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A holistic framework for wetland placement and ecosystem service delivery by integrating landscape connectivity and participatory decision analysis in two Swedish catchments

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ABSTRACT

Study region: This study focuses on two catchments in Uppsala County, Sweden, Hågaån and Enköpingsån, which differ in landscape morphology, land use, and hydrological characteristics. Both catchments drain into Lake Mälaren, a vital water resource in the region. These areas were selected for their socio-ecological relevance and the active involvement of local stakeholders in catchment management.
Study focus: The paper presents a holistic decision-support framework for optimizing wetland placement by integrating sediment connectivity modeling, hydrological assessments, and stakeholder-defined indicators using multi-criteria decision analysis (MCDA). Landscape connectivity modelling, incorporating structural and functional connectivity indices, assessed sediment transfer dynamics and prioritized potential wetland sites. A participatory process, involving municipalities and regional actors, was used to define priority ecosystem functions and evaluate candidate wetland sites based on biophysical and socio-economic criteria. An upstream–downstream analysis was also incorporated to assess interactions across landscape positions.
New hydrological insights: The study demonstrates that high-priority wetland sites are typically located at the intersection of elevated hydrological and geomorphological connectivity. Findings emphasize the value of combining landscape connectivity modeling with stakeholder knowledge to improve the spatial targeting of wetlands as nature-based solutions (NBS). The approach supports more strategic implementation of wetlands for sediment and water regulation, enhancing resilience in contrasting lowland catchments. The framework is transferable to other regions seeking integrated, stakeholder-driven wetland planning under changing land use and climate conditions.

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1. Introduction

1.1. Background

Human activities and climate change are driving profound transformations in hydrological systems, intensifying extreme events, such as floods and droughts, disrupting sediment transport, and accelerating water quality degradation worldwide (IPCC, 2021). Land use changes, including agricultural expansion, deforestation, and urbanization, have further altered natural hydrological and sediment connectivity processes, exacerbating erosion, nutrient runoff, and sediment deposition (Borselli et al., 2008; Vercruysse et al., 2017). These challenges necessitate integrated water and land management approaches, as well as more extensive stakeholder participation to enhance catchment resilience and mitigate adverse environmental impacts while maintaining essential ecosystem services (ES).

Nature-based solutions (NBS) have emerged as a sustainable alternative to traditional grey infrastructure for addressing these challenges. Wetlands, in particular, offer multifunctional benefits, including flood mitigation, sediment retention, and biodiversity conservation (Ferreira et al., 2023; Hambäck et al., 2023; Kalantari et al., 2021; Mitsch and Gosselink, 2015; Moreno-Mateos et al., 2012). By intercepting surface runoff and facilitating sediment deposition, wetlands reduce downstream sediment loads while improving nutrient cycling, water storage capacity, and water quality (Nesshöver et al., 2017; Raymond et al., 2017). This sediment retention is strongly linked to phosphorus (P) capture, as suspended sediments often carry P in agricultural landscapes (Sandström et al., 2020, 2024). However, despite these well-documented benefits, uncertainties in site selection, long-term functionality, and their integration into catchment-scale management strategies continue to hinder large-scale wetland restoration and implementation (Acreman et al., 2021; Palmer and Ruhl, 2015). Traditional wetland site selection methods have largely relied on expert-based assessments, empirical suitability scoring, and visual interpretation of topographic or land use maps (Acreman and Holden, 2013; Tomer et al., 2003). While such methods can be effective at small scales, they often lack spatial precision, do not adequately incorporate hydrological connectivity, and fail to capture upstream-downstream interactions. These approaches may not address the multi-functionality of wetlands or integrate stakeholder preferences systematically (McCartney et al., 2010; Palmer and Ruhl, 2015). Furthermore, many conventional techniques emphasize qualitative criteria, making them difficult to replicate or scale across catchments (Gann et al., 2019). This underscores the need for more spatially explicit, process-informed, and participatory frameworks to guide wetland prioritization in landscape planning.

1.2. Objective of this study

This study uses the term "wetlands" to refer to small artificial waterbodies (SAWs), including detention ponds and constructed wetlands. While definitions vary across national and disciplinary contexts, this terminology allows for a broader consideration of multifunctional water-retention features. A key challenge in wetland implementation is determining optimal placement to maximize hydrological and ecological benefits (Djodjic et al., 2020; Hambäck et al., 2023). Traditional site selection approaches often rely on expert judgment and empirical assessments, which may not fully capture the spatial complexity of hydrological/sediment connectivity and sediment transport processes (Wohl et al., 2021). Consequently, optimizing wetland placement requires an integrated approach that accounts for key biophysical processes—including hydrological connectivity and sediment transport—and local stakeholder priorities. Recent advancements in geospatial modeling and decision-support frameworks provide promising tools for optimizing wetland placement based on biophysical, hydrological, and socio-economic factors (Heckmann et al., 2018; Kalantari et al., 2017).

Sediment connectivity modeling provides a spatially explicit approach to understanding how sediment and water move across a catchment and how interventions, such as wetlands, can influence these processes (Cavalli et al., 2013). Traditionally, sediment connectivity assessments have focused on structural connectivity, evaluating static landscape characteristics such as slope, land cover, and topographic barriers influencing sediment transport potential (Bracken et al., 2015). However, functional sediment connectivity, which accounts for temporal hydrological variability and dynamic flow conditions, remains an underexplored dimension in wetland planning (Heckmann et al., 2018; Wainwright et al., 2011).

This study advances wetland placement methodologies by integrating both structural and functional connectivity indices to evaluate sediment and hydrological transport dynamics within the catchment. The Index of Connectivity (IC) is a spatially distributed, GIS-based metric designed to quantify sediment transport potential across landscapes by evaluating the degree of linkage between sediment source areas and receiving channels (Borselli et al., 2008). Originally developed as an indicator of structural connectivity, IC primarily incorporates topographic controls. However, later adaptations have expanded its scope to include surface conditions, such as land cover (Cavalli et al., 2013) and hydrological drivers (Kalantari et al., 2017), offering a more process-based representation of catchment dynamics. This flexibility makes IC a valuable tool for spatially targeting NBS, such as wetlands, by identifying critical areas where sediment transfer can be intercepted or attenuated.

In addition to assessing overall catchment sediment connectivity, this study expands on previous approaches by quantifying key hydrological and sediment transport metrics for each potential wetland site and its contributing upstream and downstream areas. We assess how wetland placement influences and is influenced by broader hydrological and sediment transport dynamics. This upstream-downstream interaction analysis, which includes land use, IC, runoff potential, and storage capacity metrics, ensures that wetland selection is not only based on localized site conditions but also accounts for large-scale sediment and water transfer processes.

Successful wetland implementation also requires stakeholder participation to ensure alignment with land-use policies and local feasibility constraints (Hernandez et al., 2024; Lindahl and Söderqvist, 2004). While scientific models provide spatial insights, stakeholder-driven prioritization ensures that site selection aligns with socioeconomic constraints, societal preferences, and governance frameworks (Grygoruk and Rannow, 2017). Many existing wetland selection frameworks lack structured participatory

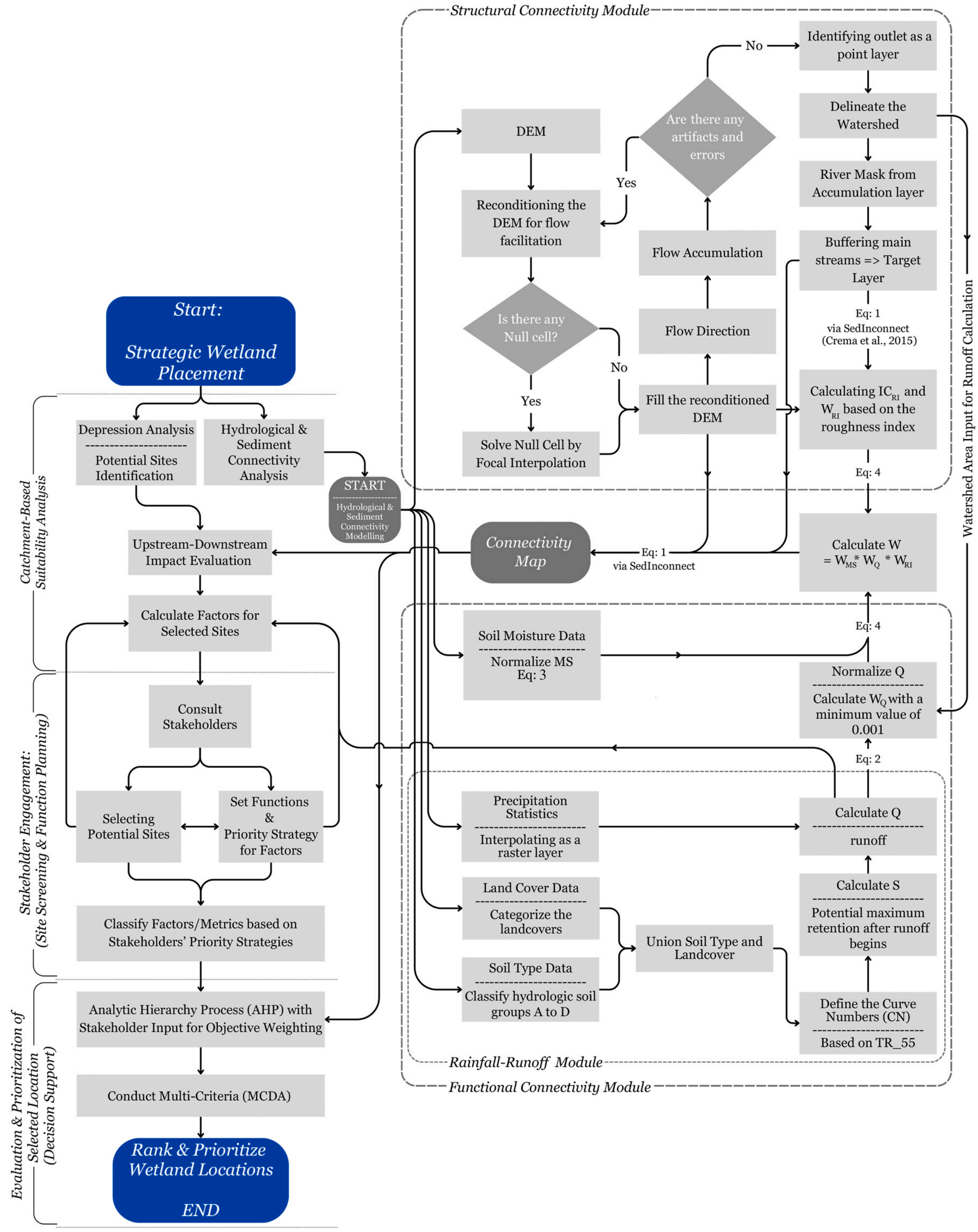

Fig. 1. Workflow diagram presenting a structured framework for strategic wetland placement. The process is divided into three core phases: (i) Catchment-Based Suitability Analysis, (ii) Stakeholder Engagement in Wetland Site Selection, and (iii) Evaluation & Prioritization of Selected Location (Decision Support).

decision-making, which can lead to suboptimal implementation success and policy misalignment (Pulido-Velazquez et al., 2023). This study integrates stakeholder-defined priorities with quantitative geospatial modeling to ensure that wetland placement addresses scientific validity and practical feasibility. The Analytic Hierarchy Process (AHP) (Saaty, 1987) within a Multi-Criteria Decision

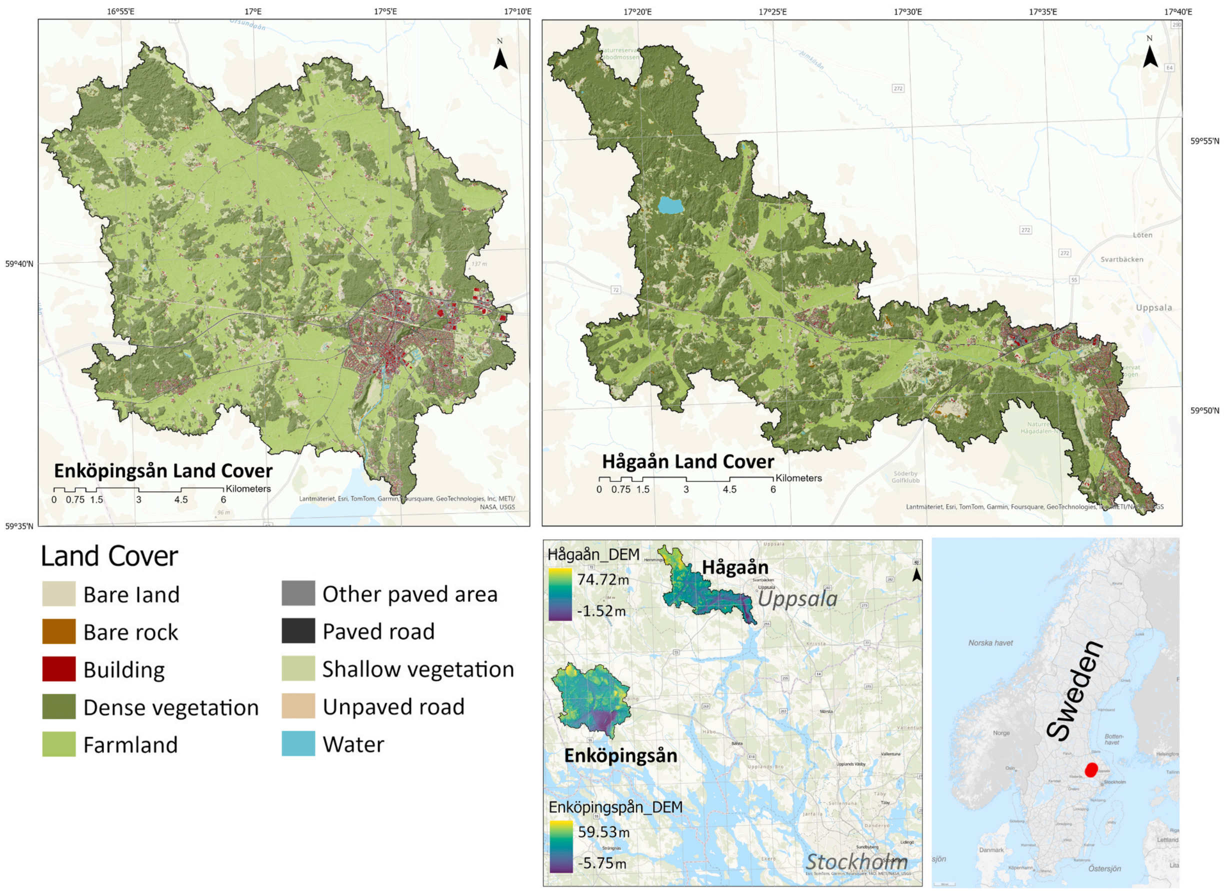

Fig. 2. Study areas encompassing urban landscapes, agricultural lands, and undisturbed natural habitats (dense vegetation). The overarching topography of the selected sites is predominantly flat or low-lying.

Analysis (MCDA) (Malczewski, 2006) framework was used to systematically incorporate expert and stakeholder input into the wetland placement ranking process, producing a transparent and participatory decision-making structure. By incorporating these perspectives, this research bridges the gap between scientific modeling and policy-driven decision-making, ensuring that wetland selection aligns with ecological effectiveness and governance requirements. The overarching aim is to develop a comprehensive, stakeholder-informed framework for prioritizing wetland placement by integrating sediment connectivity modeling, hydrological assessments, and multi-criteria decision analysis. Specifically, the objectives are to:

1. Develop a structural and functional sediment connectivity index to assess sediment and water transfer dynamics within a catchment;
2. Identify potential wetland locations using spatial analysis and hydrological assessments; and
3. Integrate stakeholder-driven prioritization with AHP and MCDA to optimize wetland placement for multiple ecosystem services.

By combining high-resolution geospatial modeling with participatory decision-support tools, this research advances landscape-scale wetland planning and contributes to the development of scalable methodologies for NBS implementation.

2. Method

This study employs a structured methodology that integrates geospatial modeling, hydrological assessments, and stakeholder-driven decision-making to optimize wetland (SAWs) placement. The approach consists of three interrelated phases (Fig. 1). First, sediment connectivity modeling is used as part of a catchment-based suitability analysis to assess sediment and water transfer dynamics. This is complemented by topographical and hydrological assessments to identify potential wetland sites based on their water storage capacity, upstream contributions, and landscape position. Second, stakeholder engagement refines site selection through a collaborative decision-making process, ensuring that wetland placement aligns with hydrological, ecological, and socio-economic priorities. This phase also defines priority strategies based on stakeholder input, guiding the assessment of wetland functions and weighting the measured metrics. Finally, the evaluation and prioritization of selected locations involve a systematic ranking of sites

Table 1
Main morphometric parameters of the study basins.

	Enköpingsån	Hågaån
Catchment area (km^2)	167.4	118.6
Minimum elevation (m a.s.l.)	−5.7	−1.5
Mean elevation (m a.s.l.)	25.1	36.7
Maximum elevation (m a.s.l.)	59.5	75.7
Average slope (degree)	5.0	8.0

Table 2
Summary of data sources and associated spatial and temporal resolutions used in the study.

Data Type	Dataset	Source	Spatial Resolution	Temporal Coverage
Topography (DEM)	Airborne LiDAR DEM	Lantmäteriet (2024)	1 m	2009–present
Hydrological Correction	Hydrography & SCALGO Live	Lantmäteriet (2024) and Scalgo (2024)	1 m	Current
Soil Data	Digital Arable Soil Map (for agricultural land) & SGU Soil Maps (for non-agricultural land)	(Piikki and Söderström, 2019), SGU	1:50,000	Current
Land Cover	SCALGO Live Land Cover (classification of vegetation, impervious surfaces, and water bodies)	Scalgo, (2024)	25 cm	Current
Precipitation	Historical Rainfall Data	(SMHI, 2024)	Point-based (interpolated)	Aug 14–17, 2021 (used to simulate extreme runoff conditions)
Soil Moisture	SLU Soil Moisture Model (integrating LiDAR-based terrain indices and machine-learning predictions)	Ågren et al. (2021)	2 m	Current
Stakeholder Prioritization	Workshop & Municipal Collaboration	Uppsala & Enköping Municipalities	N/A	2024–2025

using the MCDA framework. Within the MCDA, AHP is applied to incorporate stakeholder-defined weighting factors. The results were then used in a Multi-Objective Decision Analysis (MODA) (Ishizaka and Nemery, 2013) to synthesize multiple objectives into a composite wetland indicator-based suitability framework. Each phase of this methodology, which consists of a data-driven approach that integrates biophysical modeling with participatory decision-making for strategic wetland implementation, was applied in two catchments in central Sweden.

2.1. Study areas

The Hågaån and Enköpingsån catchments, located in Uppsala County, in east-central Sweden, their geographic locations are illustrated in Fig. 2. These catchments were selected for this study due to their hydrological significance and their role in draining into Lake Mälaren, a critical water body for regional water supply, biodiversity, and ecological stability (Fölster et al., 2014). Both catchments were selected not only for their hydrological significance but also due to their involvement in ongoing stakeholder engagement initiatives. The presence of active municipal partners, already collaborating through regional water management efforts, provided essential local knowledge and governance perspectives to guide wetland planning and prioritization. While these catchments share similarities in their topographical and hydrological characteristics (Table 1), key differences in land cover and soil type influence their sediment transport dynamics, hydrological responses, and water management challenges. Enköpingsån, with a basin area of 167 km^2, has a relatively circular morphology and a gentler average slope. This results in a more distributed hydrological response with slower runoff accumulation and lower flow concentration. In contrast, Hågaån, covering 118 km^2, has a more elongated shape, contributing to more concentrated flow pathways. The composition of the catchments' land cover (Fig. 2) presents a key distinction between them. Hågaån is predominantly covered by dense vegetation (61.2 %), while Enköpingsån has a more balanced distribution between farmland (42.1 %) and dens vegetation (38.7 %).

These variations are significant, as forested landscapes typically reduce sediment mobilization and runoff, whereas agricultural areas are more prone to soil erosion and nutrient export. Consequently, land use differences may influence the effectiveness of wetland placement strategies, with forested catchments generally requiring less intervention for sediment control than agriculture-dominated ones. Soil composition further differentiates the two catchments. Based on SCALGO Live's national soil type map, which integrates SGU's superficial deposit data (Jordartsdata), Enköpingsån contains a higher proportion of fine clay (35.9 %) and sand (27.4 %). This indicates potential susceptibility to erosion and sediment transport, especially in areas with reduced vegetation cover. In contrast, Hågaån has a more varied soil structure, with clay (25.1 %), coarse clay (15.0 %), and bedrock (19.8 %) (Appendix I, Figure S1, and Table S1).

These hydrological and geomorphological differences provide an opportunity for a comparative analysis of wetland placement strategies across but comparable landscape settings. The topographical similarities between the two catchments (Table 1) ensure that findings are applicable across diverse catchment types, while variations in land cover and soil properties enable the assessment of how different landscape configurations affect sediment connectivity and water retention. Moreover, both catchments have experienced hydrological challenges, including floods, droughts, and water quality deterioration, making them suitable candidates for nature-based interventions, such as wetlands. Reports from the Swedish Meteorological and Hydrological Institute (SMHI) and the Uppsala County Administrative Board highlight the increasing risk of extreme rainfall events, rising flood hazards, and deteriorating water quality in Uppsala County. This emphasizes the need for sustainable water management strategies, including wetland implementation as a nature-based intervention (Länsstyrelsen-Uppsala, 2022; SMHI, 2023). Developing tools to assess wetland functionality in these differing conditions will enhance our understanding of their role in mitigating hydrological extremes and contribute to the scalability of wetland-based solutions in similar Nordic landscapes.

2.2. Data collection

This study integrates spatial and participatory data sources to optimize wetland placement within the study catchments. The spatial data include topographic, land cover, soil, and hydrological datasets used for sediment connectivity modeling and hydrological analysis, while the stakeholder engagement data were collected through collaboration with municipalities and a participatory workshop to refine site selection and prioritize wetland functions. Table 2 summarizes the datasets used in this study, including their source, spatial resolution, and temporal coverage. Sediment connectivity modeling and hydrological assessments were based on high-resolution topographic and environmental datasets. The primary dataset was a 1m-Digital Elevation Model (DEM) provided by Lantmäteriet (2024) derived from airborne LiDAR scans. The DEM was hydrologically corrected using the Lantmäteriet Hydrography dataset and SCALGO Live hydrological corrections (Scalgo, 2024), which integrate machine-learning-based culvert predictions to improve the representation of water flow pathways.

All spatial datasets were resampled to 1 m x 1 m resolution for consistency and processed using ArcGIS Pro 3.2 with the Arc Hydro extension. The IC was computed using SedInConnect (Crema et al., 2015), an open-source tool tailored for IC calculations.

Beyond spatial modeling, stakeholder input was a key component of the site selection process. Data were collected through collaboration with Uppsala and Enköping municipalities, where municipal experts reviewed the initial set of 300 potential wetland locations per catchment, refining them based on feasibility, land-use constraints, and hydrological relevance. Following this, a stakeholder workshop was conducted to refine wetland site selection and prioritize wetland functions based on expert input. The weighting factors derived from the workshop directly informed the AHP pairwise comparisons, which guided the development of the final MCDA indicator-based suitability maps.

2.3. Catchment-based suitability analysis

The data assessment and identification of suitable wetland locations in this study began with hydrological preprocessing to set the stage for sediment connectivity modeling. This preparatory phase involved working with a high-resolution DEM that includes a surrounding buffer area, facilitating a comprehensive catchment-wide analysis. The DEM was reconditioned to account for physical barriers within the landscape, such as roads and railways, by integrating known culvert and underpass locations. This ensures that the model accurately represents subsurface drainage structures and allows uninterrupted flow across artificial obstructions, improving the reliability of hydrological and sediment transport simulations. After reconditioning, flow direction was established, the steepest downslope paths for water movement were delineated, and flow accumulation was calculated to identify potential stream channels. Next, the watershed boundary was delineated with respect to a defined outlet point. A river mask was created from the flow accumulation layer by applying a threshold of 0.5 km^2 of upstream contributing area, thereby distinguishing river or channel cells from non-channel cells based on hydrological significance. A buffer zone (3 m) was generated around the river channels to ensure effective targeting of the main streams. These steps set the stage for the next step to compute the sediment connectivity index.

2.3.1. Sediment connectivity index (IC)

This study extends the IC concept by integrating structural and functional connectivity attributes, incorporating roughness, soil moisture, and runoff dynamics to reflect temporal and spatial variability (Fig. 1).

The IC was computed as (Borselli et al., 2008):

$$IC = \log_{10}\left(\frac{D_{up}}{D_{dn}}\right) = \log_{10}\left(\frac{\overline{W} \times \overline{S} \times \sqrt{A}}{\sum_i \frac{d_i}{W_i \times S_i}}\right) \quad (1)$$

where D_{up} denotes upslope sediment transport potential and D_{dn} captures the downslope component, representing the distance-weighted pathway from a cell to the nearest sink or channel. W is a weighting factor accounting for impedance, S is the slope, and A represents the total area draining into a given cell.

To enhance the IC's sensitivity to catchment characteristics, we applied a composite weighting factor, W, which integrates multiple influences on sediment movement:

1. Surface Roughness (W_{RI}) measures surface impedance to sediment transport, normalized using a logarithmic transformation to more accurately represent diverse landscapes (Cavalli et al., 2013; Trevisani and Cavalli, 2016);

Table 3
Summary statistics of identified small artificial waterbodies (SAWs) across the study catchments.

Metric	Area (ha)		Storage (m^3)		Avg Depth (m)	
	Enköpingsån	Hågaån	Enköpingsån	Hågaån	Enköpingsån	Hågaån
Mean	11.0	7.5	75477.9	57080.6	0.74	0.81
Minimum	1.2	0.2	4683.4	1289.4	0.21	0.19
Maximum	148.7	37.2	1009750.0	312126.0	1.62	5.34
Standard Deviation	19.1	6.2	132805.4	49099.5	0.30	0.42

2. Runoff *(W_Q)* derived from a modified Soil Conservation Service Curve Number (SCS-CN) method (Kalantari et al., 2017) to account for rainfall-runoff variability. The CN value was derived based on the combined influence of hydrologic soil groups (HSG) and land use classifications. Both the reclassification of soil types into HSG (Appendix I, Tables S2, and S3) and the categorization of land uses with their corresponding CN values (Appendix I, Table S4) were performed following the guidelines provided by the USDA (1986). To capture the full range of runoff values with greater sensitivity, we modified the weight calculation as follows:

$$W_Q = \frac{Q - Q_{\min}}{Q_{\max} - Q_{\min}} \tag{2}$$

Q represents the calculated runoff volume at a specific location. $Q_{\min}$ and $Q_{\max}$ denote the catchment's minimum and maximum runoff values, respectively; and

3. Soil Moisture (W_{SM}) extracted from the SLU soil moisture model (Ågren et al., 2021), normalized using a logarithmic scale to ensure comparability. Higher soil moisture values indicate reduced infiltration capacity, leading to increased runoff and enhanced sediment connectivity (Kalantari et al., 2019). To account for the variability in soil moisture across the catchment, normalization was applied to ensure comparability with other weighting factors, as follows:

$$W_{SM} = \frac{\ln(SM + k) - \ln(SM_{\min} + k)}{\ln(SM_{\max} + k) - \ln(SM_{\min} + k)} \tag{3}$$

W_{SM} was calculated using the soil moisture value at a specific cell *(SM)*, with normalization applied based on the minimum $SM_{\min}$ and maximum $SM_{\max}$ soil moisture values observed within the catchment. A small positive constant (K) prevents undefined logarithmic operations when soil moisture values approach zero. This ensures numerical stability in the computation while maintaining consistency in the weighting process.

By integrating these three weighting components, we established a comprehensive weighting factor, W, ensuring a dynamic representation of hydrological and geomorphological processes influencing sediment movement.

$$W = W_{RI} \times W_Q \times W_{SM} \tag{4}$$

The sediment connectivity modeling outputs a distributed IC map, identifying high and low connectivity areas. These analyses directly inform wetland site selection by identifying areas where sediment transfer is most active and where wetlands can provide the highest retention potential. By targeting high-connectivity zones for placement, wetlands function as sediment sinks, reducing downstream sediment loads and associated nutrient transport. Conversely, sites in low-connectivity areas are more suited for hydrological storage or biodiversity conservation functions. This spatial understanding ensures that wetland functionality aligns with the dominant transport processes at each location, improving their overall effectiveness within the catchment.

2.3.2. Wetland site identification

To complement sediment connectivity modeling, this study integrates depression analysis to identify and assess potential wetland sites within the catchments. This approach leverages topographical and hydrological characteristics to evaluate storage potential and prioritize locations that require minimal excavation while maximizing the use of natural depressions. Focusing on pre-existing depressions aligns with NBS principles, promoting sustainable strategies for enhancing ecosystem services. The depression analysis was performed using high-resolution DEMs and spatial analysis techniques. Initially, all topographical depressions within the catchments were identified, defining enclosed areas where water could potentially accumulate, surrounded by higher elevations. For each depression, the contributing sub-catchment area was delineated. The lowest elevation point along the sub-catchment boundary (overflow point) was identified. This point represents the threshold at which water would overflow during high-flow events. To simulate embankment construction, the elevation of the overflow point was raised by 1 m and raster cells along the sub-catchment boundary with elevations below this new threshold were identified as embankment cells. These embankments represent a scenario where minimal intervention can create significant potential for water retention, supporting wetland establishment. Only those with a minimum potential storage capacity of 1000 m^3 were included in the analysis to ensure the hydrological significance of the depressions identified. Summary statistics of SAW size and depth characteristics are provided in Table 3. The potential locations identified were then submitted to the municipality for an initial screening, where local land-use constraints, stakeholder perspectives, and practical feasibility considerations were reviewed. This collaborative assessment helped refine the site selection process, as detailed in

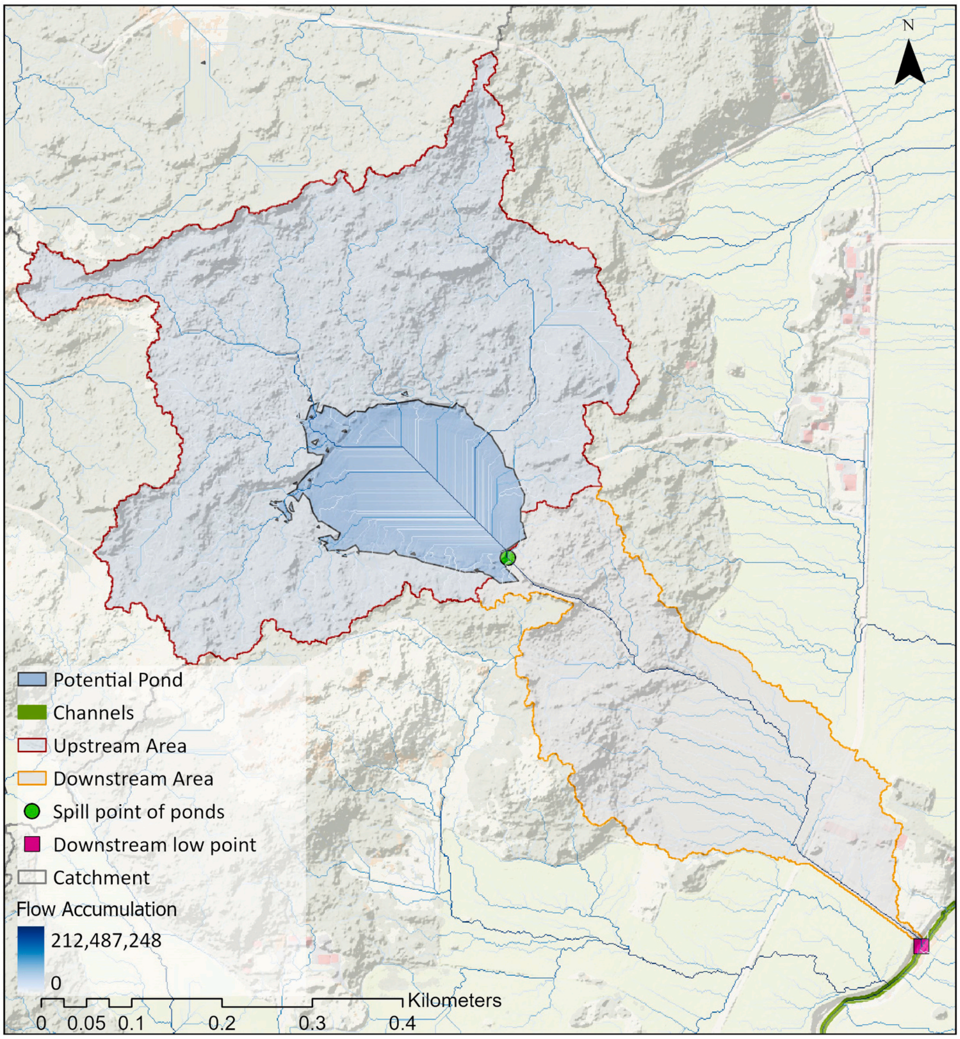

Fig. 3. Hydrological delineation of a selected Small Artificial Waterbody (SAW) and its associated contributing and receiving areas. Flow accumulation is visualized using a blue gradient, with darker tones indicating higher accumulation and streamflow potential.

Section 2.4.

To further assess the upstream-downstream dynamics of each potential wetland site (with a 1 m raised embankment), the contributing upstream catchment for each depression was delineated based on its spill point. This was identified as the intersection between the flow path originating from the center of the potential wetland polygon and its boundary. Subsequently, the direct downstream area influenced by each depression was then identified by locating the next significant stream junction or low point where water would accumulate. To isolate the specific downstream region affected by each depression, the delineated upstream area of the wetland was subtracted from this contributing area (Fig. 3).

Finally, key metrics describing the physical and hydrological characteristics of each depression, including both upstream and downstream influences, were calculated to provide quantitative indicators for prioritizing potential wetland sites. These ecological indicators include sediment connectivity within the wetland area (IC_{in}) and in the upstream catchment (IC_{up}), as well as upstream runoff contributions (Q_{up}), which quantify the extent of upstream flow contributing to the depression based on the rainfall-runoff model (Q) results from the functional connectivity module. This approach accounts for site-specific soil and land use effects, offering a tailored estimation of water availability rather than relying on standardized scenarios or generalized benchmark events. Additional metrics include storage potential (S_t) and land use classifications, categorized as the percentage of arable, urban, forest, water, and open land for the wetland area, its contributing upstream catchment, and the directly affected downstream region. Furthermore, the extent of the direct downstream area (A_{dn}) influenced by each depression was calculated. While detailed cost assessments were beyond the scope of this study, potential wetland sites were selected based on natural depressions and modeled using a minimal embankment height of 1 m, ensuring that topographic conditions are favorable for low-impact construction. Furthermore, land use within the potential SAW footprint was integrated as a key factor in the MCDA, with open and semi-natural areas given higher

Table 4
Municipal approaches for wetland site selection.

Municipality	Approach Type	Primary Objectives	Key Exclusion Criteria	Unique Considerations
Uppsala	Structured filtering	Flood mitigation, water retention, biodiversity, nutrient retention	Built-up areas, road networks, high-value agricultural land, planned urban zones	Strategic placement to maximize hydrological benefits
Enköping	Risk-based selection	Water retention, flood mitigation, landowner engagement, nutrient retention	Multi-owner or drainage company-managed land, productive farmland, roadways, and built structures	Emphasized voluntary participation and adaptive implementation

priority due to easier implementation and lower conversion costs. This strategy indirectly accounts for construction feasibility and associated cost implications while promoting practical relevance in real-world wetland planning. Detailed metrics used for site assessment and prioritization are presented in Table 5.

2.4. Stakeholder-driven wetland selection

After having identified and evaluated potential wetland sites through sediment connectivity modeling and depression analysis, stakeholder engagement was conducted to refine the site selection and prioritize wetland functions. This phase aimed to bridge model-driven analysis with practical implementation feasibility, ensuring that selected sites aligned with hydrological effectiveness and land-use constraints. Initially, approximately 300 potential locations were identified per catchment and presented as shapefiles to the Uppsala and Enköping municipalities for a first-stage screening.

A stakeholder workshop was organized to incorporate broader expertise and local knowledge. This gathered over 50 participants from municipalities, catchment officers, consultants, county administrative boards, policymakers, environmental organizations, and researchers. Participants engaged in structured discussions, interactive ranking exercises, and expert-driven evaluations of wetland functions as NBS. The workshop had three primary objectives:

- To present the modeling process and results to provide stakeholders with a clear understanding of the analyses conducted in this study. This included an overview of the sediment connectivity modeling, depression analysis, and hydrological assessments that formed the basis for wetland site identification;
- To refine the wetland selection process by reviewing the municipal approaches to wetland site selection and synergize these between municipalities; and
- To prioritize wetland functions and factors based on stakeholder input to guide the decision-making process for implementation.

After presenting the modeling process and results, municipal representatives shared their approaches to wetland site selection, detailing how they utilized the modeling outputs to refine their screening criteria. Both Uppsala and Enköping municipalities employed systematic approaches to screen and refine potential wetland sites, ensuring that selected locations align with hydrological benefits, land-use feasibility, and ecological objectives. Their screening process involved evaluating site suitability through hydrological modeling, land-use analysis, and stakeholder input while applying exclusion criteria to avoid conflicts with existing infrastructure and productive agricultural land. Table 4 summarizes the key aspects of each municipality's approach, highlighting their shared methodology and specific priorities.

The stakeholder engagement process was instrumental in refining the wetland site selection and prioritization strategy. Following this discussion, stakeholders participated in an interactive prioritization exercise. They were asked, "What functions are most important to you when planning a new wetland?" and their responses shaped the study's functional framework. The results highlighted four primary functions:

- Flood regulation, where wetlands act as natural retention areas, attenuating peak flows and mitigating downstream flooding;
- Water retention, enhancing groundwater recharge, and ensuring sustainable water availability;
- Biodiversity conservation, supporting habitat restoration and ecological diversity; and
- Sediment and nutrient retention, intercepting sediment-bound nutrients, particularly phosphorus, thereby reducing nutrient loading and improving downstream water quality.

These priority functions provided a structured foundation for evaluating potential wetland sites. The MCDA framework incorporated these stakeholder-driven priorities, ensuring that the weighting of factors extracted from the modeling phase (e.g., sediment connectivity, storage potential, land-use compatibility) is directly aligned with real-world environmental and policy considerations.

The structured priority-setting approach, summarized in Table 5, reflects how scientific assessments, municipal constraints, and stakeholder-defined objectives guided wetland implementation. Each of these objectives was represented by a set of spatial indicators reflecting the ecosystem service potential of candidate sites. These multifunctionality indicators formed the basis of the decision-support framework. Unlike purely model-driven site selection, this process ensured that wetlands were prioritized based on:

- Multi-functionality: Sites were selected for their hydrological benefits and capacity to support biodiversity and sediment retention;

Table 5
Physical and hydrological metrics of each potential site, based on sediment connectivity and depression analysis.

Factor	Wetland Focus/ Function	Description	Priority Strategy	Notes
Sediment Connectivity Index within SAW Area *(IC with main channels as targets)*, (IC_{in})	Sediment & Nutrient Retention	IC measures how efficiently sediment is transported.	Moderate-High IC → Higher priority (Wetlands in high IC zones intercept more sediment and reduce erosion).	Avoid extremely high IC areas where sediment moves too fast to be captured.
	Biodiversity	IC impacts water stability and habitat conditions.	Lower IC → Higher priority (Stable water bodies support biodiversity better).	Focus on low-disturbance areas for long-term ecosystem stability.
	Flood Regulation	IC influences how fast water is delivered downstream.	High IC (but not extreme) → Higher priority (to slow down peak flows and reduce flood risks).	Helps in reducing peak discharge and buffering flood events.
	Water Retention	IC affects how water moves through the landscape.	Low-Moderate IC → Higher priority (Wetlands in these areas maximize storage while reducing rapid outflow).	Slower-moving water increases retention time and infiltration.
Upstream IC Contribution *(IC with Potential SAW locations and channels as targets)* (IC_{up})	Sediment & Nutrient Retention	Measures the percentage of high-IC areas in the upstream watershed.	More high-IC upstream → Higher priority (Wetlands can intercept more sediment).	Helps determine how much sediment and nutrients are likely to reach the SAW.
	Biodiversity	The connectivity of upstream flow to the SAW can affect water quality and biodiversity.	Lower IC upstream → Higher priority (Less disturbance ensures habitat stability).	
	Flood Regulation	Higher IC in upstream areas may increase runoff velocity and flood risks.	High IC (but not extreme) upstream → Higher priority (to slow and manage runoff).	Ensures wetlands are positioned in areas where they can buffer peak flows.
	Water Retention	The ability of upstream areas to contribute water to the SAW.	Moderate IC upstream → Higher priority (Wetlands in areas with moderate IC upstream can store and retain more water).	Ensures sustained water supply.
Land Use within SAW Area (LU_{in}), %	All four functions	Percentage of land types within each SAW polygon: - Arable land - Urban area - Forest and water - Open land	Higher priority: Open land → easier implementation. Lower priority: Arable land and Urban area (ownership issues). Medium priority: Forest (if high IC upstream or reasonable downstream exists).	Consider land ownership and cost of land conversion.
Land Use Upstream (LU_{up}), %	Sediment & Nutrient Retention	The type of land cover contributing to the SAW's inflow.	Higher priority: Agricultural upstream → more sediment and nutrient runoff to intercept. Lower priority: Forest upstream → already acts as a natural buffer.	High arable land upstream → higher need for sediment retention.
	Biodiversity	The impact of upstream land cover on water quality.	Higher priority: Natural or semi-natural landscapes upstream ensure better water quality.	Forested upstream areas provide natural water filtration.
	Flood Regulation	The ability of upstream land cover to buffer floods.	Higher priority: Impervious land upstream (e.g., urban areas) → stronger need for retention.	Impervious upstream areas contribute more runoff, requiring wetlands for buffering.
	Water Retention	Land cover determines infiltration capacity.	Higher priority: More pervious land (grasslands, forests) upstream → Slows runoff, increases infiltration, improves groundwater recharge.	Water retention is about quantity and quality, and vegetated upstream areas enhance both.
Land Use Downstream (LU_{dn}), %	All four functions	The type of land cover affected by the SAW downstream.	Higher priority: Urban areas and Arable land → more substantial need for flood mitigation and fresh water. Lower priority: Wetlands or forests → already provide retention.	If urban areas exist downstream, the SAW may reduce flooding and sediment-related damage.
Upstream Runoff (Q_{up}), m^3	All four functions	Amount of water supply to the SAW from its upstream catchment.	Higher runoff → Higher priority (ensures SAW has sufficient water supply).	Based on the SCS-CN rainfall-runoff model.
Downstream Area Size (A_{dn}), m^2	All four functions	The area downstream directly benefits from SAW's presence.	Larger downstream area → Higher priority (Wetlands affecting larger downstream regions provide broader benefits).	Helps in identifying wetlands that benefit larger regions.
SAW Storage Potential (S_t), m^3	All four functions	Estimated storage volume of each SAW.	Higher storage potential → Higher priority.	Determines if the SAW can store enough water to be effective.

- Land availability and feasibility: Locations with minimal land-use conflicts and greater stakeholder support were prioritized; and
- Hydrological effectiveness: Wetlands were placed where they could maximize water retention and flood regulation while minimizing unintended impacts on surrounding land uses.

This participatory approach enhances the legitimacy and acceptance of wetland interventions as NBS, increasing their likelihood of

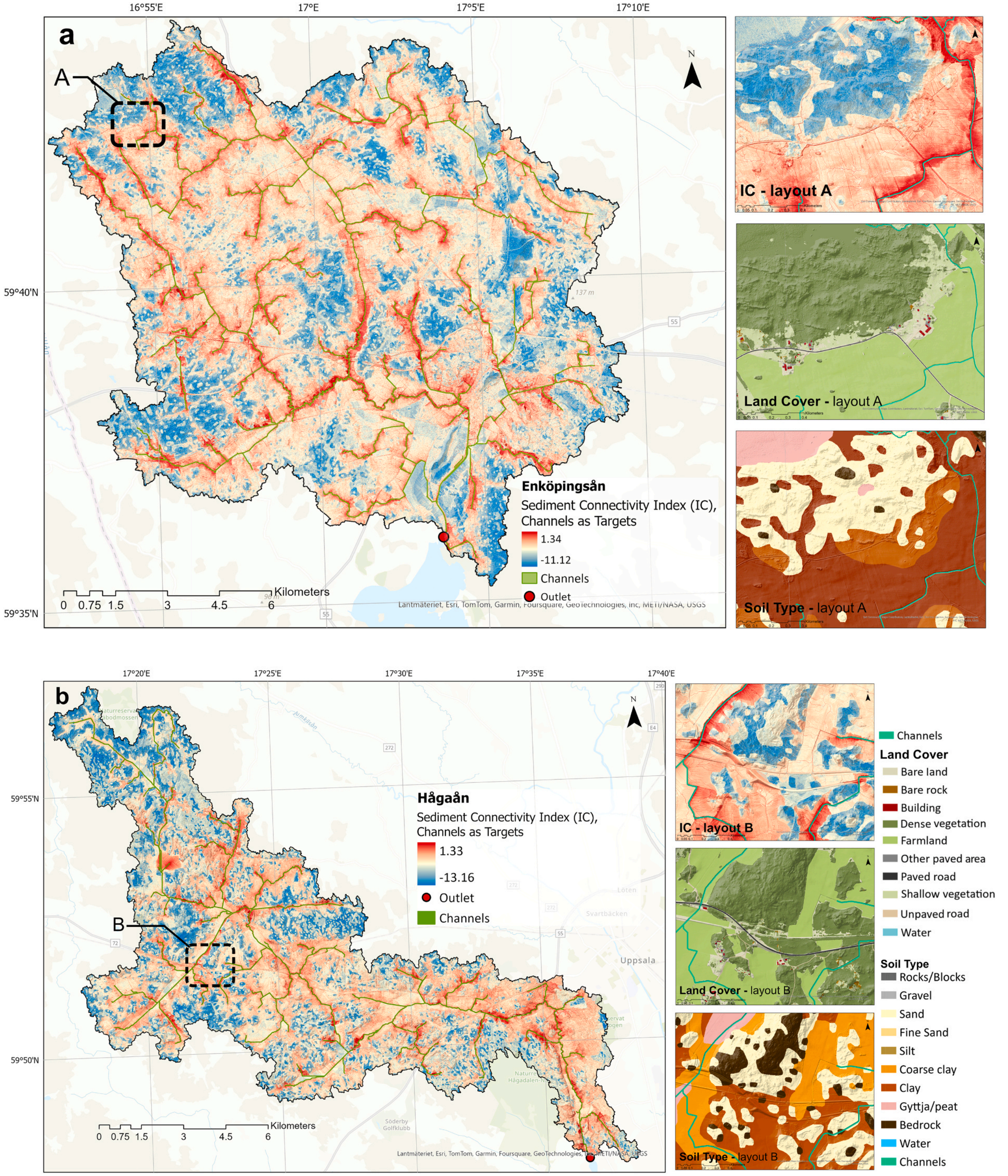

Fig. 4. The sediment Connectivity Index maps relative to the channel network. Enkapingsan (a) and Hågaån (b) catchments, illustrating spatial variations in sediment transport probability. Higher values indicate greater connectivity and increased sediment mobility, while lower values suggest sediment retention areas.

long-term success (Hernandez et al., 2024; Lupp et al., 2021).

2.5. Decision support for wetland prioritization

Effective site selection for wetlands necessitates a robust and scientifically validated decision-making framework that integrates expert judgment, stakeholder priorities, and the spatial and biophysical characteristics of the catchments. To achieve this, we employed three interrelated methodologies: AHP, MCDA, and MODA.

The AHP, developed by Saaty (1987), systematically evaluates multiple criteria through pairwise comparisons. The AHP process began by developing pairwise comparison matrices for the primary functions and indicators. To determine the relative importance of wetland functions and their corresponding spatial indicators, a structured survey was conducted with a diverse group of stakeholders, including municipal officers, environmental specialists, and catchment managers. Participants were asked to provide pairwise comparisons for two prioritization levels: a) wetland ecosystem functions, and b) decision-making criteria/factors used in the spatial analysis. All responses were structured according to the AHP, and consistency ratios ($CR < 0.1$) (Wind and Saaty, 1980) were used to validate the responses. In cases of inconsistency, follow-up clarifications were sought, or the entry was excluded. Aggregation of stakeholder input was conducted using the geometric mean method, which is widely accepted for combining multiple AHP matrices while preserving proportional relationships (Saaty et al., 2012). The resulting average weights formed the basis for the MCDA presented in Table 7. Where conflicting priorities emerged, a summary discussion with core stakeholders was facilitated to explore the rationale and align perspectives. This dual-level prioritization approach allowed for a structured and transparent integration of stakeholder values in both goal-setting and criteria weighting.

Each spatial metric was treated as a proxy indicator for specific ecosystem functions, allowing the MCDA to rank sites based on their multifunctionality potential. The matrices were then normalized by dividing each column element by the column sum. Subsequently, the normalized values were averaged to determine the priority weight of each metric.

MCDA was employed to integrate spatial data with the weighting factors derived from AHP, enabling the spatial prioritization of sites. This method is particularly suited for environmental studies where multiple, often conflicting criteria need to be balanced (Huang et al., 2011; Malczewski, 2006). To standardize the metrics, values for each factor were normalized on a scale of 0–1. Based on the Priority Strategy column in Table 5, the standardized values were reclassified into nine suitability classes (1 least suitable to 9 most suitable) to facilitate raster analysis. The spatially explicit MCDA was conducted using a weighted overlay analysis. The result was a suitability map for each objective, ranking locations.

MODA was applied to synthesize the results from the four function MCDA outputs (Sediment & Nutrient Retention, Biodiversity, Flood Regulation, and Water Retention) into a single map representing overall suitability. This method was chosen after evaluating several decision-support approaches, including Multi-Objective Optimization (MOO) (Fonseca and Fleming, 1998) and Stochastic MCDA (Linkov et al., 2006), as MODA offered an optimal balance between analytical rigor and practical applicability (Belton and Stewart, 2012). MODA provides a clear and intuitive framework for integrating multiple objectives into a single, comprehensible output. This makes it particularly effective in decision-making processes involving diverse stakeholders with varying priorities, as it accommodates trade-offs between conflicting objectives (Kirkwood, 1998). Additionally, MODA aligns well with the participatory nature of this study, ensuring that the results remain transparent and accessible for both technical experts and non-expert stakeholders. While MODA has significant advantages, its challenges must also be acknowledged. Subjective weighting, the risk of oversimplification, and limited dynamic exploration are inherent concerns. However, in this study, the weighting of objectives and factors was determined through a participatory workshop involving stakeholders and experts, which addressed the concern of subjectivity. Additionally, while aggregating objectives into a single map could obscure specific trade-offs, this limitation was mitigated by first creating detailed, objective-specific maps.

3. Results and discussion

3.1. Sediment transport dynamics and implications for wetland placement

The sediment connectivity maps for Enköpingsån and Hågaån catchments are presented in Fig. 4. These maps illustrate the spatial distribution of the IC, quantifying the probability of sediment transfer across the landscape, particularly under extreme rainfall events. In the first step of IC modeling, the sediment connectivity index was calculated with respect to the channel network, which was selected as the target layer. This step highlights regions characterized by different levels of connectivity, providing insights into soil conservation, water quality management, and hydrological processes. Additionally, this analysis was used to evaluate sediment connectivity within the identified SAW areas, providing a baseline for understanding their potential to accumulate water, retain sediment, and influence water quality. This assessment helps determine whether these locations are likely to function as effective retention areas by capturing runoff and reducing sediment transport from upstream sources. Areas adjacent to the main streams generally exhibit high connectivity due to their proximity to the fluvial system, facilitating rapid sediment transport (Kalantari et al., 2021). The influence of landscape attributes, such as land cover, soil properties, slope, and hydrological conditions, is evident in the modeling results. For instance, areas with dense vegetation and permeable soils, such as sandy deposits, tend to exhibit lower connectivity, even on steeper slopes (e.g., Layout A, Fig. 4a). This observation underscores the importance of functional connectivity rather than relying solely on structural connectivity and highlights the need for a combined approach that integrates both static and dynamic landscape parameters when assessing sediment connectivity.

Agricultural and open land areas exhibit higher connectivity values, indicating that these areas contribute more significantly to

Table 6
Statistics of the sediment connectivity index, targeting the channel network.

Catchment	IC Min	IC Max	IC Mean	IC Std. dev
Enköpingsån	−11.118	1.343	−7.307	1.086
Hågaån	−13.155	1.335	−8.093	1.545

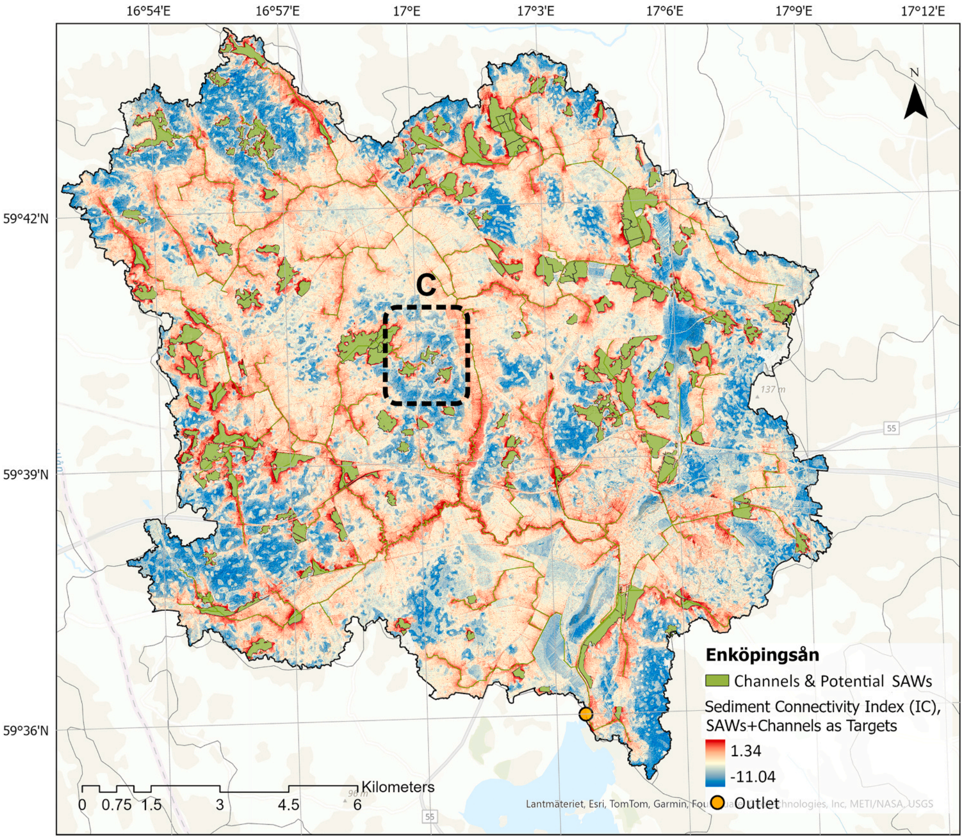

Fig. 5. Sediment Connectivity Index (IC) for the Enköpingsån catchment with both channels and selected wetland polygons as downstream targets. The dashed box (C) indicates the sub-region shown in greater detail in Fig. 6.

sediment transport, particularly where bare soils are exposed (e.g. Layout B, Fig. 4b). Road networks and urban areas display mixed connectivity patterns; while impermeable surfaces in urbanized regions limit direct sediment mobilization, they increase surface runoff. This can indirectly enhance connectivity by accelerating water flow and eroding adjacent unprotected soil. In contrast, unpaved roads and compacted tracks act as direct sediment conduits, amplifying connectivity along their paths. Wetland and forested regions serve as natural sediment buffers, reducing connectivity and promoting sediment retention. This underscores the critical role of land use management in sediment control strategies.

The IC values are log-transformed, with more negative values indicating areas of low sediment connectivity, typically where sediment is retained or disconnected from the stream network. Conversely, higher IC values indicate zones with higher connectivity, where sediment has a greater likelihood of reaching the channel network. This interpretation supports the identification of priority areas for sediment retention interventions, such as wetlands, especially in agricultural or open land zones where erosion risks are elevated. A comparative analysis of sediment connectivity between the two catchments reveals distinct differences driven by land cover composition and catchment morphology. The Hågaån catchment, characterized by higher proportions of forested and vegetated areas, exhibits lower mean connectivity (-8.09) compared to Enköpingsån (-7.30), where agriculture and open lands are more prevalent (Table 6). This suggests that Hågaån benefits from natural sediment retention, whereas Enköpingsån may require targeted sediment control interventions to mitigate erosion risks.

In addition to land cover differences, the spatial distribution of high connectivity zones varies between the two catchments. Hågaån has a more elongated shape, which naturally channels sediment transport along a linear pathway, concentrating connectivity along valley floors and agricultural corridors. In contrast, Enköpingsån's circular morphology results in a more dispersed sediment transport pattern, leading to a broader distribution of high-connectivity zones, particularly in the areas of intensive land use. This structural

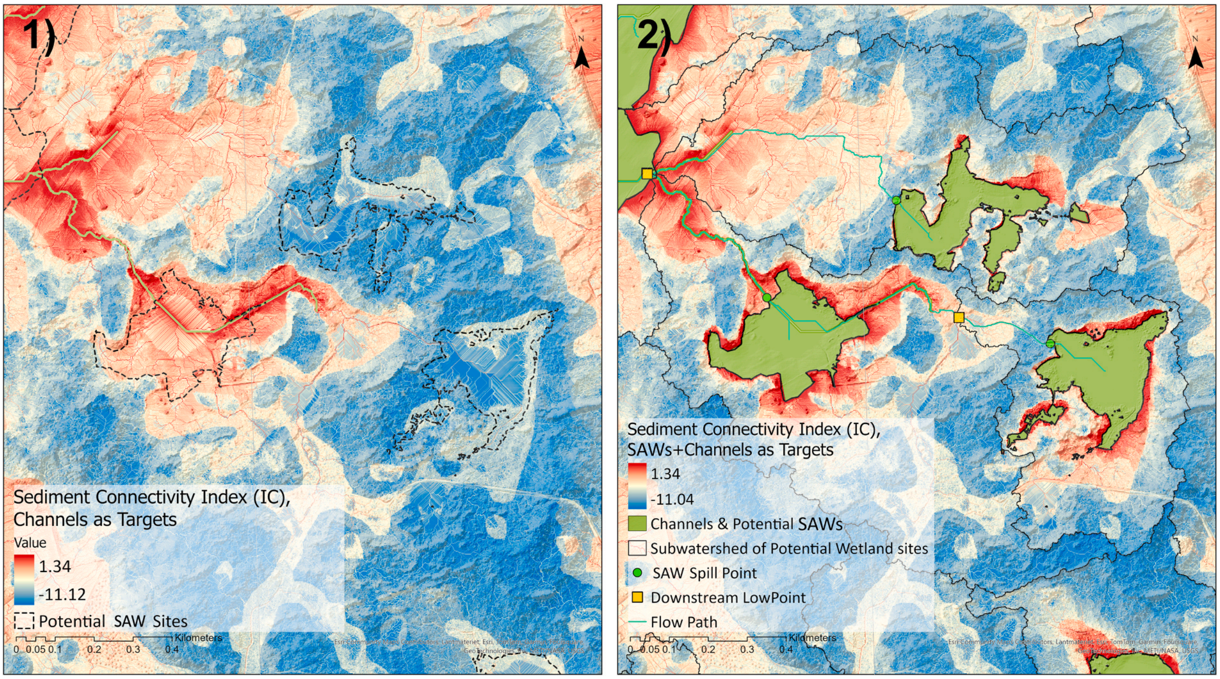

Fig. 6. IC maps for location **C** (Fig. 5) illustrate how connectivity patterns shift when wetlands are included as downstream targets. Panel 1 (on the left) shows the IC map with channels as the only targets, whereas Panel 2 (on the right) incorporates both channels and potential wetland locations as targets. Subcatchments contributing to each potential wetland are delineated.

difference implies that management strategies should be tailored accordingly, with Hågaån requiring localized interventions along transport pathways, whereas Enköpingsån may benefit from a more distributed network of interventions across the catchment.

In the second step of sediment connectivity modeling, following the identification of potential wetland locations through depression analysis and municipal selection, the IC model was recalculated using both the channels and selected wetland polygons as downstream targets (Figs. 5 and 7). This step allows for a more comprehensive assessment of the upstream-downstream dynamics of each potential wetland site, offering insights into the likelihood of sediment and water transfer to these depressions. Unlike earlier studies that assessed connectivity solely with respect to fluvial networks (Kalantari et al., 2021), this approach provides a basis for simulating how connectivity patterns would shift following wetland implementation. This illustrates how these potential wetland sites interact with sediment transport dynamics within the broader catchment (Fig. 6).

The integration of wetland site selection into sediment connectivity modeling marks a significant methodological advancement in landscape-scale sediment management. Unlike traditional hydrological models that simulate generalized sediment fluxes, this approach enables targeted identification of strategic wetland placements for various functions. By explicitly defining potential wetland locations as sediment retention nodes, this study extends the applicability of connectivity-based approaches to NBS planning.

From a management perspective, the results highlight that some wetlands are positioned in high-connectivity zones, where sediment transport is more active, reinforcing their potential to capture and retain sediment before it reaches main watercourses. Conversely, other sites are located in areas with lower connectivity, suggesting their role may be more suited to hydrological retention rather than sediment trapping. This level of spatial differentiation provides a decision-support framework for municipalities, enabling the prioritization of wetlands based on their intended ecosystem services. This methodological innovation improves spatial targeting for wetland implementation and provides a more dynamic understanding of catchment sediment fluxes. The high-resolution modeling (1-meter resolution) used in this study allows for greater spatial precision, making it particularly valuable for localized planning efforts and ensuring that wetland placement is optimized at a fine scale. While previous studies (Heckmann et al., 2018; Kalantari et al., 2017) have demonstrated the importance of land use and terrain-based connectivity in sediment transport, this research advances the field by incorporating site-specific NBS planning into sediment connectivity frameworks. As a result, this approach offers a scalable and adaptable methodology for integrating hydrological restoration measures into sediment management strategies, making it especially relevant for catchment-wide conservation planning and adaptive land management. This study paves the way for future research on dynamic sediment retention strategies in hydrologically sensitive landscapes by bridging the gap between theoretical connectivity indices and real-world implementation.

Additionally, the upstream-downstream delineation highlights areas within the catchment that remain uncovered by potential wetland sites, neither serving as upstream contributors nor being within the direct downstream influence of selected locations. As shown in Fig. 8, these uncovered regions are more prominent in the central part of Enköpingsån, predominantly encompassing arable lands and urban areas. Similarly, the delineation for Hågaån (Fig. 9) indicates uncovered areas near urban zones, suggesting potential

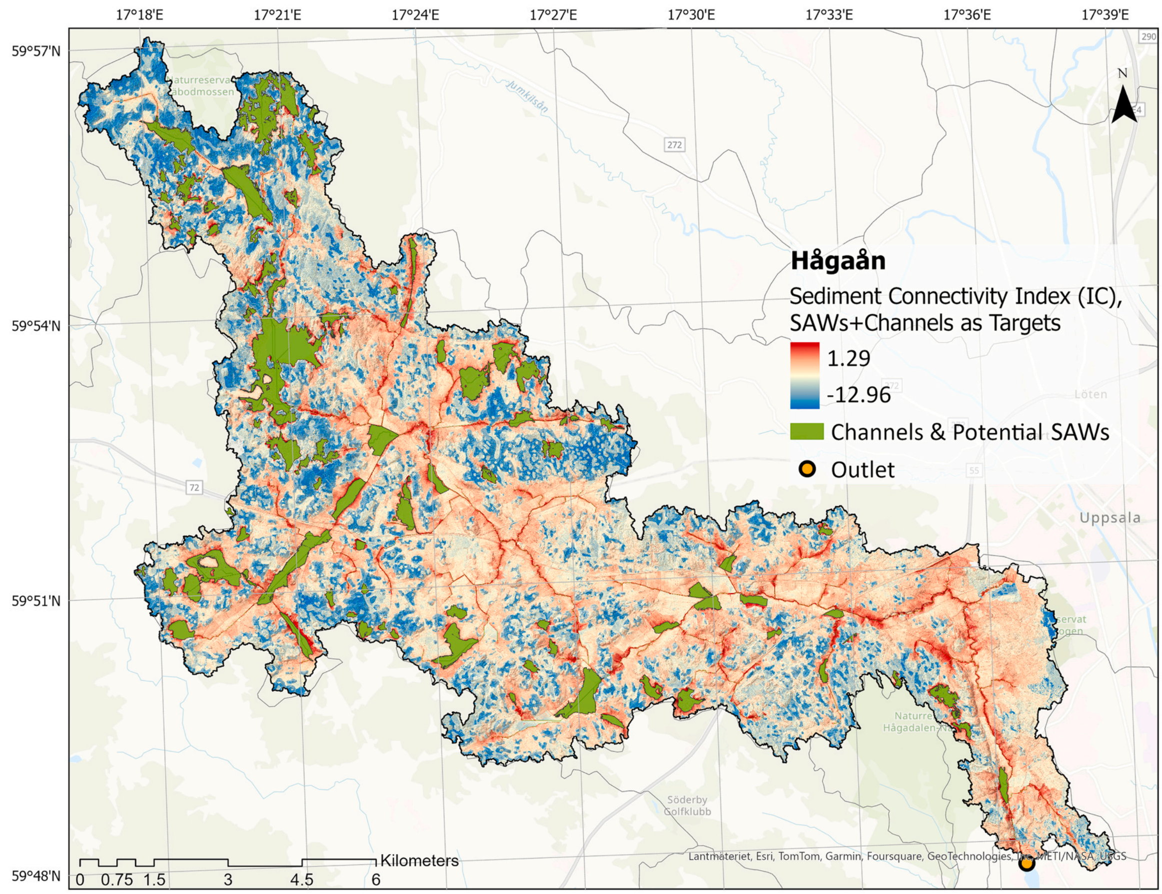

Fig. 7. IC for the Hågaån catchment; channels and selected wetland polygons as downstream targets.

gaps in wetland coverage around densely populated or rapidly urbanizing locations.

This observation underscores the need for future wetland planning efforts to specifically target sub-catchments adjacent to urban regions, addressing the unique challenges associated with urban runoff, flood mitigation, and water quality improvement. Although the sites currently selected effectively capture key hydrological and sediment transport pathways, complementary strategies are recommended to address water retention and nutrient regulation more comprehensively, particularly within agricultural and urban landscapes. It should also be noted that the downstream delineation in this study was limited to the first significant stream junction for practical modeling purposes and to define the immediate downstream area most directly influenced by each wetland site. This approach ensures spatial relevance for localized impact assessment while allowing for consistent and scalable prioritization across multiple candidate sites. However, the hydrological and biogeochemical effects of wetlands are likely to extend well beyond these boundaries. For instance, sediment and nutrient attenuation benefits may continue downstream toward the main outlet, underscoring the importance of considering cumulative effects in future catchment-scale evaluations (Djodjic et al., 2020).

3.2. Multi-criteria decision support and stakeholder insights for wetland prioritization

According to the priority strategy of each normalized metric for each function (Table 5), separate raster layers were created as the foundational input for the MCDA process. The AHP results provided a structured weighting of these factors, ensuring that the stakeholder-driven prioritization strategy was systematically integrated into the decision-making framework. As indicated in Table 7, the highest-priority factors included Land Use within the SAW Area (LU_{in}) (29.1 %), followed by IC within the SAW Area (IC_{in}) (18.4 %), and SAW Storage Potential (S_t) (17.6 %). The Consistency Ratio (CR) of 0.013 confirms that the AHP judgments were consistent and reliable, ensuring the validity of the weighting structure. These weights were subsequently applied in the MCDA process, where the relative importance of each factor was incorporated into a weighted overlay analysis, producing suitability maps for wetland prioritization for each function (Fig. 10).

Although this study does not explicitly simulate hydroperiods, some of the hydrological indicators used, such as upstream runoff contribution (Q_{up}), pond storage potential (S_t), and contributing area, can indirectly inform about potential inundation frequency and duration. Since the hydrological assessments were based on modeled runoff under extreme rainfall conditions, the framework focuses on wetland functionality during peak flow events rather than long-term inundation dynamics. While this aligns with the flood

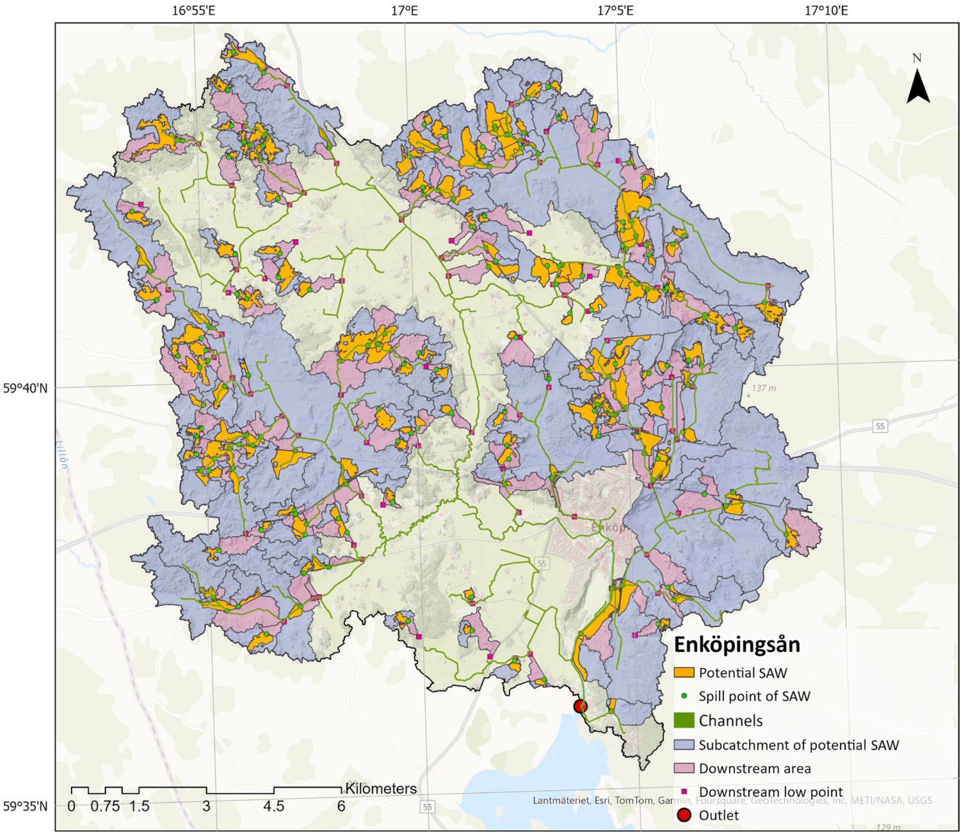

Fig. 8. Coverage of potential wetland locations, their contributing subcatchments, and the directly influenced downstream areas within Enköpingsån, showing uncovered areas mainly in central arable lands and urban zones.

regulation and sediment control goals of many SAWs, future work could incorporate hydroperiod modeling using dynamic simulations or remote sensing time series to address ecological functions more comprehensively (Junk et al., 2013).

The MCDA-generated suitability maps reveal that high-priority wetlands are often located in areas where hydrological and geomorphological factors converge. This reinforces previous findings that multi-criteria spatial analysis enhances wetland planning efficiency (Huang et al., 2011). Compared to previous studies that applied MCDA for flood mitigation and sediment retention separately (Abdullah et al., 2021; Kafle and Shakya, 2018), this research presents a more integrated approach, demonstrating how multi-objective wetland planning can be operationalized at the catchment scale. Additional metrics were analyzed to refine prioritization further, considering site-specific characteristics and upstream and downstream influences. For instance, if the upstream area is predominantly forested, the potential wetland would likely prioritize biodiversity conservation due to lower sediment and nutrient loads, creating a favorable habitat environment. Conversely, if agricultural land dominates upstream, the wetland's primary function would shift toward sediment and nutrient retention, targeting nitrogen and phosphorus removal to enhance downstream water quality (Djodjic et al., 2022, 2020). Similarly, the characteristics of downstream areas influenced site prioritization; wetlands positioned upstream of urban areas were prioritized for flood regulation functions to protect downstream infrastructure and communities. This spatially explicit approach provides a comprehensive evaluation of wetland functionality, ensuring site selection captures critical local conditions and broader catchment-wide hydrological interactions.

The AHP-MCDA approach, while robust, has certain limitations. Assigning weights to various criteria can introduce subjectivity, even with stakeholder engagement enhancing transparency. To mitigate this, future research could employ machine learning-based sensitivity analyses to refine these weighting schemes. Techniques such as Random Forest feature importance, SHapley Additive Explanations (SHAP), and permutation importance can systematically assess how individual variables influence the overall suitability scores. These methods offer transparent and data-driven insights and have been increasingly used in environmental and hydrological modeling to reduce subjectivity and improve interpretability (Mahdavi-Meymand et al., 2024). Additionally, the static nature of the current suitability analysis offers a snapshot based on existing conditions. Incorporating dynamic hydrological modeling tools would allow for simulations of wetland effectiveness under varying climate scenarios, providing a more comprehensive understanding of potential changes over time. Another important consideration is the role of landowners, who ultimately determine whether a site can be developed as a SAW. Although this study involved municipal stakeholders and environmental experts, future planning efforts would benefit from more direct engagement with landowners to ensure feasibility, acceptance, and long-term success.

The MODA results (Fig. 10), synthesized from the MCDA suitability maps, serve as an integrated decision-support tool for

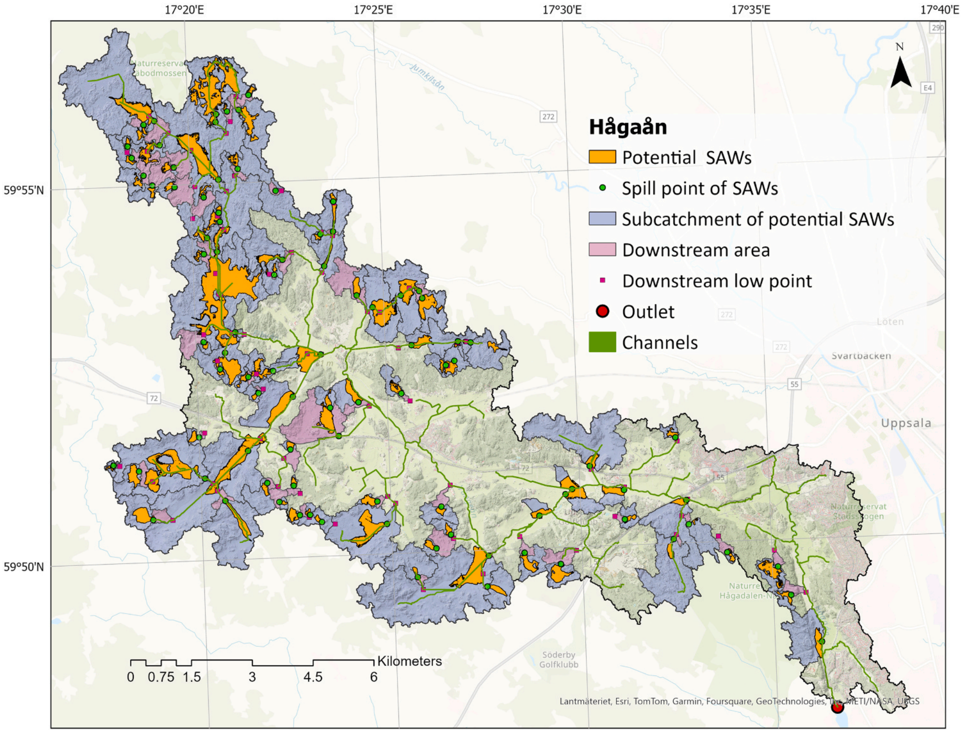

Fig. 9. Spatial distribution of potential wetland sites within the Hågaån catchment. Areas not covered by selected wetlands highlight potential gaps near urban zones for future wetland planning and intervention.

Table 7
AHP, pairwise comparisons matrix.

Factors		IC_{in}	IC_{up}	LU_{in}	LU_{up}	LU_{dn}	Q_{up}	A_{dn}	S_t	Priority Weight	CR
IC within SAW Area, channels as targets	IC_{in}	1.00	2.00	0.50	4.00	3.00	2.00	5.00	1.00	18.4	0.013 < 0.1
Upstream IC Wetlands and channels as targets	IC_{up}	0.50	1.00	0.33	2.00	1.00	1.00	3.00	0.50	9.4	
Land Use within Wetlands	LU_{in}	2.00	3.00	1.00	5.00	5.00	3.00	5.00	2.00	29.1	
Land Use Upstream	LU_{up}	0.25	0.50	0.20	1.00	1.00	1.00	2.00	0.33	6.2	
Land Use Downstream	LU_{dn}	0.33	1.00	0.20	1.00	1.00	0.50	2.00	0.33	6.4	
Upstream Runoff	Q_{up}	0.50	1.00	0.33	1.00	2.00	1.00	3.00	0.50	9.4	
Downstream Area Size	A_{dn}	0.20	0.33	0.20	0.50	0.50	0.33	1.00	0.20	3.6	
SAW Storage Potential	S_t	1.00	2.00	0.50	3.00	3.00	2.00	5.00	1.00	17.6	
SUM		5.78	10.84	3.27	17.50	16.50	10.83	26.00	5.87	100.0	

identifying optimal wetland sites. By aggregating the four primary objectives, the final composite suitability map highlights sites where multiple wetland functions overlap and reinforce each other, providing a holistic approach to site prioritization. While the original suitability classification ranged from 1 to 9, the final composite map primarily includes classes 3–7. This is because extremely low or high values across all four functions rarely co-occur at a single location after overlay. The analysis revealed that high-priority wetland locations were predominantly in areas with both high sediment connectivity and strong retention potential, reinforcing the role of sediment retention in flood mitigation efforts. However, certain locations exhibited trade-offs, where biodiversity-rich sites ranked lower in flood mitigation effectiveness, necessitating a balanced approach in site selection to ensure that no single objective disproportionately influences the final decision. These findings align with Belton and Stewart (2012), who highlight MODA's strength in balancing competing objectives, demonstrating its applicability to catchment-wide wetland planning and supporting the integration of multi-functional NBS in landscape management.

4. Conclusion

This study presents an innovative, integrated framework for optimizing wetland placement that bridges advanced hydrological modeling with participatory, stakeholder-driven decision-making. By combining both structural and functional sediment connectivity analyses with rigorous hydrological assessments and multi-criteria decision analysis, this framework offers a holistic tool for

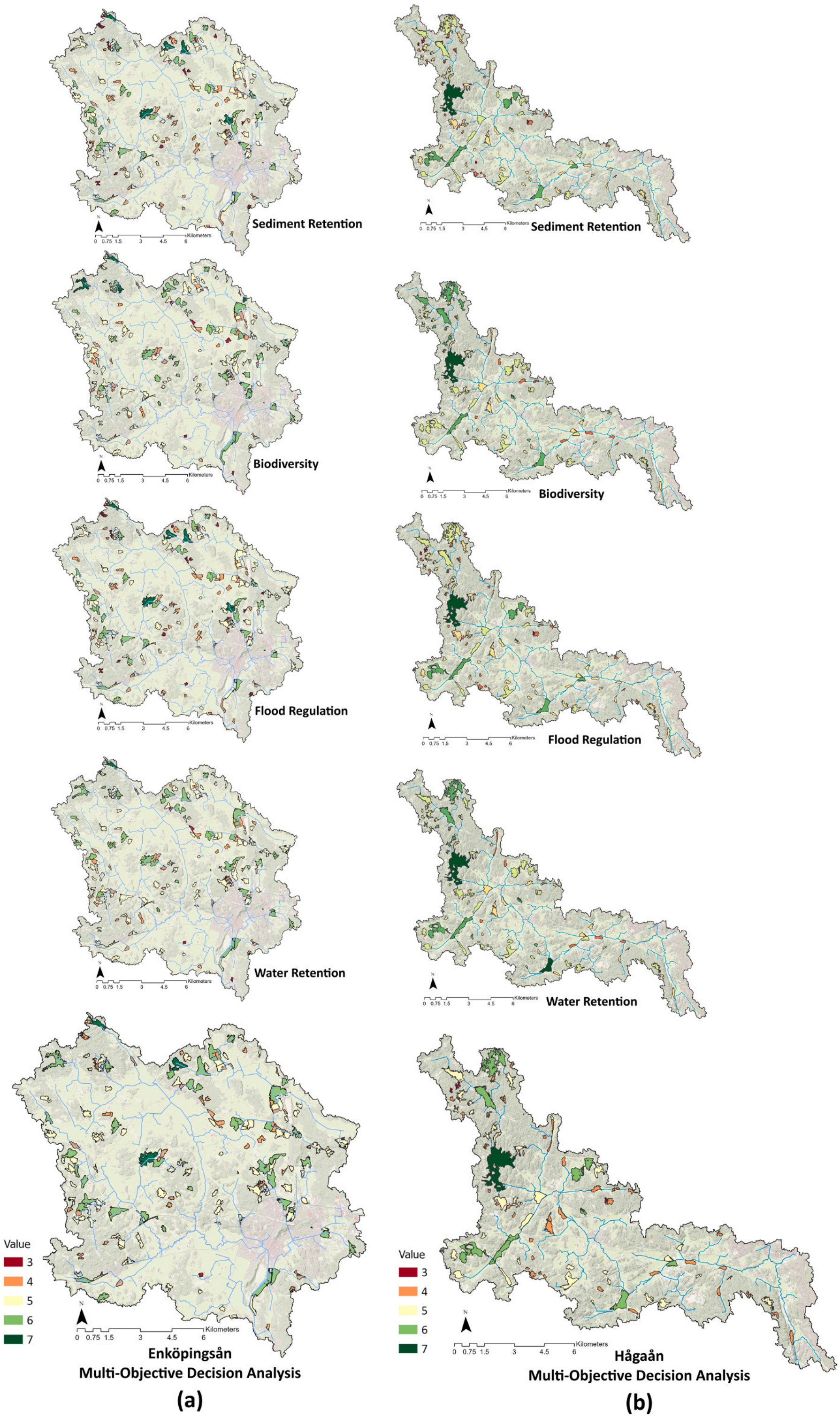

Fig. 10. Multi-Criteria Decision Analysis (MCDA) suitability maps for wetland site prioritization within Enköpingsån (a) and Hågaån (b) catchments. Individual maps depict prioritized wetland locations for sediment retention, water retention, biodiversity conservation, and flood regulation. The final composite map illustrates integrated multi-objective decision analysis (MODA), highlighting locations where multiple wetland functions converge, indicating optimal sites for multifunctional wetland implementation. Each map panel uses a standardized scale from 3 to 7, reflecting the aggregated suitability score derived from MCDA. The values represent relative priority classes, where 7 indicates the highest suitability.

identifying wetland locations that can deliver multiple ecosystem services simultaneously, ranging from flood mitigation and sediment retention to enhanced water regulation and biodiversity conservation.

The findings demonstrate that wetlands strategically located in high-connectivity zones can significantly intercept sediment flows and reduce erosion, while also buffering downstream areas against extreme flood events. The upstream-downstream evaluation further refines site selection by accounting for the interdependencies within catchment dynamics, ensuring that interventions are not only effective at a local scale, but also contribute to broader watershed resilience. Moreover, the active engagement of stakeholders throughout the process ensures that scientific insights are grounded in local knowledge and practical constraints, thereby enhancing the feasibility and long-term success of wetland implementation efforts.

Despite these promising outcomes, some uncertainties and limitations remain that warrant future exploration. The current framework offers a static representation of landscape conditions based on high-resolution data and extreme rainfall events, which provides valuable insights into wetland performance under intense hydrological scenarios. However, it does not explicitly account for future changes in land use, climate variability, or long-term hydroperiod dynamics. The weighting of indicators, though grounded in a structured stakeholder-driven AHP-MCDA process, inherently includes a degree of subjectivity. While this was mitigated through stakeholder participation and consistency checks, integrating machine learning–based sensitivity analyses in future research could improve transparency and robustness. Additionally, while site selection prioritizes low-intervention zones using topography and storage capacity, practical feasibility, such as construction costs and landowner willingness, may still influence implementation outcomes. Nonetheless, the framework provides a scalable, transferable foundation for integrating hydrological, ecological, and stakeholder considerations in catchment-scale wetland planning, while remaining adaptable for future enhancement as new data and modeling capabilities become available. This integrated approach lays a strong foundation for resilient, sustainable catchment management strategies that balance ecological, hydrological, and socio-economic objectives in a rapidly changing world.

CRediT authorship contribution statement

Pan Haozhi: Writing – review & editing. **Martyn Futter:** Writing – review & editing. **Carla Sofia Santos Ferreira:** Writing – review & editing. **Stefano Crema:** Methodology. **Faruk Djodjic:** Writing – review & editing, Methodology. **Amir Rezvani:** Writing – review & editing, Writing – original draft, Software, Methodology, Formal analysis, Conceptualization. **Marco Cavalli:** Writing – review & editing, Methodology. **Zahra Kalantari:** Writing – review & editing, Supervision, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2025.102669.

Data availability

Data will be made available on request.

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