findings from paddy-terrace research elsewhere. In rice terrace cascades in northern Vietnam, Schmitter et al. (2010, 2011) demonstrated that sediment deposition along irrigation toposequences systematically alters paddy soil texture and fertility, producing position-dependent yield variation that is not explained by management or fertiliser input alone; similarly, Clemens et al. (2010) showed that the texture and quantity of sediment reaching different slope positions differ systematically, with consequences for both upland and paddy productivity. The magnitude of sediment delivery identified here is also broadly consistent with comparable RUSLE-based catchment studies elsewhere on the continent, where topographically concentrated sediment transport was similarly shown to threaten downstream water and land-use infrastructure (Aldrees et al., 2024). The Nyiramageni STI results extend this logic from a terrace cascade to a catchment-scale marshland system: rather than sediment uniformly enriching or uniformly degrading downstream rice plots, its effect depends on where in the channel network a given zone sits—a finding that would not be visible from soil-loss totals alone and that directly justifies the zone-stratified statistical design used.

3.4 Rice Production Trends and Relationship to Sedimentation

Total paddy rice production across all three zones and six years (2020–2025) was 16,574.28 tonnes. Annual production rose from 2,644.95 t in 2020 to a peak of 2,901.83 t in 2023, coinciding with the highest annual R-factor year before stabilising at 2,757.91 t in 2025.

Descriptive statistics show within-season coefficients of variation of only 3.27–5.32% across all zone-season combinations, confirming high year-to-year stability within each zone; that is, the differences described below are stable structural differences between zones, not noise.

A one-way ANOVA on Season B harvests produced $F(2,15) = 15.17$ ($p = 0.000249$, $\eta^2 = 0.669$), indicating that zone membership alone explains 66.9% of all variance in Season B yield—a very large effect. Levene's test confirmed homogeneity of variance ($W = 0.2687$, $p = 0.768$), supporting the validity of the ANOVA assumptions. Tukey HSD post-hoc comparisons identified the Middle-Vs-Upper Zone contrast as highly significant (mean difference = −80.47 t, $p = 0.0002$, Hedges' $g = -3.015$, very large), and the Lower-Vs-Upper Zone contrast as significant (mean difference = −44.99 t, $p = 0.020$); the Lower-Vs-Middle contrast was not significant (mean difference = +35.48 t, $p = 0.069$). The Season A ANOVA was borderline non-significant overall ($F(2,15) = 3.66$, $p = 0.051$, $\eta^2 = 0.328$), plausibly because irrigation-water scarcity acts as a universal stressor across all zones in the dry season, partially masking the sedimentation signal; even so, the Middle-Vs-Upper contrast remained significant in Season A (mean difference = −29.75 t, p = 0.042, Hedges' g = −1.559). Over the six-year period, the Middle Zone deficit translates to a cumulative shortfall of 661.35 tonnes of paddy, equivalent to roughly 77 t of processed rice per year.

Table 2. One-way ANOVA and Tukey HSD post-hoc comparisons of zone-level paddy rice production, Season A and Season B (2020–2025)

Test	Season A	Season B
ANOVA: zone effect	F (2,15) = 3.66, p = 0.051, η² = 0.328	F (2,15) = 15.17, p = 0.000249, η² = 0.669
Levene's test (homogeneity of variance)	—	W = 0.2687, p = 0.768
Tukey HSD: Middle vs. Upper	Mean diff. = −29.75 t, p = 0.042, Hedges' g = −1.559	Mean diff. = −80.47 t, p = 0.0002, Hedges' g = −3.015
Tukey HSD: Lower vs. Upper	Not significant	Mean diff. = −44.99 t, p = 0.020
Tukey HSD: Lower vs. Middle	Not significant	Mean diff. = +35.48 t, p = 0.069 (n.s.)
Six-year cumulative Middle Zone deficit	—	661.35 t paddy (≈ 77 t processed rice yr^{-1})

Note: n = 6 years × 2 seasons = 12 seasonal observations per zone. The Middle-vs-Upper Zone deficit is significant in both seasons, indicating a season-independent structural effect rather than a single-season anomaly

The consistency of the Middle-Vs-Upper Zone deficit across Season A (p = 0.042), Season B (p = 0.0002), and the combined analysis is the result that most directly answers the study's research problem: it shows that the productivity penalty is a robust, season-independent structural feature of the production system rather than a single-season anomaly attributable to weather, price, or labour effects. This pattern is mechanistically consistent with the STI results, in which the Middle Zone is specifically supplied by 2nd-order channels delivering moderate, chronic sediment loads, distinct from both the negligible deposition reaching better-protected zones and the different sediment regime associated with the trunk channel. The result is also consistent with the wider literature on wetland and valley-bottom agriculture in Rwanda: Nabahungu and Visser (2011) documented that farmers in Rwandan wetland-hillside systems experience declining wetland productivity that they directly attribute to upstream over-cultivation and soil erosion on the surrounding hillsides, a farmer-perceived pathway that the Nyiramageni statistical results now substantiate quantitatively at zone scale. Internationally, the same general mechanism—yield variation driven by sediment deposition position along a hydrological gradient rather than by sediment quantity alone—has been demonstrated in paddy terrace systems by Schmitter et al. (2010, 2011), reinforcing that the Middle Zone effect identified here is not catchment-specific but reflects a more general property of sediment-fed paddy systems. Two findings qualify this interpretation and are worth stating plainly rather than glossing over. First, the positive aggregate regression ($Y = 1{,}550.6 + 2.14R$, $R^2 = 1.00$) shows that, summed across the whole catchment, wetter years are associated with higher total production; the water-supply benefit of rainfall dominates at the catchment scale. This appears, at first glance, to contradict the erosion-driven productivity loss described above. It does not: the two results operate at different spatial scales and capture different mechanisms. Aggregate production responds to total water supply, while the zone-stratified ANOVA isolates a within-catchment redistribution effect in which the Middle Zone systematically underperforms relative to the Upper Zone regardless of the overall wetness of the year. High-R years are therefore likely to simultaneously raise total catchment production and worsen the relative Middle Zone shortfall, since greater rainfall erosivity also drives more sediment transport through the 2nd-order corridors. Second, the perfect $R^2 = 1.00$ obtained from only six annual R–production pairs reflects the very small sample size available from a six-year record and should be reported as a descriptive trend rather than treated as a generalisable predictive relationship.

4. Limitations of the Study

Several limitations should be considered when interpreting these findings. First, rice production data were obtained as secondary records from COOPRORIZ Nyiramageni Cooperative and were not independently cross-validated against field-level yield measurements; any recording or aggregation inconsistencies in the cooperative's records would propagate into the zone-level statistics. Second, the statistical analyses rest on a relatively small number of observations (six years × two seasons = 12 seasonal observations per zone; six annual R-production pairs for the aggregate regression), which constrains statistical power and means that very high R^2 values (e.g., $R^2 = 1.00$ for the annual rainfall-production regression) should be read as descriptive trends rather than generalisable predictive relationships, as already noted in Section 3.4. Third, the RUSLE model and the Sediment Transport Index are empirically validated proxies for erosion and sediment-delivery potential rather than direct field measurements of sediment flux; no sediment traps or turbidity monitoring were installed to independently verify modelled sediment loads reaching each marshland zone. Fourth, the C-factor was derived from a single-date Sentinel-2 land-cover classification and therefore represents a snapshot rather than the full 2020–2025 land-cover trajectory; any land-use change within the study period is not captured. Finally, the findings are specific to one marshland-catchment system in Gisagara District; while the erosion-sedimentation-yield mechanism identified is consistent with evidence from other Rwandan and international paddy systems, the quantitative relationships (e.g., the LS- and A-based regressions) should be locally recalibrated before being applied to other catchments.

5. Conclusion

Taken together, the results show that erosion risk in the Nyiramageni catchment is driven primarily by extreme topographic amplification (LS) interacting with the near-total absence of effective conservation practice (P) and protective cover (C), while rainfall erosivity (R) and soil erodibility (K) act as comparatively fixed background conditions; this pattern, and the scale of mean annual soil loss (326.35 t ha^{-1} yr^{-1}, roughly 33 times the tolerable threshold), are consistent with and in several respects more severe than patterns reported elsewhere in Rwanda (Karamage et al., 2016; Rutebuka et al., 2021). Sediment-transport modelling further shows that this erosion does not affect downstream rice production uniformly: the 2nd-order channel network delivers chronic, intermediate sediment loads specifically to the Middle Zone, producing a statistically robust, season-independent yield deficit relative to the Upper Zone (−80.47 t, $p = 0.0002$ in Season B; −29.75 t, $p = 0.042$ in Season A) that has cost the Middle Zone an estimated 661.35 tonnes of paddy over six years. This zone-specific mechanism, consistent with comparable evidence from Rwandan wetland systems and international paddy-terrace research (Nabahungu & Visser, 2011; Schmitter et al., 2010, 2011), indicates that interventions targeting bench terracing and cover management on the slopes draining into the Middle Zone's 2nd-order channels are likely to yield disproportionate productivity returns relative to catchment-wide, undifferentiated conservation investment.

Data Availability Statement

The RUSLE input rasters, zone-level soil-loss and Sediment Transport Index outputs, and the six-year seasonal rice-production dataset (COOPRORIZ Nyiramageni Cooperative, 2020–2025) underlying the summary statistics and statistical tests reported in Tables 1 and 2 are available from the corresponding author upon reasonable request.

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Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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