Stockage de contaminants dans les environnements de dépôt induit par l'aménagement de l'estuaire amont de la Seine

Contaminant storage in depositional environments induced by river engineering in the upper Seine Estuary (France)

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RÉSUMÉ

L'aménagement croissant de l'estuaire de Seine en amont de Rouen depuis les années 1950, visant à s'adapter au développement du trafic fluvial, a largement recalibré le lit mineur. Ces modifications morphologiques ont favorisé la sédimentation au sein d'annexes hydrauliques, connues pour accumuler les contaminants lorsqu'elles se situent en aval de bassins versants anthropisés. Dans le cadre du projet DESTOX, cinq environnements de dépôt aménagés de 1953 à 1981, ayant accumulé chacun jusqu'à 1.10^5 m^3 de sédiments, ont été investigués. Dix carottes de sédiment ont été prélevées sur une vasière endiguée en 1972. Les concentrations en HAP, PCB, alcanes, métaux ainsi que l'activité du ^{137}Cs sont en cours d'analyse le long de l'une des carottes (1,62 m). Les concentrations en HAP seront déduites sur les 9 autres carottes par imagerie hyperspectrale (méthode de Jacq *et al.*, 2024) puis interpolées pour évaluer le stock de HAP à l'échelle du site. Les premiers résultats révèlent notamment des concentrations en PCB atteignant 3,9 ± 0,4 mg kg^{-1}, soit 50 fois supérieures à la concentration moyenne mesurée dans les matières en suspension circulant actuellement dans la Seine. L'objectif de ce travail est de mesurer l'étendue et l'ampleur de la contamination des stocks sédimentaires de l'estuaire amont pour mieux appréhender le risque potentiel en cas de remobilisation de ces sédiments causée par des événements hydrologiques extrêmes, des aménagements de renaturation, à l'élévation du niveau marin ou d'autres processus.

ABSTRACT

The extensive engineering of the Seine estuary upstream of Rouen (France) since the 1950s to support the growth of river transport has led to a significant recalibration of the riverbed. These morphological changes have enhanced sedimentation in sheltered areas, which are known to trap contaminants from upstream anthropized watersheds. As part of the DESTOX project, five depositional environments, constructed between 1953 and 1981, and each of them storing up to 1.10^5 m^3 of sediment, are being investigated. Ten sediment cores were collected

from a mudflat embanked in 1972. Concentrations of PAHs, PCBs, alkanes, metals and ^{137}Cs activities are being measured along one of the cores (1.62 m). PAH concentrations will be estimated on the 9 other cores using hyperspectral imaging (following the method from Jacq *et al.*, 2024) and interpolated to assess the PAH stock at the site scale. Preliminary results show PCB concentrations of up to 3.9 ± 0.4 mg kg^{-1}, which is 50 times higher than the average concentration measured in suspended particulate matters currently circulating in the Seine Estuary. The aim of this work is to measure the extent of contamination in sediment stocks in the upper estuary in order to better understand the potential risk associated with the remobilization of these sediments. Such remobilization could be triggered by extreme hydrological events, restoration work, sea-level rise or other processes.

KEYWORDS

Aménagement, Contaminants, Estuaire de Seine amont, Sédiment, Stock

Contaminants, River engineering, Sediment, Stock, Upper Seine estuary

1 INTRODUCTION

The extensive engineering of the Seine navigation channel upstream of Rouen since the mid-20th century has unintentionally resulted in the deposition of large amounts of sediment in sheltered areas. At the same time, the upper estuary has been identified as a *hot spot* for organic (Dendievel *et al.*, 2020) and metallic (Chastanet *et al.*, 2024) contaminants, many of which are now banned or strictly regulated. These sediment stocks can be eroded during extreme hydrological events (Habersack *et al.*, 2016), restoration works (Gardes, 2020) or due to sea-level rise (Khojasteh *et al.*, 2021). Although there is a potential risk of contaminant remobilization associated with these sediments, the extent of contamination in the upper estuary remains poorly documented. In the DESTOX project (https://www.seine-aval.fr/projet/destox/), 5 depositional environments - mudflat, dead arm, dock, embanked basin and flooded banks (fig.1) - are being investigated to evaluate the storage of organic contaminants (PAHs, PCBs, alkanes) and historical and emerging metals in the Seine riverbed. In this initial stage of the project, particular focus is placed on one site to test the relevance of a hyperspectral imaging (HSI) approach for quantifying PAH stocks.

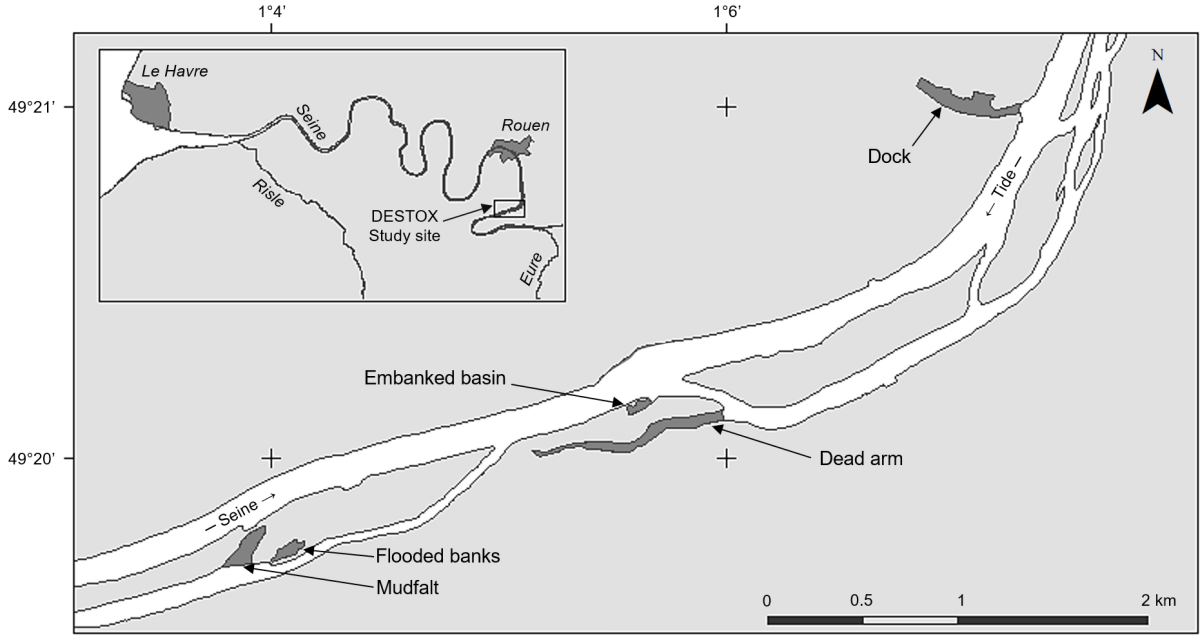

Fig. 1. Location of the DESTOX project study sites in the upper Seine estuary, France

2 ASSESSMENT OF POLYCYCLIC AROMATIC HYDROCARBON (PAH) STOCK

2.1 Coring site

The Legarée mudflat was formed behind a dike constructed in 1972 to close the connection between the secondary channel and the navigation channel. A comparison of a bathymetric map from before the diking and a recent LiDAR survey revealed that 4.6 $.10^4$ m^3 have been deposited over 50 years, with a thickness of up to 3.3m. This sedimentation may be spatially and temporally heterogeneous, thereby affecting the contaminant stock assessment. Geophysical methods failed to capture the spatial variability of the deposit and, accordingly, 10 sediment cores were collected using a UWITEC® gravity corer (fig.2).

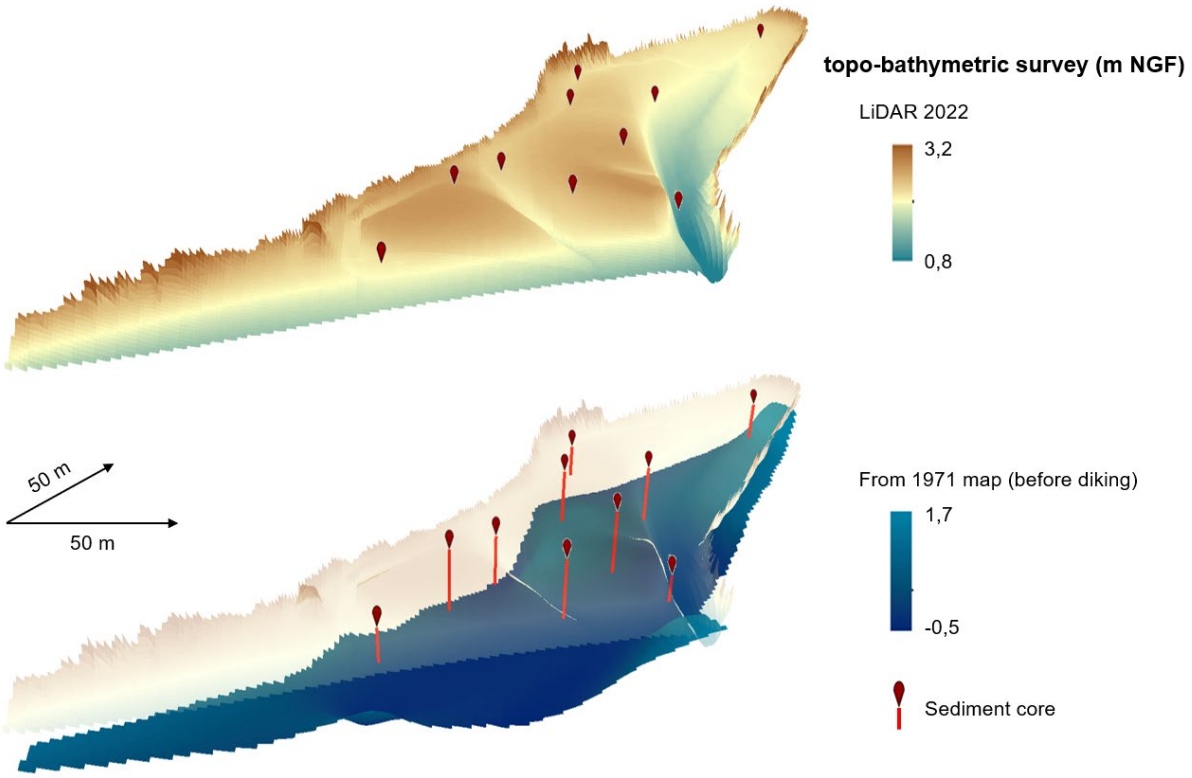

Fig.2. 3D Topo-bathymetric view of the Legarée mudflat in 2022 (top panel) and 1971 (before diking, bottom panel) showing the location and length of the sediment cores marked in red.

2.2 Distribution of Polycyclic Aromatic Hydrocarbons by hyperspectral imaging

A master core was sliced at 3 cm intervals, freeze-dried, and crushed for chemical analysis. PAHs were extracted using microwave-assisted extraction (MAE) and analyzed by gas chromatography-mass spectrometry (GC-MS). Performing MAE-GC-MS analysis with the same resolution for all cores would be time-consuming, expensive, and challenging to reproduce at multiple sites. However, aromatic organic matters, including PAHs, absorb in the near infrared (1600-1700nm) and can be measured with suitable spectroscopic sensor. Accordingly, a fast, cost-effective, and non-destructive method (from Jacq *et al.*, 2024) using hyperspectral imaging (HSI) is applied. Briefly, HSI is conducted on all cores using a short wave-infrared (SWIR) camera (spectral range of 968-2574 nm, 288 spectral bands, spatial resolution of 230 µm). A model is calibrated using the GC-MS dataset obtained from the master core and then applied to the SWIR images of the 9 other cores. The purpose is to interpolate PAHs concentrations on a 3D mudflat scale, derive measurements for stock and storage rates.

3 OUTLOOK

Further questions are being explored:

- (i) The number of cores required to accurately assess the contaminant stock will be determined to optimize stock assessment across multiple sites. Subsequently, the influence of the type of depositional environments (intertidal vs. supratidal, connection level to the Seine, *etc.*) on contaminant storage will be analyzed and discussed;
- (iii) PCB and metal stocks will also be quantified;
- (iii) The current contaminant fluxes in the Seine River is monitored using sediment traps, providing a benchmark for evaluating the significance of stocks and the risk associated with their potential remobilization;
- (iv) the toxicological effects of organism exposure to sediment will be tested.

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