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Assessment of Soil Erosion and Sediment Transfer Using the InVEST-SDR Model: A Case Study of the Lobo Watershed

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Abstract

Sediment transfer represents a major challenge for the sustainability of hydroelectric reservoirs, particularly in watersheds subject to intense anthropogenic pressure. This study aims to spatially characterize erosion and sediment transfer processes in the Lobo watershed and to assess their potential contribution to sedimentation in the Soubré hydroelectric reservoir. The approach combines the InVEST-SDR model, the RUSLE equation, Geographic Information Systems (GIS), remote sensing, and field observations. The results indicate an estimated mean soil loss of 21.24 $t \cdot ha^{-1} \cdot yr^{-1}$, with low erosion levels predominating across 87.44% of the watershed. The estimated mean sediment transfer reaches 8.12 $t \cdot ha^{-1} \cdot yr^{-1}$, corresponding to approximately 38% of soil loss, while 62% of the eroded material is temporarily retained on hillslopes or in intermediate depositional areas. High Sediment Delivery Ratio (SDR) values are mainly concentrated along the drainage network, tributaries, and steep-slope areas, identifying these zones as preferential pathways for sediment transfer to streams. Agricultural areas, bare soils, and mining sites appear to be significant potential sources of sediment.

Keywords

Lobo Watershed, InVEST-SDR, Soil Erosion, Sediment Transfer, Soubré Dam, Reservoir Sedimentation

1. Introduction

Water resources play an essential role in the socioeconomic and energy development of countries. In West Africa, hydroelectric dams constitute strategic infrastructure for electricity generation and water resources management (Diabagaté et al., 2016; Anoh et al., 2021). However, their sustainability is threatened by reservoir siltation, a process resulting from the transport and deposition of sediments generated by erosion within watersheds (Akognongbe et al., 2014; Faye et al., 2015).

In Côte d'Ivoire, the Soubré hydroelectric dam plays an important role in the national energy system. However, the reservoir is subject to sediment inputs that may reduce its storage capacity and compromise its long-term operation (Groga et al., 2017; Gauze et al., 2018; Anoh et al., 2021). Among the main contributing tributaries, the Lobo River stands out due to its location immediately upstream of the reservoir. This configuration favors the direct transfer of eroded materials from the Lobo watershed to the reservoir, thereby contributing to sediment accumulation in certain areas of the reservoir.

The Lobo watershed is also experiencing profound environmental changes related to the expansion of agricultural activities, deforestation, land exploitation, and the increase in bare land areas (N'go et al., 2018; Vami Hermann et al., 2022; Deguy et al., 2024). These changes in land cover modify hydrological processes and intensify soil erosion by water, leading to an increase in the sediment loads transported by the drainage network (Koffi, 2022). Faced with this issue, understanding the mechanisms governing sediment production, transport, and spatial distribution is essential for the sustainable management of the Soubré dam reservoir. Advances in Geographic Information Systems (GIS), remote sensing, and hydro-sedimentary models now make it possible to analyze sediment dynamics at different spatial scales and to develop appropriate management strategies. The present study falls within this context. It aims to analyze the dynamics of sediment transport in the Lobo watershed using the InVEST-SDR model (Integrated Valuation of Ecosystem Services and Tradeoffs-Sediment Delivery Ratio) in order to better understand its contribution to the siltation of the Soubré hydroelectric dam reservoir.

2. Study Area

The Lobo watershed is located within the forest domain of central-western Côte d'Ivoire, in the Haut-Sassandra region (**Figure 1**). It covers an area of approximately 12,767 km^2 and constitutes one of the main sub-watersheds of the Sassandra River (Vami Hermann et al., 2022). Its main river, approximately 355 km long, generally flows in a north-south direction. The relief is relatively gentle and homogeneous, with a maximum elevation of approximately 640 m (Koffi, 2022). It is dominated by peneplains characterized by alternating crystalline domes reaching elevations of 300 - 400 m and low plateaus ranging from 200 to 300 m in elevation (Koffié-Bikpo & Kra, 2013). This gentle morphology favors the development of agricultural activities, which occupy an important share of the land cover within the watershed.

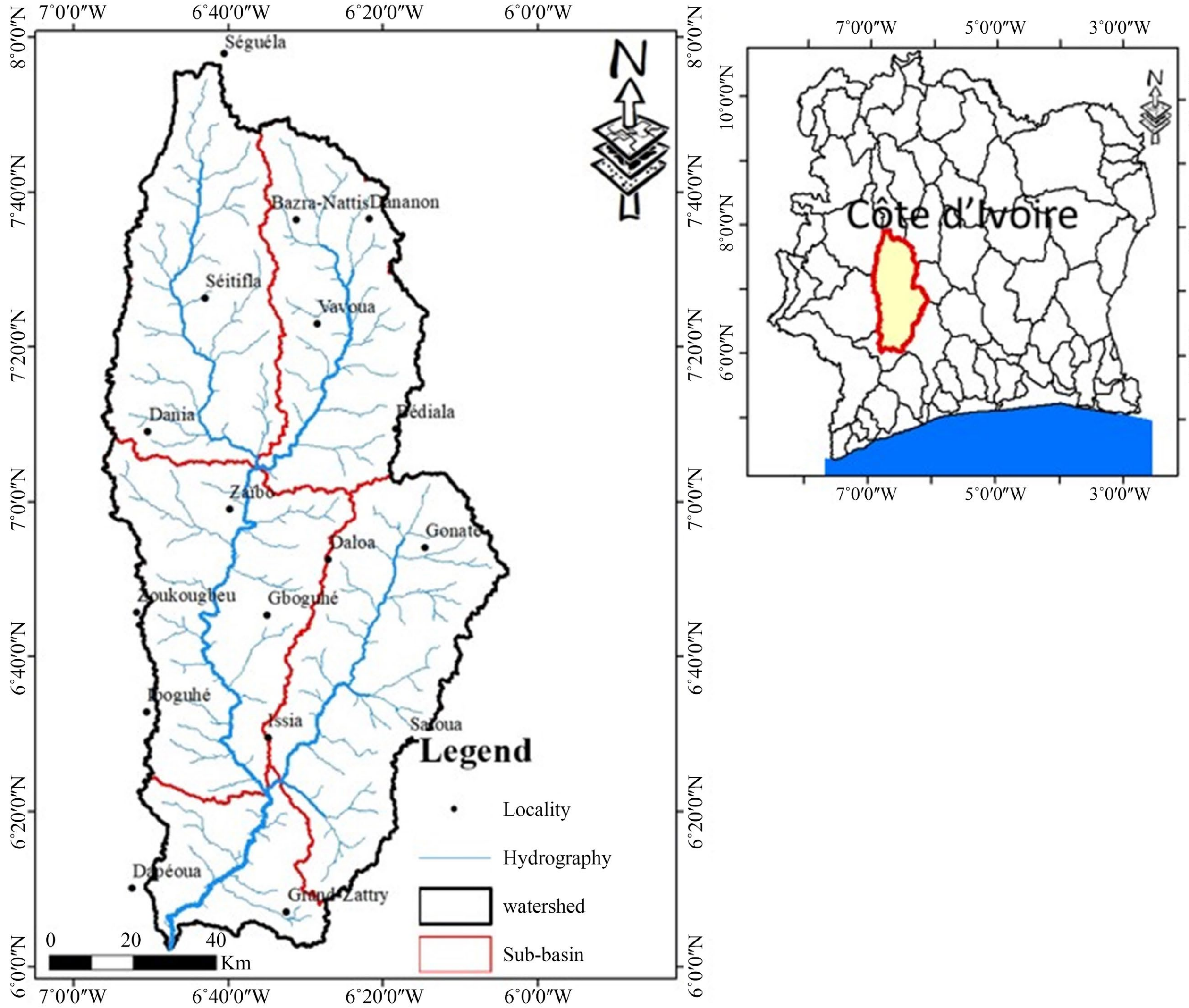

Figure 1. Lobo watershed.

3. Materials and Methods

3.1. Materials

The materials used in this study consisted of data, field sampling equipment, and data-processing tools.

The datasets comprised a Landsat 8 OLI/TIRS satellite image acquired in 2024 and a 30 m Digital Elevation Model (DEM), both of which were freely available and downloaded from the USGS EarthExplorer platform (http://earthexplorer.usgs.gov/).

Climate data consisted of monthly rainfall totals recorded at five meteorological stations, namely Séguéla, Vavoua, Zoukougbeu, Daloa, and Buyo, operated by the Société d'Exploitation et de Développement Aéroportuaire, Aéronautique et Météorologique (SODEXAM). The rainfall records covered the 2003-2023 period. These 21-year rainfall data were used to calculate the rainfall erosivity factor (R).

Soil data were obtained from field surveys conducted in the Lobo watershed.

They consisted of 145 soil samples collected between September 20 and September 30, 2025, from the surface soil horizon (0 - 30 cm), as well as soil permeability measurements performed in situ using a double-ring infiltrometer. These parameters were used to determine the soil erodibility factor (K factor).

The field equipment consisted of a Garmin GPSMAP 62x GPS receiver for georeferencing observation points, a double-ring infiltrometer for measuring soil permeability, and a soil auger for collecting soil samples.

For data processing and analysis, ENVI 5.3 was used to process the satellite imagery. ArcGIS was used to determine the different factors of the Universal Soil Loss Equation (USLE) and to prepare the input data required for the InVEST-SDR model.

3.2. Methods

The InVEST-SDR approach is based on the use of two nested models (**Figure 2**), which provide information on: 1) erosion processes and 2) sediment transport.

3.2.1. Estimation of Specific Surface Erosion

The assessment of water erosion in the Lobo watershed was based on the determination of the different factors of the Universal Soil Loss Equation (USLE) (Wischmeier & Smith, 1978; Renard et al., 1997).

The R factor (rainfall erosivity), which represents the erosive potential of rainfall, was estimated using monthly rainfall data collected from five SODEXAM meteorological stations (Daloa, Buyo, Zoukougueu, Vavoua, and Séguéla) over the 2003-2023 period. The empirical formula proposed by Roose (1994), adapted to West African conditions, was used to estimate the R factor from mean annual rainfall. The resulting R values were spatialized across the Lobo watershed using the Inverse Distance Weighted (IDW) interpolation method in ArcGIS. The interpolation was performed using a power parameter of 2 and a variable search radius. The resulting R-factor raster was generated at a spatial resolution of 30 m.

The K factor (soil erodibility) was determined from 145 soil samples collected between 20 and 30 September 2025 at a depth of 0 - 30 cm. The sampling sites were distributed across the four sub-watersheds of the Lobo watershed to capture spatial variability in soil properties. Site selection considered soil types, land-use/land-cover classes, topographic conditions, and field accessibility. The geographic coordinates of all sampling points were recorded using a GPS. Particle-size analyses conducted at the Centre de Recherche en Écologie of Université Nangui Abrogoua were used to characterize soil texture, while field permeability was measured using a double-ring infiltrometer (**Figure 2**). Texture, organic matter content, and permeability were incorporated into the Wischmeier and Smith (1978) equation to calculate the K factor. The resulting K values were subsequently spatialized using the IDW interpolation method in ArcGIS, using the same interpolation parameters as for the R factor.

The LS factor, which combines the effects of slope length and slope steepness on soil erosion, was derived from a 30 m-resolution Digital Elevation Model (DEM). The LS factor was calculated using the multiple-flow direction algorithm developed by Freeman (1991), which accounts for the distribution of surface runoff among multiple downslope flow directions. The resulting LS raster was generated at a spatial resolution of 30 m to ensure consistency with the R and K factor layers.

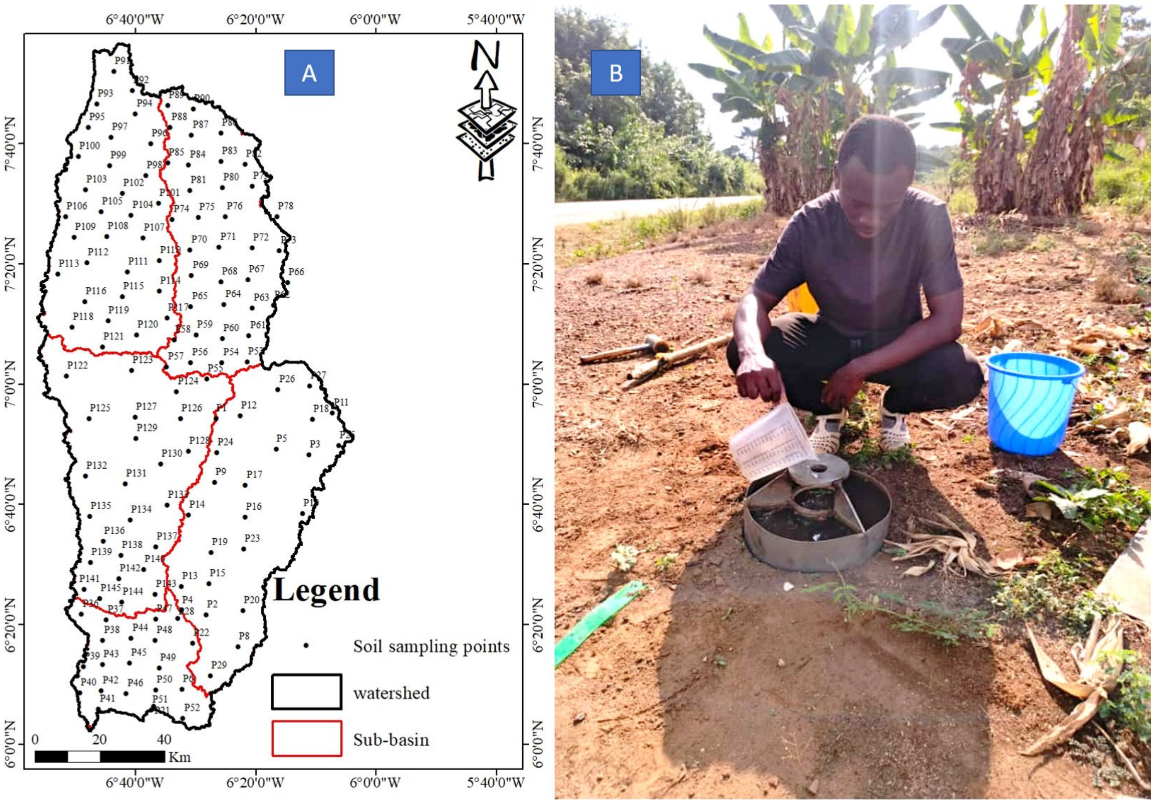

Figure 2. (A) Localization of soil sampling points; (B) Measurement of soil permeability.

The C factor was derived from a land-use/land-cover map produced from a 2024 Landsat 8 OLI/TIRS image, classified in ENVI 5.3 using the Maximum Likelihood Classification method (Kouassi et al., 2016). Seven major land-use/land-cover classes were identified: water bodies, forest, plantations, croplands, lowlands, built-up areas, and bare soil. The classification accuracy was assessed using independent validation samples. The confusion matrix yielded an overall accuracy of 98.25% and a Kappa coefficient of 0.97, indicating a very high level of agreement between the classified land-cover map and the reference data. The seven major land-use/land-cover classes identified in the Lobo watershed were assigned C-factor values according to their degree of soil protection against water erosion. These classes were subsequently assigned soil erosion protection coefficients (**Table 1**) based on Lufafa et al. (2003), N'go et al. (2018), and Kanga et al. (2025).

Table 1. C-factor values assigned to land-use.

Land-use	C-factor	Level of soil protection
Water bodies	0.000	Very high
Forest	0.001	Very high
Plantations	0.180	High
Croplands	0.500	Low to moderate
Lowlands	0.150	Moderate to high
Built-up areas	0.200	Moderate
Bare soil	1.000	Very low

The P factor, which represents soil conservation practices, was determined based on field observations. Given the absence of structured erosion-control measures, a uniform value of 1 was assigned to the entire watershed (N'go et al., 2018; Kanga et al., 2025).

All R, K, LS, C, and P factors were integrated into the InVEST-SDR model to calculate the mean annual soil loss according to the RUSLE equation.

3.2.2. Sediment Delivery Rate Modeling

The Sediment Transfer Ratio (SDR) was mapped on a pixel-by-pixel basis through two successive steps: calculation of the Connectivity Index (IC) and determination of the sediment transfer rate.

Based on the work of Borselli et al. (2008), the model first calculates the Connectivity Index (IC) for each pixel. This index describes the hydrological linkage between sediment source areas, such as hillslopes or agricultural plots, and sediment-receiving areas, particularly the stream network. High IC values indicate that a large proportion of the sediment eroded upstream is likely to be transported to the stream network; the corresponding pixel is therefore considered highly connected. Conversely, low IC values indicate limited hydrological connectivity, which is typically associated with areas characterized by dense vegetation cover or gentle slopes.

The sediment transfer rate is subsequently estimated from the Connectivity Index (IC) using the equation developed by Vigiak et al. (2012).

$$\mathrm{SDR} = \frac{\mathrm{SDR}_{\max}}{1 + \exp\left(\frac{IC_0 - IC_i}{k_b}\right)} \tag{1}$$

where SDR is the Sediment Delivery Ratio; $\mathrm{SDR}_{\max}$ corresponds to the maximum sediment delivery ratio; IC is the Connectivity Index; and IC_0 and k_b are the calibration parameters proposed by Borselli.

Due to the absence of long-term observed sediment-export data for the Lobo watershed, the SDR calibration parameters were not locally calibrated. The default values recommended for the InVEST-SDR model, namely SDRmax = 0.8, IC_0 = 0.5, and k_b = 2, were therefore adopted, following Borselli et al. (2008) and Vigiak et al. (2012). These values provide a standardized parameterization when field observations are insufficient for site-specific calibration.

The product of the RUSLE and SDR results makes it possible to estimate the contribution of each pixel to sediment transport from hillslopes to the stream network. The drainage network was delineated by reclassifying the flow-direction raster derived from the DEM. The flow accumulation threshold used to identify stream channels was defined manually in order to best match the drainage network observed on the topographic map.

4. Results

4.1. Specific Surface Erosion

The rainfall erosivity factor (R), calculated over the 2003-2023 period, ranges from 159.35 to nearly 800 MJ·mm·ha^{-1}·yr^{-1}, with an increasing gradient from the northern to the southern part of the watershed. The soil erodibility factor (K) ranges from 0.08 to 0.39 t·h·MJ^{-1}·mm^{-1} (**Figure 3**).

The analysis of the C factor indicates that areas with a high level of protection against erosion account for only 3.57% of the total watershed area. Areas with low to moderate protection dominate the watershed, accounting for 29% and 42.86%, respectively. In contrast, areas highly exposed to erosion, characterized by bare soils, built-up areas, or recently cultivated lands, cover 24.57% of the watershed. The LS factor map shows that low to moderate values are widely distributed across the watershed, covering more than 92% of its total area. However, high LS values, mainly located on the steepest slopes, account for 7.26% of the watershed area (**Figure 3**).

The analysis of the spatial distribution of annual soil loss across the watershed (**Figure 4**) indicates a mean estimated soil loss of 21.24 t·ha^{-1}·yr^{-1}, with a clear predominance of areas characterized by negligible to low erosion rates. The 0 - 5.81 t·ha^{-1}·yr^{-1} class, corresponding to negligible erosion, covers 7162.50 km^2, representing 57.26% of the watershed. It is followed by the 5.82 - 17.44 t·ha^{-1}·yr^{-1} class, corresponding to low erosion, which covers 3775.83 km^2, or 30.18% of the watershed. Together, the negligible and low erosion classes account for 10938.33 km^2, representing 87.44% of the total watershed area. Moderate erosion (17.45 - 37.79 t·ha^{-1}·yr^{-1}) covers 1290.50 km^2, corresponding to 10.32% of the watershed. Areas characterized by high erosion (37.80 - 79.93 t·ha^{-1}·yr^{-1}) remain relatively limited, covering 257.41 km^2 (2.06%), while areas subject to severe erosion (79.94 - 370.61 t·ha^{-1}·yr^{-1}) cover only 22.76 km^2, representing 0.18% of the watershed (**Table 2**).

The spatial analysis shows that these areas of high to severe erosion are mainly concentrated in the southern part of the watershed and in the vicinity of major urban centers such as Daloa, Issia, Zoukougbeu, and Grand-Zattry. They also coincide with areas where vegetation cover is highly degraded, particularly bare soils, agricultural lands, and artisanal and semi-industrial mining sites.

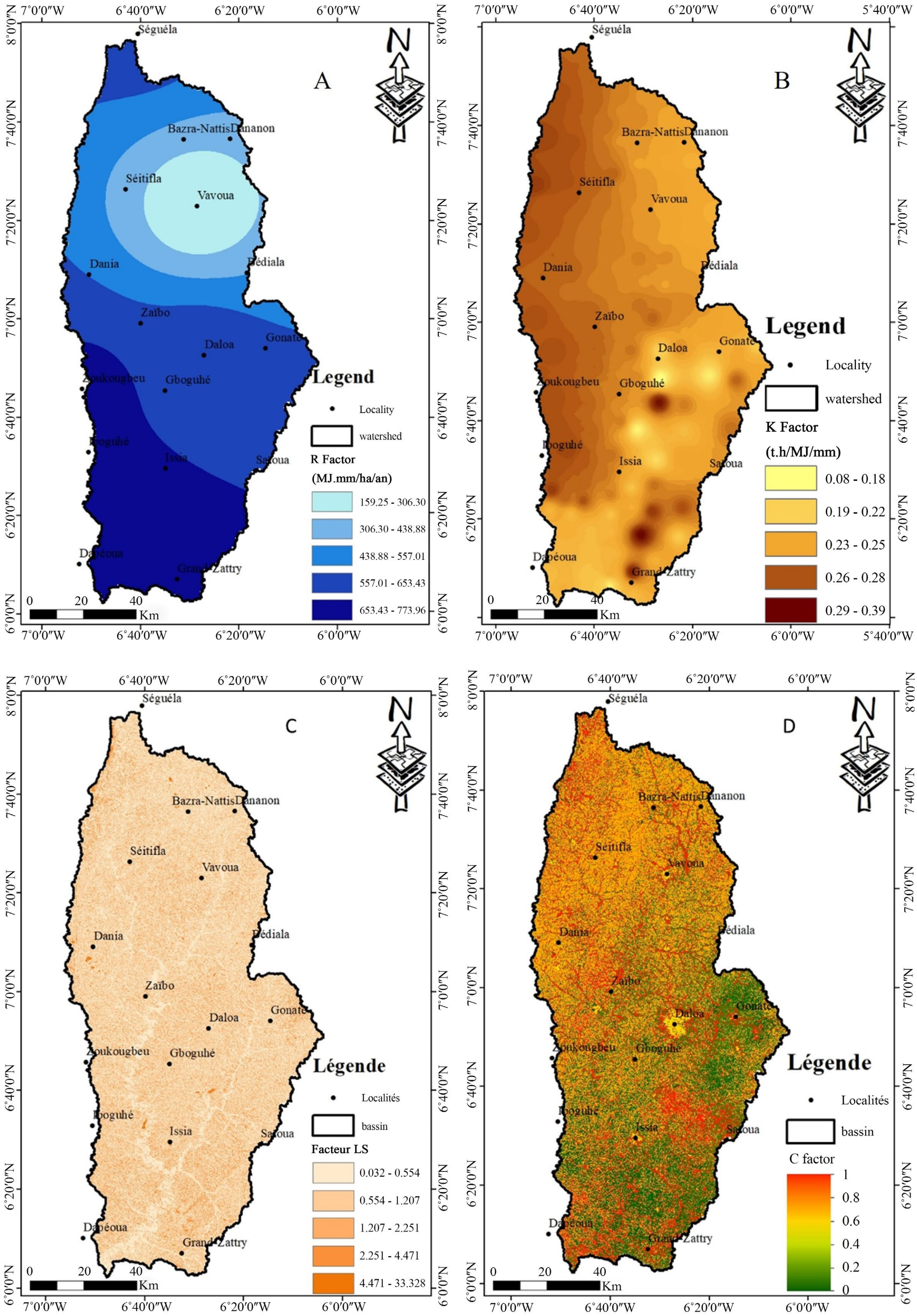

Figure 3. Maps of the basic water erosion factors: (A) Rainfall erosivity factor (R); (B) Soil erodibility factor (K); (C) Cover-management factor (C); and (D) Slope length and steepness factor (LS).

Table 2. Categories of soil erosion risks in the Lobo watershed.

Erosion class	Soil loss ($t \cdot ha^{-1} \cdot yr^{-1}$)	Area (%)
Negligible	0 - 5.81	**57.26**
Low	5.82 - 17.44	**30.18**
Moderate	17.45 - 37.79	**10.32**
High	37.80 - 79.93	**2.06**
Very high	79.94 - 370.61	**0.18**

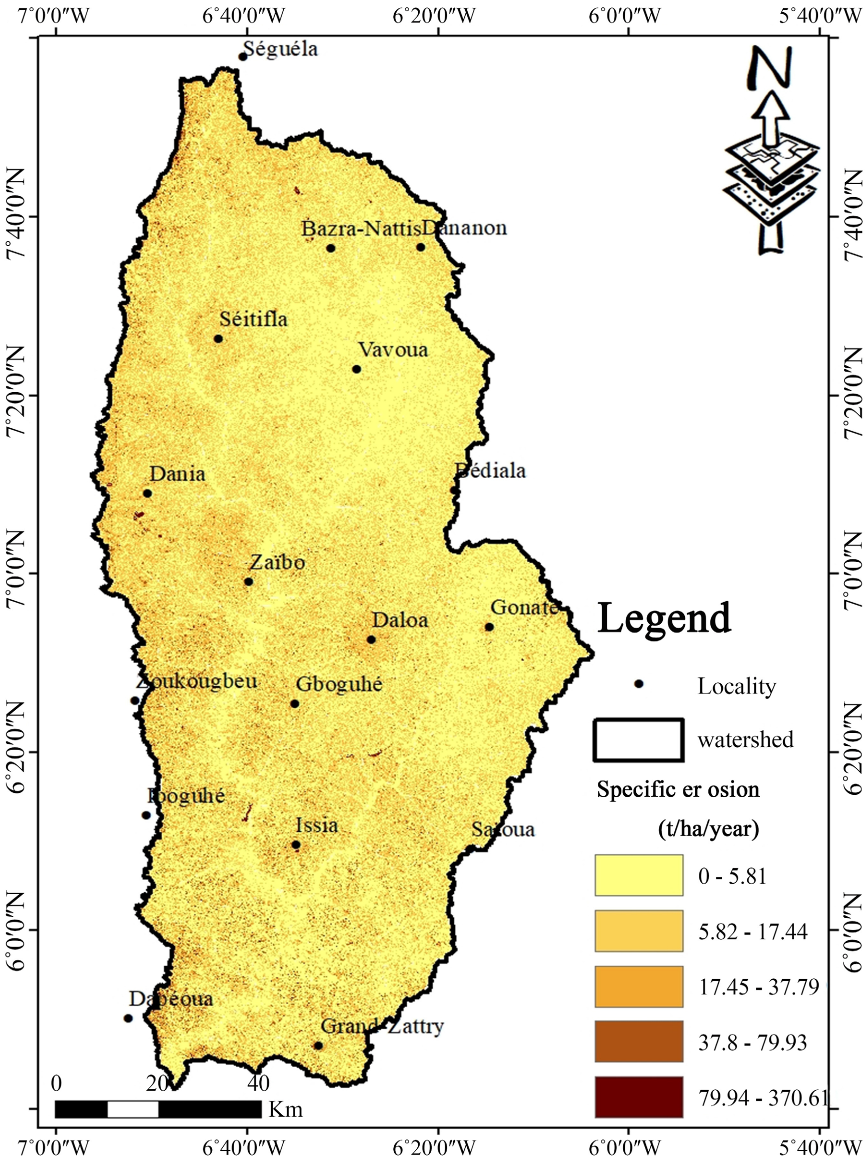

Figure 4. Soil loss map in lobo watershed.

4.2. Spatial Distribution of Sediment Delivery Ratio

Figure 5 presents the Sediment Delivery Ratio (SDR), which represents the probability that a locally eroded particle will be transported to the stream network. The low-connectivity classes (SDR < 0.109) are spatially dominant and are mainly located in interfluve areas, whereas intermediate values (0.109 - 0.169) occur in transitional areas. Conversely, high SDR values (≥0.169) are strongly concentrated along the main drainage network and its tributaries, as well as on steeper hillslopes.

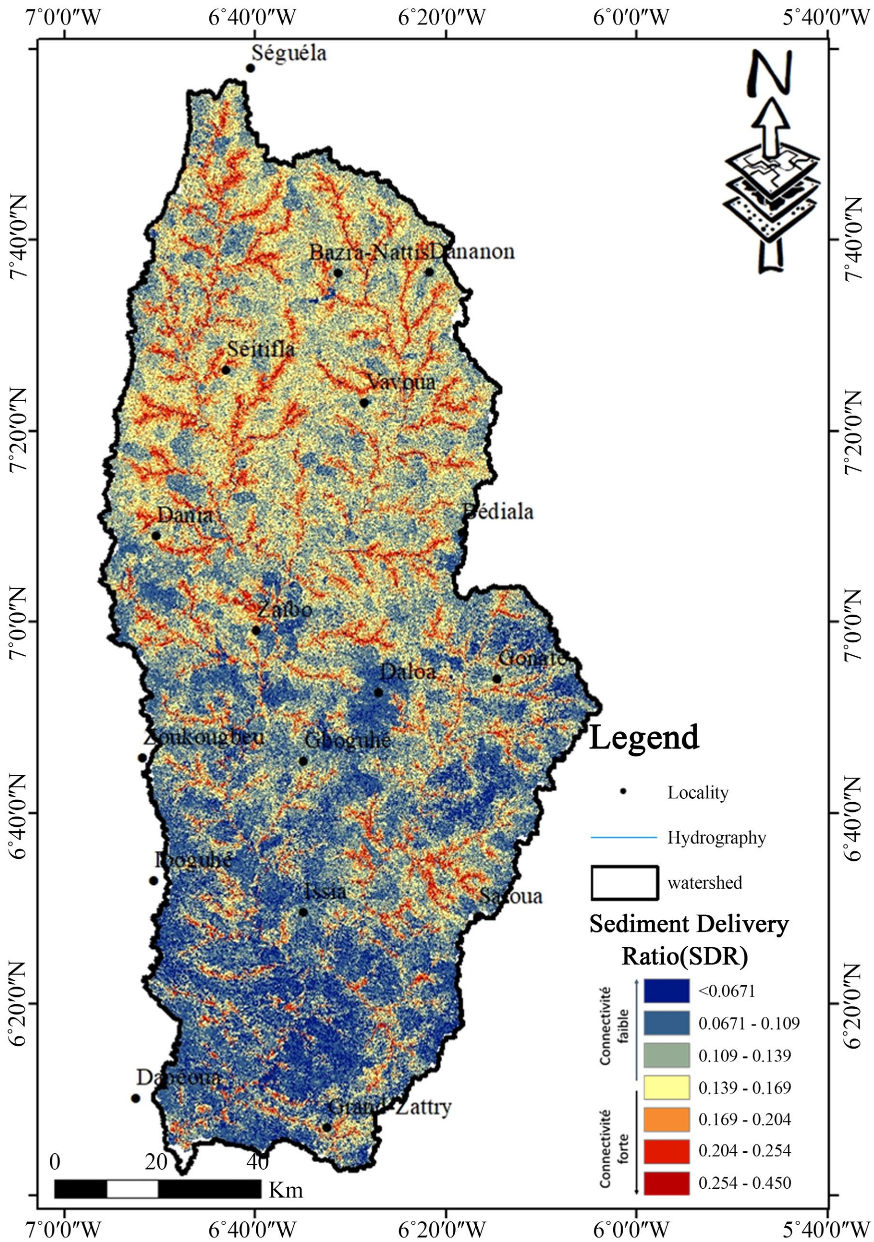

Figure 5. Sediment Delivery Rate (SDR) map.

Figure 6 presents the mean annual sediment export estimated using the InVEST-SDR model, corresponding to the proportion of soil loss that effectively reaches the watershed outlet. The mean sediment export is estimated at 8.12 $t \cdot ha^{-1} \cdot yr^{-1}$. The 0 - 1 $t \cdot ha^{-1} \cdot yr^{-1}$ class covers 30.74% of the total watershed area and corresponds to areas where sediment export remains low. Areas exhibiting moderate sediment export rates, ranging from 1 to 3.3 t·ha^{-1}·yr^{-1}, are the most extensive, accounting for 50.71% of the total area. The highest sediment export classes, ranging from 7.28 to 84.25 t·ha^{-1}·yr^{-1}, cover only 8.55% of the total watershed area and are mainly located in steep-slope areas and around mining sites.

The comparison between the mean soil loss (21.24 t·ha^{-1}·yr^{-1}) and the mean sediment export (8.12 t·ha^{-1}·yr^{-1}) indicates that approximately 38% of the eroded soil is effectively exported to the drainage network, while the remaining fraction is retained on hillslopes or deposited in intermediate depositional areas. This effective sediment export results in a substantial sediment load, as evidenced by the brownish coloration of the Lobo River, particularly during the rainy season (Figure 6).

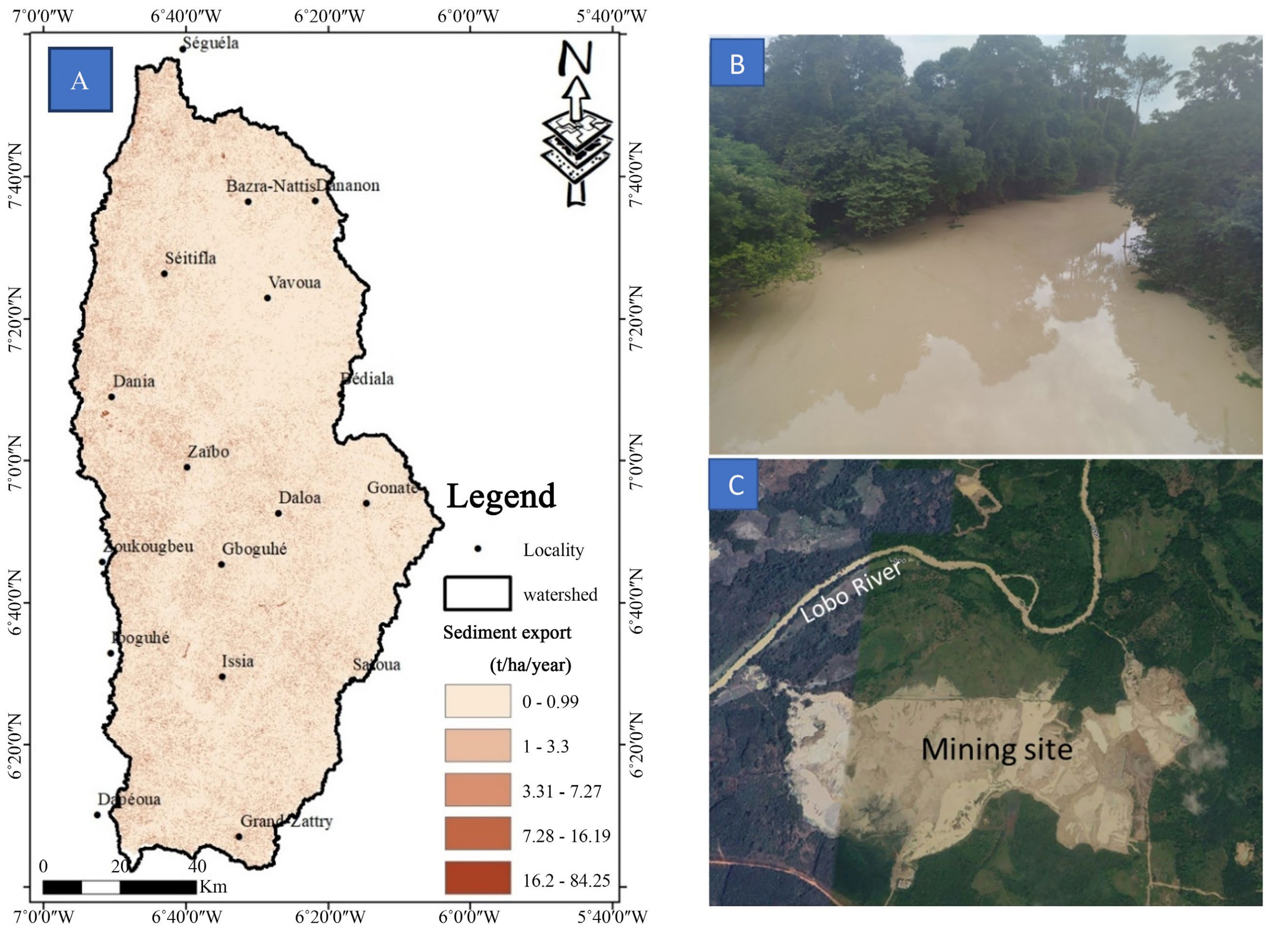

Figure 6. (A) Mean annual sediment export estimated using the InVEST-SDR model; (B) Condition of the Lobo River during the rainy season; (C) Google Earth image of a mining site near the Lobo River.

5. Discussion

The estimated mean soil loss of 21.24 t·ha^{-1}·yr^{-1} indicates a moderate level of erosion in the Lobo watershed. This value is close to that reported by Kouakou and Tra Bi (2025) for the N'zi watershed (20 t·ha^{-1}·yr^{-1}). However, the spatial distribution of erosion classes shows a clear predominance of areas characterized by negligible to low erosion, which together account for 87.44% of the total watershed area. Areas experiencing high to severe erosion rates (37.80 - 370.61 $t \cdot ha^{-1} \cdot yr^{-1}$), mainly located on bare soils and agricultural lands, constitute the primary potential sediment source areas. This situation is mainly associated with the expansion of agricultural activities and the development of artisanal gold mining, which promote soil exposure and intensify surface runoff, as also reported by N'go et al. (2018), Koua et al. (2019), and Deguy et al. (2024).

The integration of the Sediment Delivery Ratio (SDR) provides a better understanding of sediment transfer mechanisms. The low SDR values (<0.109), which are widely dominant across the watershed, indicate low hydrosedimentary connectivity, suggesting that a substantial proportion of the sediment produced is temporarily stored before reaching the drainage network. In contrast, the high SDR values observed along watercourses and on the steepest hillslopes reveal areas where sediment transfer is particularly efficient, in agreement with the findings of Borselli et al. (2008), Cavalli et al. (2013), Gashaw et al. (2021), and Ekanayaka et al. (2025).

These areas constitute the main sediment source zones feeding the drainage network. The results of the InVEST-SDR model show that approximately 38% of the eroded soil is effectively exported to the streams, while the remaining 62% is temporarily stored on hillslopes or in intermediate depositional areas. This proportion is consistent with the predominance of low SDR values observed across the watershed.

Nevertheless, the sediment effectively transported is sufficient to generate a high suspended sediment load, as evidenced by the brownish coloration of the waters of the Lobo River, particularly during flood periods. This observation is consistent with the findings of Koffi (2022), who measured sediment inputs of up to 1074.2 t/month during high-water periods, thereby confirming the importance of downstream sediment transfer.

This high turbidity results from the combined effects of agricultural land erosion, deforestation, and artisanal gold-mining activities, which increase sediment production and mobilization (Koua et al., 2019; N'go et al., 2018; Adon et al., 2017; Coulibaly et al., 2021). Given the position of the Lobo River as the last major tributary directly feeding the Soubré hydroelectric reservoir, these sediment fluxes progressively contribute to reservoir siltation.

6. Conclusion

This study assessed soil loss and sediment transfer in the Lobo watershed using the InVEST-SDR model coupled with GIS and remote sensing. The results indicate a mean soil loss of 21.24 $t \cdot ha^{-1} \cdot yr^{-1}$, with areas characterized by negligible to low erosion predominating and accounting for 87.44% of the total watershed area. Areas with high to severe soil loss are mainly located on steep hillslopes, bare soils, and agricultural lands, where agricultural activities and artisanal gold mining contribute to increased sediment production.

The analysis of the Sediment Delivery Ratio (SDR) showed that the watershed is characterized overall by low hydrosedimentary connectivity. Approximately 38% of the sediment produced is exported to the drainage network, while 62% is temporarily retained on hillslopes or in depositional areas. Areas located near watercourses and on the steepest hillslopes constitute the main sediment transfer zones. Nevertheless, despite the relatively low proportion of sediment export, areas with limited vegetation protection, particularly agricultural lands and mining sites, generate substantial sediment transfers that contribute to stream sediment loads, especially during the rainy season, when surface runoff is more intense.

Due to its position as the last major tributary directly feeding the Soubré hydroelectric reservoir, the Lobo River contributes significantly to the sediment inputs responsible for the progressive siltation of the reservoir. These findings highlight the importance of implementing soil conservation measures in critical areas to reduce sediment transfers and sustainably preserve the storage capacity and hydroelectric power generation capacity of the Soubré Dam.

Author Contributions

Conceptualization: K. J.-C. Tanoh, K. H. Kouassi; Methodology: K. J.-C. Tanoh, K. H. Kouassi, K. E. Kanga; Data collection: K. J.-C. Tanoh, K. E. Kanga, Y. E. D. Konan, V. M. Nonde, S. A. Gbaho; Data analysis: K. J.-C. Tanoh; Writing—original draft: K. J.-C. Tanoh; Writing—review and editing: K. H. Kouassi, K. E. Kanga, J. P. A. Deguy, and the other co-authors; Supervision: K. H. Kouassi. All authors have read and approved the final version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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