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FELLOWSHIP FINAL REPORT

Satellite-based mapping of sediment dynamics and planform mobility in large river basins

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REPORT INFO

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ABSTRACT

Suspended sediment concentration (SSC) is a key indicator of river morphodynamics and water quality, yet long-term spatial monitoring remains constrained by sparse in-situ measurements. This study develops a satellite-based framework to estimate SSC along the Loire River (France) over 2005–2025 by combining Landsat 5/7/8/9 imagery processed in Google Earth Engine (GEE) with field SSC observations. A feed-forward neural network (R^2 = 0.94, RMSE = 3.65 mg/l) was trained on five spectral bands across three turbidity regimes and approximated by a compact surrogate model (R^2 = 0.89) suitable for operational GEE deployment. SSC maps reveal contrasting morphodynamic behaviour along the reach, with secondary-channel connectivity upstream and channel deepening downstream. River discharge emerged as the dominant SSC control, while rainfall has secondary importance. The approach demonstrates the scalability of combining machine learning and satellite imagery for long-term sediment monitoring in large rivers.

1- Introduction

Sediment dynamics govern fluvial morphology, habitat quality, and water uses like hydropower, navigation, and potable supply. Suspended sediment concentration (SSC) is a central diagnostic variable, as it controls light penetration and primary production, influences fish migration and estuarine dynamics, and transports carbon, nutrients, and contaminants. Despite this importance, the long-term influence of human activities and climate variability on SSC patterns remains poorly quantified, largely because in-situ monitoring networks are sparse and the spatial coverage they provide is inherently limited (Syvitski et al., 2005; Gardner et al., 2023).

Satellite remote sensing addresses this gap by enabling spatially continuous, multi-decadal observations at low operational cost. The Landsat archive, spanning over five decades, has been used to study planform change and to derive SSC through empirical reflectance-to-concentration relationships (Nones, 2021; Nones et al., 2024). Recent machine-learning approaches substantially outperform traditional band-ratio regressions, yet basin-scale, long-period SSC mapping in river channels remains rare (Dethier et al., 2022; Jiang et al., 2026).

The Loire River is a system of major ecological significance, yet long-term SSC studies at the basin scale are scarce (Gay et al., 2014; Moatar et al., 2022). Furthermore, correlating SSC and planform dynamics with land-use/land-cover (LULC) change, retrievable from established databases like CORINE and ESRI, has received little attention despite the well-documented impact of LULC on sediment production (Regasa & Nones, 2023; Gardner et al., 2023). This study addresses these gaps by: (i) developing a neural-network SSC retrieval model from Landsat imagery; (ii) deploying a compact surrogate for operational GEE mapping; (iii) analysing spatio-temporal SSC patterns over the period 2005–2025; and (iv) identifying the primary hydrological drivers of SSC variability along the Loire.

2- Methodology

2.1- Study Area and Hydrological Data

The study focuses on the Loire River (1020 km; 117 000 km² catchment), the longest river in France. Specifically, the study area covers the reach from Nevers to Sainte-Luce-sur-Loire, excluding the upper mountainous and downstream estuarine sections. In this corridor, the active channel width ranges from 100 to 500 m, and land use is dominated by cropland, permanent grassland, forest, and urban areas. Although often described as the last natural large river of Western Europe, the Loire has experienced intensive gravel extraction, flow regulation, and bank stabilisation, leading to significant channel incision during the 20th century (Dhivert et al., 2016; Andréault, 2024).

Daily discharges for 2005–2025 were downloaded from HydroPortail for all stations between Nevers and Sainte-Luce-sur-Loire and averaged across the reach to obtain a single hydrological proxy. Precipitation was derived from the CHIRPS daily dataset in Google Earth Engine (GEE), clipped to the Loire corridor within the main levees. SSC field data were obtained from the NAIADES database for all gauging stations in the study reach; values represent filtered and weighted water samples from the main channel.

2.2- Satellite Data Processing

Landsat surface-reflectance data were harmonised in Google Earth Engine for 2005–2025, with a 20 % cloud-cover threshold. Images were matched to SSC measurements within a ±5-day temporal window. A 50 m buffer around each gauging station was applied to extract spatially averaged reflectance values and reduce sensitivity to local features. Five spectral bands were retained for modelling (B2, B3, B4, B5, B7), selected on the basis of past studies (Wang et al., 2009; Qiu et al., 2024). The wet channel was delineated using the Modified Normalised Difference Water Index (MNDWI, threshold = -0.05) prior to spatial SSC mapping (Boothroyd et al., 2021).

2.3- Neural Network and Surrogate Model

More than 2000 SSC–reflectance pairs were split into calibration (70 %) and validation (30 %) sets. SSC data were divided into three turbidity regimes: low (< 10 mg/l), intermediate (10–90 mg/l), and high (> 90 mg/l), with a separate feed-forward neural network trained for each. Weighted training was applied in the high-SSC regime to compensate for data imbalance. Predictors were standardised by z-score normalisation; and each network used a single hidden layer of 10 neurons with ReLU activation. Predictions from the three regime models were blended using piecewise linear interpolation near regime boundaries to ensure continuity.

Because neural networks cannot be directly implemented in GEE, a compact surrogate was derived via quadratic feature expansion and ridge regression with cross-validated regularisation. The surrogate produces explicit analytical equations that approximate neural-network behaviour efficiently. Model skill was assessed using R^2, RMSE, and PBIAS. SSC drivers were identified through standardised ordinary-least-squares regression against daily discharge, precipitation, and antecedent rainfall indices at 3, 5, 7, and 14 days.

3- Results and Discussion

3.1- Model Performance

Both models achieved strong predictive skill (Table 1). The neural network reached R^2=0.94 across calibration and validation, with slight underestimation at very high SSC (> 100 mg/l), attributable to dataset imbalance, as fewer than 3% of observations exceed this threshold. The compact surrogate retained R^2=0.89, confirming that the simplification introduces only marginal accuracy loss while enabling GEE deployment. Both models exhibit a small positive PBIAS, indicating a slight tendency to overestimate measured SSC under average flow conditions.

Table 1. SSC retrieval model performance.

Model	R^2	RMSE [mg/l]	PBIAS [%]
Neural network	0.94	3.65	6.50
Compact surrogate	0.89	5.18	9.81

3.2- Spatial SSC Patterns and Planform Dynamics

SSC maps were produced in GEE, and reveal contrasting behaviour along the reach when comparing decadal summer values, corresponding to relatively low flow conditions. In the upstream sector near Nevers, secondary channels were more actively connected to the main river by 2015, suggesting a rise in mean bed elevation that enhances lateral connectivity, whether through natural aggradation or management operations such as vegetation removal and secondary-channel deepening (Grosbois et al., 2025). In the downstream sector, near Tours, an opposite pattern was observed: progressive channel deepening led to secondary channels disconnection, with SSC increasingly confined to the main thread. These patterns are consistent with independent topo-bathymetric LiDAR analyses (Andréault, 2024) and confirm that MNDWI-based water masks combined with satellite SSC can serve as indirect indicators of broader morphodynamic processes in multi-channel systems. Disentangling short-term management interventions from longer-term anthropogenic incision driven by historical extraction remains an open research question, and will be addressed in the future through additional collaborations (see Sections 5 and 6)

3.3- SSC Drivers and Uncertainties

River discharge dominated SSC variability across the study reach, consistent with findings for other large regulated rivers, including the Changjiang, Yellow, and Rhine (Vercruysse et al., 2017; Dai et al., 2016). Precipitation and antecedent rainfall indices played a secondary role, suggesting that SSC is primarily driven by in-channel remobilisation rather than direct catchment supply under the cloud-free conditions analysed. This result should be interpreted cautiously: the 20% cloud-cover filter systematically excludes high-flow events when external sediment inputs are highest, so the regression describes normal-to-moderate hydrological conditions rather than extreme episodes. SAR sensors, unaffected by cloud cover, should be incorporated in future work to extend coverage to flood conditions.

Key uncertainties include the discrepancy between satellite surface-signal retrieval and depth-integrated field measurements, atmospheric correction artefacts, particularly in turbid conditions, land adjacency effects in the SWIR band, and the under-representation of high-SSC events in the training dataset. The multi-band approach and regime-specific weighted training partly mitigate these issues. A historical decline in chlorophyll-a concentrations after 2005, linked to the proliferation of invasive Asian clam (Corbicula spp.), reduces the risk of confounding SSC estimates with organic-matter signals (Pigneur et al., 2014; Minaudo et al., 2016). Finally, it was shown that a constant MNDWI threshold (-0.05) performed adequately given the relatively stable spectral properties of the Loire within the study reach.

4- Conclusions

This study developed and validated a satellite-based SSC monitoring framework for the Loire River (France) over 2005–2025, combining Landsat multispectral imagery with in-situ measurements and machine learning. The neural-network model (R^2=0.94) and its compact surrogate (R^2=0.89) provide reliable SSC estimates under normal-to-moderate flow conditions and enable operationally efficient spatial mapping in Google Earth Engine.

SSC maps exposed morphodynamic contrasts along the reach that cannot be recognised from point-based monitoring: secondary-channel reconnection upstream and progressive channel deepening and disconnection downstream, in agreement with independent LiDAR-based analyses. River discharge emerged as the dominant SSC control, reflecting strong coupling between hydrodynamics and sediment remobilisation despite decades of human intervention in the basin.

The framework is transferable to other large rivers and provides a foundation for linking SSC dynamics with planform evolution and LULC change across the Loire basin and beyond. Future work should incorporate SAR imagery to extend SSC retrieval to cloudy, high-flow conditions, collect additional in-situ data during flood events to improve high-SSC model calibration, and integrate bank-erosion estimates from repeat LiDAR surveys to disentangle external and in-channel sediment sources.

5- Perspectives of future collaborations with the host laboratory

During the final weeks of the fellowship, a joint proposal for the PHC Polonium 2026 programme was developed, and is entitled "Integrated acoustic and remote sensing monitoring for estimation of total sediment fluxes and bar morphodynamics in large lowland rivers: Loire and Vistula". This proposal is currently under evaluation.

Additional discussions between the team based in Tours and the one in Warsaw are currently underway, to develop future collaborations in the frame of competitive research programmes run by national entities or at the international/European level.

6- Articles published in the framework of the fellowship

No articles were published during the fellowship, while one was submitted and another one is currently under preparation.

The submitted article is entitled "Satellite-driven monitoring of suspended sediment concentration in large river systems: an application to the Loire River, France" and is currently under evaluation for the Open Access journal Earth Observation, edited by EGU.

The work under preparation focuses on a combination of LiDAR data and remote sensing to depict the long-term evolution of the Loire River planform. This work, planned to be submitted to the River Research and Application journal, will showcase the opportunity to combine different methods to detect changes acting at multiple spatiotemporal scales.

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