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Research Article

Landscape connectivity and sediment regulation ecosystem services in a semi-arid Mediterranean watershed: Insights from the Nfifikh basin (Morocco) using the InVEST SDR model

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Abstract

Soil erosion and sediment transport represent major environmental challenges in semi-arid Mediterranean watersheds, where high erosion rates do not necessarily translate into high sediment delivery to river systems. This study assesses sediment regulation ecosystem services in the Nfifikh watershed (Morocco) to clarify how landscape connectivity controls sediment export, retention, and internal buffering processes. A spatially explicit connectivity-based modelling approach was implemented using the InVEST Sediment Delivery Ratio (SDR) model, integrating a 30 m digital elevation model, land use and land cover data (2019), soil properties, and rainfall erosivity factors within a GIS environment. The results reveal a marked decoupling between potential soil erosion and effective sediment transfer. Despite high erosion potential in upstream areas, sediment export remains spatially limited due to reduced connectivity, whereas midstream sectors with moderate erosion exhibit higher sediment delivery efficiency. High SDR values are confined to a limited number of well-connected zones, while large portions of the basin function as sediment sinks. Valley-floor deposition locally exceeds 1100 kg yr^{-1}, underscoring their buffering capacity. Ecosystem service indicators further show spatial differentiation between avoided soil erosion and avoided sediment export, reflecting the role of land-cover configuration in regulating sediment fluxes. Overall, the findings demonstrate that sediment regulation is primarily governed by landscape connectivity and land-cover structure rather than erosion intensity alone, providing transferable insights for ecosystem-based watershed management in semi-arid Mediterranean environments.

Key words: Ecosystem services assessment, geographic information systems, sediment delivery processes, sediment retention, soil erosion modelling, spatial modelling

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1. Introduction

Soil erosion and sediment transfer represent major environmental challenges in Mediterranean watersheds, particularly under semi-arid conditions where land-use change and climate variability interact to intensify hydrological instability. In Morocco, erosion processes contribute to soil fertility decline, reservoir siltation, and long-term landscape degradation, especially in basins characterized by strong topographic gradients and fragile soil systems (Manaouch et al.

2021; Lamane et al. 2022). These pressures are further amplified by recurrent droughts and increasing water demand, placing many Moroccan watersheds among the most vulnerable systems in the Mediterranean region (Schilling et al. 2020). Within this context, soil-related regulating ecosystem services, and particularly sediment regulation through erosion control and sediment retention, play a crucial role in maintaining watershed functioning and supporting land-use planning and environmental management decisions (Grizzetti et al. 2016).

Most erosion assessments in semi-arid Mediterranean basins, including those in Morocco, have traditionally relied on soil loss estimates derived from empirical models such as the Universal Soil Loss Equation (USLE) or the Revised Universal Soil Loss Equation (RUSLE). While these approaches are effective for identifying areas susceptible to soil detachment, they provide limited insight into whether eroded material is effectively transferred to the drainage network or retained within the landscape. Recent research has highlighted that sediment delivery is strongly controlled by landscape connectivity, which governs the efficiency of sediment transfer from hillslopes to channels. As a result, areas experiencing high soil loss do not necessarily correspond to dominant sediment source zones, revealing a critical gap between conventional erosion mapping and the assessment of sediment regulation ecosystem services.

The Nfifikh watershed, located in western Morocco within the Atlantic coastal system, provides a representative example of this challenge in semi-arid Mediterranean environments. The basin combines steep upstream reliefs, heterogeneous land-use patterns, erosion-sensitive soils, and expanding agricultural and urban activities. These characteristics promote active soil erosion while simultaneously favoring internal sediment storage within midstream and downstream valley floors. Although erosion processes and land degradation in the Nfifikh watershed are widely recognized, the extent to which eroded material is effectively exported downstream or retained within the basin remains insufficiently understood. In particular, the role of landscape connectivity in mediating the transition from potential soil erosion to effective sediment export and retention has not yet been explicitly examined for this watershed.

Spatially explicit ecosystem service models provide a suitable framework for addressing this limitation by linking erosion processes with sediment transfer and retention dynamics. The InVEST Sediment Delivery Ratio (SDR) model integrates soil loss estimates with topographic controls and connectivity-based routing to distinguish between potential soil detachment and effective sediment export (Natural Capital Project 2025; Li et al. 2025). In this framework, sediment regulation is assessed through indicators that reflect both erosion mitigation and sediment retention within the landscape. Such approaches are particularly relevant in semi-arid Mediterranean environments, where topography, vegetation cover, and soil properties exert strong controls on sediment pathways and internal buffering processes (Marques et al. 2021). However, many existing applications remain largely descriptive, focusing on the spatial distribution of model outputs without explicitly analysing how landscape connectivity structures sediment regulation processes and ecosystem service delivery (López-Vicente and Ben-Salem 2019; Hooke and Souza 2021).

In this context, the present study applies the InVEST SDR model to the Nfifikh watershed to examine how landscape connectivity controls sediment regulation ecosystem services in a semi-arid Mediterranean setting. The study explicitly links soil loss, sediment delivery efficiency, sediment export, and deposition to connectivity patterns across major geomorphic units. By operationalising sediment regulation through indicators such as avoided soil erosion and avoided sediment export, this work addresses the following research question: how does landscape connectivity mediate the transformation of potential soil erosion into effective sediment export and retention within semi-arid Mediterranean watersheds? The study aims to contribute to the international literature by providing a connectivity-based interpretation of sediment regulation ecosystem services that is transferable to other data-scarce Mediterranean and dryland basins, and by supporting more targeted and spatially differentiated soil and water conservation strategies.

The main objectives of this study are to:

- Assess sediment regulation ecosystem services in a semi-arid Mediterranean watershed by linking soil erosion, sediment delivery, export, and deposition processes.
- Analyse the role of landscape connectivity in controlling sediment transfer efficiency and internal sediment retention across major geomorphic units.
- Apply the InVEST Sediment Delivery Ratio model as an operational tool to derive spatial indicators of sediment regulation, including avoided soil erosion and avoided sediment export.
- Provide a connectivity-based interpretation of sediment regulation processes with relevance for watershed management and land-use planning in semi-arid Mediterranean environments.

2 Materials and methods

2.1. Study area and data sources

The Nfifikh watershed is located in western Morocco within the Casablanca-Settat region and forms part of the Atlantic coastal hydrographic system (Fig. 1).

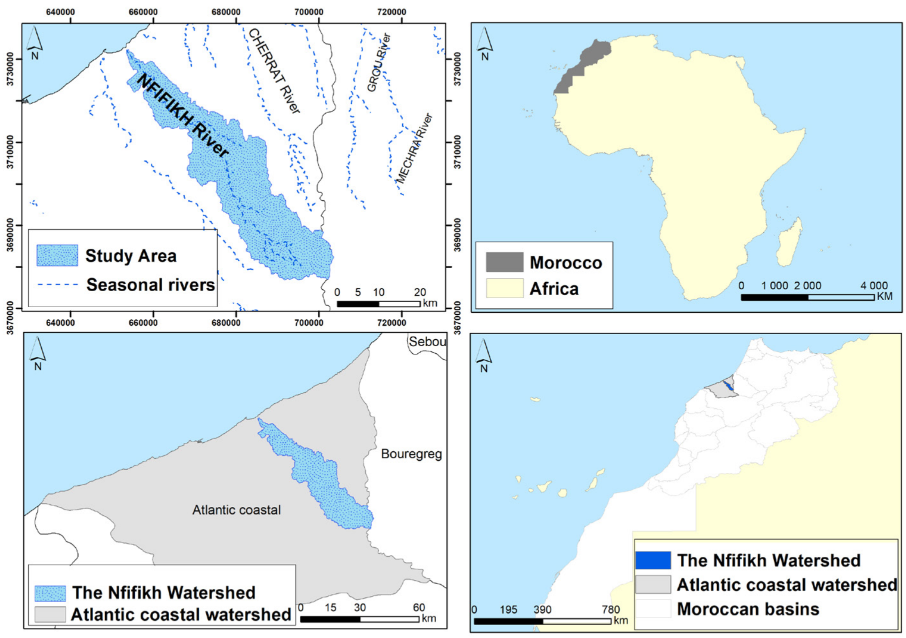

Figure 1. Study Area of the Nfifikh Watershed.

The basin exhibits pronounced topographic variability, with elevations ranging from approximately 2 m in the downstream plains to more than 800 m in the upstream mountainous sectors. These sharp elevation gradients strongly influence slope steepness, drainage density, and sediment transfer pathways, making the watershed particularly sensitive to erosion and sediment redistribution processes that are central to sediment regulation in semi-arid Mediterranean environments (Fig. 2).

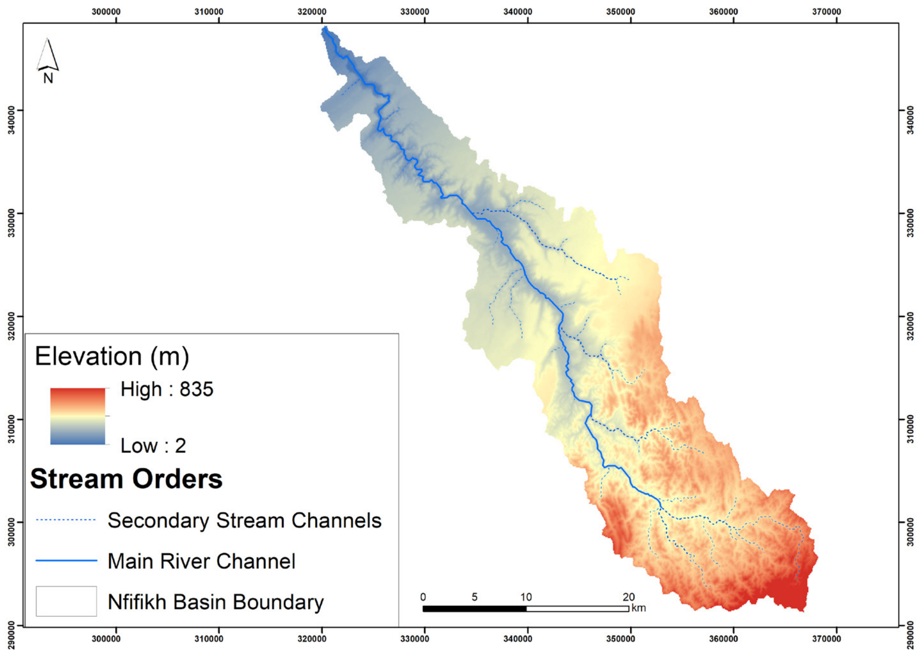

Figure 2. Digital Elevation Model (DEM) and stream network of the Nfifikh Watershed.

For interpretation purposes, the watershed was divided into four geomorphic units representing major landscape settings: upstream steep hillslopes, central dissected terrain, mid-basin agricultural slopes, and downstream plains. The geomorphic units were delineated based on elevation, slope gradients derived from the DEM, and visual interpretation of topography and drainage patterns. These units were used for zonal statistics of soil loss, SDR, and sediment export in order to compare sediment dynamics across the watershed.

The climate of the Nfifikh Watershed is semi-arid to sub-humid Mediterranean, characterized by high interannual rainfall variability. Mean annual precipitation ranges between 350 and 600 mm, with rainfall concentrated mainly during winter months, while mean annual temperatures vary between 16°C and 20°C. Recurrent droughts and irregular rainfall events linked to regional climate variability further enhance runoff generation and erosion susceptibility across the basin (Schilling et al. 2020).

Land-use and land-cover patterns in the watershed are highly heterogeneous (Fig. 3A). Agricultural land, dominated by cereal cultivation and grazing, covers large portions of the basin and frequently extends onto sloping terrain, increasing erosion risk (Gourfi et al. 2018). Forest cover is fragmented and primarily concentrated in upstream areas, while urban zones are expanding in downstream sectors. Soil types (Fig. 3B) range from sandy to clay-rich textures, with marked spatial variability in organic carbon (OC) content, cation exchange capacity (CEC), and $CaCO_3$ concentration (Table 1), all of which influence soil erodibility and sediment detachment potential.

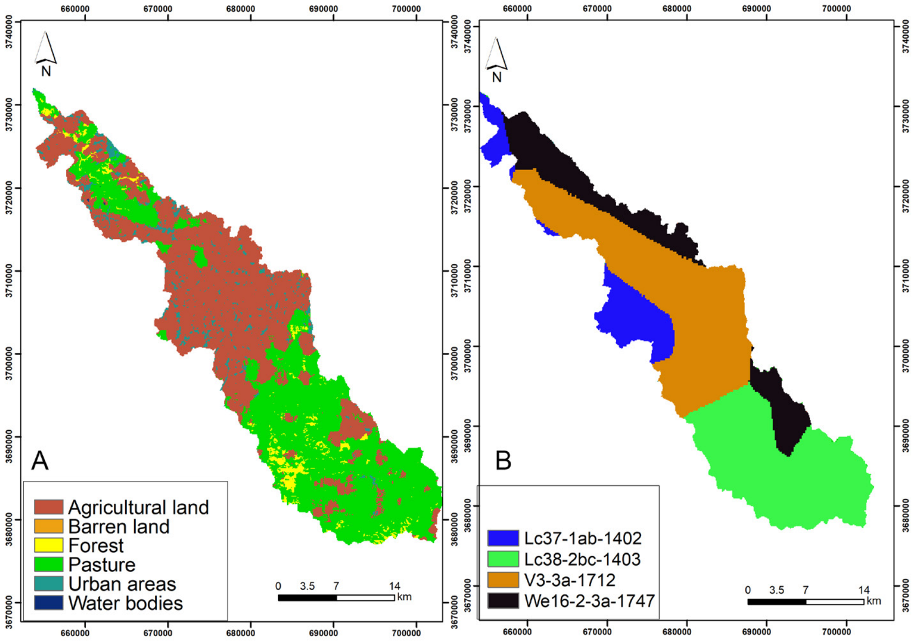

Figure 3. Nfifikh Watershed characteristics. **A** land use categories **B** soil mapping for InVEST modeling.

Table 1. Soil properties of the main soil units in the Nfifikh Watershed.

Soil unit	Sand % (Top/Sub)	Silt % (Top/ Sub)	Clay % (Top/ Sub)	pH (Top/ Sub)	OC % (Top/ Sub)	CEC (cmol/kg) Top/Sub	CaCO3 % Top/ Sub
LC37-1ab-1402	64.3 / 59	12.2 / 11.2	23.5 / 29.8	6.4 / 6.5	0.63 / 0.35	13.1 / 14.7	0.2 / 0.9
LC38-2bc-1403	29.2 / 31.4	13.6 / 12.3	57.3 / 56.6	6.5 / 6.8	1.51 / 0.48	21.7 / 19.1	0.5 / 6.5
V3-3a-1712	24.6 / 22.4	14.4 / 13.4	61.0 / 64.2	7.3 / 7.7	0.68 / 0.61	48.7 / 56	1.8 / 4.7
We16-2-3a-1747	76.6 / 68.9	10.3 / 7.5	13.1 / 23.4	6.2 / 6.4	0.46 / 0.24	8.4 / 14	0.0 / 0.1

The Nfifikh watershed is characterized by a dense dendritic drainage network shaped by steep slopes and incised channels. High values of the slope length-steepness (LS) factor (Fig. 4A) and the Index of Connectivity (IC) (Fig. 4B) indicate strong hydrological and sediment connectivity, consistent with patterns reported in other Moroccan semi-arid basins (Alitane et al. 2022; Lamane et al. 2022). These characteristics make the watershed a representative case study for analysing sediment regulation ecosystem services, as they directly control sediment transfer efficiency, internal sediment retention, and the spatial organization of connectivity-driven sediment pathways.

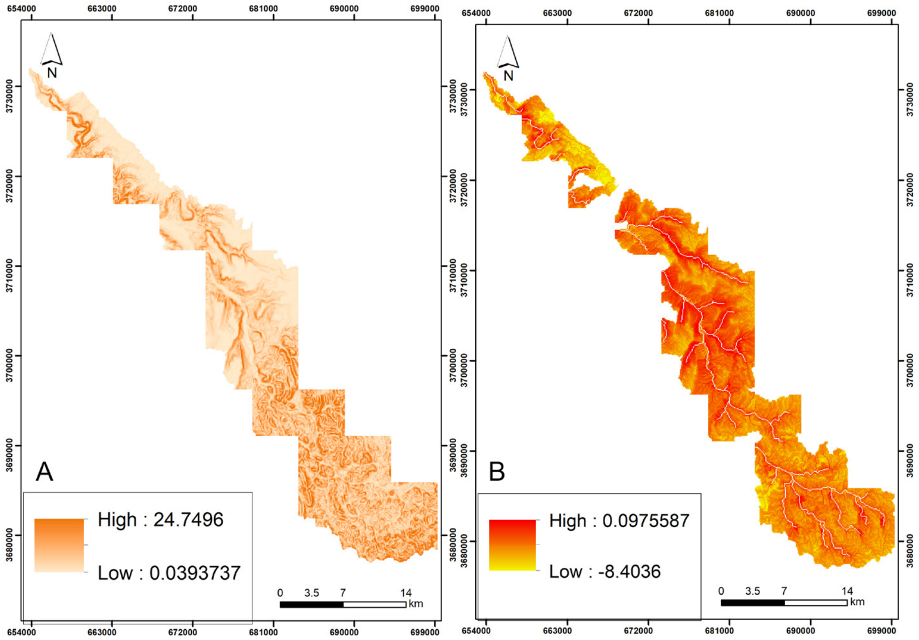

Figure 4. Topographic controls on erosion processes in the Nfifikh Watershed. **A** slope length-steepness factor **B** Index of Connectivity.

2.2. Methodological approach

This study adopts a connectivity-based methodological approach to assess sediment regulation ecosystem services in a semi-arid Mediterranean watershed. The approach is conceptually structured around the relationships between soil erosion, sediment transfer efficiency, and sediment retention, and is operationalized through the InVEST SDR model. Rather than developing an independent modelling workflow, the approach relies on the InVEST SDR model as an integrated operational tool to quantify erosion-related processes and to derive spatial indicators relevant for sediment regulation.

As illustrated in Fig. 5, the methodological approach follows four main analytical steps. First, potential soil loss is estimated using USLE-based factors in order to represent spatial patterns of soil detachment. Second, sediment transfer efficiency is characterized through landscape connectivity metrics derived from topographic attributes, reflecting the capacity of the landscape to route sediment from hillslopes to the drainage network. Third, sediment export and deposition are simulated using the InVEST SDR model, which integrates soil loss estimates with connectivity-driven routing to distinguish between potential erosion and effective sediment delivery. Finally, sediment regulation ecosystem services are assessed through derived indicators of avoided soil erosion and avoided sediment export, which represent the capacity of existing land cover and landscape structure to mitigate soil loss and retain sediment within the watershed.

This approach enables an explicit differentiation between potential soil detachment and effective sediment contribution to the river network, which is essential for interpreting sediment regulation processes in semi-arid environments. By linking erosion processes with landscape connectivity and internal

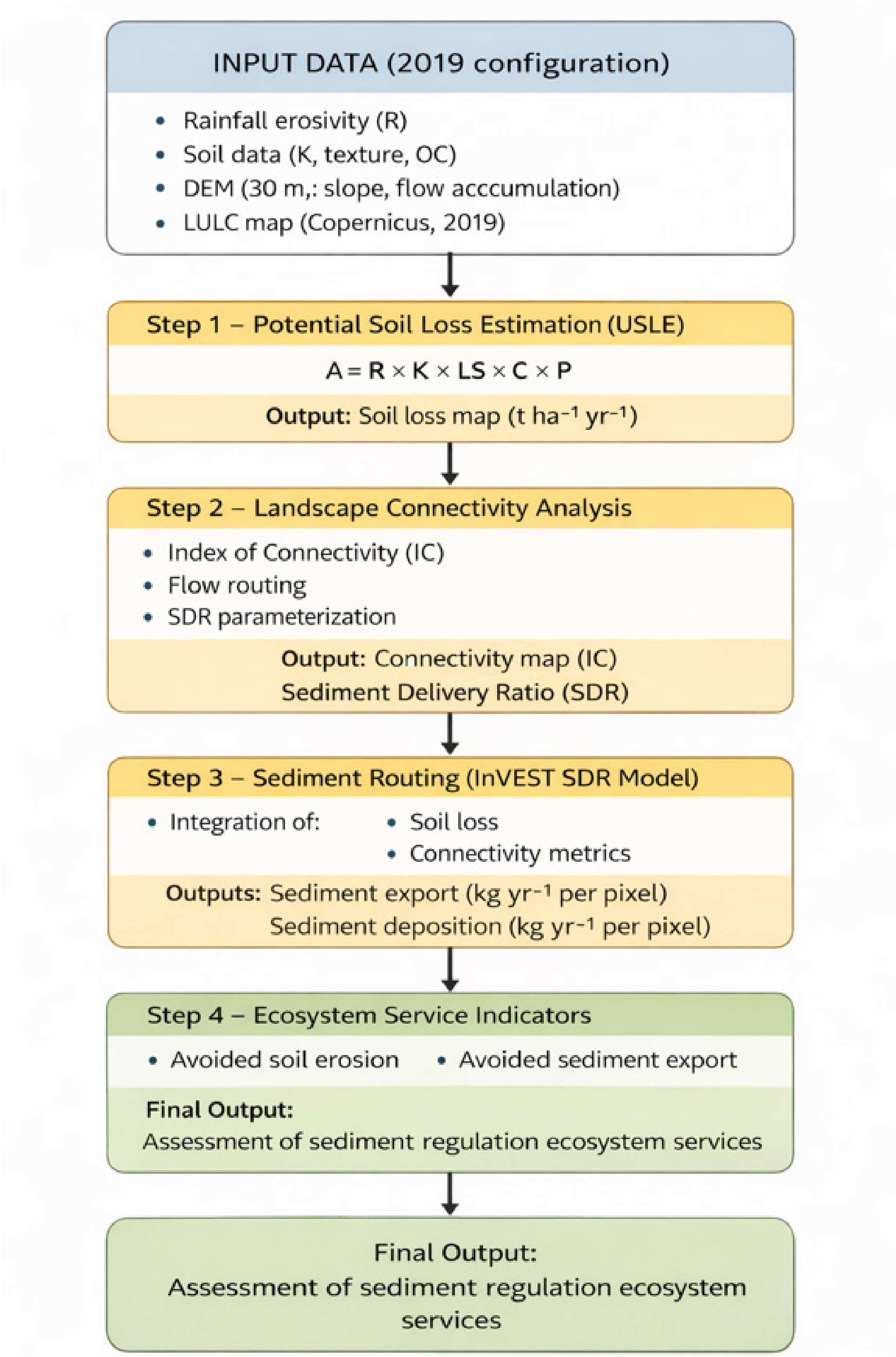

Figure 5. Methodological approach for sediment regulation assessment in the Nfifikh Watershed.

sediment buffering mechanisms, the approach provides a coherent basis for assessing sediment regulation ecosystem services rather than focusing solely on erosion intensity.

Fig. 6 presents the configuration and parameterisation of the InVEST SDR model used to operationalize this approach. The model inputs include the digital elevation model, rainfall erosivity factor, soil erodibility factor, land use and land cover data, and the associated biophysical table, all prepared at a consistent spatial resolution and coordinate system. The hydrological and sediment-routing settings, including the watershed boundary, D8 flow direction algorithm, flow accumulation threshold, and Borselli connectivity parameters, define the model's internal workflow for simulating soil loss, sediment transfer efficiency, sediment export, and sediment retention within the Nfifikh watershed.

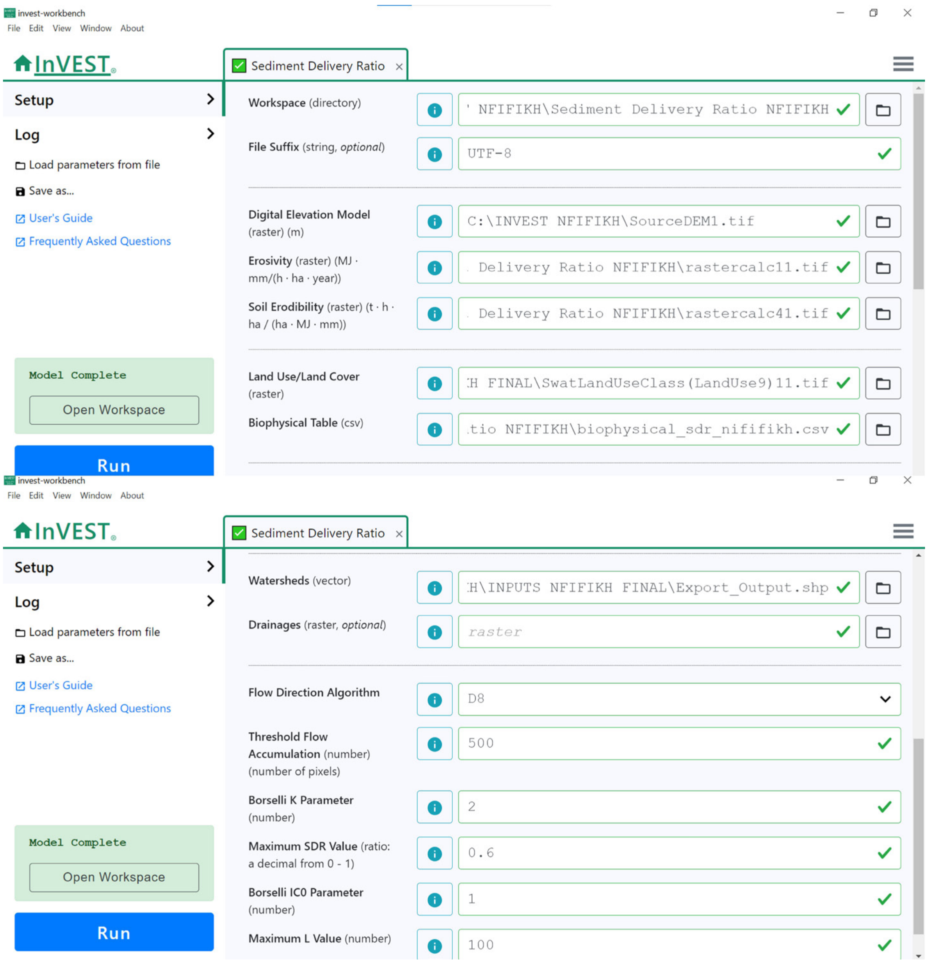

Figure 6. InVEST SDR model interface used for parameter configuration.

2.3. Input datasets and spatial preprocessing

A set of spatial datasets was prepared to operationalize the connectivity-based assessment of sediment regulation ecosystem services using the InVEST SDR model. All datasets were selected based on their spatial coverage, temporal representativeness, and suitability for watershed-scale modelling in semi-arid Mediterranean environments such as Morocco.

A Digital Elevation Model (DEM) with a spatial resolution of 30 m was derived from the Shuttle Radar Topography Mission (SRTM v3, NASA/USGS, year 2000) and downloaded from the USGS EarthExplorer platform (USGS 2000). The dataset provides near-global coverage and fully covers Morocco. The DEM was projected to WGS84 / UTM Zone 29N and used to derive slope, flow routing, drainage network, LS factor and Index of Connectivity.

Land-use and land-cover data were obtained from the Copernicus Global Land Cover product (Collection 3, reference year 2019, 100 m spatial resolution) (ESA 2019), which provides consistent global coverage, including North

Africa. The dataset was reclassified to match the requirements of the InVEST SDR model and to assign USLE C and P factors. Although land-cover datasets are available for multiple years, the present study uses a single reference year (2019) to represent current watershed conditions. The analysis, therefore, represents a static assessment rather than a multi-temporal comparison. Soil properties were derived from the FAO Harmonized World Soil Database (HWSD version 1.2) (FAO 2012), which provides consistent soil information for Morocco and was used to characterize soil erodibility. Rainfall erosivity (R factor) and soil erodibility (K factor) layers were obtained from the European Soil Data Centre (ESDAC) global soil erosion database (ESDAC 2015). These datasets provide continuous spatial coverage for Europe and North Africa and are consistent with the RUSLE modelling framework. Although originally developed for European applications, they have been successfully used in Mediterranean and semi-arid environments where local rainfall erosivity and soil erodibility data are limited. All spatial datasets were resampled to a common spatial resolution of 30 m and projected to WGS84 / UTM Zone 29N prior to modelling in order to ensure spatial consistency during sediment routing.

Table 2. Spatial datasets used in the InVEST SDR model.

Dataset	Product name	Version / Year	Resolution	Coverage	CRS	Source	Suitability for Moroccan context
DEM	Shuttle Radar Topography Mission (SRTM)	Version 3 – 2000	30 m	Global (Morocco included)	WGS84 / UTM Zone 29N	USGS EarthExplorer	Widely used in hydrological and erosion modelling in Moroccan watersheds and suitable for basin-scale analysis
Land Use/ Land Cover	Copernicus Global Land Cover (CGLS-LC100)	Collection 3 – 2019	100 m	Global (North Africa included)	WGS84 / UTM Zone 29N	Copernicus Programme	Provides consistent land-cover information for North Africa and suitable for ecosystem service modelling
Soil data	Harmonized World Soil Database (HWSD)	Version 1.2 – 2012	1 km	Global (Morocco included)	WGS84	FAO	Provides consistent soil information for Morocco and supports derivation of soil erodibility
Rainfall erosivity (R)	Global Rainfall Erosivity Database	ESDAC – 2015	1 km	Europe + North Africa	WGS84	European Soil Data Centre (ESDAC)	Compatible with Mediterranean semi-arid environments and suitable for regional erosion modelling
Soil erodibility (K)	Global Soil Erodibility Dataset	ESDAC – 2015	500 m–1 km	Europe + North Africa	WGS84	European Soil Data Centre (ESDAC)	Provides consistent K factor values in data-scarce regions, including Morocco

Table 2 summarizes the data requirements and sources used to implement the InVEST SDR model for assessing sediment regulation ecosystem services in the Nfifikh watershed. Biophysical parameters required by the model, including C and P factors, were assigned to each land-use class based on values reported in the literature and InVEST documentation. This preprocessing ensured coherence between erosion estimation, landscape connectivity analysis, and sediment routing within the modelling framework.

All spatial datasets were projected to the WGS84 / UTM Zone 29N coordinate system and resampled to a common spatial resolution of 30 m to ensure spatial consistency in the InVEST SDR model. Land use/land cover data were obtained from the Copernicus Global Land Cover product (Collection 3, 2019, 100 m resolution) and resampled to match the 30 m DEM resolution used for terrain analysis.

2.4. InVEST SDR parameterization and reproducibility

The sediment delivery process was simulated using the SDR module of the InVEST model. The model was parameterized following the recommendations of the InVEST User Guide and previous applications in semi-arid Mediterranean environments. Parameter values were selected to ensure consistency between erosion estimation, landscape connectivity analysis, and sediment routing within the Nfifikh watershed. Table 3 summarizes the main parameters used in the SDR model configuration.

Table 3. InVEST SDR model parameters.

Parameter	Value	Unit	Source / Justification
Pixel size	30	m	Consistent with DEM resolution
k parameter	2	–	Default InVEST value (Sharp et al. 2020)
IC0	0.5	–	Default InVEST parameter
SDRmax	0.8	–	Recommended value for Mediterranean basins
Threshold flow accumulation	1000	pixels	Defines stream initiation
Flow routing	D8	–	Standard hydrological routing
Watershed shapefile	Nfifikh basin	–	Derived from DEM

The complete biophysical table, including the C and P factors assigned to each land-use class, is provided in Suppl. material 1. Providing the full parameter set and biophysical table ensures full reproducibility of the SDR modelling procedure.

2.5. InVEST SDR model and sediment regulation indicators

InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) is a suite of spatially explicit ecosystem service models developed by the Natural Capital Project to support decision-making in land-use planning and natural resource management. The framework is designed to translate biophysical processes into ecosystem service indicators relevant for policy makers, planners, and researchers, rather than to simulate detailed process-based hydrological dynamics. In this study, InVEST provides an appropriate modelling environment for addressing sediment regulation ecosystem services, as it explicitly links land cover, topography, and sediment transfer pathways within a spatially explicit, decision-support perspective.

Within this framework, the InVEST SDR model was employed as an operational tool to characterize spatial patterns of soil loss, sediment delivery efficiency, sediment export, and sediment retention. The model integrates USLE-based soil loss estimates with a connectivity-driven routing function, allowing differentiation between potential soil detachment and effective sediment delivery to the drainage network. This approach explicitly accounts for topographic controls, flow accumulation, and downslope sediment transfer pathways, which are known to strongly influence erosion and sediment redistribution processes under variable climatic and land-cover conditions (Li and Fang 2016). Connectivity-based modelling frameworks of this type are increasingly recognized as essential for capturing the spatial complexity of regulating ecosystem services in heterogeneous landscapes (Nedkov et al. 2022).

To operationalize sediment regulation ecosystem services, two quantitative indicators were derived from the InVEST SDR model outputs: avoided soil erosion and avoided sediment export. Avoided soil erosion represents the reduction in potential soil loss attributable to existing vegetation cover and land-use conditions, while avoided sediment export quantifies the proportion of mobilized sediment that is retained within the landscape before reaching the river network through internal buffering mechanisms and disrupted connectivity. These indicators translate biophysical erosion and sediment transfer processes into spatially explicit measures of sediment regulation capacity, consistent with ecosystem service assessments that emphasize the role of land management and vegetation dynamics in moderating erosion and material fluxes across geomorphic units (Li et al. 2021).

The resulting indicators are analysed and interpreted in the Results section as representations of sediment regulation ecosystem services across major geomorphic units and land-use classes. In this way, the InVEST SDR model outputs are not treated as descriptive maps of erosion or sediment fluxes, but as quantitative indicators that support the assessment of sediment regulation services for land-use planning and watershed management. This interpretation is consistent with previous applications of InVEST in water-related ecosystem service modelling (Zhang et al. 2012; Redhead et al. 2016; Yin et al. 2020).

2.6. Model outputs and ecosystem-service indicator definition

All model outputs were generated using the InVEST SDR model at a spatial resolution of 30 m, corresponding to the resolution of the digital elevation model and the land-use dataset. Soil loss values represent average annual erosion rates expressed in t ha^{-1} yr^{-1} and correspond to pixel-based estimates derived from the RUSLE formulation implemented within the SDR module.

Sediment export and sediment deposition are expressed in kg yr^{-1} per pixel and represent the annual mass of sediment effectively delivered to the stream network or retained within each grid cell. Basin-scale sediment export was obtained by spatial aggregation of pixel-based values over the entire watershed.

These definitions ensure consistency between spatially distributed results and basin-scale estimates.

Sediment regulation ecosystem-service indicators were derived from the comparison between potential soil erosion and effective sediment export simulated by the SDR model. Avoided soil erosion (Eq. 1) was defined as the difference between potential soil loss and estimated soil loss under current land-cover conditions:

Avoided soil erosion = A_potential – A_actual (Eq. 1)

Where A_potential represents soil loss assuming minimal vegetation protection (C = 1 and P = 1), and A_actual corresponds to soil loss calculated using observed land-use conditions.

Avoided sediment export (Eq. 2) was defined as the difference between total soil loss and effective sediment export:

Avoided sediment export = Soil loss – Sediment export (Eq. 2)

These indicators represent the sediment-retention capacity of the landscape and quantify the buffering role of vegetation cover and low-connectivity areas in reducing sediment transfer. The definitions adopted in this study are consistent with the sediment regulation framework implemented in the InVEST SDR model and ensure the physical consistency of ecosystem-service estimates.

2.7. Data analysis and result synthesis

Model outputs were analysed through spatial cross-comparison of soil loss, SDR, sediment export, and sediment deposition in order to distinguish between potential soil erosion, effective sediment transfer to the drainage network, and internal sediment retention within the landscape. This analysis provided the basis for identifying dominant sediment source areas, zones of efficient sediment delivery, and effective sediment sinks across the watershed.

Zonal statistics were applied to synthesise model outputs across major geomorphic units and land-use classes, allowing comparison of erosion intensity, sediment transfer efficiency, and deposition patterns under contrasting topographic and land-cover conditions. Particular attention was given to the spatial relationships between these processes and landscape connectivity.

In addition, selected model outputs were interpreted as indicators of sediment regulation ecosystem services, focusing specifically on avoided soil erosion and avoided sediment export. These indicators were analysed in the Results section to evaluate the capacity of existing land cover and landscape configuration to mitigate soil loss and retain sediment within the watershed.

3. Results

3.1. Spatial patterns of soil loss and sediment delivery potential

Soil loss and sediment transfer processes exhibit pronounced spatial variability in semi-arid Mediterranean watersheds, where steep topography and heterogeneous land cover strongly modulate erosive responses to rainfall. In the Nfifikh watershed, the combined analysis of USLE-based soil loss estimates and the SDR provides insight into the distinction between potential soil detachment and effective sediment transfer, which is essential for identifying dominant sediment source areas.

Fig. 7A illustrates clear geomorphic contrasts in soil loss (e') across the watershed. Low to moderate soil loss values (<2 t/ha/year) dominate the southern and downstream plains, reflecting gentler slopes and relatively denser vegetation cover. In contrast, high soil loss values (>16 t/ha/year) are concentrated on steep and sparsely vegetated northern and central hillslopes, consistent with erosion patterns reported in Mediterranean and North African environments (García-Ruiz et al. 2013).

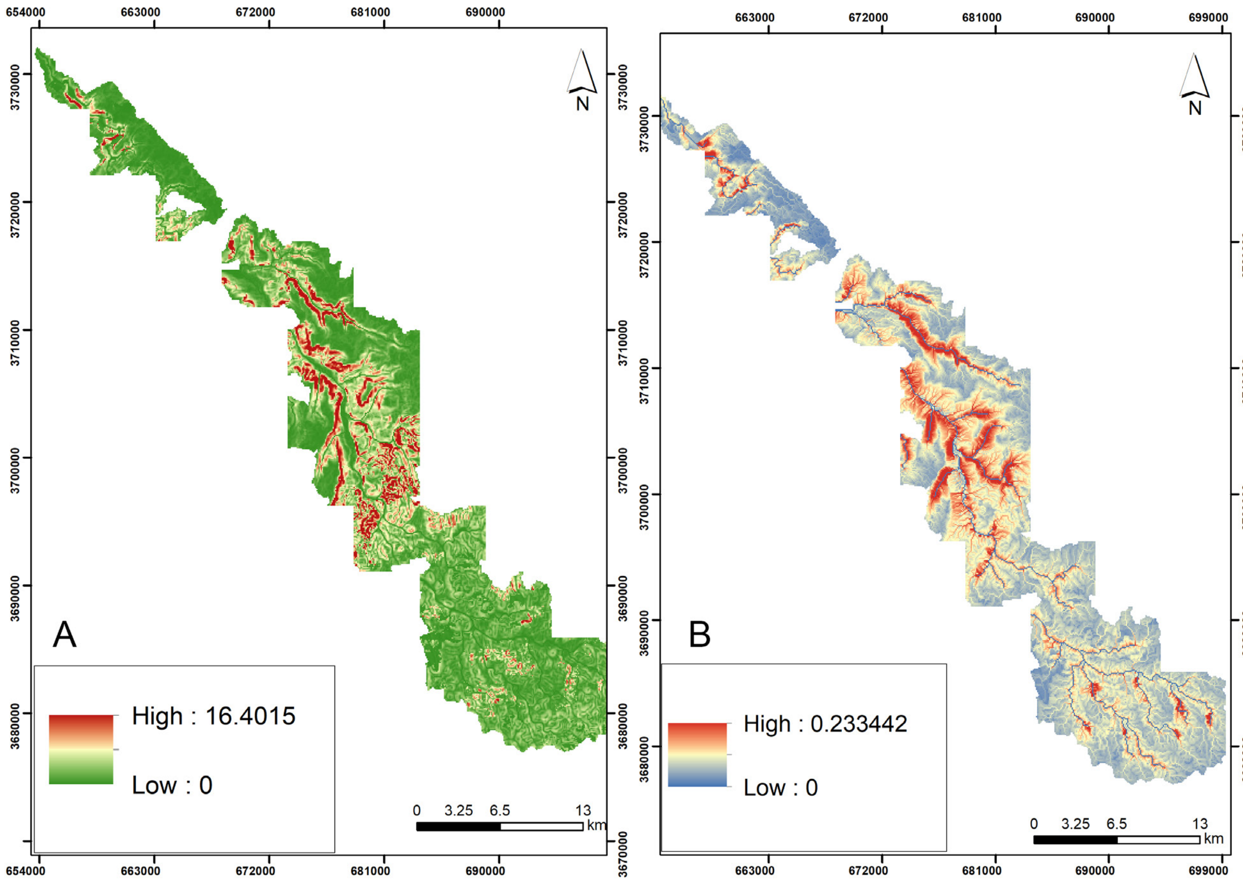

Figure 7. Spatial patterns of soil loss and sediment delivery potential across the Nfifikh Watershed. **A** soil loss (t ha^{-1} yr^{-1}) **B** sediment delivery ratio factor.

The spatial distribution of the SDR factor (Fig. 7B) reveals a markedly different pattern. High SDR values (>0.15) are primarily associated with rugged and highly connected upstream sub-watersheds, indicating efficient sediment routing toward the drainage network (Crema and Cavalli 2018). Conversely, low SDR values (<0.05) prevail across large portions of the mid- and downstream basin, where wide valley floors, agricultural land use, and reduced slope gradients limit sediment connectivity and promote local deposition.

Cross-comparison of soil loss and SDR highlights a clear decoupling between erosion intensity and sediment delivery efficiency. Several areas characterized by high soil loss exhibit low SDR values, reflecting strong local detachment but limited sediment transfer due to disrupted connectivity, a pattern widely documented in sediment transfer studies (Heckmann et al. 2018). In contrast, zones where high soil loss coincides with high SDR define the principal sediment-contributing sectors of the watershed and represent priority areas for erosion control and conservation interventions.

This relationship is summarized in Table 4, which demonstrates how landscape units with similar soil loss intensities may display contrasting sediment delivery behavior depending on their connectivity level. Steep northern hillslopes combine high soil loss with high SDR, functioning as major sediment source zones with rapid downstream transfer. Central dissected terrains show active detachment but only partial delivery, while mid-basin agricultural slopes and downstream plains act as sediment buffering zones characterized by moderate to low connectivity. These patterns are consistent with regional findings on connectivity-controlled sediment dynamics in Mediterranean basins (Borrelli et al. 2017).

Table 4. Summary of soil loss, SDR values and connectivity characteristics across geomorphic units in the Nfifikh Watershed.

Geomorphic unit	Soil loss (t/ha/year)	SDR range	Connectivity level	Sediment dynamics interpretation
Upstream steep hillslopes	12–21+	0.12–0.18	High	Major sediment source areas with efficient sediment transfer toward the drainage network
Midstream dissected terrain	6–14	0.08–0.12	Moderate–High	Active erosion with partial sediment delivery and intermediate connectivity
Mid-basin agricultural slopes	2–6	0.04–0.08	Moderate	Moderate erosion with limited sediment transfer efficiency
Downstream plains and valley floors	<2	0.01–0.05	Low	Sediment deposition zones acting as natural sediment buffers

3.2. Sediment export and deposition patterns

Spatial patterns of sediment export and deposition simulated by the InVEST SDR model further clarify the distinction between potential sediment production and effective downstream transfer in the Nfifikh watershed. As shown in Fig. 8A, sediment export is strongly concentrated along steep northern and central hillslopes, where high landscape connectivity and short flow paths promote efficient sediment routing toward the drainage network. Export values in these sectors reach nearly 5 kg/year, consistent with sediment transfer dynamics reported for semi-arid Mediterranean basins characterized by rugged terrain and limited internal buffering (Crema and Cavalli 2018).

In contrast, downstream and low-gradient areas exhibit consistently low sediment export rates. Gentler slopes, wider valley floors, and denser vegetation cover in these sectors reduce sediment connectivity, enhance infiltration, and favor local sediment trapping, thereby limiting effective sediment delivery to the river system (Heckmann et al. 2018). These spatial contrasts confirm that sediment export is not solely controlled by erosion intensity but is strongly mediated by the efficiency of sediment transfer pathways.

Sediment deposition patterns provide complementary insight into internal sediment buffering processes within the watershed. High deposition values, exceeding 1100 kg/year, are concentrated in low-lying alluvial pockets and wide valley floors (Fig. 8B), highlighting the role of these areas as natural sediment sinks. Such depositional zones intercept sediment mobilized from upstream hillslopes before it reaches the main channel network, a behavior widely documented in North African and Mediterranean landscapes (Gourfi et al. 2018).

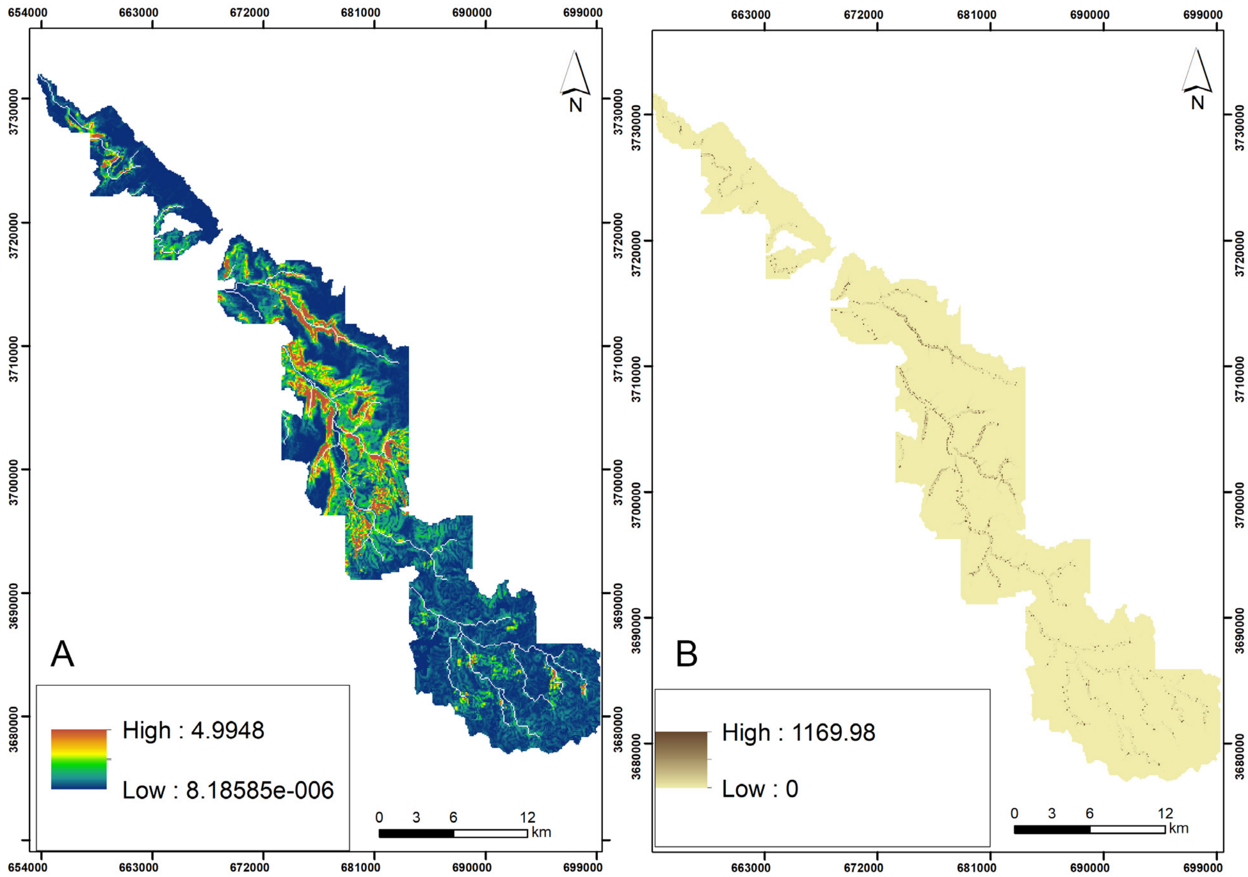

Figure 8. Spatial distribution of sediment simulated by the InVEST SDR model in the Nfifikh Watershed. **A** sediment export (kg yr^{-1} per pixel) **B** sediment deposition (kg yr^{-1} per pixel).

Cross-comparison of sediment export and deposition patterns reveals that some steep hillslopes generate sediment but do not contribute proportionally to downstream sediment loads. This decoupling reflects connectivity thresholds that limit sediment transfer despite active erosion processes, underscoring the central role of landscape connectivity in defining effective sediment source and sink areas (Fryirs 2013). Together, these results emphasize that sediment export and deposition patterns represent emergent properties of the watershed's internal connectivity structure rather than simple reflections of erosion magnitude.

3.3 Sediment regulation ecosystem services: avoided soil erosion and avoided sediment export

The InVEST SDR model outputs provide spatially explicit indicators of sediment regulation services delivered by existing land cover in the Nfifikh watershed. In particular, the avoided soil erosion and avoided sediment export maps (Fig. 9) illustrate the capacity of forests, rangelands, agricultural mosaics, and riparian vegetation to mitigate erosion processes and to limit the transfer of mobilized sediment toward the river network.

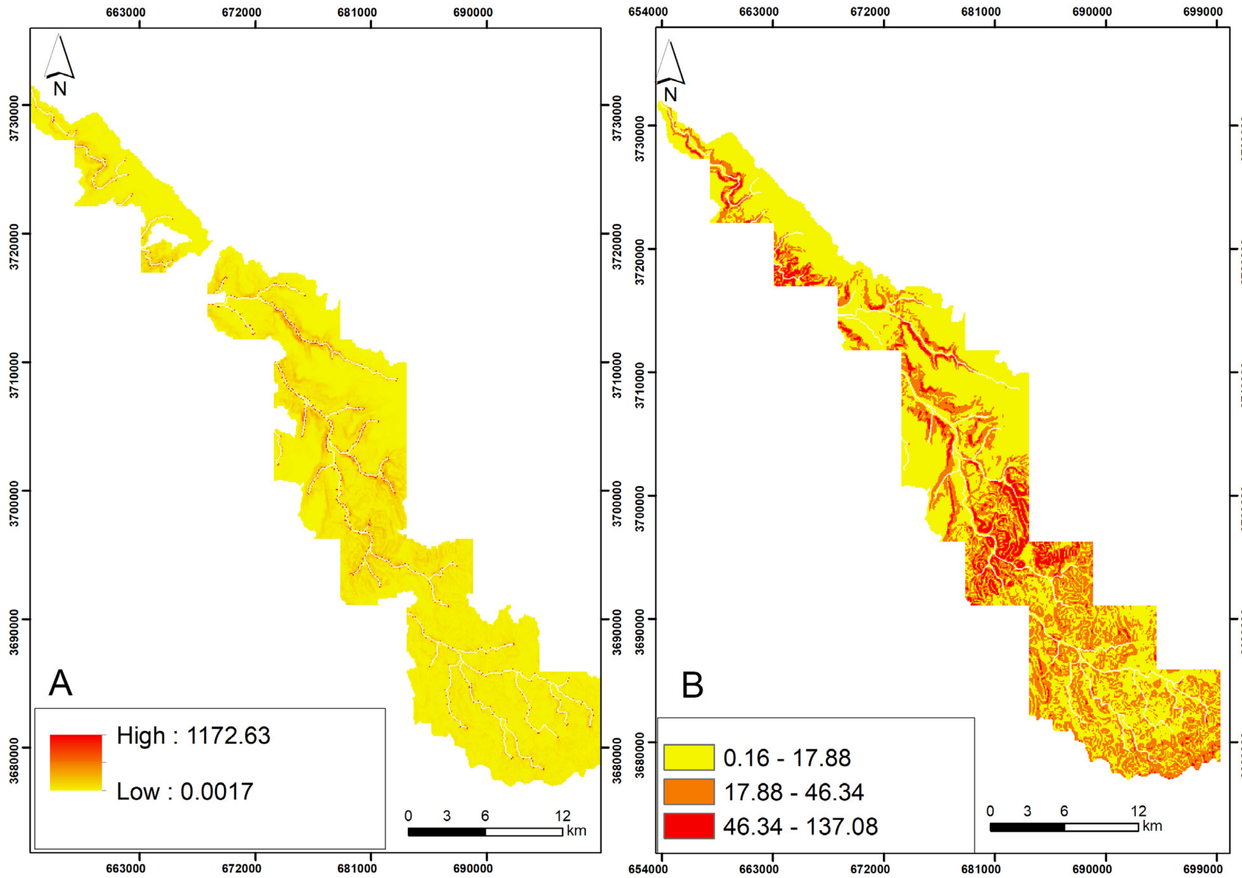

Figure 9. Spatial distribution of sediment regulation ecosystem services in the Nfifikh Watershed under current land-cover conditions. **A** avoided sediment export (kg yr^{-1}) **B** avoided soil erosion (t ha^{-1} yr^{-1}).

The spatial distribution of avoided sediment export shows relatively uniform values across much of the watershed, with pronounced hotspots exceeding 1170 kg/year in midstream and downstream sectors (Fig. 9A). These areas are typically characterized by gentle slopes, agricultural land interspersed with riparian buffers, and wide valley floors that favor sediment deposition and retention. Such land-cover mosaics enhance internal sediment trapping and reduce effective sediment delivery, a pattern consistent with observations from Mediterranean basins where vegetation heterogeneity plays a key role in sediment regulation (Mueller et al. 2010).

In contrast, avoided soil erosion (Fig. 9B) exhibits strong spatial variability, with the highest values, reaching up to 137 t/ha/year, concentrated in steep and dissected northern and central hillslopes. Despite high erosion potential in these areas, vegetation cover and surface roughness substantially reduce soil detachment, reflecting erosion mitigation processes widely documented in mountainous and semi-arid drylands (Borrelli et al. 2017). These results indicate that erosion control services are most pronounced in topographically constrained sectors where slope-driven erosion forces are strongest.

Comparison of avoided erosion and avoided sediment export patterns highlights a clear functional distinction between erosion mitigation and sediment retention services. Avoided soil erosion is primarily controlled by slope gradients and soil erodibility, whereas avoided sediment export is more strongly influenced by landscape connectivity and downstream deposition potential. Consequently, areas exhibiting high avoided erosion in upstream sectors do not necessarily correspond to high avoided sediment export, as mobilized sediment may still be retained within internal buffering zones before reaching stream channels. This decoupling reflects connectivity thresholds that regulate sediment transfer efficiency and has been widely reported in sediment cascade studies (Heckmann et al. 2018).

To complement the spatial analysis, Table 5 synthesizes avoided soil erosion and avoided sediment export values across the main geomorphic units of the Nfifikh watershed. Steep northern slopes show high avoided erosion due to vegetation cover despite intense erosive forces, while central dissected hillslopes exhibit intermediate regulation capacities associated with mixed land cover and moderate connectivity. Midstream riparian corridors emerge as effective sediment retention zones, whereas downstream agricultural plains display low avoided export values, reflecting their natural function as sediment sinks. Together, these results confirm that sediment regulation services in the watershed arise from the combined influence of topography, land-cover configuration, and landscape connectivity, in agreement with findings reported by Mueller et al. (2010), Borrelli et al. (2017), and Heckmann et al. (2018).

Table 5. Summary of avoided soil erosion and avoided sediment export across major geomorphic zones in the Nfifikh Watershed (based on Fig. 9).

Geomorphic zone	Avoided soil erosion (t/ha/year)	Avoided sediment export (kg/year)	Dominant controlling factors
Steep northern slopes	46–137	150–420	High relief, dense vegetation patches, disrupted connectivity
Central dissected hillslopes	18–46	300–1170	Mixed land cover, moderate connectivity, transitional slopes
Midstream riparian corridors	5–18	500–900	Riparian vegetation, flow concentration, sediment trapping
Downstream agricultural plains	0.2–5	0.1–50	Gentle slopes, high infiltration, low connectivity

3.4. Quantitative relationship between connectivity and sediment export

The connectivity-based interpretation proposed in this study was further evaluated through a quantitative analysis of the relationships between connectivity indicators and sediment export. Pixel-based values of the IC, SDR, soil loss, and sediment export were extracted from the model outputs and compared using Pearson correlation analysis.

Results indicate a strong positive relationship between connectivity indicators and sediment export, whereas the relationship between soil loss and sediment export is considerably weaker. Sediment export shows a strong correlation with SDR (r = 0.72) and IC (r = 0.68), while the correlation with soil loss is lower (r = 0.39).

These results demonstrate that areas characterized by high erosion rates do not necessarily correspond to high sediment export, particularly in upstream zones where connectivity is limited. Conversely, areas with moderate erosion but higher connectivity exhibit higher sediment delivery efficiency.

This quantitative analysis confirms that sediment delivery in the Nfifikh Watershed is primarily controlled by landscape connectivity rather than erosion intensity alone. The results therefore provide quantitative support for the connectivity-based interpretation and demonstrate that connectivity metrics provide additional explanatory power beyond erosion intensity alone.

4. Discussion

The results of this study demonstrate that sediment regulation ecosystem services in the Nfifikh Watershed are governed by the combined influence of soil erosion potential, landscape connectivity, and land-cover configuration. Rather than being a direct function of erosion intensity alone, effective sediment transfer and sediment retention emerge as spatially heterogeneous processes controlled by connectivity-driven pathways and internal buffering mechanisms. This finding is consistent with a growing body of international research emphasizing that sediment dynamics in Mediterranean and semi-arid environments cannot be fully understood through erosion mapping alone, but require explicit consideration of landscape connectivity and sediment cascades.

4.1. Connectivity-controlled sediment dynamics and international context

The combined analysis of soil loss and SDR reveals a clear decoupling between potential soil detachment and effective sediment delivery to the river network. Although high soil loss values are concentrated on steep and sparsely vegetated northern and central hillslopes, only a subset of these areas exhibits high sediment delivery efficiency. This confirms that landscape connectivity plays a critical role in regulating sediment transfer, as areas with disrupted or low connectivity may generate sediment without contributing significantly to downstream sediment loads. Similar connectivity-controlled sediment dynamics have been widely documented in Mediterranean and mountainous environments, where threshold-driven transport and internal storage processes limit sediment propagation (García-Ruiz et al. 2013; Heckmann et al. 2018).

The sediment export and deposition patterns further reinforce this interpretation. High sediment export is restricted to well-connected upstream sectors characterized by short flow paths and limited depositional opportunities, whereas extensive mid- and downstream zones function as sediment sinks. These internal buffering areas intercept mobilized sediment before it reaches the main drainage network, reflecting sediment cascade behaviour reported in semi-arid

Mediterranean and North African basins with complex valley morphology and heterogeneous land-cover mosaics (Mueller et al. 2010; Gourfi et al. 2018). Comparable spatial contrasts between erosion-prone source areas and downstream depositional zones have also been identified in recent basin-scale erosion studies, which highlight the role of topography and land cover in controlling erosion sensitivity and sediment redistribution (Gerdjikov et al. 2022; Durak 2024).

From an international perspective, the present study contributes to this literature by explicitly integrating connectivity metrics with sediment export and deposition modelling, thereby moving beyond erosion susceptibility mapping toward a process-oriented interpretation of sediment dynamics.

4.2. Sediment regulation ecosystem services: novelty and contribution

The analysis of avoided soil erosion and avoided sediment export provides direct evidence of sediment regulation ecosystem services delivered by existing land cover in the Nfifikh Watershed. High avoided erosion values in steep upstream sectors indicate that forests and shrublands substantially reduce soil detachment despite strong erosive forces. This erosion mitigation effect is consistent with global and regional assessments highlighting the protective role of vegetation cover in erosion-prone landscapes (Panagos et al. 2015; Borrelli et al. 2017).

In contrast, avoided sediment export exhibits a distinct spatial logic, with the highest values occurring in midstream and downstream areas characterized by gentler slopes, agricultural land interspersed with riparian vegetation, and wide valley floors. These zones enhance sediment retention through reduced connectivity and increased deposition potential, confirming that sediment retention services are primarily controlled by landscape structure and connectivity rather than erosion intensity alone. Similar patterns have been reported in Mediterranean catchments, where heterogeneous land-cover mosaics and riparian buffers act as effective sediment traps (Mueller et al. 2010; Heckmann et al. 2018), as well as in GIS-based erosion studies from southeastern Europe (Durak 2024).

The key novelty of this study lies in the explicit differentiation between erosion mitigation and sediment retention services within a connectivity-based framework. While many previous studies focus on soil erosion susceptibility or sediment yield estimation, the present approach demonstrates that high erosion control in upstream areas does not necessarily translate into proportional reductions in downstream sediment export. This distinction represents an important conceptual advance for ecosystem service assessments in semi-arid Mediterranean environments.

4.3. Advantages, limitations, and implications for watershed management

A major advantage of the proposed approach is its ability to combine widely available spatial data with a connectivity-based modelling framework to assess sediment regulation ecosystem services in data-scarce environments. The integration of InVEST SDR outputs with landscape connectivity analysis allows identification of priority erosion source areas as well as key sediment retention zones, providing information that is directly relevant for spatially targeted watershed management. This is particularly valuable in semi-arid Mediterranean regions, where land-use change and climate variability intensify erosion risks and sediment redistribution processes.

At the same time, several limitations should be acknowledged. The analysis represents long-term average spatial patterns and does not capture event-scale sediment fluxes associated with extreme rainfall or flood events. In addition, model outputs are sensitive to input data resolution and parameterisation, particularly with respect to land-cover classification and topographic representation. These limitations are inherent to spatially explicit, GIS-based modelling approaches and should be considered when interpreting the results for operational decision-making.

Despite these limitations, the study provides a transferable methodological contribution for assessing sediment regulation ecosystem services in semi-arid Mediterranean watersheds. By demonstrating how connectivity-based interpretations of InVEST SDR outputs can enhance the understanding of sediment dynamics, this work complements and extends previous erosion-focused studies (Gerdjikov et al. 2022; Durak 2024). The approach supports more robust, ecosystem-based strategies for soil and water conservation and offers a valuable framework for future comparative studies across Mediterranean and dryland regions.

4.4. Model validation and uncertainty assessment

The reliability of the model outputs was evaluated using an indirect validation approach and an assessment of potential sources of uncertainty. Direct observations of sediment yield, turbidity measurements, or reservoir siltation data were not available for the Nfifikh Watershed, which prevented a formal calibration and validation of the InVEST SDR model. Consequently, the model results should be interpreted primarily as spatially distributed indicators of relative erosion intensity and sediment delivery rather than exact quantitative estimates.

An indirect validation was performed through comparison with previously published erosion modelling results in Moroccan semi-arid environments. In particular, a recent study conducted in the High and Middle Drâa watershed using a RUSLE–SDR modelling framework reported soil loss values ranging from very low classes below 14 t ha^{-1} yr^{-1} to extreme classes exceeding 500 t ha^{-1} yr^{-1}, with low and moderate erosion classes dominating most of the watershed area and localized upstream hotspots contributing disproportionately to total sediment production (Zahli 2026). Sediment yield values in the Drâa watershed were generally below 5 t ha^{-1} yr^{-1} over large portions of the drainage network, with higher values concentrated in steep and highly connected upstream sectors.

The magnitude and spatial organization of soil loss and sediment export estimated for the Nfifikh watershed are consistent with these results. In both basins, large areas are characterized by low to moderate erosion rates, while relatively small upstream sectors exhibit high erosion potential. Similarly, sediment export is controlled by a limited number of highly connected areas, whereas large portions of the watershed function as zones of sediment retention. This agreement supports the plausibility of the model outputs and confirms the applicability of connectivity-based erosion modelling approaches in semi-arid Moroccan environments.

Uncertainty in the model outputs mainly arises from the parameterization of the SDR model and from the assignment of C and P factors to land-use classes. Variations in parameters such as k, SDRmax, IC0, threshold flow accumulation, and biophysical coefficients may influence the magnitude of estimated soil loss and sediment export. However, the main spatial patterns identified in this study are largely controlled by topography and landscape organization, which are less sensitive to moderate parameter variations. Similar considerations regarding uncertainty in ecosystem service assessments have been highlighted in recent studies (Walther et al. 2025; Demirel et al. 2026).

Future work should include calibration against field measurements and a structured sensitivity analysis involving systematic variations of key parameters and biophysical coefficients in order to further improve the quantitative reliability of sediment export estimates.

5. Conclusion

This study applied a connectivity-based analytical framework operationalized through the InVEST Sediment Delivery Ratio (SDR) model to assess sediment regulation ecosystem services in the semi-arid Nfifikh Watershed, Morocco. By jointly analysing soil loss, sediment delivery efficiency, sediment export and deposition, and selected sediment regulation indicators, the results demonstrate that effective sediment transfer within Mediterranean dryland watersheds is not solely governed by erosion intensity, but is strongly mediated by landscape connectivity and internal sediment buffering processes.

The findings show that steep and sparsely vegetated upstream hillslopes exhibit high soil loss potential, yet only a fraction of these areas contribute significantly to downstream sediment loads due to contrasts in sediment delivery efficiency. In contrast, extensive midstream and downstream sectors function as natural sediment sinks, where gentle slopes, depositional environments, and vegetated buffers intercept mobilized sediment before it reaches the drainage network. This spatial decoupling between soil detachment and sediment export highlights the limitations of erosion-focused assessments and underscores the importance of connectivity-informed approaches for identifying dominant sediment source and retention areas.

The analysis of avoided soil erosion and avoided sediment export further illustrates the regulating role of existing land cover in controlling sediment dynamics. Vegetation cover in steep upstream sectors substantially mitigates soil detachment, while agricultural mosaics and riparian corridors in midstream and downstream areas enhance sediment retention through reduced connectivity and increased deposition potential. These results confirm that sediment regulation ecosystem services emerge from the combined influence of topography, land-cover configuration, and landscape connectivity, rather than from any single controlling factor.

Overall, the study demonstrates the added value of interpreting InVEST SDR outputs within a process-oriented, connectivity-based framework. This approach strengthens the scientific understanding of sediment regulation ecosystem services and provides a robust basis for spatially differentiated soil and water conservation strategies in semi-arid Mediterranean watersheds. The proposed framework is transferable to other data-scarce basins facing similar erosion, land-use, and climate pressures, and supports more effective ecosystem-based watershed management from an international perspective.

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Data availability

All of the data that support the findings of this study are available in the main text or Supplementary Information.