Sediment sources and phosphorus availability in agricultural streams at catchment scale

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Abstract

Agricultural streams play a key role in transporting sediment-associated phosphorus (P) from land to water. Yet the relative importance of different sediment sources remains poorly understood in Swedish catchments. This study integrates GIS-based erosion risk assessment, sediment colour analysis and phosphorus fractionation to improve process-level understanding of sediment and P mobilisation in the Lejstaån catchment, a small agricultural stream in Uppsala, Sweden. A GIS-based Erosion Index (EI) was adapted for use in a narrow, meandering headwater stream and identified several near-stream segments with elevated susceptibility to bank erosion. The EI-classes guided a sampling campaign where soil and sediment from fields, bank sediment, bed sediment, drainage pipes and floodplains from the catchment were represented (n=34). A Phillips sampler was deployed downstream during the period Jan-April representing a time-integrated sample of suspended sediment. Sediment colour analysis using scanned samples and RGB-based metrics showed that suspended sediment collected with a Phillips sampler most closely resembled a mixture of bank, bed and drainage material. However, substantial overlap between source types indicated that colour alone provides limited discriminatory power in this geologically homogeneous catchment. P fractionation revealed that bank material contained both stable (Ca-P, Al-P) and reactive P forms (Fe-P, part of Org-P), demonstrating that bank erosion can mobilise P with differing environmental relevance. Together, the results show that sediment-associated P transport in Lejstaån is strongly influenced by the interaction between geomorphological erosion risk, hydrological connectivity and the chemical reactivity of mobilised material. The findings highlight the importance of near-channel sources for P delivery and underscore the need to consider bank stability, vegetation cover in the near-stream zone and riparian processes in mitigation strategies for small agricultural streams.

Keywords: sediment sources, erosion, phosphorus mobilisation, agricultural streams, erosion risk assessment, colour print method, phosphorus fractionation

Statement on the use of generative AI

Generative AI tools (Microsoft Copilot) were used in this thesis to support minor tasks such as troubleshooting GIS workflows, generating short code snippets (e.g., for convex hull operations), and refining wording at the sentence level. All scientific interpretations, methodological decisions, data analyses, and conclusions are entirely my own. No AI tools were used to generate references, create original scientific content, or preform any form of data analysis. All text has been reviewed and edited by me to ensure accuracy and academic integrity.

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Abbreviations

Abbreviation	Description
Al-P	Aluminium-bound phosphorus
B	Channel width parameter (EI)
Ca-P	Calcium-bound phosphorus
CSA	Critical source area
DEM	Digital elevation model
E	Soil erodibility parameter (EI)
EI	Erosion Index
Fe-P	Iron-bound phosphoru
G	Water-surface gradient parameter (EI)
GIS	Geographic Information System
K	Channel curvature parameter (EI)
L	Bank Slope parameter (EI)
Org-P	Organic phosphorus
P	Phosphorus
PCA	Principal Component Analysis
RGB	Red – Green – Blue colour values
SS	Suspended sediment
SGI	Swedish Geotechnical Institute
SGU	Geological Survey of Sweden
SLU	Swedish University of Agricultural Sciences
TP	Total phosphorus
TPI	Topographic Position Index
USPED	Unit Stream Power Erosion and Deposition model

1. Introduction

Many lakes and streams in Sweden, as well as globally fail to reach good ecological status and one of the main reasons is diffuse phosphorus (P) pollution from agriculture. Society depends on a sustainable and productive agricultural sector for food production, employment, and biodiversity. At the same time, losses of P from agricultural land contribute to nutrient loading in surface waters which can reduce water quality (Withers & Jarvie, 2008). Because P is often the limiting nutrient in freshwater systems, elevated inputs can stimulate algal growth and lead to eutrophication (Swedish Agency for Marine and Water Management, 2024a).

Eutrophication is driven by nutrient enrichment and in agricultural landscapes P is often the limiting nutrient in freshwater systems. High P concentrations stimulate the growth of phytoplankton and filamentous algae and during summer this can lead to extensive algal blooms that negatively affect both human and animal health. Eutrophication also alters ecological relationships in aquatic environments and can reduce biodiversity (Sharpley et al., 2013). Large amounts of plant material may accumulate on the streambed, where decomposition can create oxygen-poor conditions. The Baltic Sea is one of the most affected marine areas around Sweden, with the highest nutrient concentrations near urbanized coastal zones. Within Sweden, eutrophication pressures are greatest in southern Skåne, the Mälaren region, Östergötland, and areas south of Lake Vänern (Swedish Agency for Marine and Water Management, 2024a).

To address eutrophication effectively, it is important to understand the processes that control P transport from agricultural land to receiving waters. Sediment is mobilised through surface runoff and subsurface flow, often originating from soils and streambanks enriched in P due to long-term fertilisation, known as legacy P (Sharpley et al., 2013). Agricultural streams can act as efficient pathways for P transport and even relatively small erosion events can have significant downstream effects, despite generally low erosion rates in Sweden (Djodjic & Markensten, 2019).

P losses from agricultural land occur through several hydrological and biogeochemical processes, including surface runoff, subsurface flow, soil erosion, and streambank instability. These processes vary across space and time depending on soil properties, topography, land use, and hydrological connectivity (Haygarth & Jarvis, 1999; 2002; Swedish Agency for Marine and Water Management, 2024b). During rainfall events, water moving across or through the soil profile mobilises both dissolved and particulate forms of P. In many agricultural catchments particulate transport dominates, meaning that P is primarily exported attached to fine sediment particles rather than in dissolved form (Sharpley et al., 2013).

Suspended sediment (SS) plays a central role in P transport because P strongly sorbs to mineral surfaces, particularly iron (Fe) and aluminium (Al) oxides and fine clay particles. As a result erosion and sediment mobilisation directly influence the magnitude of P losses from agricultural land. High-flow events are especially important, as they generate both increased erosion and enhanced hydrological connectivity between fields, ditches, riparian zones and streams. Consequently, a large proportion of annual P export can occur during a small number of storm events when SS concentrations peak (Haygarth & Jarvis, 1999).

Not all sediment-associated P has the same environmental relevance. The mobility and bioavailability of P depend on its chemical form, mineral associations, and redox conditions. Previous work in Swedish agricultural streams shows that Fe-bound P often occurs in relatively low proportions but can vary substantially between sites and under different redox conditions (Lannergård et al., 2020). P bound to Fe-oxides can become bioavailable under reducing conditions, whereas P associated with Al-oxides is instead sensitive to pH changes (Lannergård et al., 2020; Sharpley et al., 2013). Calcium (Ca)-bound P is typically more stable, whereas Fe- and Al-associated form are more sensitive to redox and pH changes (Lannergård et al., 2020).n Fine particles with large surface areas often carry high P loads and can be transported long distances downstream (Withers & Jarvie, 2008). Understanding both the quantity and characteristics of SS is therefore essential for evaluating its contribution to eutrophication, particularly because SS often contains higher proportions of reactive P than bed material in Swedish agricultural stream (Sandström et al., 2021).

P losses are highly spatially heterogeneous. Only a small fraction of the landscape, known as critical source areas (CSAs) contributes the majority of P export. These areas are characterised by the simultaneous occurrence of high P availability, erosion potential, and hydrological connectivity (Haygarth & Jarvis, 2002). Spatial heterogeneity is a key challenge for mitigation, as different parts of the landscape vary greatly in their contribution to sediment and P losses. High-resolution modelling in Sweden has shown that SS loads, especially during extreme episodes strongly control losses of unreactive and total P (TP) at both field and catchment scale (Djodjic & Markensten, 2019). Their work also demonstrates that GIS-based erosion modelling can successfully identify CSAs and capture fine-scale spatial variation, highlighting the importance of topography, soil texture, and flow pathways for P transport. Although erosion-prone areas can be identified using topography, soil maps, and field observations, it remains challenging to determine which landscape units actually contribute to SS loads in streams (Djodjic & Markensten, 2019).

Riparian zones can function in contrasting ways. Under stable conditions they act as buffers that retain sediment and nutrients. But when banks are unstable or hydrological connectivity is high they can instead become major sources of SS and particulate P (Kronvang et al., 2012; Pulley & Collins, 2024). Legacy P stored in riparian soils and sediments can further amplify these losses. International studies show that streambank erosion can be a dominant source of sediment and particulate P in agricultural catchments (Kronvang et al., 2012; Pulley & Collins, 2024), yet similar assessments are still lacking for Sweden.

The role of bank erosion has likely been underestimated in temperate agricultural catchments (Pulley & Collins, 2024). In addition, the environmental relevance of sediment associated P depends not only on the amount transported but also on its bioavailability, which remains poorly understood in Swedish agricultural streams. This study will give insight into one of the main mechanisms in diffuse agricultural pollution: the transport of phosphorus from land to water by examining sediment and P dynamics with a particular focus on streambank erosion. This work addresses a critical knowledge gap in understanding P mobilisation in Swedish agricultural landscapes.

1.1 Aim

This study aimed to integrate spatial erosion risk assessment, P fractionation and sediment source tracing to improve process understanding of sediment-associated P transport in agricultural landscapes.

1.2 Research questions

1. Which sections of small agricultural streams are most susceptible to bank erosion based on GIS-based spatial analysis?
2. To what extent can sediment colour serve as a rapid and simple indicator of sediment sources contributing to suspended sediment in the stream?
3. How does the proportion of total phosphorus (TP) and potentially bioavailable P forms vary across different sediment sources?
4. How can the integration of spatial erosion risk assessment, sediment colour analysis and phosphorus fractionation improve understanding of sediment and P mobilisation in small agricultural streams?

1.3 Background

To understand the mechanisms behind sediment-associated P transport introduced in the previous section, this background outlines the key processes, spatial controls and methodological approaches relevant to erosion processes and P mobilisation in agricultural streams.

1.3.1 Phosphorus (P) transport and suspended sediment (SS)

P losses from agricultural land are controlled by hydrological and geomorphological processes that mobilise both dissolved and particulate forms of P. SS plays a central role in P mobilisation because P strongly sorbs to mineral surfaces, particularly Fe and Al oxides and fine clay particles. High-flow events enhance erosion and hydrological connectivity between fields, ditches, riparian zones, and streams, causing a large proportion of annual P export to occur during a small number of storm events (Withers & Jarvie, 2008).

In Swedish agricultural streams SS exerts strong control on P transport, particularly during intermediate to high flows when fine particles dominate the load (Lannergård, 2021). Similar patterns have been observed for P fractions where SS often contains higher proportions of reactive P than bed material due to episodic mobilisation during storm events (Sandström et al., 2021). These findings highlight that understanding SS dynamics is essential for interpreting both the timing and magnitude of P export in small catchments. Small agricultural streams are particularly sensitive to sediment and P inputs due to their limited buffering capacity and high responsiveness to hydrological events (Lannergård, 2021).

1.3.2 Spatial heterogeneity, critical source areas (CSAs) and riparian zones

Sediment and P losses are highly spatially heterogeneous. Only a small fraction of the landscape known as critical source areas (CSAs), contributes the majority of P export. These areas are characterised by the co-occurrence of high P availability, erosion potential, and hydrological connectivity (Haygarth & Jarvis, 1999; Sharpley et al., 2013). High-resolution modelling in Sweden has shown that SS loads, particularly during extreme flow events strongly control losses of unreactive P and TP at both field and catchment scale (Djodjic & Markensten, 2019).

Hydrological connectivity plays a central role in determining which parts of the landscape contribute sediment and P to streams. Swedish studies have demonstrated that near-stream areas with strong surface or subsurface connectivity can rapidly transmit sediment and nutrients to receiving waters, even when erosion rates are low at the field scale. As a result, riparian zones often function as CSAs, especially during storm events when connectivity peaks (Haygarth & Jarvis, 1999; Sandström, 2022).

Riparian zones can act either as sinks or sources of sediment and P (Kronvang et al., 2012). Under stable conditions they retain sediment and nutrients, but when banks are unstable or connectivity is high they can become major contributors of SS and particulate P. Legacy P stored in riparian soils can further amplify these losses (Lannergård et al., 2020). International studies show that bank erosion can be a dominant sediment source in agricultural catchments (Kronvang et al., 2012; Pulley & Collins, 2024), yet similar assessments remain limited for Sweden. This gap is particularly relevant for small, meandering streams where bank erosion may be underestimated despite its potential to mobilise large quantities of P-rich sediment.

To effectively assess where erosion and sediment mobilisation occur in the landscape, a range of methodological approaches can be used. These include field-based assessments, geochemical tracing techniques, and GIS-based spatial models. The following sections outline the main approaches relevant to this study.

1.3.3 Approaches for assessing erosion risk and sediment sources

A range of approaches exists to identify erosion-prone areas and sediment sources in agricultural landscapes. Traditional assessments rely on field-based techniques such as visual bank stability inspections, erosion pins, repeated cross-section surveys, and photographic monitoring (Lawler, 1993). These methods provide detailed local information but are labour-intensive, spatially limited, and difficult to standardise across large areas. Process-based hydrological and erosion models, such as WEPP and SWAT can simulate sediment mobilisation and transport. But they require extensive calibration and high-quality input data (Nearing et al., 2011).

As a complement to field-based and process-based approaches GIS-based tools enable efficient, catchment-scale screening of erosion risk by integrating topography, soil properties, and hydrological indicators. In Sweden, the Swedish Geotechnical Institute (SGI) has developed a GIS-based Erosion Index (EI) that incorporates parameters such as bank slope, soil erodibility, channel curvature, and water-surface slope to identify riverbank sections susceptible to erosion (SGI, 2025). Such tools provide an efficient first step for locating erosion-prone riparian areas that may contribute to SS and P export.

Identifying the origin of SS is equally important for understanding P transport. Sediment source tracing is commonly performed using geochemical fingerprinting, where sediment samples are analysed for their elemental composition, mineralogy, isotopic signatures, or organic markers. These tracers are then used in statistical mixing models to quantify contributions from different landscape units (Collins & Walling, 2007). While geochemical fingerprinting provides high-resolution source attribution, it is analytically demanding, costly, and requires specialist laboratory facilities, which limits its routine application in small catchments.

Recent work has therefore explored low-cost alternatives, such as using sediment colour as an indicator of source material. In the study by Pulley and Collins (2021), colour measurements obtained using a standard office scanner were tested as a simple and accessible alternative to conventional fingerprinting. Their work across eight agricultural catchments in England showed that colour-based approaches can distinguish major sediment sources and function as an initial screening tool, although with lower resolution than advanced geochemical methods.

Together these approaches provide complementary perspectives on erosion processes, sediment sources, and P mobilisation, forming a theoretical basis for the methods applied in this study.

2. Materials and Methods

2.1 Study site

The study was conducted in the Lejstaån catchment, located near Ingvasta approximately 19 km northeast of Uppsala. Lejstaån is a naturally meandering stream and erosion-prone system characterised by agricultural land and forest patches (see Figure 1). The catchment forms a headwater basin (Vattenwebb, SUBID:8359) and is known to exhibit elevated background concentrations of P (Lannergård, 2021). Long-term stream water chemistry data are available from the monitoring station "Sävjaån, Ingvasta" (ID: 164, MVM data, 2026), providing valuable information on nutrient dynamics in the system.



Figure 1. Satellite view of Lejstaån catchment. The image shows the meandering stream and the surrounding landscape consisting of agricultural fields and forest patches. Source: Google Earth (screenshot captured 6 May 2026). Map data © Google, Maxar Technologies.

2.2 GIS-based Erosion Index (EI)

As a complement to traditional field assessments and sediment tracing techniques, GIS-based methods provide an efficient way to screen erosion risk at the catchment scale. The Swedish Geotechnical Institute (SGI) has developed a GIS-based Erosion Index (EI) to systematically identify riverbank sections susceptible to erosion and potential slope failure (SGI, 2025). The method integrates national geospatial datasets, including elevation models, soil maps, and hydrological data, to automatically calculate erosion susceptibility along stream reaches.

The EI method combines six parameters: soil erodibility (E), bank slope (L), relative elevation position (P), channel curvature (K), channel width (B), and water-surface slope (G), into a single index value using SGI`s equation. EI values are classified into five levels using Jenks natural breaks, allowing high-risk sections to be distinguished from more stable reaches. SGI recommends using EI as an initial screening tool followed by field verification where necessary.

In this study, the EI method required several adaptations to function in a small agricultural stream. SGI developed the index for large watercourses with wider channels and more pronounced geomorphological features, meaning that parameters such as channel width, curvature and bank slope had to be adjusted to the spatial scale and morphology of Lejstaån. These adaptations represent an important methodological development, enabling EI to be applied in narrow, meandering headwater streams where erosion processes operate at finer spatial scales.

2.2.1 Data sources and preprocessing

To derive EI for Lejstaån, calculations were done in ArcGIS Pro 3.5.0 (Esri, 2025). A detailed GIS workflow is provided in Appendix 1, here follows a brief description. A 1-m resolution digital elevation model (DEM) and hydrological vector data were obtained from SLU GET (2025). DEM tiles were mosaicked (merged) into a single raster and used to derive slope, focal-mean surfaces and hillshade. The hydrological dataset was used to extract the centreline of Lejstaån, which was dissolved into a continuous polyline. The stream was segmented into 50-m units by generating equidistant points along the centreline and splitting the line at these locations. This segmentation formed the basis for all subsequent EI parameter calculations.

2.2.2 Parameter extraction

Each of the six EI parameters was derived following SGI's definitions but adapted to the spatial characteristics of Lejstaån (Table 1). These parameter values were subsequently combined using SGI´s EI formula (see section 2.2.3).

Table 1. Overview of the six parameters used in the Erosion Index (EI) and their methodological derivation. Each parameter was calculated following SGI´s definitions but adapted to the spatial characteristics of the Lejstaån stream.

Parameter	Description
E – Soil erodibility	Soil data from SGU (2024) were reclassified into erosion-sensitivity classes using the erodibility lookup table provided in the SGU product description. A 15m buffer around each segment was used to extract the dominant soil class.
L – Bank slope	Slope (degrees) was calculated from the DEM and reclassified using SGI´s threshold ($\geq 25°$). Maximum slope values within a 20m buffer were extracted and converted into binary L-values.
P – Relative elevation	A 50m focal-mean DEM was subtracted from the original DEM to produce a TPI surface. The raster was reclassified into a binary layer and aggregated to segment level using zonal statistics.
K – Channel curvature	Sinuosity was calculated using the River Sinuosity Tool in ArcGIS. Segment-level values were classified according to SGI´s recommended threshold (≥ 1.15).
B – Channel width	Channel width was measured manually using orthophotos and hillshade. Three measurements per segment were averaged and divided by two to represent bank distance. Values were normalised and classified into a 1 – 9 scale.
G – Water-surface gradient	A 2m buffer around each segment was used to extract mean slope values from the DEM. These were normalised and classified into a 1 – 9 scale.

2.2.3 Calculation of the Erosion Index

All parameters were joined to the segment layer and combined using SGI's EI formula:

$$EI = E \times (L + P + K) \times (B + G)$$

The resulting EI values were visualised using graduated colours to identify segments with elevated erosion susceptibility along Lejstaån. A detailed GIS workflow is provided in Appendix 1.

2.3 Erosion map (USPED)

High-resolution erosion risk data were obtained from the Swedish County Administrative Boards online GIS platform, which provides national erosion maps based on 2 x 2 m USPED modelling developed by Djodjic and Markensten (2019). The USPED model identifies where erosion is initiated in the landscape and how sediment is mobilised and transported from agricultural land to surface waters.

USPED incorporates topography, flow convergence, soil erodibility, and vegetation cover to estimate both net erosion and accumulated sediment transport. This enables identification of

areas where sediment is likely to be detached, deposited, or routed through the landscape. Model evaluation has shown strong agreement with field observations and measured losses of suspended sediment and P (R^2 = 0.81), demonstrating that erosion is highly spatially concentrated.

USPED outputs were used in this study as a complementary spatial dataset to the EI results, supporting the identification of erosion-prone reaches and potential sediment source areas.

2.4 Sediment source tracing – Colour print method

The colour-scanning method applied in this study was based on Pulley and Collins (2021), who demonstrated that red, green, and blue (RGB) colour values obtained using a standard office scanner can serve as a low-cost proxy for sediment source tracing. While less detailed than geochemical fingerprinting, the method has been shown to distinguish major sediment sources in agricultural catchments and is suitable as an initial screening tool.

In this study, RGB values were extracted from scanned sediment samples and compared across sample types (field soil, bank material, bed sediment, floodplain, drainage material) to assess whether colour differences could indicate likely sediment sources contributing to SS in Lejstaån.

2.5 Sample preparation

Prior to scanning, all samples were stored in a cold room until laboratory processing. Because of this storage, each sample was thoroughly homogenised with a spatula before sieving. All samples were wet-sieved using a stainless-steel mesh in order to minimise uncertainty related to particle-size variation. The sieved material was placed in aluminium trays or ceramic crucibles.

Samples were then dried in an oven at 105°C for 24 hours. After drying the material was gently ground using a mortar and pestle, and approximately 3-5 g of each sample was packed into small transparent zip-lock bags. The bags were labelled according to sample type (F, B, BS, SP, DR), consistent with the field sampling scheme (see Figure 2 for sample preparation workflow). Equipment was rinsed thoroughly between samples to avoid cross-contamination.

The prepared sample bags were placed on a standard office scanner, scanned at A3 size, and the resulting images were exported as PDF files. Image processing was conducted in the open-source software GIMP 2, where mean values of reflected red, green, and blue light (RGB values) were quantified (Appendix 2).

Before applying the method to Lejstaån samples, the procedure was tested on reference samples from the soil and crop inventory archive at SLU. This preliminary test was performed to verify that the software could detect measurable differences between light-coloured and dark-coloured samples (Appendix 2).

For P analyses a separate subsample of homogenised wet sediment was prepared from each depth interval and bank sample. These subsamples were used for the sequential P fractionation described in the section below.

2.5.1 Principal Component Analysis (PCA)

Principal Component Analysis (PCA) was used to explore patterns in RGB colour data and to assess whether sediment sources formed distinguishable clusters. PCA reduces multivariate data into orthogonal components that explain the maximum variance in the dataset(Jolliffe & Cadima, 2016). This approach is commonly used to visualise multivariate structure and identify gradients in colour-based sediment properties.

A PCA was performed in R (version 2023.06.2) to examine variation in the spectral variables of RGB colour values obtained from scanned sediment samples. Prior to analysis, two Excel datasets were merged by sample ID. The first dataset contained RGB values (red, green, blue), while the second dataset included environmental and site-related information such as sample category (field soil, bank material, bed sediment, floodplain soil, drainage material), Erosion Index (EI), distance to the Phillips sampler, geology, soil type, and land use.

The PCA was based on centred and scaled RGB values using the prcomp function. In the PCA visualisation, EI was included as a continuous explanatory variable represented by a colour gradient, while sample category was included as a categorical explanatory variable.Variable loadings were displayed as arrows to illustrate the contribution of each variable to the ordination and to support interpretation of potential sediment source groupings.

2.5.2 Convex hull analysis

A convex hull diagram was used to visualise the multivariate range of colour values associated with each sediment source. A convex hull represents the smallest polygon that encloses all points belonging to a group in multivariate space (Barber et al., 1996). Overlapping hulls indicate similarity between sources, whereas separation suggests distinct colour signatures. Convex hulls were calculated in R (ver 2026.04.0-526) and plotted in RGB space to compare the distribution of colour values among sample types.

2.6 Sample collection

Sampling locations were selected based on the EI map developed for the Lejstaån catchment, the existing erosion map, and field observations made during site visits. Based on these maps and observations, sampling sites were primarily chosen in areas identified as having a high erosion risk in order to pinpoint potential sediment source locations.

Soil and sediment samples were collected using a metal garden spade and placed in labelled plastic containers. Sample types included field soil (F), bank material (B), bed sediment (BS), floodplain soil (SP), and drainage pipe material (DR).Topsoil samples from agricultural and forested areas were collected from the uppermost 2 cm of the soil profile and classified as field samples. Bank samples were taken from visibly eroded channel banks, specifically from the lower two-thirds of the exposed profile. This approach was used to avoid topsoil contamination and to better distinguish between surface and subsurface sediment sources.

Bed sediment samples were collected directly from the stream using a modified plastic water-sampling bottle attached to a sampling pole. Each sample consisted of a composite of three subsamples collected within a 1m radius of the sampling point.

Suspended sediment was collected using a Phillips sampler (Phillips et al., 2000) installed downstream in the stream channel. The sampler was positioned at approximately 60% of the water depth and emptied after approximately 1.5 months into two plastic buckets with lids before being reinstalled. The Phillips sampler was deployed between 27 January and 16 April 2026. Sampling of potential erosion sources was conducted on four occasions: 10 March, 17 March, 19 March and 16 April 2026. In total, 34 samples were collected.

Additional streambed sediment cores and bank material were collected for P fractionation. Sampling was designed as a transect across the stream corridor to capture the full range of geomorphological environments influencing sediment and P dynamics (Figure 2). This included actively eroding bank sections, depositional zones on inner bends and in-channel bed sediment representing recently mobilised material. Each core was sliced at 2-cm intervals and stored in labelled containers. Depending on site characteristics, cores were divided into either three layers (0 – 2 cm, 2 – 4 cm, 4 – 6 cm) or two layers (0 – 3 cm, 3 – 5 cm). Bank material was sampled from four distinct bank environments representing upper-bank erosion, upper-bank deposition, lower-bank erosion and lower-bank deposition. All samples were refrigerated until laboratory processing. In total, 12 sediment samples and core sections were prepared for P fractionation.

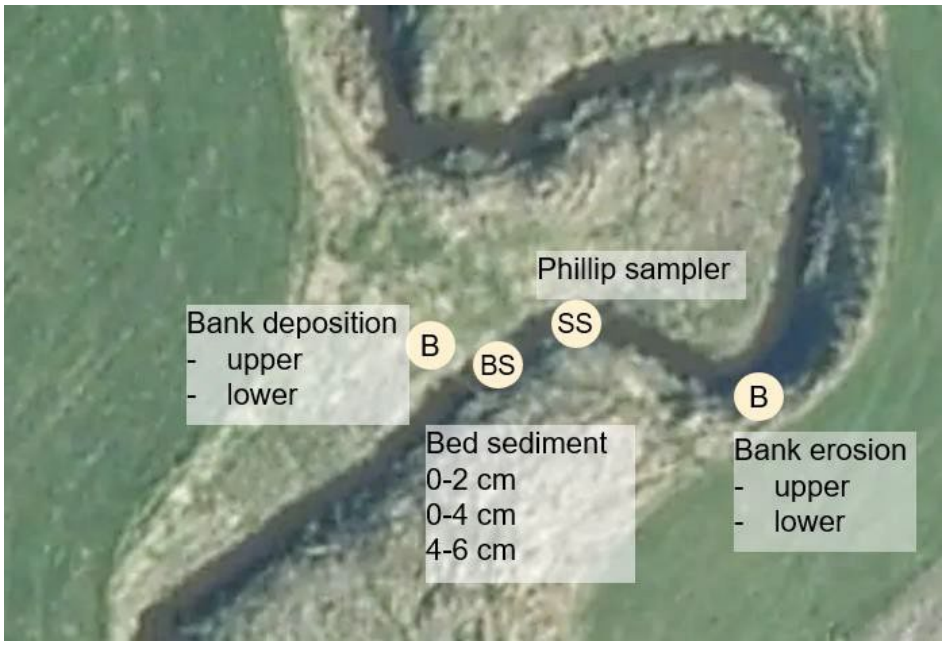


Figure 2: Location of sampling for P fractionation (bank erosion, upper/lower), bed sediment and bank deposition (upper/lower).

2.7 Sediment phosphorus fractionation

Phosphorus speciation in the sediment samples was determined using a modified sequential extraction procedure based on Psenner & Pucsko (1988) and Hupfer et al. (1995; 2009). For clarity, each fraction is referred to by its dominant binding form throughout the thesis, MQ-P (loosely bound P), BD-P (hereafter Fe-P), NaOH-P (hereafter Al-P and Org-P) and HCl-P (hereafter Ca-P). These abbreviated forms are used consistently in the results and discussion

sections. The method operationally separates sediment P into four fractions according to solubility and dominant binding form:

1. MQ-extractable P (loosely bound and pore-water P)
2. BD-extractable P (Fe/Mn-bound P)
3. NaOH-extractable P (Al-bound and organic P)
4. HCl-extractable P (Ca-bound P)

Approximately 100 – 200 mg of homogenised wet sediment was weighed into 15 ml centrifuge tubes. All extractions were performed at room temperature. Before each step, samples were mixed to ensure full suspension and each extraction was followed by centrifugation at 3000 rpm for 10 minutes. The specific extractants, extraction times and targeted P-forms for each step are summarised in Table 2.

Table 2. Overview of the sequential P extraction procedure.

Step	**Fraction**	**Extractant & Conditions**	**Target P-form**	**Notes**
1	MQ-extractable P	10 mL ultrapure water 2h	Loosely bound & pore-water P	Supernatant diluted to 10 mL
2	BD-extractable P	10 mL bicarbonate-dithionite (BD) 1h	Fe/Mn-bound P	Supernatant oxidised overnight in fridge
3	NaOH-extractable P	10 mL 0.1M NaOH $\geq 16\ h$	Al-bound P + organic P	Split into RP (direct) and NRP (persulfate digestion, 120 °C 60 min)
4	HCl-extractable P	10 mL 0.5 M HCl 16-24 h	Ca-bound P	Supernatant neutralised with 2 M NaOH

All extracts were analysed using the molybdate blue method with ascorbic acid reduction at 880 nm, with a six-point calibration curve (0 – 800 µg L^{-1}) prepared from a phosphate standard solution. Reagents were freshly prepared for each analytical session, and samples were allowed to react with the mixed reagent for at least 40 minutes before measurement.

To express P concentrations on dry-weight basis, dry weight (DW) and loss on ignition (LOI) were determined. Wet sediment was freeze-dried, oven-dried at 60 °C and weighed. LOI was

measured by combusting approximately 1 g of freeze-dried sediment at 550 °C for 2 hours in pre-weighed crucibles.

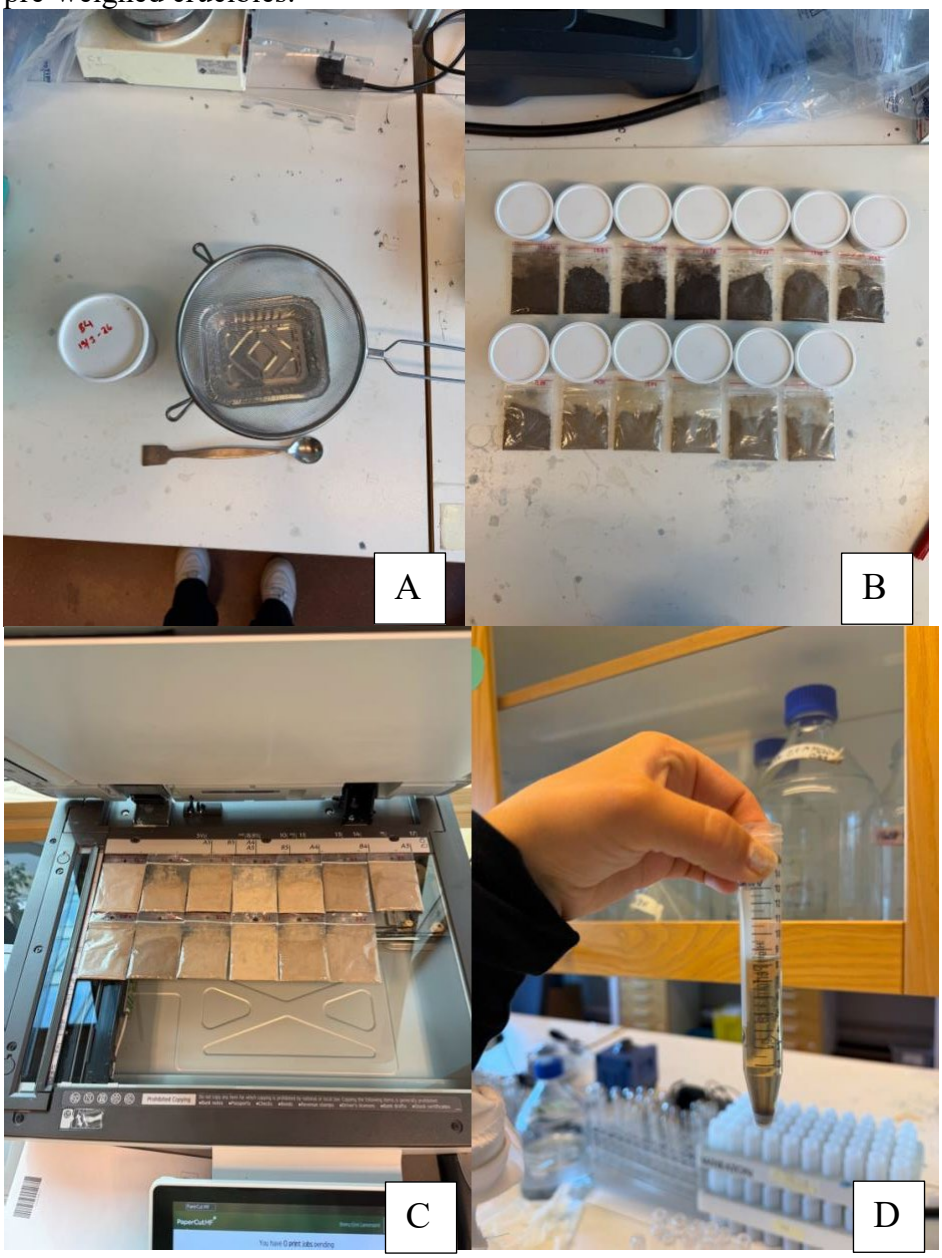


Figure 3. Visual overview of the sample processing workflow. (A) Sieving of sediment samples. (B) Sieved and dried samples packed into labelled zip-lock bags. (C) Scanning of samples on an office scanner to obtain RGB values for colour-based analysis. (D) Example of a fractionation step showing a centrifuged sample prior to mixing the sediment with the supernatant.

3. Results

3.1 GIS Erosion Index

The GIS-based Erosion Index (EI) reveals distinct spatial patterns in erosion susceptibility along Lejstaån (Figure 4, Appendix 3). EI values range from 0 to 66 and are classified into five levels.

The spatial distribution of EI values shows that erosion risk is strongly concentrated in the meandering sections of the stream. Segments located on the outer bends of sharp meanders consistently display high to very high EI values, shown in orange and red on the map. These areas correspond to locations where channel curvature is greatest and where bank slopes are steep or undercut. In contrast, straight or gently curving reaches were predominantly classified as low or moderate risk, shown in green and yellow.

Sampling locations for the following colour print method (grey points in Figure 3) were intentionally placed near segments classified as high or very high erosion risk. The spatial alignment between sampling points and EI hotspots confirms that field sampling successfully targets erosion-prone areas.

Field observations supported the EI results. Segments classified as high-risk frequently showed visible signs of active erosion, including exposed roots, slumping banks, and sediment deposits. By contrast low-risk segments typically exhibit stable, vegetated banks with minimal evidence of recent erosion.

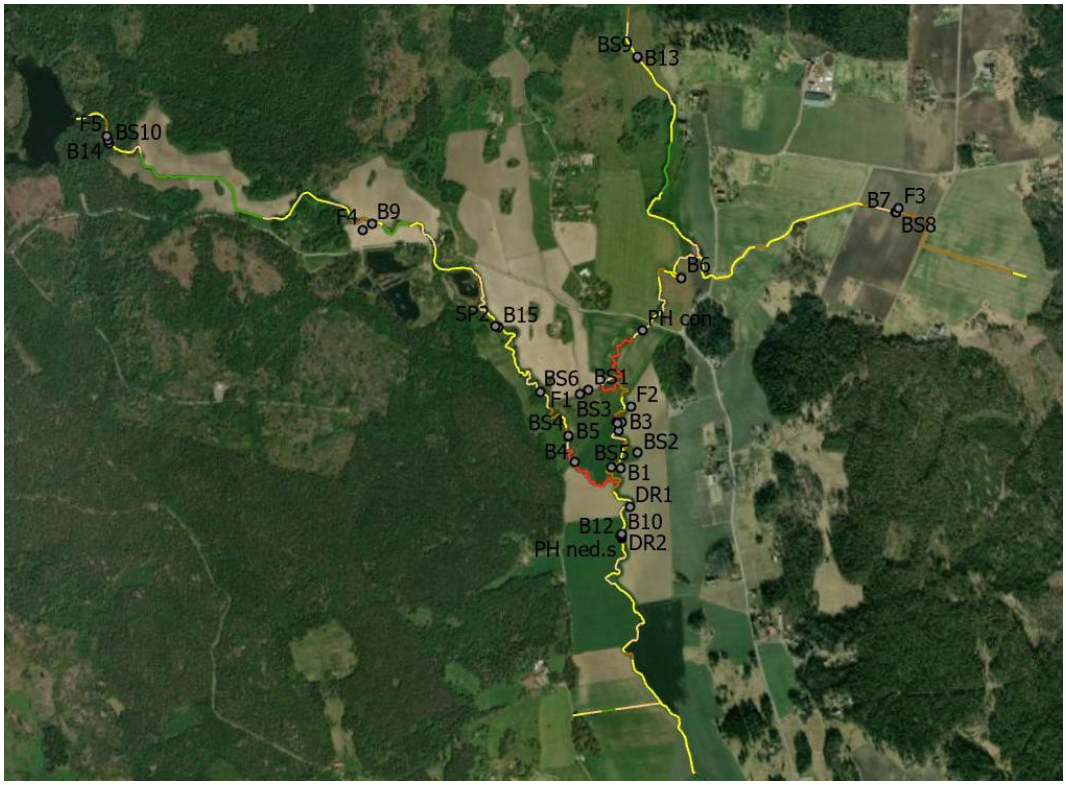


Figure 4. GIS-based Erosion Index (EI) for Lejstaån. EI values (0-66) were classified into five erosion-susceptibility levels using Jenks natural breaks: very low (0, green), low (0.01-24, yellow), moderate (25-36, orange), high (37-48, brown), and very high (49-66, red). Sampling locations are shown as grey points.

3.2 Colour print results

The colour-based analysis of the scanned sediment samples shows patterns in RGB space. Noticeable colour differences were observed in the scanned sediment samples (Figure 4). For each sample, the mean red (R) and blue (B) values correspond to the single mean value displayed by GIMP when selecting the red or blue channel, and these mean values were subsequently compiled in an Excel file for further analysis.

In the RGB-plot based on the scanned image bank material (B, orange) appears mainly on the central part of the diagram (Figure 6). The samples are somewhat spread out but still lie relatively close to each other, showing that bank material had broadly similar colour values. Bed sediment (BS, blue) is also spread out but forms a slightly narrower band, overlapping partly with both bank and field samples. Field soils (F, brown) are more scattered and cover a wider area, indicating greater variation in colour within this group.

The Phillips sampler samples (PH, purple) representing suspended sediment, plot close to the main cluster of B samples and also near some BS and the drainage sample. The drainage material (DR, green) is positioned near the centre of the diagram, close to several B and BS samples. The floodplain samples (SP, grey) is located near the middle of the plot and does not stand out from the other groups, showing overlap with both F and BS.

Overall, Figure 6 shows that some source types form loose groupings, while others overlap. B, BS, and F samples are partly separated but still share common areas in the diagram. The suspended sediment samples (PH) lie within the same central areas as many B samples, while the SP and DR samples also fall within this region. Complete separation between groups is not observed, but the method captures differences in colour between the sediment sources.

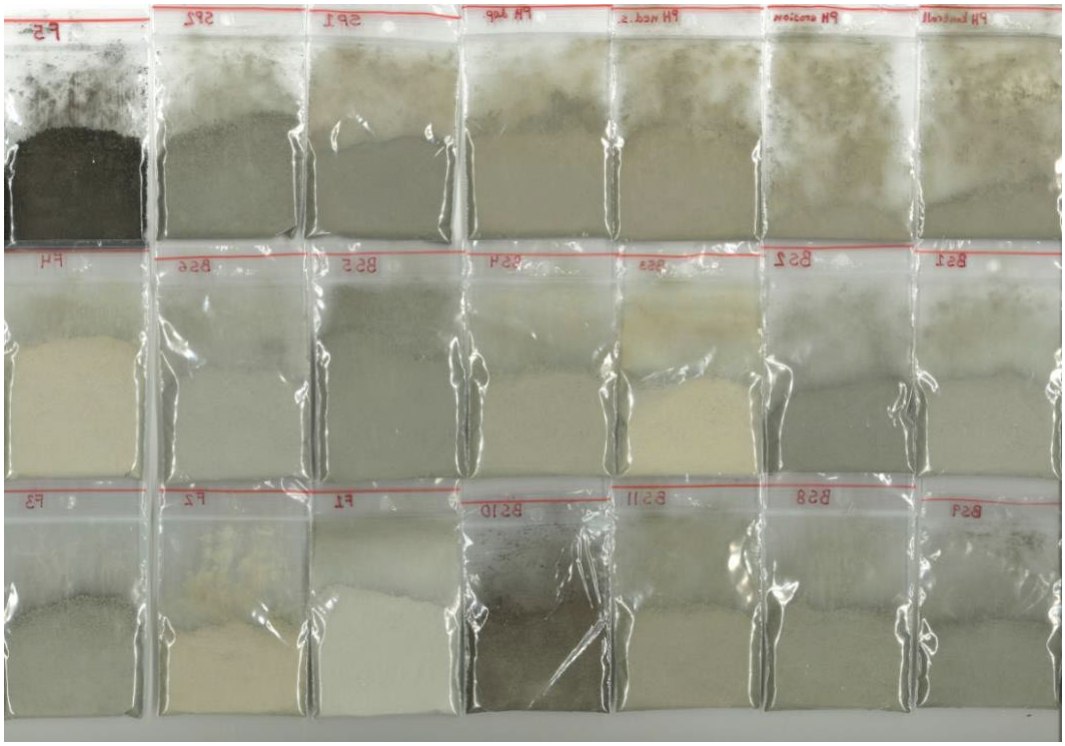


Figure 5. Scanned soil and sediment samples used for RGB analysis.The image was used for the colour-print analysis.

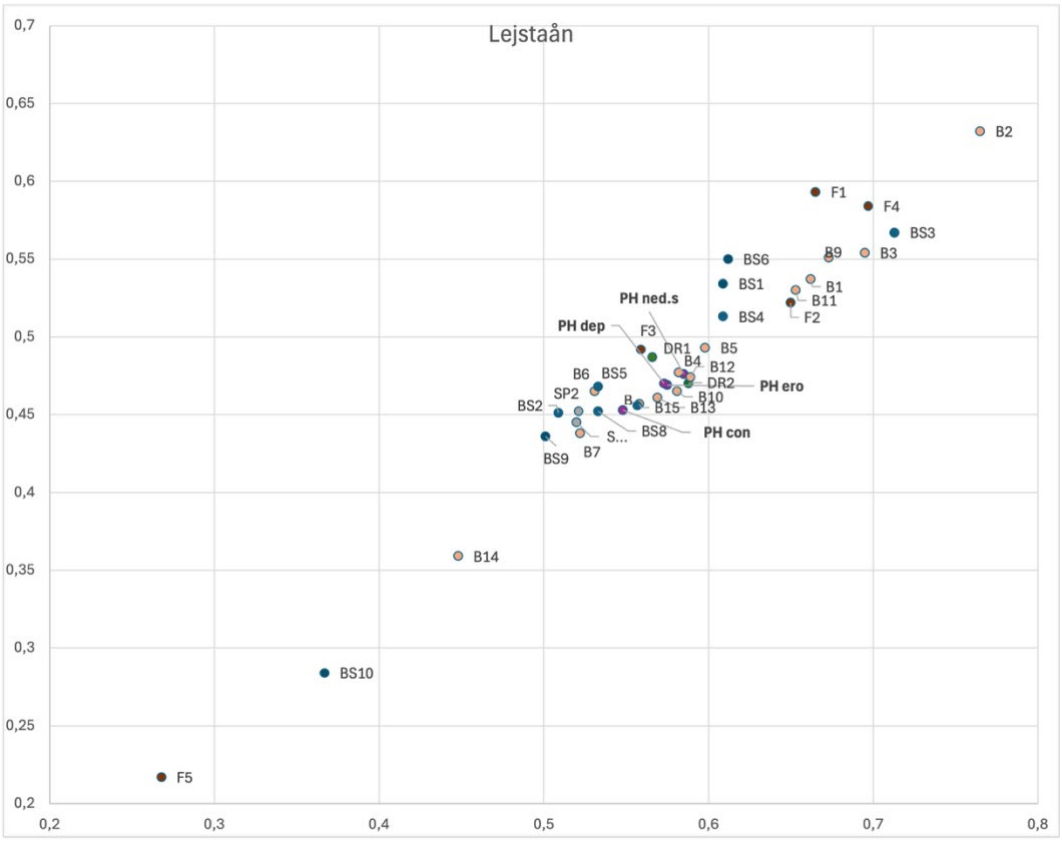


Figure 6. RGB scatter plot of scanned sediment samples from Lejstaån. Each point represents one sample (n=33) plotted by its mean red (R) and blue (B) values. Colours indicate source types: bank material (B, orange), bed sediment (BS, blue), field soil (F, brown), floodplain soil (SP, grey), drainage material (DR, green), and suspended sediment from the Phillips sampler (PH, purple).

3.2.1 PCA of RGB values

PCA was used to explore variations in RGB colour values among sediment sources (figure 7). PC1 explained 98.6% of the total variance, indicating that most colour variation was driven by a single dominant gradient related to red and blue intensity. PC2 explained 1.4% of the variance and captured minor variation associated with the explanatory variables that load weakly along this axis, such as soil type, geology and land use, as indicated by the upward-pointing vectors. The PCA biplot showed substantial overlap between bank, bed sediment and drainage samples, suggesting that these near-channel materials share similar colour characteristics. Field samples displayed a wider spread along PC1, reflecting greater heterogeneity in surface soil colour, while floodplain samples clustered closer to bed sediment.Overall, the PCA demonstrates that RGB colours alone provide limited discriminatory power for separating sediment sources in this catchment.

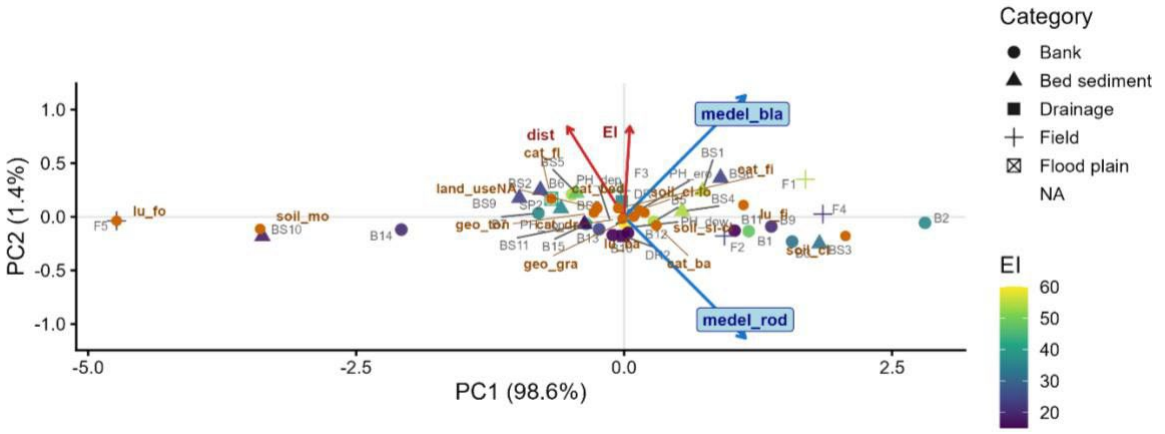


Figure 7. PCA-biplot of RGB values and explanatory variables. The first two principal components (PC1 = 98.6%, PC2 = 1.4%) illustrate variation in RGB colour values among sediment sources. Sample types are shown with different symbols and arrows represent explanatory variables (soil type, land use, geology, EI, distance). Soil types: silty clay=soil_si-cl, clay=soil_cl, moraine=soil-mo, clay loam=soil_cl-lo. Geology: granodiorite granit=geo_gra, tonalit granodiorite=geo_ton. Land use: field=lu_fi, forest=lu_fo, bank=lu_ba. Categories: field= cat_fi, flood plain=cat_fl, drainage=cat_dr, bank=cat_ba, bed sediment=cat_bed, Phillip sampler=cat_ph. Colour scale indicates EI values for each sampling location.

3.2.2 Convex hull analysis

Convex hulls were used to visualise the multivariate range of RGB values for each sediment source. The smallest hulls were formed by floodplain and drainage pipe samples, indicating low variability in their colour signatures. Bed sediment also showed relatively low variability but did not form the smallest hull. Bank material displayed moderate variability while field samples formed the largest hull reflecting their greater heterogeneity (Figure 8).

The hulls for bank, bed sediment and drainage material overlapped substantially, demonstrating that these near-channel sources share similar colour characteristics. The Phillips sampler points fell inside or at the edges of multiple hulls, suggesting that SS represents a mixture of several source types rather than a single dominant contributor. Together with the PCA results, the convex hulls confirm that RGB colour alone has limited discriminatory power for separating sediment sources in this catchment.

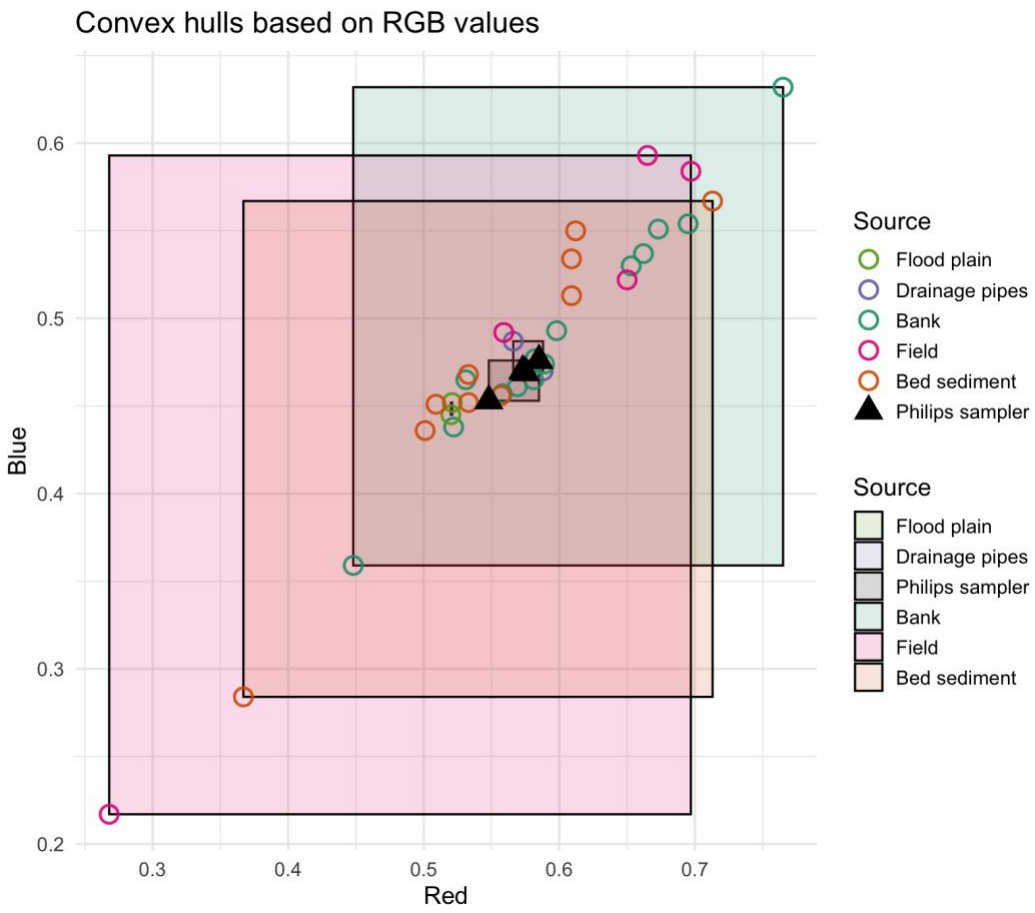


Figure 8.Convex hulls based on RGB values for each sediment source. Convex hulls illustrate the multivariate range of red and blue colour values for field, bank, bed sediment, drainage pipe material, floodplain soils and suspended sediment (Phillips sampler). Smaller hulls indicate low within-source variability, while larger hulls reflect greater heterogeneity. Overlapping hulls show that several sources share similar colour signatures.

3.3 Phosphorus fractionation

The P fractionation results show clear differences in both total P content and the distribution of individual fractions across the sampled materials (Figure 9). The sediment samples (Sed 0 – 2 cm. Sed 2 – 4 cm. Sed 4 – 6 cm) contain the highest total P concentrations of all sample types, with the uppermost layer (0 – 2 cm) showing the largest values. Total P decreases with depth in the streambed.

Across all sediment depths, Org-P (green) forms the largest proportion of total P. Ca-P (blue) also contributes substantially, making these two fractions the dominant forms of P in the sediment. Fe-P (orange) is present at moderate levels, while MQ-P (light blue) and Al-P (grey) make up smaller portions of the total P content.

The bank samples (B upper ero, B lower ero, B upper dep, B lower dep) contain lower total P concentrations than the sediment samples but show a similar pattern in the relative distribution of fractions. In all bank samples, Org-P and Ca-P dominate with Fe-P contributing a smaller but still noticeable share.

Overall, the results show that phosphorus in Lejstaån is mainly present in the organic (Org-P) and Ca-bound (Ca-P) fractions across all sample types.

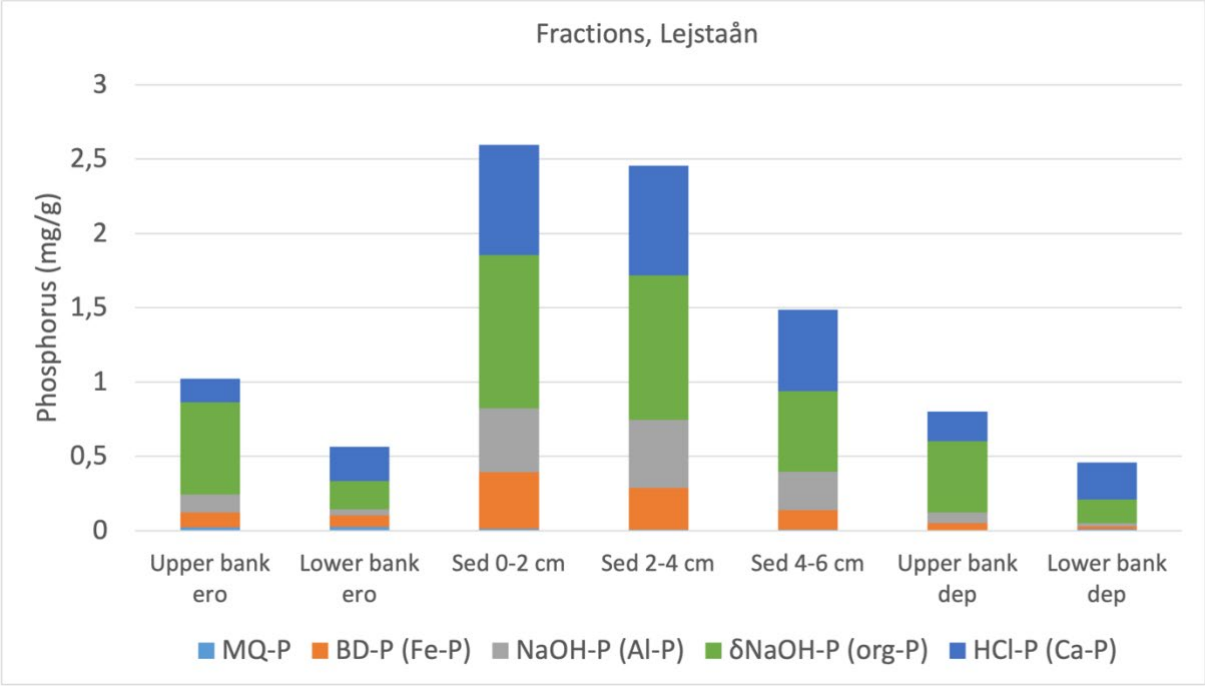


Figure 9. Phosphorus fractions (MQ-P, Fe-P, Al-P, Org-P and Ca-P) in sediment and bank samples from Lejstaån. Bars show the distribution of P fractions across depth-averaged stream sediments (0 – 2, 2 – 4, 4 – 6 cm) and bank samples from erosion and deposition sites.

4. Discussion

This study aimed to integrate spatial erosion risk assessment, sediment colour analysis and phosphorus fractionation to improve understanding of sediment-associated P transport in a small agricultural catchment. The following sections discuss these results in more detail.

4.1 Spatial erosion risk assessment in small streams

The spatial erosion risk assessment reveals clear and meaningful patterns along Lejstaån. Providing important insights into how erosion processes operate in small, vegetation-covered streams. Several near-stream segments show elevated susceptibility to erosion, highlighting geomorphological controls that are highly relevant for understanding sediment and P mobilisation in this type of system. These findings form a crucial foundation for interpreting the colour analysis and P-fractionation results presented later.

However, several methodological considerations must be taken into account when interpreting the EI results. Because the EI method was originally developed for wider watercourses. Some parameters may behave differently when applied to a narrow and densely vegetated stream such as Lejstaån. This is particularly relevant for channel width (B) and curvature (K), where small geometric deviations in the DEM or centreline can have proportionally larger effects. In such settings even minor positional uncertainties may influence the final index values. This interpretation is supported by SGI (2025) which identifies channel width as a particularly sensitive parameter.

It is also important to note that vegetation cover is not included in the EI calculation itself. In a stream like Lejstaån where several reaches are densely vegetated this exclusion may influence the result. Vegetation can obscure bank edges in both DEMs and orthophotos, potentially leading to under- or overestimation of slope and width in the index calculation. In addition to affecting how banks are represented in the DEM, vegetation also reduces actual erosion rates by reinforcing bank surfaces and protecting them from shear stress. This means that vegetated banks may appear erosion-prone in the EI model despite being more stable in reality. Similar challenges are described by Sandström (2022) who notes that high-resolution terrain models often struggle to accurately represent bank geometry in small vegetated streams. Seasonal variation in vegetation density may therefore influence both how erosion risk is represented in the EI and how erosion processes operate in the field.

Regarding parameter sensitivity the results from Lejstaån indicate that B, K and E exert the strongest influence on the final EI values. This conclusion is based on the observed spatial variation, segments with small differences in width, curvature or slope produced disproportionately large differences in EI. In contrast the parameters P and G showed relatively little variation between segments suggesting that they had a more limited influence on the final EI values in this catchment. Although a formal sensitivity analysis was not conducted these patterns suggest that uncertainties in these parameters can substantially affect the index. Particularly in small streams where channel geometry changes rapidly over short distances and where DEM resolution is critical for representing bank morphology.

Despite these limitations the EI results follow geomorphological patterns that would be expected. High EI values are primarily located on the outer bends of meanders where shear stress is greatest and bank undercutting is most likely to occur (Figure 4). This is consistent with established geomorphological theory and with national-scale modelling such as the USPED-based analyses by Djodjic & Markensten (2019). The overlap between high-EI segments and bank samples with elevated P concentrations supports the interpretation that bank erosion may be an important source of particulate P in Lejstaån. This pattern is consistent with findings from Pulley & Collins (2024) who demonstrated that bank erosion can be a major contributor of particulate P in agricultural catchments.

A key limitation is that EI identifies potential erosion risk rather than actual erosion or sediment delivery. The index does not account for bank material cohesion, vegetation reinforcement, or hydrological connectivity. As highlighted by Lannergård (2021) connectivity largely determines whether eroded material actually reaches the stream. This means that segments with high EI values do not necessarily contribute large amounts of sediment, while segments with moderate EI values may contribute significantly during high-flow events.

When comparing the results to SGI´s application of EI both similarities and differences emerge. The spatial patterns in Lejstaån are consistent with SGI´s findings in larger watercourses, particularly the concentration of high EI values on the outer bends of meanders. At the same time the method´s limitations become more pronounced in a narrow system, parameters such as width and curvature are more sensitive, vegetation has greater influence than in wider channels and the exclusion of vegetation from the EI calculation becomes more consequential. Additionally, curvature was calculated using ArcGIS in this study, which may produce slightly different classification compared to SGI´s MATLAB-based workflow. Overall the comparison suggests that EI is useful even in small streams, but that its uncertainties, especially the relative influence of the different components of the EI equation need to be addressed more explicitly.

One limitation of the current EI implementation is that vegetation was not explicity included, despite its known influence on bank stability. A simple way to incorporate vegetation would be to apply a scaling factor similar to the cover-management factor (C-factor) used in USLE-based models, where dense riparian vegetation reduces erosion susceptibility and sparse or absent vegetation increases it. Such an approach could be implemented by assigning vegetation classes (e.g., grass, shrubs, trees, bare soil) to each segment and adjusting EI scores accordingly. Intergrating vegetation in this manner would likely improve the ability of EI to capture fine-scale variation in bank stability in small agricultural streams.

4.2 Colour print method

The colour print method provides a rapid and low-cost indication of potential sediment sources in Lejstaån and directly addresses the research question concerning whether sediment colour can be used to identify contributing source areas. In an ideal application of the method, distinct RGB signatures would separate source materials into clearly defined clusters, allowing SS to be matched to one or two dominant contributors. However, the convex hull analysis shows substantial overlap between most source types in Lejstaån, indicating that colour variation

among sources is limited and that the method has reduced capacity to separate them in this catchment.

A key reason for this overlap is the relatively homogeneous geology and soil parent material in the Lejstaån catchment (SGU, 2024). Most source materials derive from clay-rich glacial till and riparian clay deposits with similar mineralogical compositions. As a result RGB variation is driven primarily by brightness, light vs. dark rather than colour tone with red and blue values being nearly identical across sources. This pattern is clearly visible in the convex hull plot (Figure 8) where bank, bed and drainage samples overlap extensively. While field and floodplain soils show only slightly greater separation. The dominance of brightness suggests that organic matter and moisture content influence the colour signal more strongly than mineralogical differences. Pulley & Collins (2021) similarly note that colour-based discrimination is weakest in catchments with uniform soil types and limited mineralogical contrast.

Another important methodological factor is that unlike Pulley & Collins (2021; 2022) this study did not apply hydrogen peroxide (H_2O_2) pre-treatment to remove organic matter before colour extraction. Pulley & Collins demonstrated that peroxide treatment improves the ability to distinguish between sources by removing organic layers that darken samples and hide colour differences caused by mineral composition. Without this step organic matter remains a major driver of colour variation which likely contributes to the clustering and overlap observed in Lejstaån. A peroxide treatment would probably have increased separation between sources.

The colour results also show that high EI values do not automatically correspond to the strongest colour matches with SS. Several high-EI segments did not produce material that matched the Phillips sampler, while some moderate-EI segments showed closer similarity. This highlights that erosion susceptibility and actual sediment contribution are not equivalent. A bank may be highly erodible but hydrologically disconnected during baseflow. While a moderately eroding bank with direct hydraulic contact may contribute more sediment. The colour method therefore complements the EI analysis by providing data-based evidence of which source types most closely resemble the suspended material.

The results also raise the question of whether sediment originates from specific parts of the catchment. The colour clusters suggest that most contributing material resembles in-channel and near-channel sources rather than upland fields. This is consistent with the geomorphology of Lejstaån where narrow meanders, cohesive clay banks and variable flow conditions promote local bank erosion. The convex hull overlap further indicates that the dominant colour signal is driven by shared mineralogy rather than distinct land-use signatures. Supporting the interpretation that sediment contributions are spatially concentrated near the stream corridor. Pulley & Collins (2021) similarly found that colour-based tracing performs best when source areas differ in soil type or land use and less well in geologically homogeneous catchments, which is consistent with the patterns observed in the Lejstaån catchment.

A PCA of RGB values and explanatory variables further supports these interpretations. PC1 explained 98.6% of the total variation, indicating that colour differences between sources are almost entirely driven by brightness rather than colour. This aligns with the convex hull results and explains the substantial overlap between source types. The PCA also revealed a gradient where moraine/forest samples tend to separate slightly from clay-rich agricultural soils,

suggesting that land use and soil type have some influence on colour. As a result bank, bed and drainage samples remained grouped while field and floodplain samples showed separation.

Overall, the colour print method suggests that suspended sediment in Lejstaån is most similar to bank and bed material. Supporting the hypothesis that streambank erosion is an important sediment source. However the method´s ability to distinguish between sources is limited by the catchment´s homogeneous geology, the absence of peroxide pre-treatment and the similarity in RGB values across sources. Despite these limitations the method provides valuable complementary evidence when interpreted alongside the EI analysis and P-fractionation and is contributing to a more integrated understanding of sediment and P mobilisation in small agricultural streams.

In addition to visual inspection and multivariate ordination, several statistical approaches could be applied to evaluate differences in RGB distributions between sediment sources. For example, non-parametric tests such as the Komogorov-Smirnov test could be used to compare cumulative distributions of individual colour channels between source groups. Similarly, permutation-based MANOVA or distance-based tests could quantify multivariate differences in RGB space. Such approaches may help determine whether colour distributions differ significantly between sources even when visual overlap is substantial and could therefore strengthen the interpretation of colour-based sediment tracing.

4.3 Sediment P fractionations

The P fractionation results provide important insights into the reactivity and environmental relevance of sediment-associated P in Lejstaån, and directly address the research questions concerning how P speciation varies between sediment sources. The most prominent pattern is the dominance of Org-P and Ca-P across all sample types (Figure 9). This indicates that a substantial share of the sediment-associated P is stored in moderately reactive or stable pools, consistent with the strong affinity of P for organic matter, Al-oxides and Ca-minerals described by Wither & Jarvie (2008) and Sharpley et al. (2013). Although these forms are not immediately bioavailable, they may become mobilised under changing geochemical conditions, particularly through pH-driven dissolution processes or gradual mineralisation of organic P.

A notable finding is the relatively high proportion of Fe-P in both bank material and the uppermost streambed sediment layer (0 – 2 cm). Compared with values reported in Swedish agricultural streams by Lannergård et al. (2020) and Sandström et al. (2021) the Fe-P concentrations in Lejstaån appear elevated. This suggests that the stream contains a larger pool of redox-sensitive P than what is commonly observed in similar catchments. Because Fe-bound P can be released under reducing conditions, these elevated values imply a greater potential for internal loading during periods of low oxygen availability such as during summer low flow, organic matter decomposition or under ice cover. Similar patterns have been reported in international studies, where Fe-rich bank material has been shown to contribute substantially to bioavailable P pools (SanClements et al., 2009; Judett et al., 2018).

The fractionation pattern also supports the hypothesis that different sediment sources contribute distinct P signatures. The uppermost streambed sediment layer (0 – 2 cm) contains the highest total P concentration, consistent with the accumulation of recently mobilised fine material. This aligns with findings from Sandström et al. (2021) who showed that SS often

carries higher proportions of reactive P compared to bed material due to episodic mobilisation during high-flow events. Bank samples, although lower in total P, contain similar proportions of Org-P, Ca-P and Fe-P, indicating that bank erosion can supply both stable and potentially mobile P forms to the stream. In contrast, bed sediment shows a more stable P composition with a higher proportion of Ca-P and lower proportions of reactive Fe-P and Org-P, which may indicate that bed sediment represents more stable material with longer residence times and limited recent remobilisation.

4.3.1 Linking erosion processes and P transport

The presence of reactive P fractions in bank and bed material complements the erosion risk patterns identified by the EI analysis. Several high-EI segments are similar to locations where bank samples contain elevated proportions of Fe-P and Al-P, suggesting that geomorphologically unstable reaches may also be biogeochemically important contributors to P export. However, the colour print results show that SS represents a mixture of several source types, which complicates the interpretation of which specific bank segments are actively contributing material at the time of sampling. This raises the possibility that the sampling strategy may have captured only the most active or accessible sources, rather than the full range of potential contributors.

Importantly, EI describes potential erosion risk, not actual sediment delivery. Hydrological connectivity ultimately determines whether eroded material reaches the stream, as emphasised by Lannergård (2021). A bank segment may have high EI but remain hydrologically disconnected during baseflow. While a moderately eroding bank with direct hydraulic contact may contribute disproportionately during storm events. This helps explain why some high-EI segments did not match the SS in the colour analysis, whereas some moderate-EI segments showed closer similarity. It also highlights that not all erosion sources are equally relevant for P transport, even if they appear geomorphologically unstable.

The combined results from EI, colour print and P fractionation therefore point towards a system where sediment and P mobilisation are concentrated in near-channel areas with strong hydrological connectivity. The SS appears to reflect a blend of bank, bed and drainage material which is consistent with the concept of variable source areas where the location and magnitude of sediment contributions shift dynamically with flow conditions. During snowmelt when the samples in this study were collected, banks are largely vegetation-free and connectivity is high, favouring mobilisation of fine reactive material. It is likely that sampling during summer or autumn when vegetation stabilises banks and flow paths differ would produce a different P-speciation pattern and potentially a different mixture of sediment sources.

Another important consideration is that the three methods used in this study operate at different spatial scales. EI provides a landscape-scale assessment of erosion susceptibility, and P fractionation reflects biogeochemical properties at the sample scale. Integrating these scales reveals that while EI identifies where erosion is likely, colour and P-speciation data indicate what material is actually mobilised and transported. The overlap between reactive P fractions in bank material and the colour similarity between SS and near-channel sources suggest that bank erosion is a possible contributor to P export. But the mixed colour signature also indicates that multiple sources are active simultaneously.

Taken together, these findings support a process understanding where sediment-associated P transport in Lejstaån is governed by the interaction between geomorphological instability, hydrological connectivity and the chemical reactivity of mobilised material. The presence of both stable (Ca-P) and reactive (Fe-P, Al-P) fractions in bank material underscores that bank erosion can supply P forms with differing environmental relevance. Reinforcing the need to consider both erosion risk and P speciation when assessing P mobilisation in small agricultural streams.

4.3.2 Method development and future outlook

Several methodological considerations should be acknowledged when interpreting the P-fractionation results in relation to erosion processes and sediment sources. Sequential extraction schemes provide operationally defined pools rather than discrete mineral phases, and small variations in extraction conditions can influence the distribution between fractions. Moreover, the samples represent snapshots in time and may not fully capture the dynamic shifts in P speciation that occur during storm events, when SS composition can differ substantially from that of bed or bank material. Sampling during snowmelt when banks are largely vegetation-free and hydrological connectivity is highly likely favoured mobilisation of fine, reactive particles. Sampling during summer or autumn when vegetation stabilises banks and flow pathways differ, may have produced a different mixture of sediment sources and P fractions.

A broader methodological limitation is that the three approaches capture processes at different spatial scales. The EI provides a landscape-scale assessment of potential erosion risk, the colour print method captures source similarity at the reach scale and P fractionation reflects biogeochemical properties at the sample scale. Integrating these scales is essential for understanding sediment-associated P transport. But it also introduces uncertainty, EI identifies where erosion is likley, colour analysis indicates what material is similar, and P fractionation reveals what material is reactive. The SS signature suggests a mixture of sources, which makes it difficult to determine whether the limited separation observed in the colour analysis reflects methodological constraints or genuine mixing of material during transport.

Future work could therefore benefit from combining the colour print method with additional tracing techniques, such as geochemical fingerprinting, mineralogical characterisation or spectroscopic analyses. Pulley & Collins (2021; 2022) highlight that colour-based tracing performs best when supported by independent tracers that capture mineralogical or elemental differences between sources. Integrating colour data with elemental ratios, stable isotopes or X-ray diffraction could improve source discrimination, particularly in geologically homogeneous catchments like the one studied here. Repeated sampling across seasons and flow conditions would also capture temporal variability in both sediment sources and P speciation providing a more complete understanding of when and where reactive P forms are mobilised.

Overall, the P-fractionation results demonstrate that sediment-associated P in Lejstaån consists of both stable and potentially bioavailable forms. With elevated Fe-P suggesting a larger redox-sensitive P pool than typically reported for Swedish agricultural streams. By linking P speciation to sediment sources and erosion risk, the findings contribute to a more nuanced understanding of P mobilisation in small agricultural streams and highlight the value

of integrating multiple complementary methods to capture the spatial and temporal complexity of sediment-associated P transport.

There is also potential to explore links between sediment colour and P fractionation patterns. Colour metrics may reflect mineralogical or organic characteristics that correlate with specific P forms, for example Fe-rich materials that influence both colour and Fe-bound P.

Although this study did not explicity test such relationships, future work could examine whether RGB values correlate with reactive P fractions or with indicators of redox-sensitive minerals. Is such associations exist, colour-based screening could provide a rapid first approximation of P reactivity in suspended sediment, complementing more detailed fractionation analyses.

4.4 Conclusion

This study shows that combining GIS-based erosion risk assessment, sediment colour analysis and phosphorus fractionation provides a complementary and effective framework for understanding sediment P mobilisation in small agricultural streams. The EI analysis identified geomorphologically unstable reaches in Lejstaån, with several near-stream segments showing elevated susceptibility to bank failure. The colour print method indicated that SS most closely resembles a mixture of bank, bed and drainage sources, although substantial overlap between source types made it difficult to clearly separate them. The PCA further supports this pattern by showing only weak gradients between moraine/forest soils and clay-rich agricultural soils, likely reflecting the catchment´s homogeneous parent material, similar land use and mixing processes during transport.

P fractionation reveals that bank material contains both stable (Ca-P) and reactive (Fe-P, Al-P, Org-P) forms, demonstrating that bank erosion can supply P with differing environmental relevance. Together, these results highlight that sediment-associated P transport in Lejstaån is shaped by the interaction between erosion susceptibility, hydrological connectivity and the chemical reactivity of mobilised material. The combined findings suggest that near-channel sources play a key role in sediment delivery and that their contribution to SS implies a risk for substantial P transport during high-flow events. During snowmelt, when the samples in this study were collected, banks are largely vegetation-free and hydrological connectivity is high, conditions that favour the mobilisation of fine, reactive material from near-channel sources.

4.4.1 Implications for future use of methods

The combined approach used in this study can support more targeted management in agricultural catchments. The Erosion Index (EI) is well suited as a first-step tool to identify erosion-prone reaches, even in small streams such as Lejstaån. However, EI should be complemented with field verification and connectivity assessments to determine which segments actively deliver sediment.

The colour print method provides a rapid and low-cost way to assess broad sediment source patterns, but the results from this study and from Pulley and Collins (2021) show that its ability to clearly separate source types is limited in geologically homogeneous catchments. For this reason, the method is likely not well suited for routine monitoring in such environments.

However, it may still be valuable to test in landscapes with stronger contrast in soil colour or parent material, where clearer source separation could potentially be achievable.

P fractionation adds essential biogeochemical context by identifying which sediment sources contain environmentally relevant P forms. Applying these methods across seasons would further improve understanding of temporal variability in sediment sources and P speciation, and help prioritise mitigation measures such as bank stabilisation, importance of vegetation cover in riparian buffers or targeted field interventions in the near stream area.

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Popular science summary

Many Swedish lakes and streams suffer from eutrophication, a process where excess nutrients especially phosphorus lead to algal blooms, oxygen depletion and declining water quality. A larger part of this phosphorus comes from agricultural land, but it is often unclear exactly where in the landscape the phosphorus originates. Understanding these sources is crucial for designing effective measures that actually reduce nutrient loss.

This study investigates how sediment and phosphorus are mobilised and transported in Lejstaån, a small agricultural stream outside Uppsala. Including GIS-based analysis, field sampling and laboratory work, the study provides new insights into how erosion processes and phosphorus chemistry interact in Swedish agricultural catchments.

The erosion model showed that several near-stream areas in Lejstaån are particularly prone to bank erosion. These sections are important because eroding streambanks can release large amounts of fine sediment enriched in phosphorus. Sediment colour analysis, based on scanned samples, indicates that the suspended sediment in the stream most likely comes from a mixture of bank material, bed sediment and drainage sources. However, the method did not clearly separate the different sources, likely because the catchment has relatively homogeneous soils and geology.

Phosphorus fractionation, a method that separates phosphorus into different chemical forms revealed that bank material contains both stable and reactive phosphorus. This means that when banks erode, they can release phosphorus that is not only abundant but also environmentally relevant, potentially contributing to eutrophication downstream.

Together, the results show that streambank and near-channel areas play a key role in phosphorus transport in small agricultural catchments. The study highlights the importance of considering bank stability, hydrological connectivity and sediment chemistry when designing mitigation measures. Strengthening riparian buffers, stabilising vulnerable banks and targeting interventions to erosion-prone areas could therefore be effective strategies for reducing phosphorus losses in Swedish agricultural landscapes.

Appendix 1. Full GIS Workflow for Erosion Index (EI) Calculation in Lejstaån

This appendix provides a step-by-step description of the GIS workflow used to calculate the Erosion Index (EI) for Lejstaån. The workflow follows the GIS-based method developed by the Swedish Geotechnical Institute (SGI, 2025), but is adapted to the spatial datasets and characteristics of the Lejstaån catchment. The purpose of this appendix is to document the full technical procedure to ensure reproducibility, while the main Materials and Methods section provides a conceptual overwiew. All tools used are marked in bold.

A1. Proect Setup:

1. Create a new ArcGIS Pro project
2. Set the coordinate system to **SWEREF 99 TM**.

A2. DEM preparation:

A2.1 Import and mosaic DEM tiles

- Load all DEM tiles from Lantmäteriet (Markhöjdmodell Grid 1+).
- Use **Mosaic To New Raster** (Data Management Tools):
  - *Input rasters:* all DEM.tif files
  - *Output:* Mosaic.tif
  - *Pixel type* 32-bit float
  - *Bands:* 1
  - *Mosaic operator:* First

A2.2 Calculate statistis

- Run *Calculate Statistics* on Mosaic.tif to improve rendering.

A3. Extracting and Segmenting Lejstaån

A3.1 Extract stream centreline

- Load **Hydrografi (hl_riks.shp)**.
- Manually select Lejstaån using *Select by Polygon*.
- Export selection as Lejstaan_centreline.

A3.2 Dissolve to a single polyline

- Use **Dissolve:**
  - *Input:* Lejstaan_centreline
  - *Output:* Lejstaan_dissolved
  - *Dissolved fields:* none
  - *Create multipart:* checked
  - *Unsplit lines:* checked

A3.3 Generate 50-m points

- Use **Generate Points Along Lines:**
  - *Input:* Lejstaan_dissolved
  - *Distance:* 50 m
  - *Include end points:* checked
  - *Add accumulated distance:* checked

A3.4 Split line ino 50-m segments

- Use **Split Line at Point:**
  - *Input features:* Lejstaan_dissolved
  - *Point features:* Lejstaan_points_50m
  - *Output:* Lejstaan_segments
  - *Search radius:* 1 m

A4. P-Parameter (Relative Elevation)

A4.1 Create 50-m focal-mean raster

- Use **Focal Statistics:**
  - *Input:* Mosaic.tif
  - *Neighborhood:* Circle, radius 50 m
  - *Statistic:* Mean
  - *Output:* DEM_mean_50m

A4.2 Compute TPI

- Use **Raster Calculator:** "Mosaic.tif " – "DEM_mean_50m "
- *Output:* TPI_50m

A4.3 Reclassify TPI to binary

- Use **Raster Calculator:** Con("TPI_50m" > 0, 1, 0)
- *Output:* P_50m_bin

A4.4 Zonal statistics

- Use **Zonal Statistics as Table:**
  - *Zone data:* Lejstaan_segments
  - *Zone field:* OBJECTID
  - *Value raster:* P_50m_bin
  - *Statistic:* Mean
  - *Output:* P_50m_per_segment

A4.5 Join and classify

- Join table to segments.
- Create field P_50m (Short)
- Use **Field Calculator:**

```
def calc_p(mean):
  if mean >= 0.5:
    return 1
  else:
    return 0
```

A5. E-Parameter (Soil Erodibility)

A5.1 Import soil raster

- Load **SOIL_SGU_DSMS2019.tif**

A5.2 Prepare lookup table

- Export Excel sheet to a new table Jordklassning.
- Add fields E_SGU and E_K.

A5.3 Reclassify soil raster

- Use **Reclass by table:**
  - *Input raster:* SGU soil raster

- *Remap table:* Jordklassning
- *From value:* SGUSLUSOILKOD
- *To value:* SGUSLUSOILKOD
- *Output value:* E_SGU and E_K
- *Output:* E_SGU_jordart, E_K_jordart

A5.4 Buffer and zonal statistics

- Create **15-m buffer** around segments: E2_buffer_15m.
- Use **Zonal Statistics** (Majority) with E_SGU_jordart.
- Join results to segments.
- Rename field to E_Majority.

A6. L-Parameter (Bank Slope)

A6.1 Compute slope

- Use **Slope** (Spatial Analyst):
- *Input:* Mosaic.tif
- *Output:* Slope_raw
- *Units:* Degrees

A6.2 Reclassify slope

- Use **Reclassify:**
  - 0°-25° ➔ 0
  - 25°-90° ➔ 1
- Output: L_slope_0_1

A6.3 Buffer and zonal statistics

- Create **20-m buffer:** L2_buffer_20m.
- Use **Zonal Statistics** (Min/Max/Mean) with Slope_raw.
- Join MAX to segments.
- Rename to L_raw.

A6.4 Ninary classification

- Create field L_bin.
- Field Calculator: 1 if !L_raw! >= 25 else 0

A7. K-Parameter (Sinuosity)

A7.1 Add toolbox

- Add **Stream Gradient & Sinuosity 10_1.txb.**

A7.2 Run sinuosity tool

- *Input:* Lejstaan_segments_gdb
- *DEM:* Mosaic.tif
- *Output* stored in project geodatabase.

A7.3 Classify

- Create field K_sinuosity
- Field Calculator: 1 if !Sinuosity! >= 1.15 else 0

A8. B-Parameter (Channel Width)

A8.1 Manual width measurements

- Use **orthophoto + hillshade.**
- Measure width at:

    - Segment start
    - Midpoint
    - Segment end
- Enter values in field B_width.

A8.2 Compute half-width

- Create field B_half.
- Field Calculator: !B_width! / 2

A8.3 Normalise

- Compute standard deviation from B_half.
- Create field B_norm: 1 - (!B_half! / 0.334093)

A8.4 Classify 1 – 9

- Use min/max values:
    - Min = -3.491018
    - Max = -0.497006
- Field Calculator:
  ((!B_norm! - (-3.491018)) / (-0.497006 - (-3.491018))) * 8 + 1

A9. G – Parameter (Water-Surface Gradient)

A9.1 Buffer

- Create **2-m buffer:** G_buffer_2m.

A9.2 Zonal statistics

- Use **Zonal Statistics** with Slope_raw.
- Extract MIN, MAX, MEAN.
- Join to segments and rename fields.

A9.3 Normalise and classify

- Create field G_raw = G2_MEAN
- Use min/max values:
    - Min = 0.923485
    - Max = 26.113681
- Field Calculator:
  ((!G_raw! - 0.923485) / (26.113681 - 0.923485)) * 8 + 1

A10. EI Calculation

A10.1 Create EI field

- Add field EI_index (Float).
- A10.2 Compute EI
- Field Calculator: !E! * (!L! + !P! + !K!) * (!B! + !G!)

A10.3 Visualisation

- Use **Graduated Colours**
- Classes: 5
- Method: Jenks natural

Appendix 2. Sediment sample scanning and RGB value extraction

The images show the dried sediment samples used for the colour-print analysis. Each sample was placed in a transparent plastic bag and scanned on a office scanner. The scanned images were later imported into GIMP 2.3.4, where the mean red and blue colour values were extracted for each sample. These RGB values formed the basis for the colour-based source tracing, following the procedur adapted from Pulley and Collins (2021). The bottom image shows the GIMP 2.3.4 interface used to extract the RGB values from the scanned samples.

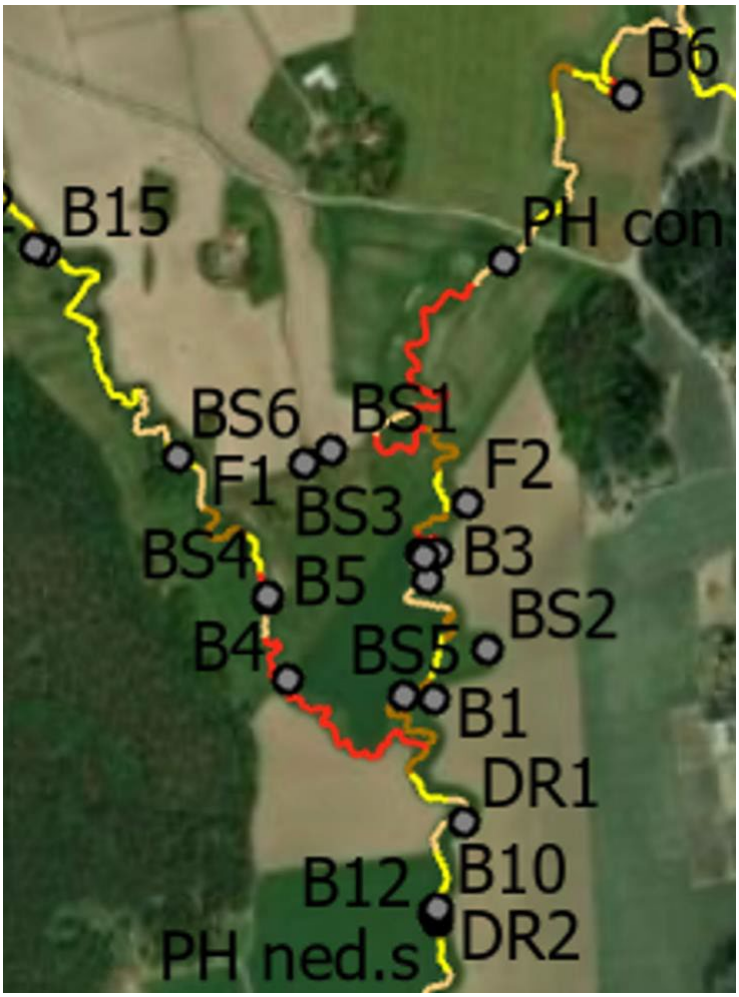


Appendix 3. GIS EI map

The figure shows the GIS-based map illustrating the calculated Erosion Index (EI) along the stream Lejstaån. EI values (0 – 66) were classified into five categories to represent increasing erosion susceptibility. The colour scheme ranges from green (0.0; very low susceptibility), yellow (0.0010 – 24; low), orange (25 – 36; moderate), brown (37 – 48; high), to red (49 – 66); very high susceptibility). Higer EI values shown in red and brown are primarily concentrated along meandering sections and sharper bends of the channel, indicating areas with elevated erosion risk.

An additional inset map shows an enlarged view of the sampling locations along the stream. This close-up illustrates the spatial distribution of filed, bank, bed, drainage pipes and floodplain sampling points in relation to the EI-classified stream segments.




B6
B15
PH con
BS6
BS1
F1
F2
BS3
BS4
B3
B5
BS2
B4
BS5
B1
DR1
B12
B10
DR2
PH ned.s

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