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ABSTRACT

Focusing on the Upper Seine River Basin (France), the study explores how a GIS tool can conduct pre-field analyses to identify potential flood expansion areas, addressing the demand from French authorities to map priority restoration and preservation areas. This paper also investigates the extent to which GIS digital data must be supplemented with field data to accurately define and characterize flood expansion areas. The methodology automates the identification and analysis of flood expansion areas using GIS and high-quality LiDAR DEM data and by extracting hydro-morphological parameters to evaluate a river's connectivity to its floodplain. The results of the study are overall encouraging, as the automated analysis aligns well with both field measurements and hydraulic models used as control data. However, challenges remain, particularly in accurately estimating floodplain boundaries or river depth due to limitations of the input data. Addressing these will be critical to further enhance the tool's precision and applicability. GIS-derived data can provide valuable insights into the functioning of Upper Seine River and its hydrological dynamics. While not developed to replace fieldwork, the tool establishes a general methodology that can be applied to hydrologically similar regions, ensuring a consistent approach to identifying and analyzing floodplain expansion areas. These findings are particularly significant given the fundamental role of flood expansion areas in mitigating flood risk, not only for downstream areas such as Paris, but also for local communities within the basin.

Keywords : flood-plain analysis, flood-expansion areas, floodplain restoration, GIS, LiDAR, river restoration, floods, Parisian basin.

RÉSUMÉ

Centrée sur deux territoires du bassin-versant de la Seine amont, cette étude s'attelle à démontrer que le SIG peut être utilisé pour réaliser des analyses préliminaires et identifier ainsi de potentielles zones d'expansion des crues. Cette recherche est une réponse à la demande, forte, des autorités françaises locales, de cartographier les zones de préservation et de restauration de ces espaces stratégiques. L'article examine également dans quelle mesure les données provenant du SIG doivent être complétées par des données de terrain pour définir et caractériser précisément les zones d'expansion des crues. La méthodologie proposée se base sur l'extraction et l'analyse automatisée de paramètres hydro-géomorphologiques, pour évaluer la connectivité des rivières avec leurs plaines alluviales. Les résultats sont globalement satisfaisants, les données produites étant en adéquation avec les mesures de terrain et les modèles hydrauliques ayant servis de données de référence. Cependant, quelques limites subsistent, notamment pour estimer avec précision les limites du lit majeur ou la profondeur du lit, en raison de la nature des données d'entrée. Traiter ces points en vue d'une prochaine version, sera essentiel pour améliorer davantage la précision et l'applicabilité de l'outil. L'article montre que les cartographies dérivées du SIG peuvent fournir des informations précieuses sur le fonctionnement du bassin amont de la Seine. Bien qu'il n'ait pas vocation à se substituer au travail de terrain, l'outil établit une méthodologie générale, qui peut être appliquée à des régions géomorphologiquement similaires, tout en garantissant une approche cohérente pour l'identification des zones d'expansion des crues. Les données produites et les conclusions de l'étude sont particulièrement intéressantes pour les gestionnaires du territoire, étant donné le rôle clé des zones d'expansion des crues sur l'exposition au risque inondation, non seulement pour une grande capitale comme Paris, à l'aval, mais aussi pour les collectivités impactées localement sur les territoires amont.

Mots-clés : *analyse du lit majeur, zones d'expansion des crues, SIG, LiDAR, restauration de rivières, inondations, Bassin parisien.*

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1. Introduction

In the coming decades, Europe is expected to face an increased risk of flooding and greater economic damage due to the combined effects of climate change and human activities (Estrela et al., 2001). In response to these challenges, European Union member states adopted two key directives at the beginning of the 21th century: the Water Framework Directive (WFD) and the Floods Directive (FD). The WFD set ambitious goals for the protection and restoration of surface and groundwater quality, while the FD focuses on mitigating the impacts of major floods on territories. The implementation of both the WFD and FD, which pertains to the management of rivers and floodplain areas, faces several challenges, including: administrative complexity; the mobilization of sufficient financial and human resources; the scientific standardization of data collection and management; conflicts of use (agriculture *vs* industry *vs* urban development), climate change and its varied impacts on different types of rivers, which vary between the north and south, between mountains and plains; coherent integration of the floodplain hydrological functioning with other sectoral policies such as agriculture, energy, or urban planning; the necessary support of the public and local stakeholders; and the adoption of new technologies and practices (Loupsans and Gramaglia, 2011; Bouleau and Pont, 2014; Maillet, 2015). The 'on-the-field' implementation of the WFD and FD also presents several specific challenges: the diversity of landscapes and hydrological conditions across different river basins, which complicates the uniform application of measures; encounters with private properties and land rights; the need to rethink the role of preexisting infrastructures (dams, levees, canals, *etc.*) in valley floors where floods are controlled; local resistance to proposals for modifying or adapting the functions of the floodplain; potential impacts on biodiversity and aquatic ecosystems; and the need for effective coordination and communication among all stakeholders involved.

The EPTB Seine Grands Lacs, which stands for Territorial Public Basin Establishment, aimed to address these challenges through an integrated approach to the WFD and FD in the upstream part of the Seine basin. In France, both directives have been transposed into national law – one via the LEMA (Law on Water and Aquatic Environments, 2006) and the other through the LENE (Law on National Commitment for the Environment, 2010). These laws set specific objectives for major hydrological basins. The planning documents related to these laws are the SDAGE (Master Plan for Water Development and Management) and the PGRI (Flood Risk Management Plan). The Seine Normandy Water Agency is responsible for implementing these documents at the local level. As part of executing the SDAGE and PGRI, the agency prioritized the goal of "*acting on the flood hazard by preserving and restoring flood expansion areas and wetlands that contribute to slowing down water flows*". This primary objective was divided into specific actions, one of which involved "*identifying and categorizing flood expansion areas*" within the Seine River Basin. Developing the PGRI program required establishing a precise definition of a flood expansion area, which needed to account for both hydro-geomorphological characteristics and a legal definition. After extensive discussion, flood expansion areas were defined as "*non-urbanized or minimally urbanized floodplain spaces that can naturally store water temporarily during a flood. These areas contribute to the structuring of landscapes and the balance of hydro-systems, acting as buffer zones – like 'sponges' – by mitigating flood peak flows, reducing downstream water levels, and spreading the flow over time. They should not be confused with 'over-flooding' areas, where flooding or over-flooding is intentional and may involve natural fields or artificially created areas, either within or outside the floodplain. These are generally the result of engineered retention structures. It is important to differentiate floodplain expansion, a natural phenomenon involving flood overflow, from storage or over-storage, which is specifically designed to retain water for flood management purposes*" (Laurent et al., 2022).

Recognizing the need for tailored regional implementation and to ensure a cohesive approach, the Seine Normandy Water Agency assigned EPTB Seine Grands Lacs to manage the deployment of the action in the upstream part of the Seine basin. The EPTB Seine Grands Lacs is responsible for facilitating flood prevention, the sustainable management of water resources, and the preservation, management, and restoration of aquatic ecosystems and wetland biodiversity across the upper Seine hydrographic basin. The overall territorial coordination is inspired by a methodology that the AREAS association has successfully implemented for thirty years in Normandy to limit runoff and erosion of agricultural soils (AREAS, 2024). Given the extensive geographical scope that needs to be investigated and inventoried, EPTB Seine Grands Lacs explored several options. Multiple studies were commissioned to engineering consultants and graduate students to develop a reproducible methodology. While these studies effectively explained local floodplain functions and identified disruptions, their methodologies could not be systematically deployed across the entire EPTB Seine Grands Lacs territory within the PGRI timeframe (2022-2027), as they required extensive fieldwork. In light of these constraints, it became evident that conducting this analysis in a fully automated manner using GIS was necessary.

As digital databases, whether hydrological, hydraulic, topographic, hydrogeological, or related to land use, become more numerous, extensive, and accessible, water territories facing flood risk have never been more strained, with increasingly critical human and financial stakes in valley floors (Barraqué, 1999; Carré, 2006; Klijn et al., 2008; Schanze, 2013; Junger et al., 2022). The necessary restoration of floodplain functions to mitigate downstream flood risk involves leveraging these digital databases, which are often disparate and of uneven quality, in order to address the problem on the scale of several tens of thousands of square kilometers. The fundamental research question is to what extent do GIS digital data need to be supplemented by field data to provide an acceptable response in defining and characterizing flood expansion zones. This question, relevant to all major European water territories, has been specifically addressed in the case of the Upper Seine River Basin. Based on an accepted definition of flood expansion areas and in response to the political demand from French authorities to map and inventory potential restoration and preservation priority areas, this paper aims to demonstrate that a GIS tool can perform a pre-field analysis to identify probable flood expansion areas over large territories and basins.

2. Study area

The GIS tool was developed for implementation in the upstream Seine River Basin, encompassing an area of 44,000 km², which accounts for 56 % of the entire basin located upstream of Paris (fig. 1).

The upper basin is positioned in the southeastern part of the Paris Basin, a geological unit comprised of sedimentary rocks dating from the early Secondary era (Triassic) to the Upper Tertiary (Miocene). These rocks, an alternating mix of loose materials (such as sands, marls, and clays) and coherent formations (such as limestones and sandstones), are arranged in concentric rings and rise towards the periphery, forming a monocline structure where they contact ancient crystalline massifs like the Morvan. The basin's margin features cuesta

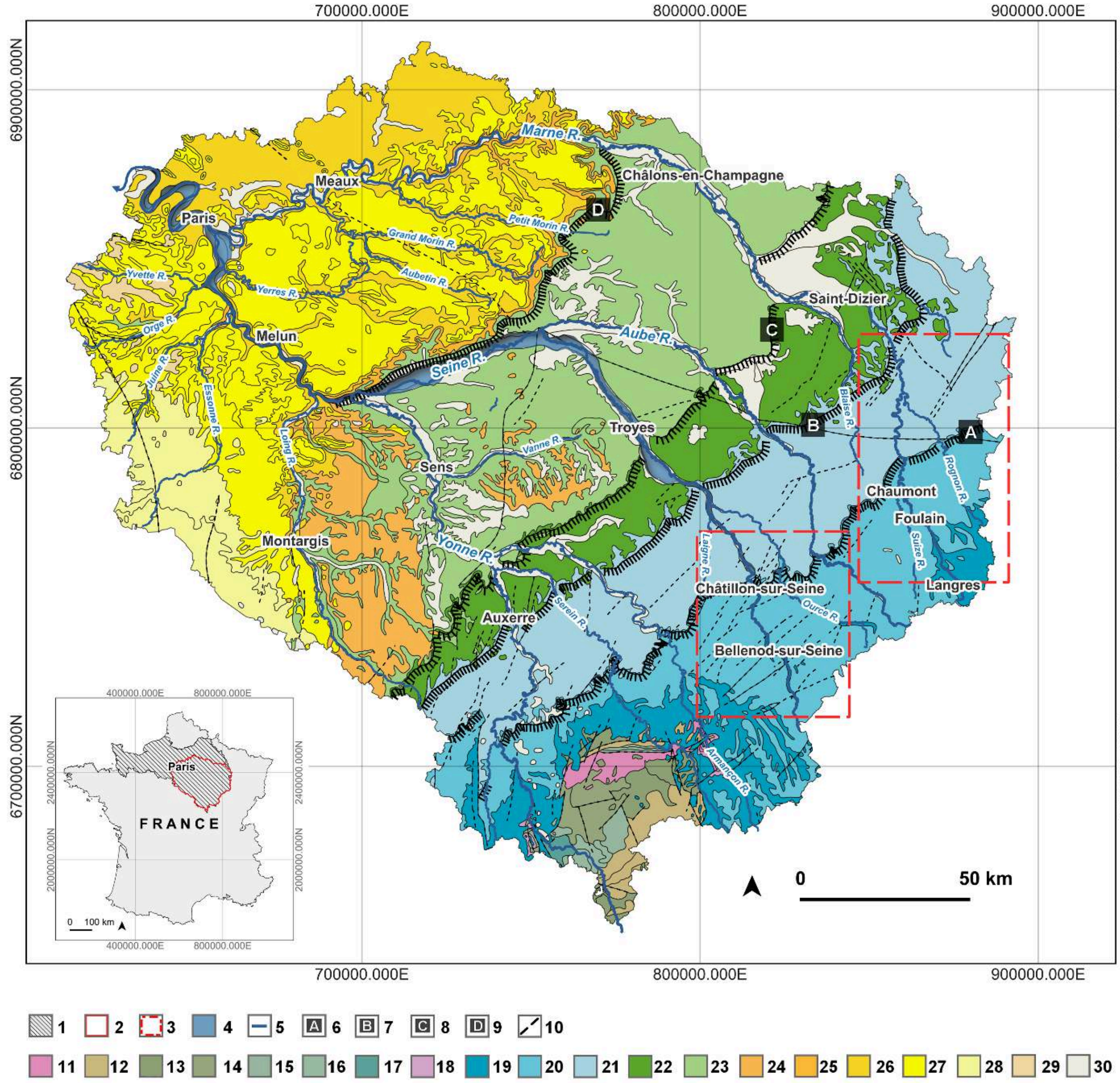


Fig. 1 – Location map and geomorphological context of the Upper Seine River Basin.

1. Seine River Basin; 2. Upper Seine River Basin; 3. Study areas; 4. Seine floodplain; 5. Main rivers; 6. Meuse cuesta; 7. Bar cuesta; 8. Champagne cuesta; 9. Île-de-France coteau; 10. Main faults; 11. Briovarian and Cambrian; 12. Tournaisian, Early Visean; 13. Late Visean, Namurian; 14. Dinantian, Namurian, and Westphalian; 15. Namurian, Westphalian, Stephanian; 16. Stephanian; 17. Permian; 18. Middle-Late Triassic; 19. Early Jurassic; 20. Middle Jurassic; 21. Late Jurassic; 22. Early Cretaceous; 23. Late Cretaceous; 24. Paleocene, Early Eocene; 25. Paleocene, Eocene; 26. Eocene; 27. Oligocene; 28. Miocene; 29. Pliocene; 30. Quaternary.

Fig. 1 – Localisation et contexte géomorphologique du bassin amont de la Seine.

1. Bassin-versant de la Seine ; 2. Bassin-versant de la Seine amont ; 3. Zones d'étude ; 4. Plaine alluviale de la Seine ; 5. Principaux cours d'eau ; 6. Côte de Meuse ; 7. Côte des Bar ; 8. Côte de Champagne ; 9. Côte d'Île-de-France ; 10. Faille ; 11. Briovérien, Cambrien ; 12. Tournaisien, Viséen inférieur ; 13. Viséen supérieur, Namurien ; 14. Dinantien, Namurien, Westphalien ; 15. Namurien, Westphalien, Stéphanien ; 16. Stéphanien ; 17. Permien ; 18. Trias moyen-supérieur ; 19. Jurassique inférieur ; 20. Jurassique moyen ; 21. Jurassique supérieur ; 22. Crétacé inférieur ; 23. Crétacé supérieur ; 24. Paléocène, Eocène inférieur ; 25. Paléocène, Eocène ; 26. Eocène moyen-supérieur ; 27. Oligocène ; 28. Miocène ; 29. Pliocène ; 30. Quaternaire.

reliefs. The permeability of certain rocks (sands and limestones) helps to reduce runoff, while other facies (clays and marls) tend to limit infiltration. The Seine River originates at an elevation of 446 m a.s.l. on the Langres Plateau at Source-Seine in Côte d'Or and flows northwest. Initially, it runs as a small stream through a porous limestone terrain beyond Chatillon-sur-Seine. It enters Champagne, cuts through the dry chalk plateau, and is joined by the Aube River near Romilly-sur-Seine. Skirting the Île-de-France, the Seine River meets the Yonne River at Montereau, noteworthy for its origin in the Paleozoic Morvan massif. The river continues in a northwesterly direction, passing Melun and Corbeil-Essonnes before reaching Paris, where it runs at an elevation of 26 m a.s.l. The Seine basin experiences a temperate oceanic climate, tending towards a modified oceanic climate in its most upstream parts, with average annual precipitation of about 820 mm. This precipitation is relatively evenly distributed throughout the year, although there is a slight seasonal variation that results in higher water levels during winter (Feuillette et al., 2016). The Seine's hydrologic regime is pluvial, with aquifers making a significant contribution to its flow (Gob et al., 2010). From its source to Paris, the Seine spans a length of 495 km, with a gradient varying from 0.005 (upstream) to 0.0001 m/m (downstream). The width of the Seine floodplain ranges from 100 to 5500 m. The river's average monthly discharge increases downstream from 15.7 m^3/s at Troyes to 392 m^3/s at Paris. The specific stream power at bankfull stage of the Seine River is very low, measuring 21 W/m^2 at Méry-sur-Seine and 5,8 W/m^2 at Paris. The flood prevention plan for the upstream Seine River, approved on March 10, 2017, uses the January 1910 flood as the reference hydrological event for the valley (Gache, 2013), during which the Seine reached 450 m^3/s at Troyes and 2650 m^3/s at Paris. Since their construction between 1949 and 1989, reservoir lakes have been used to mitigate floods.

The study specifically focuses on the territories of EPAGE Sequana, an association of public intercommunal cooperation establishments organized as a mixed syndicate, and SMBMA – *Syndicat mixte du bassin de la Marne et de ses affluents*. Both entities are local authorities responsible for managing aquatic environments and flood prevention. They are long-standing partners of the EPTB Seine Grands Lacs and operate under a partnership agreement:

- EPAGE Sequana encompasses a 1900 km^2 area located in the Châtillonnais of Côte-d'Or within the Bourgogne-Franche-Comté region. The Châtillonnais, situated on limestone plateaus, is part of the Langres Plateau where the Seine River originates. These expansive Jurassic limestone plateaus, ranging in elevation from 400 to 500 m a.s.l., are intersected by numerous valleys fed by tributaries (Ource, Brevon, Digeanne, and Laigne) of the Seine River (Debesse-Arviset, 1928). The rivers Seine, Ource and Digeanne have very similar annual specific discharges (± 12 l/s/km^2). The mean annual rainfall is also comparable for these rivers: 388 mm for the Seine, 378 mm for the Ource, and 387 mm for the Digeanne. Their seasonal discharge curves are typical of pluvio-nival regimes, with high winter flows (> 20 l/s/km^2 from December to February) and low summer flows (< 5 l/s/km^2 in July and August). The Laigne River, by contrast, has a significantly lower annual specific discharge of 5.3 l/s/km^2. This is also reflected in its mean annual rainfall, which is considerably lower (167 mm). The Laigne River is particularly influenced by its pronounced karstic context. Low-flow periods are longer and more intense with values dropping below 1.5 l/s/km^2 between August and September. The Seine River Basin within the EPAGE Sequana territory is predominantly rural and forested. Land use is primarily composed of agricultural parcels (50 %) and forests (45 %). Urban areas are scattered, with key activity and population centers in Châtillon-sur-Seine and Sainte-Colombe-sur-Seine;
- SMBMA covers a 3100 km^2 area in the Haute-Marne department and includes the upper basin of the Marne River, one of the main tributaries of the Seine River originating in the Jurassic limestone of the Langres Plateau, while the flood plains consist of clay sediment. The upper Marne watershed reaches a maximum altitude of 520 m a.s.l. at its southern limit, descending to 125 m a.s.l. at its northernmost point in Saint-Dizier. The landscape is characterized by the flows of the Marne's main tributaries (Traire, Suize, Rognon, and Blaise). Tributaries in the upstream part of the Marne watershed are often small and can experience severe low-water levels or even droughts, as is the case of the Suize River. This tributary has the lowest-yielding basin, with a specific discharge of less than 10 l/s/km^2 occurring 94 % of the time. The rivers Rognon and Traire present similar specific discharge patterns, with a discharge produced of less than 10 l/s/km^2 60 % of the time. This is followed by a sharp increase within the 20 % of the highest specific discharges, which shows the high production and reactivity of these rivers during flood-generating rainfall events. The Blaise and the Marne, although more productive on average (around 15 l/s/km^2, 80 % of the time), present lower values for the remaining 20 % than the Traire and Rognon extremes (SETEC HYDRATEC, 2022). In general, the hydraulic regimes of these headwater streams are strongly influenced by groundwater and karstic discharges. This context results in significant spatial and temporal heterogeneity in discharge (Lejeune et al., 1989). The Marne floodplain is also marked by the presence of an important artificial body of water; the Champagne-Burgundy Canal, built during the 19th century, it is supplied by three reservoir dams located upstream of Langres. The construction of both the canal and the railway line (Langres - Saint-Dizier line) within the Marne floodplain led to profound changes in its course. These structures still restrict the lateral mobility of the Marne River. The Marne valley is wide and dominated by meadows (15 %) and cultivated plots (40 %), with forests occupying a significant portion (40 %). The territory is sparsely urbanized, with developed areas mainly concentrated around Chaumont, Joinville, and Saint-Dizier (Aubert et al., 1985).

3. Methods

A prototype version of the tool was tested in two upstream areas: the EPAGE Sequana and SMBMA territories. These areas were chosen for the prototype development primarily because they had existing hydraulic models capable of identifying flood expansion zones, as defined in the PGRI, at the time of the study. Specifically, 2D modeling for the EPAGE Sequana was carried out in 2023 by CEREMA while for the SMBMA, it was completed in 2022 by SETEC HYDRATEC. The use of these hydraulic models, in conjunction with local field surveys, was expected to provide sufficient and reliable control data. Field measurements were conducted in the Châtillonais between October 2023 and May 2024, and in Haute-Marne in April 2024 and October 2024. In detail, the methodology is designed to enable the automated identification and analysis of floodplain expansion areas by leveraging advancements in GIS-related fields and significant improvements in DEM data quality. This is accomplished by automatically extracting hydromorphological parameters from LiDAR DEM data and available vector data, assuming they offer sufficient indications of a river's connectivity to its floodplain.

3.1. Process for delineating the floodplain

Identifying flood expansion areas using a GIS tool requires, first and foremost, a clear understanding of floodplain boundaries and the translation of this information into GIS-compatible data. Most contemporary flood inundation maps are derived from computer models. However, these models demand an extensive array of data, from very high-resolution DEMs to discharge values, and their deployment can be costly. Given this, several studies (Samela et al., 2018; Nardi et al., 2019; Prakash et al., 2024) have demonstrated the feasibility of approximating hazard maps using lower-resolution global DEM data or freely available satellite data. As noted by these authors, such methods are subject to approximations and artifacts, making them more suitable for large-scale maps where precision is not a primary concern.

In parallel, French authorities in the 2010s developed a GIS layer known as the *Enveloppe approchée des inondations potentielles* (EAIP), which represents "*the potential impact of overflows from all watercourses, including small and intermittent streams, torrents, and thalwegs*" (Ministère de l'écologie, du développement durable, des transports et du logement, 2011). This layer was designed to outline the extent of extreme events, excluding the effects of hydraulic structures like dikes and dams. The EAIP was created by compiling various information sources: where local inundation maps produced either by hydraulic models or specific field studies were unavailable, the floodplain was delineated using recent digitized alluvial deposit maps. The resulting map is prone to inaccuracies, often overestimating the floodplain's extent, but offers the advantage of being ready-to-use and provides comprehensive coverage of all watercourses within the EPTB Seine Grands Lacs territory.

Given the similar limitations of each approach explored and to minimize costs and efforts, the EAIP data was considered sufficiently relevant for a preliminary delineation of the floodplain and the easiest to implement. To assess the accuracy of the EAIP data, the floodplain boundaries are mapped for several zones using a Trimble TDC100 GPS device and topographic maps in the field. This GPS allows for metric accuracy. These surveys are then compared against both the EAIP boundaries and the 100-year return flood boundaries delineated by hydraulic models, when available.

3.2. Procedure for flood plain characterization

Within the flood plain, it is essential to distinguish hydraulically functional flood-expansion areas from those that are disconnected and non-functional. As described by several authors (Schumm, 1977; Degoutte, 2006; Bravard and Petit, 2000), "natural" river forms are dictated by geological, climatic and auto-cyclic factors, which they refer to as control variables. Analyzing how response variables react to these control variables highlights potential disturbances. The 2-year return flood discharge, being the most morphogenically influential, should naturally shape the theoretical geometry of the active channel (Degoutte, 2006). In the Seine basin, one would generally expect single-channel, sinuous, and shallow streams (Rosgen, 1994). If observed field conditions deviate from these expected forms, it suggests possible human interventions. Rivers exhibit myriad response variables that influence their morphology, but A. Brookes (1988) specifically identifies certain variables and features – such as widening and deepening of the channel, straightening, and the presence of embankments – as evidence of human alterations and river

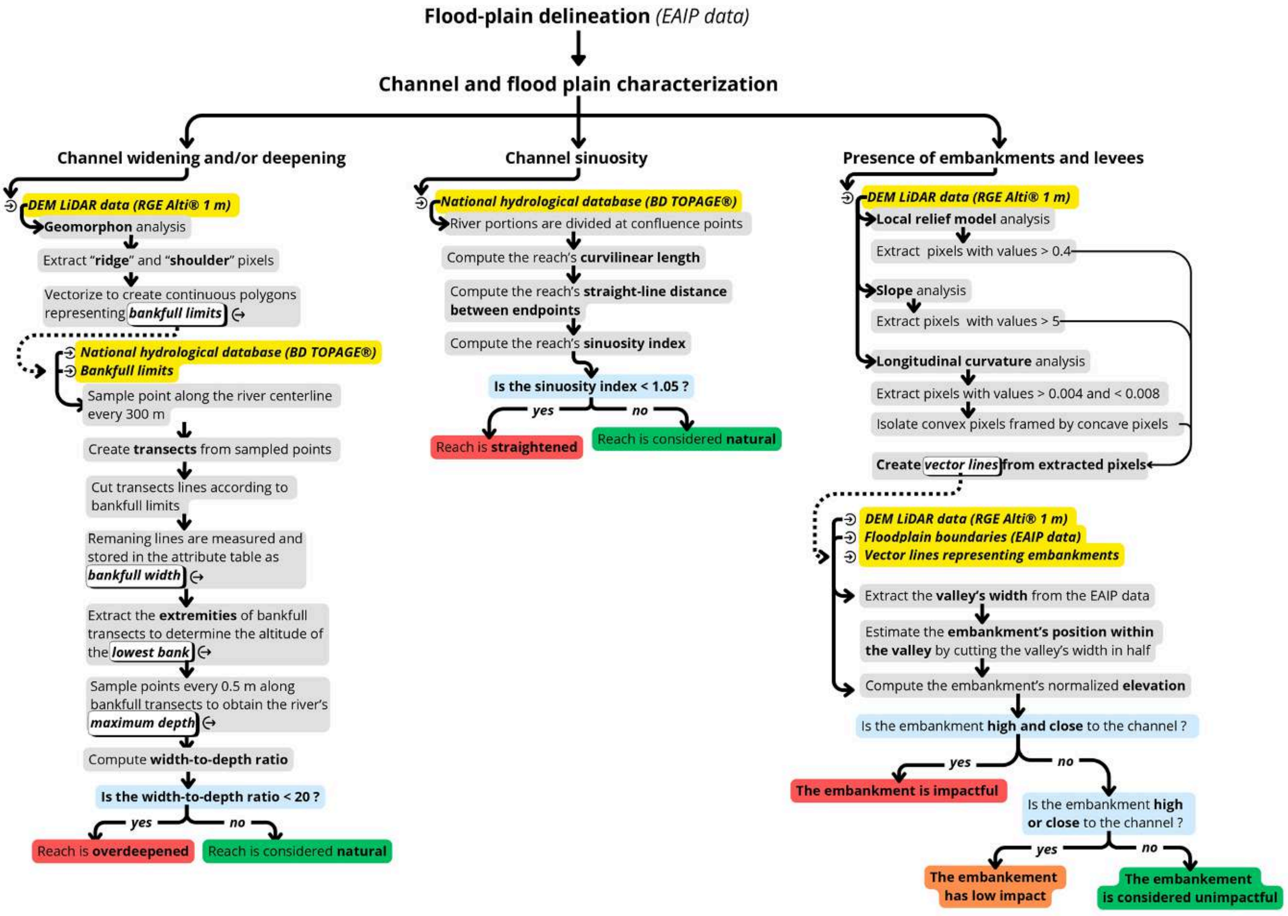


Fig. 2 – Channel and flood plain characterization methodology.

Fig. 2 – Méthodologie de caractérisation du chenal et de sa plaine inondable.

channelization. These parameters are considered in this analysis to demonstrate possible connectivity disruptions between the river channel and the flood plain. The full methodology outlined in the text below is summarized in Figure 2.

3.2.1. Available data

In line with the requirements of the FD, which mandates the development of risk maps, French authorities have produced high-resolution DEM LiDAR data, known as RGE Alti® 1 m, covering flood-prone areas in France since 2014. Most floodplains are now mapped with highly precise altimetric (20 cm) and planimetric data (60 cm; IGN, 2021). Such precision allows the detection of even the smallest landforms and detailed analysis of river landscapes. Previous studies (Cavalli et al., 2008) have shown that LiDAR elevation data can aid in recognizing channel morphology and identifying riffle-pool and step-pool reaches, as well as analyzing long-term morphological river evolution (Genuite et al., 2021; Andualem et al., 2024). Given these successes, RGE Alti® 1 m is deemed a reliable data source for extracting evidence of river channelization. In the Châtillonnais, the DEM LiDAR data was acquired between March 5 and March 22, 2013. According to data measured by the two hydrometric stations available in the area, located in Nod-sur-Seine and Quemigny-sur-Seine, water levels in early March 2013 were relatively low for the Seine River, averaging 0.4 m. However, starting on March 16, water levels rose considerably, reaching up to 0.95 m by March 22. In Haute-Marne, LiDAR acquisitions were made over the Marne River during a 4-month period from mid-November 2012 to mid-March 2013. During this timeframe, water levels reached over 2.5 m (notably in late December and early February) at the Marnay-sur-Marne and Chaumont hydrometric stations. Considering the technical limitations of LiDAR in penetrating the water surface, this could influence the computed metrics. Simultaneously, this study also utilizes the national hydrological database, BD TOPAGE®, a detailed vector dataset representing the hydrographic network of France, including rivers, canals, and significant ditches. Created through the visual interpretation of aerial photographs and validated via field surveys, it is produced at a 1:5000 scale (SANDRE, 2020).

3.2.2. Estimation of channel widening and/or deepening

The width-to-depth ratio is a widely used metric in fluvial geomorphology for evaluating the shape and dynamics of river channels, calculated by dividing the channel's bankfull width by its depth. Although a low width-to-depth ratio alone does not necessarily indicate a hydromorphological disruption (Malavoi and Bravard, 2010), channels in the upstream Seine River Basin are generally expected to display high width-to-depth ratios (Whiting and Stamm, 1995). Thus, in this study, a low width-to-depth ratio might suggest abnormal deepening of the channel and can help evaluate the river's lateral connectivity to its flood plain.

To estimate this ratio, bankfull width is extracted first. Several methods for computing bankfull width from DEM data exist (Faux et al., 2009; Sofia et al., 2015; De Rosa et al., 2019). De Rosa et al. (2019) developed a QGIS plugin for estimating bankfull width by analyzing hydraulic depth across elevations for each cross-section, demonstrating good accuracy with an average error of 5 % compared to field surveys, achieving ± 2 m accuracy for single-channel rivers. However, the plugin is not updated for newer QGIS versions and uses an unsupported Python version. Due to lack of documentation and response from the author, this method, though promising, was not applicable. The Laboratoire de Géographie Physique (LGP-UMR 8591) is currently refining De Rosa's methodology; results are pending but may become viable in the near future (Rétat et al., 2024). Meanwhile, this study proposes a simpler approach using geomorphons to determine bankfull limits. Geomorphon analysis elevates DEM-based landform elements, assigning each raster cell a corresponding geomorphon type (Jasiewicz and Stepinski, 2013). These 498 geomorphons classify into 10 landform types: flat, peak, ridge, shoulder, spur, slope, hollow, footslope, valley, and pit. Bankfull limits should correspond to a "shoulder" or possibly a "ridge" geomorphon. Relevant cells are extracted and vectorized to form continuous polygons (fig. 3A).

Transects are generated by sampling points every 300 m along river centerlines, as represented in BD TOPAGE® vector data, initially 200 m long. The generated vector lines are then segmented based on estimated bank limits. Remaining lines are measured and stored in the attribute table as "bankfull width".

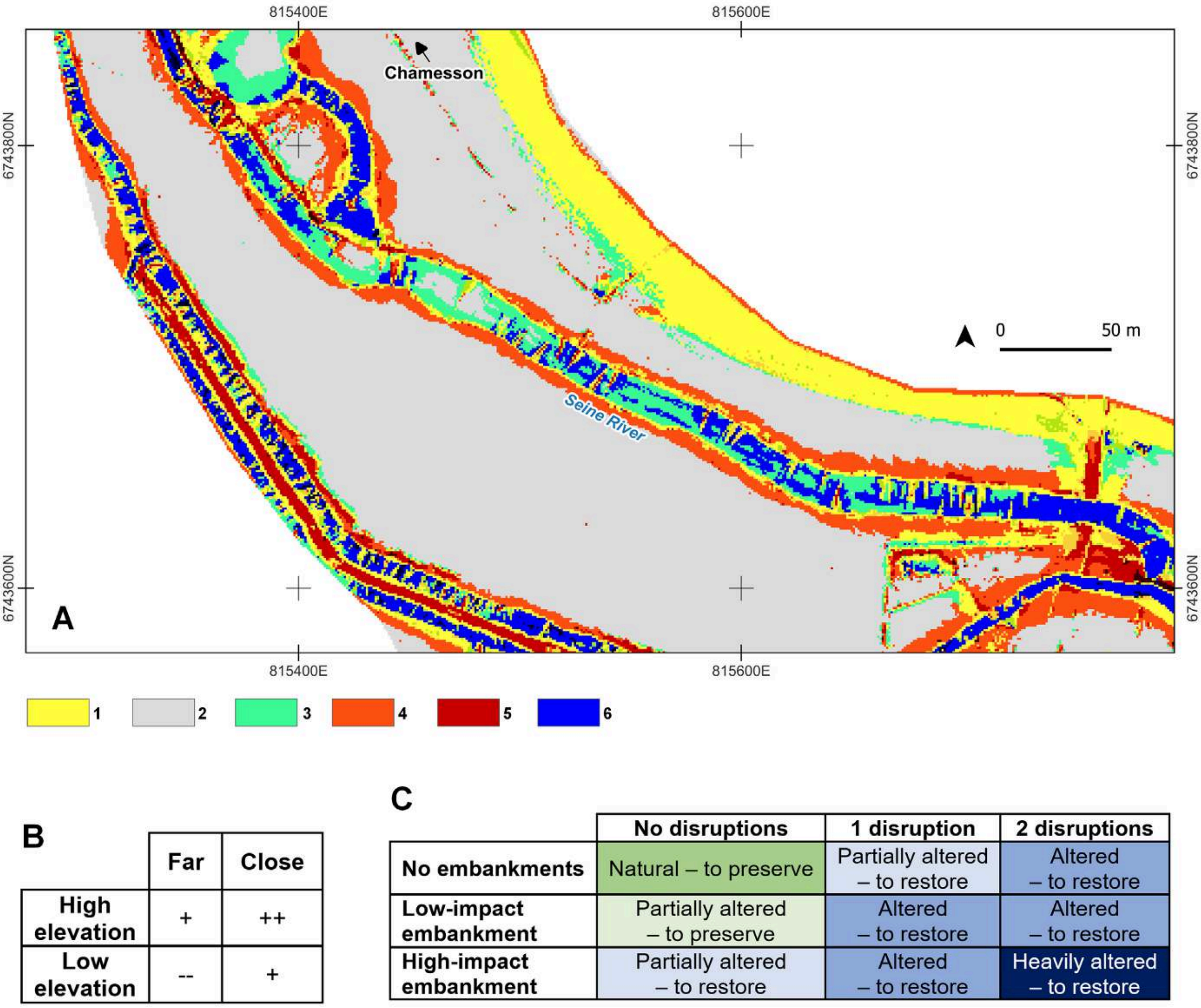
To estimate cross-section depth, the altitude of the lowest bank is determined by extracting the extremities of bankfull transects. Points are sampled every 0.5 m along transects to obtain the river's maximum depth at the cross-section from DEM data. The lowest elevation point sampled is considered the maximum depth; the elevation difference between the lowest bank and the channel's lowest point constitutes the depth. From these attributes, the width-to-depth ratio is calculated, using an automated method. Reaches with width-to-depth ratios > 20, indicating strong lateral erosion and significant sediment input (Malavoi and Bravard, 2010), are considered likely natural. Conversely, reaches with ratios < 20 are deemed overdeepened. The plan also includes employing a hydraulic equation to calculate theoretical width from a 2-year discharge, proposed by R.D. Hey and C.R. Thorne (1986), though untested in the prototype version of this study.

3.2.3. Estimation of channel sinuosity

Natural channels should exhibit a certain sinuosity (Leopold et al., 1964), appreciable through the sinuosity index (SI), the ratio of a river's curvilinear length to the straight-line distance between endpoints. According to conventional SI classes, a non-straightened channel should exhibit a sinuosity index > 1.05. This metric is computed using BD TOPAGE® vector data. Each river reach is processed individually – defined here as a continuous river portion divided at confluence points – and attributed a SI value. Segments with an SI > 1.05 are assumed natural and labeled accordingly in the attribute table.

3.2.4. Automated mapping of embankments and levees

Currently, there are no pre-existing maps of embankments, dikes, levees, and merlons in the Seine River Basin. Such inventories are created for specific studies, like hydraulic models, and are thus locally scaled. Inspired by previous studies proving the feasibility of using LiDAR DEM data to automatically extract these landforms with good accuracy (Sofia et al., 2014; Van Nieuwenhuizen et al., 2021; Sasaki et al., 2023), this tool seeks to map smaller, irregular embankments, corresponding to merlons. Sampled objects display common characteristics extractable from DEM data: (*i*) these topographic forms stand as small positive anomalies compared to their immediate surroundings; (*ii*) as human-modified features, they exhibit strong slope gradients; and (*iii*) they form "bumps," featuring strong convexity at the summit and slightly concave surrounding terrain. Positive topographic anomalies are assessed via a local relief model – a low-pass filter enhancing smaller landscape shapes from DEM data – previously used effectively to extract small negative anomalies (De Matos Machado et al., 2016). The use of a low-pass filter, the Local Relief Model (LRM) algorithm was preferred over a terrain form analysis like Geomorphon, although the latter is capable of detecting ridges-like features. The comparison of the two methods showed that Geomorphon is overly discriminating, classifying many elements corresponding to merlons as 'shoulder' features. This classification is too broad, making it difficult to distinguish merlons from riverbanks, which limits its usefulness for identifying specific landforms. In contrast, the application of a low-pass filter allows for the identification of smaller "anomalous" elements and therefore provides a better ability to highlight features such as merlons. The anomaly's convexity and slope are gauged by calculating longitudinal curvature and slope from LiDAR DEM data. Once



B

	Far	Close
High elevation	+	++
Low elevation	--	+

C

	No disruptions	1 disruption	2 disruptions
No embankments	Natural – to preserve	Partially altered – to restore	Altered – to restore
Low-impact embankment	Partially altered – to preserve	Altered – to restore	Altered – to restore
High-impact embankment	Partially altered – to restore	Altered – to restore	Heavily altered – to restore

Fig. 3 – Mobilization of GIS and LiDAR DEM data to identify flood expansion areas.

A: the geomorphon algorithm highlights, among other features, the banks of the river; B: criteria for differentiating mapped embankments; C: combined characterization parameters allow for an estimation of the floodplain functionality.

1. Slope pixels; 2. Flat pixels; 3. Footslope pixels; 4. Shoulder pixels; 5. Ridge pixels; 6. Valley pixels

Fig. 3 – Mobilisation de données MNT LiDAR et du SIG pour l'identification de zones d'expansion des crues.

A : l'algorithme geomorphon permet de mettre en évidence, entre autres, les berges de la rivière ; B : critères retenus pour différenciés les remblais cartographiés ; C : la combinaison des paramètres de caractérisation permet une estimation de la fonctionnalité de la plaine inondable.

1. Pixels de type pente ; 2. Pixels de type surface plate ; 3. Pixels de type rupture de pente ; 4. Pixels de type épaulement ; 5. Pixels de type crête ; 6. Pixels de type vallée.

specific landforms are extracted and mapped, evaluating their potential flood dynamic impact remains. Differentiation considers three parameters: the valley's width, the embankment's position within the valley and its normalized elevation. Observations show: the higher and closer an embankment is to the river, the more it impacts lateral connectivity (fig. 3B).

3.2.5. Combined parameters

Hydromorphological parameters are combined to estimate global functionality. Alteration presence or accumulation indicates a degree of restoration needed for the studied reach. Meanwhile, disruption-free reaches are considered natural and functional and therefore candidates for preservation. The reach's overall state is distributed to adjacent land parcels (fig. 3C). The characterization protocol should ultimately differentiate areas in the floodplain. It must identify floodplain expansion spaces to preserve, where, based on automatically extracted channel geometry and absence of impactful embankments, overflows occur at biennial flood levels. It should also identify areas for restoration, where vortex presence or disruptions hint at a probable disconnection between the channel and its floodplain.

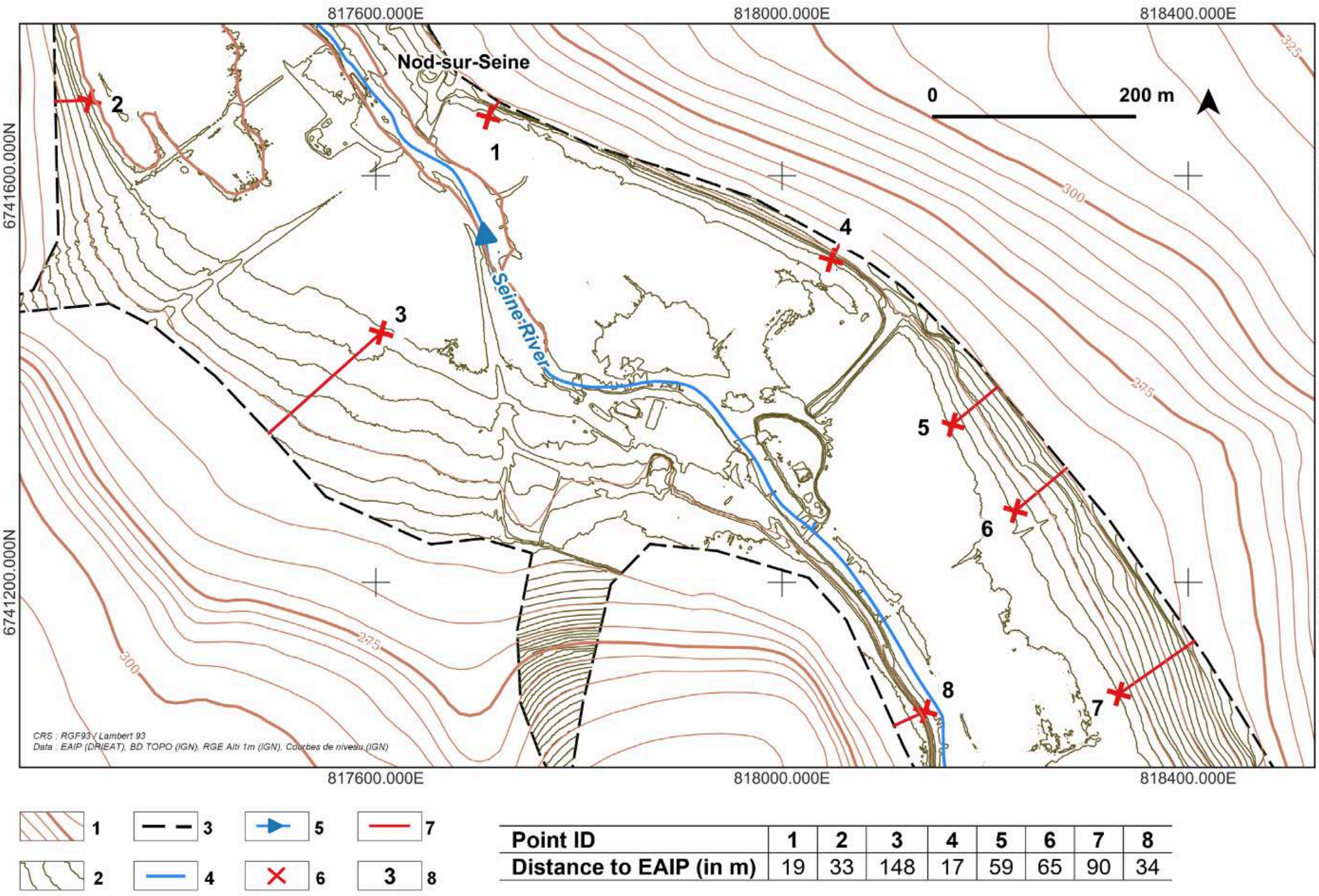
4. Results

The comparison between field surveys and the EAIP data shows the true boundaries of the floodplain are generally much narrower than those depicted in the EAIP (fig. 4).

This observation holds for the Nod-sur-Seine area where points were sampled, and similar patterns are evident along the Seine River and its tributaries in the Châtillonais. On average, the EAIP overestimates the floodplain boundaries by 58 m and up to 148 m on point no.3. In Haute-Marne, the accuracy of the EAIP for floodplain delineation was evaluated near Foulain in the Marne River, with measurements taken along a 2.5 km stretch of the riverbed (fig. 5).

The surveys once again revealed a significant discrepancy with the input data, showing that the EAIP overestimates floodplain boundaries by as much as 55 m in this area. The average difference observed is 32.5 m.

The automated mapping of embankments and merlons gives satisfactory results. In the Bellenod-sur-Seine area, the tool successfully detected 100 % of the embankments observed in the field, which were predominantly road and footpath embankments. However, a few artifacts were also mapped. Similarly, the tool tends to slightly overestimate the presence of merlons in the Ampilly-le-Sec area. Two



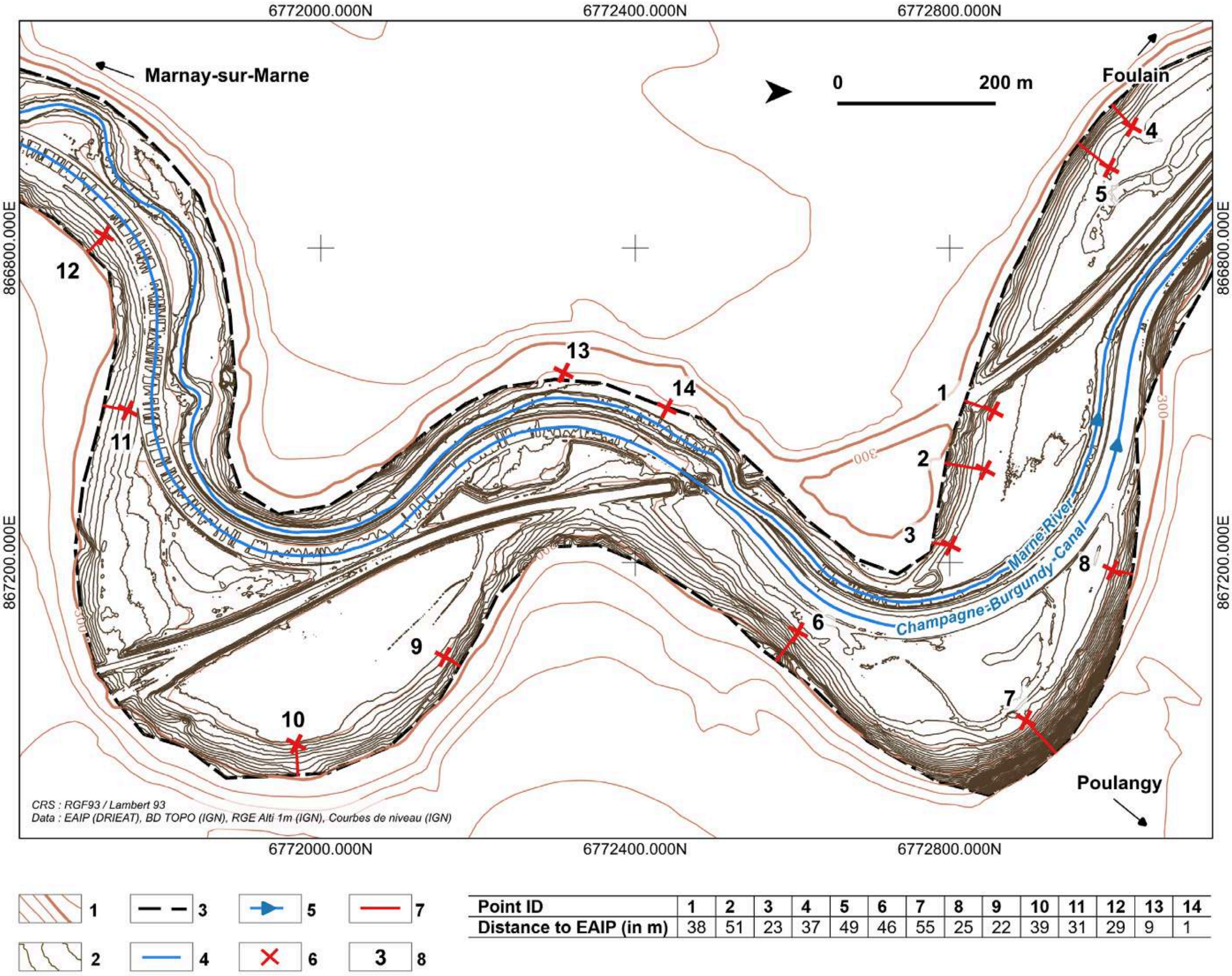
Point ID	1	2	3	4	5	6	7	8
Distance to EAIP (in m)	19	33	148	17	59	65	90	34

Fig. 4 – Difference map between the floodplain delineated by the EAIP and the floodplain observed in the field at Nod-sur-Seine, Côte d'Or department.

1. Index curves; 2. Contour lines (1 m intervals); 3. Flood-plain boundaries delineated by the EAIP data; 4. Seine River; 5. Flow direction of the river; 6. Surveyed flood plain boundaries points; 7. Distance between the surveyed points and the EAIP boundaries; 8. Surveyed point ID.

Fig. 4 – Différence entre le lit majeur délimité par l'EAIP et le lit majeur relevé sur le terrain à Nod-sur-Seine, Côte d'Or.

1. Courbes maitresses ; 2. Courbes de niveau (intervalle 1 m) ; 3. Limites du lit majeur telles que définies par l'EAIP ; 4. la Seine ; 5. Sens d'écoulement de la Seine ; 6. Limites du lit majeur relevées sur le terrain ; 7. Distance entre les limites relevées sur le terrain et l'EAIP ; 8. Identifiant du point relevé sur le terrain.



Point ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Distance to EAIP (in m)	38	51	23	37	49	46	55	25	22	39	31	29	9	1

Fig. 5 – Difference map between the floodplain delineated by the EAIP and the floodplain observed in the field at Foulain, Haute-Marne department.

1. Index curves; 2. Contour lines (1 m intervals); 3. Flood-plain boundaries delineated by the EAIP data; 4. Seine River; 5. Flow direction of the river; 6. Surveyed flood plain boundaries points; 7. Distance between the surveyed points and the EAIP boundaries; 8. Surveyed point ID.

Fig. 5 – Différence entre le lit majeur délimité par l'EAIP et le lit majeur relevé sur le terrain à Foulain, Haute-Marne.

1. Courbes maitresses ; 2. Courbes de niveau (intervalle 1 m) ; 3. Limites du lit majeur telles que définies par l'EAIP ; 4. la Seine ; 5. Sens d'écoulement de la Seine ; 6. Limites du lit majeur relevées sur le terrain ; 7. Distance entre les limites relevées sur le terrain et l'EAIP ; 8. Identifiant du point relevé sur le terrain.

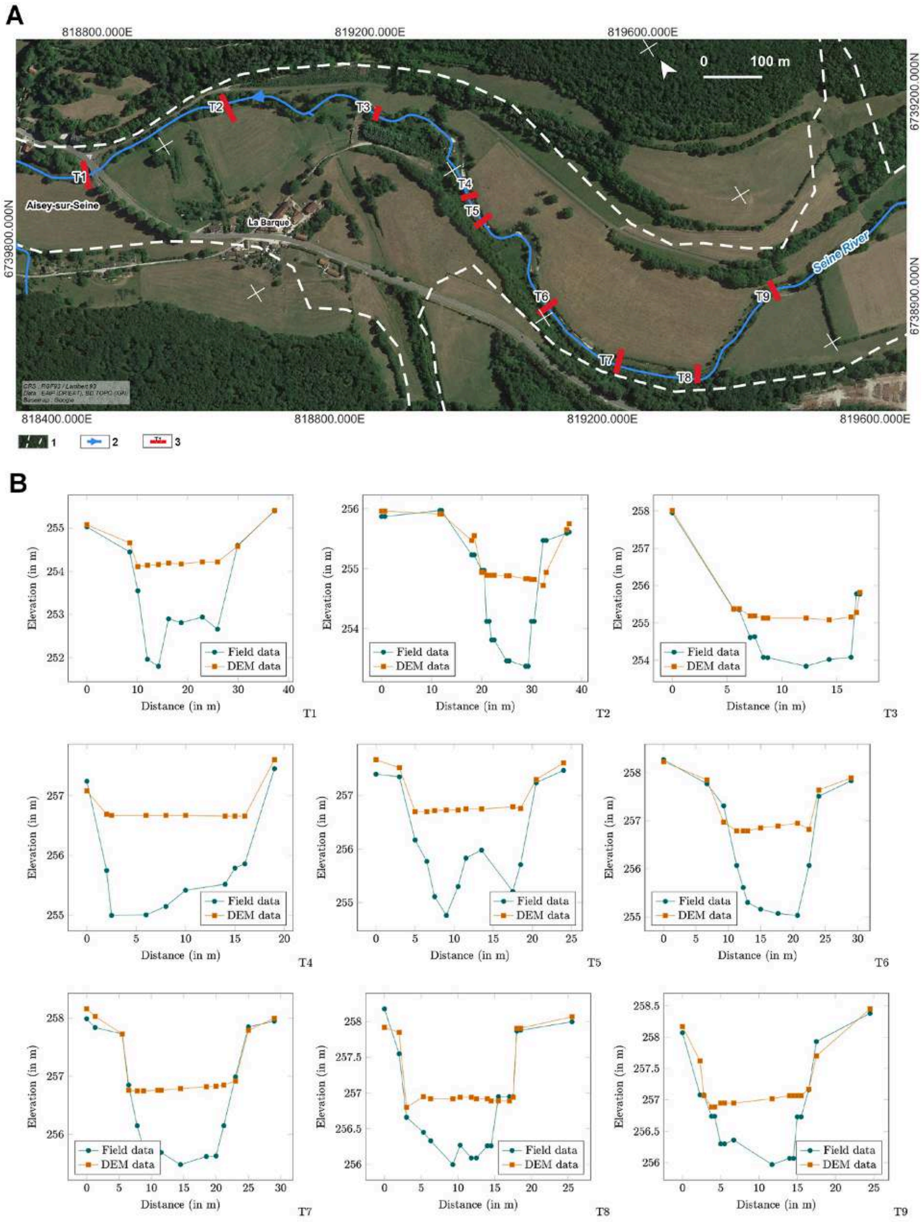
objects were recorded, although neither could be observed in profile from the DEM data or field measurements. All other mapped objects could be identified in the field. Field surveys in the Chaumont and Foulain areas reveal the Marne is heavily constrained by road and railway embankments, as well as the Haute-Marne Canal. Automated mapping successfully identified all structures present within the floodplain. Smaller features, such as merlons, are notably absent.

The methodology and accuracy of the automated calculations for river depth and width at bankfull stage were tested across nine cross-sections near Aisey-sur-Seine. Both the depth and the width of the reach tend to be underestimated by the LiDAR DEM, by 0.7 to 1.35 m for the channel depth (fig. 6B).

On average, the computed bankfull width corresponds to 94 % of the true bankfull width observed on-site (fig. 6C). The maximum observed discrepancy is a 2.54 m difference in cross-section no.4. The accuracy of the calculated bankfull width and depth was also tested for nine cross-sections in the SMBMA territory near Chaumont. These cross-sections were conducted on-site by certified surveyors as part of a recent development of hydraulic models (2021-2022) and are expected to provide the highest reliability. The comparison between the automated analysis and the field cross-sections shows similar results to those observed in the Chatillonais, with the depth of the reach being underestimated by the LiDAR DEM data. The difference exceeds 1 m for all cross-sections studied and reaches up to 3.07 m for cross-section no.4 (fig. 7B). While the computed widths were constantly underestimated in the Chatillonais, the tool also tends to overestimate the bankfull width in Haute-Marne, with computed widths ranging from 91.8 % to 122 % of the actual bankfull width (fig. 7C).

Regarding the combination of characterization criteria, the GIS tool identifies the entire segment in Aisey-sur-Seine as "partially altered" as all calculated cross-sections indicate potential bed deepening (W/D ratio < 20; fig. 8A).

This indicates that the tool classifies the area as a zone where



C

	T1	T2	T3	T4	T5	T6	T7	T8	T9
Real bankfull channel width (in m)	20.51	15.67	20.55	22.6	20.95	17.51	21.51	19.19	21.29
Computed bankfull channel width (in m)	18.58	14.927	20.05	20.06	19.46	16.04	20.54	18.4	20.16
Difference (in m)	-1.93	-0.74	-0.5	-2.54	-1.49	-1.47	-0.97	-0.79	-1.13

Fig. 6 – Comparison of profiles produced by field topography and generated from LiDAR DEM on selected cross-sections at Aisey-sur-Seine, Côte d'Or departement.

A: localisation of the selected cross-sections; B: difference between bathymetric data measured by the LiDAR DEM and field measurements at Aisey-sur-Seine; C: difference between bankfull channel width measured in the field and calculated by the GIS tool.

1. Flood-plain boundaries delineated by the EAIP data; 2. Seine River and its flow direction; 3. Transect ID.

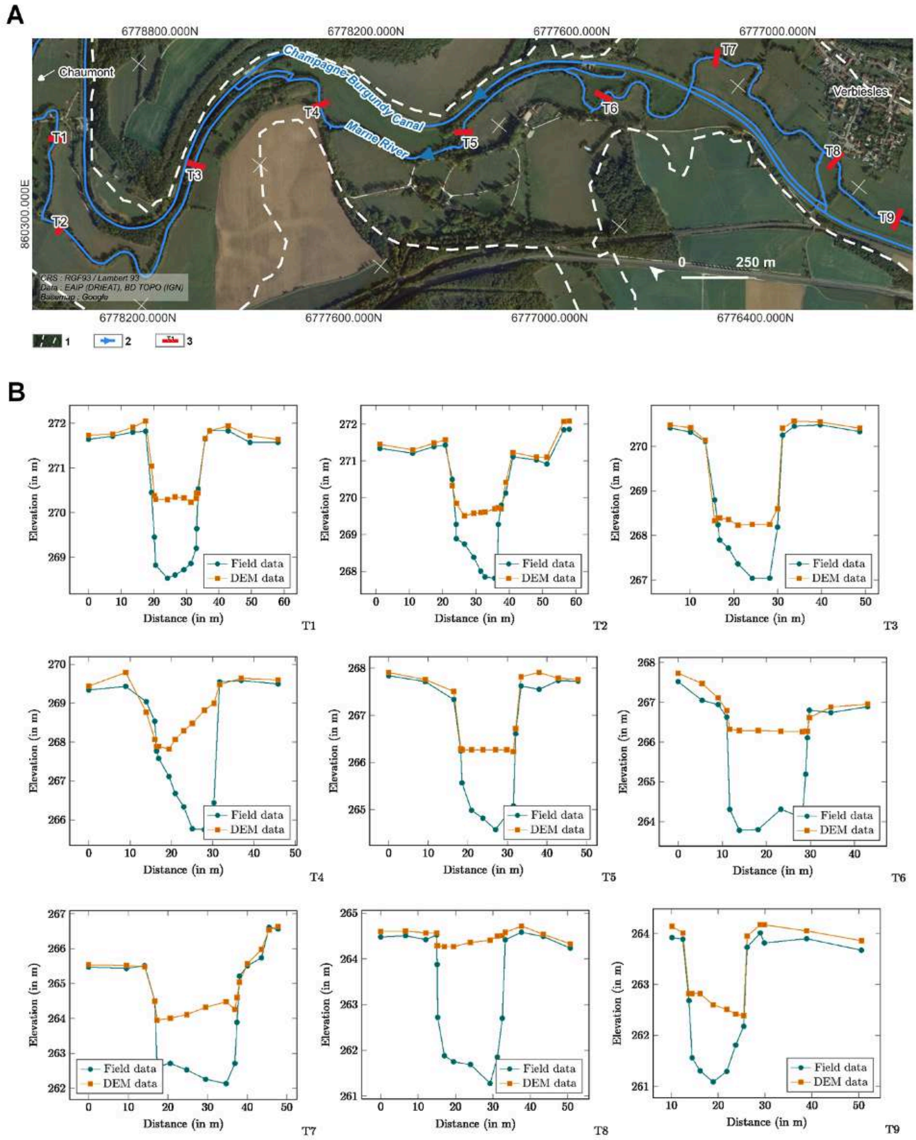
Fig. 6 – Comparaison des profils réalisés par topographie de terrain et générés à partir du MNT LiDAR sur des tronçons sélectionnés à Aisey-sur-Seine, Côte d'Or.

A : localisation des transects ; B : différence entre les données bathymétriques mesurées sur le MNT et celles mesurées par profil en travers sur le terrain à Aisey-sur-Seine ; C : différence entre la largeur du chenal à pleins bords réelle à Aisey-sur-Seine et la largeur calculée par l'outil SIG.

1. Limites du lit majeur telles que définies par l'EAIP ; 2. La Seine et son sens d'écoulement ; 3. Identifiant des transects sélectionnés.

overflows are unlikely to occur, when the 2-year return flood is taken into consideration. The hydraulic model for Aisey-sur-Seine suggests that overflows still occur during a 5-year return flood, with the floodplain being almost fully utilized during such an event (fig. 8B). Approximately one kilometer upstream from these cross-section verification areas, a significant portion of the floodplain in Brémur-et-Vaurois appears disconnected in the GIS tool (fig. 9B).

This observation arises from two generated cross-sections in the zone, which indicate potential reach deepening and the presence of a substantial footpath embankment near the river. The hydraulic model also identifies this area as a flood expansion zone that remains unutilized during floods with return periods of less than 10 years. For this type of event, as in April 2024, the water level recorded at Nod-sur-Seine is around 2.5 m, about 2 m higher than the annual minimum, whereas the hydraulic model estimates a water level of less than 50 cm in the area. Furthermore, the upstream part of the area, where cross-section 2 is located, appears less functional in the hydraulic model compared to cross-section 1 (fig. 9A), as it is not mobilized during floods with return periods of less than 20 years. Overall, despite approximations, the combined parameters provide an analysis that is consistent with data derived from hydraulic models and field observations. For instance, in Chanoy, upstream of Chaumont, the tool identifies the whole segment



C

	T1	T2	T3	T4	T5	T6	T7	T8	T9
Real bankfull channel width (in m)	20.24	20.01	18.66	21.69	20.02	24.21	29.85	25.26	17.83
Computed bankfull channel width (in m)	19.03	19.03	22.91	21.39	20.57	23.53	31.58	21.01	16.38
Difference (in m)	1.21	0.98	-4.25	0.3	-0.55	0.68	-1.73	4.25	1.45

Fig. 7 – Comparison of profiles produced by field topography and generated from LiDAR DEM on selected cross-sections at Chaumont, Haute-Marne department.

A: localisation of the selected cross-sections; B: difference between bathymetric data measured by the LiDAR DEM and field measurements at Chaumont; C: difference between bankfull width measured in the field at Chaumont and calculated by the GIS tool.

1. Flood-plain boundaries delineated by the EAIP data; 2. Marne River and its flow direction; 3. Transect ID.

Fig. 7 – Comparaison des profils réalisés par topographie de terrain et générés à partir du MNT LiDAR sur des tronçons sélectionnés à Chaumont, Haute-Marne.

A : localisation des transects ; B : différence entre les données bathymétriques mesurées sur le MNT et celles mesurées par profil en travers sur le terrain à Chaumont ; C : différence entre la largeur à plein bords réelle à Chaumont et la largeur calculée par l'outil SIG.

1. Limites du lit majeur telles que définies par l'EAIP ; 2. La Marne et son sens d'écoulement ; 3. Identifiant des transects sélectionnés.

as 'Heavily altered' as the two calculated cross-sections show the Marne River was deepened (W/D ratio < 10), straightened and is constrained by high-impact embankments (fig. 10B).

From these parameters, the tool states overflows are extremely unlikely or impossible. This statement is verified by both field survey and hydraulic model. On the field, the Marne River exhibits significant constraints due to extensive human modifications. Its functionality is heavily influenced by the presence of the Haute-Marne Canal and an adjacent railway embankment, which limit its lateral connectivity to its surrounding floodplain. In Chanoy, the hydraulic modeling identifies this section as a priority restauration area as it is unaffected by the three reference floods considered (1982, 2013, 2018), while the water levels at the nearest station in Marnay-sur-Marne reached more than 3 meters during the 2018 event. Field observations also confirm the river was substantially deepened and straightened over time, further restricting its natural dynamics (fig. 10A). These alterations have rendered overflows impossible in this section, as corroborated by the local authority, SMBMA.

5. Discussion

5.1. The tool

The tool demonstrates overall promising outcomes, with comparisons to hydraulic modeling and field surveys yielding satisfactory results. Preliminary findings were presented to the field staff of both EPAGE Sequana and SMBMA, who confirmed the results based on their field experience. As anticipated, the EAIP data used to delineate the

A

	Width (*W*) in m	Depth (*D*) in m	W/D ratio	Sinuosity	Embankment	Characterization
Cross-section ❶	18.13	1.16	15.63	1.432	No	Partially altered
Cross-section ❷	17.1	0.97	17.63	1.432	No	Partially altered
Cross-section ❸	15.58	1.26	12.37	1.432	No	Partially altered
Cross-section ❹	15.83	1.34	11.43	1.432	No	Partially altered

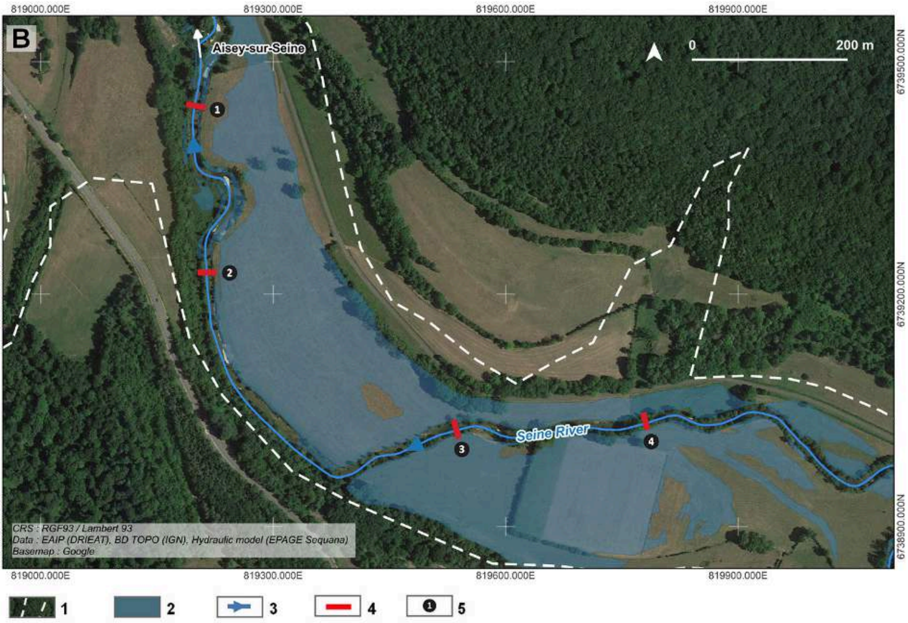


Fig. 8 – Flood expansion area identified as partially altered by the tool, compared to the hydraulic model of the EPAGE Sequana at Aisey-sur-Seine, Côte d'Or departement.

A: comparison of bathymetric and geometric characteristics across four cross-sections at Aisey-sur-Seine, Côte d'Or department. These cross-sections were automatically generated by the tool and serve as a reference for assessing the functionality of the area; B: study-area mapping.

1. Floodplain boundaries; 2. Flooded area for a 5-year return flood; 3. Channel and flow direction; 4. Reference cross-sections computed by the tool; 5. Cross-section ID.

Fig. 8 – Zone d'expansion des crues identifiée comme partiellement altérée par l'outil, comparée à la modélisation hydraulique de l'EPAGE Sequana, Aisey-sur-Seine, Côte d'Or.

A : comparaison des caractéristiques bathymétriques et géométriques sur 4 profils transversaux à Aisey-sur-Seine, Côte d'Or. Ces profils ont été générés automatiquement par l'outil et servent de référence pour évaluer la fonctionnalité de la zone ; B : cartographie de la zone d'étude.

1. Limites du lit majeur ; 2. Zone inondées pour une crue de retour 5 ans ; 3. Tronçon et sens d'écoulement du cours d'eau ; 4. Profils obtenus par l'outil ; 5. Identifiant du profil.

floodplain exhibits significant accuracy issues. To address these and make the EAIP suitable for detailed analysis, the boundaries are currently being refined through a more in-depth analysis of slope changes using the DEM. The new, refined EAIP is expected to be available by the first quarter of 2025 and will lead to an update of the tool. This update will also incorporate the concept of riverbed widening, derived from the calculation of a theoretical width, allowing for an even more accurate and comprehensive characterization of the studied river reaches.

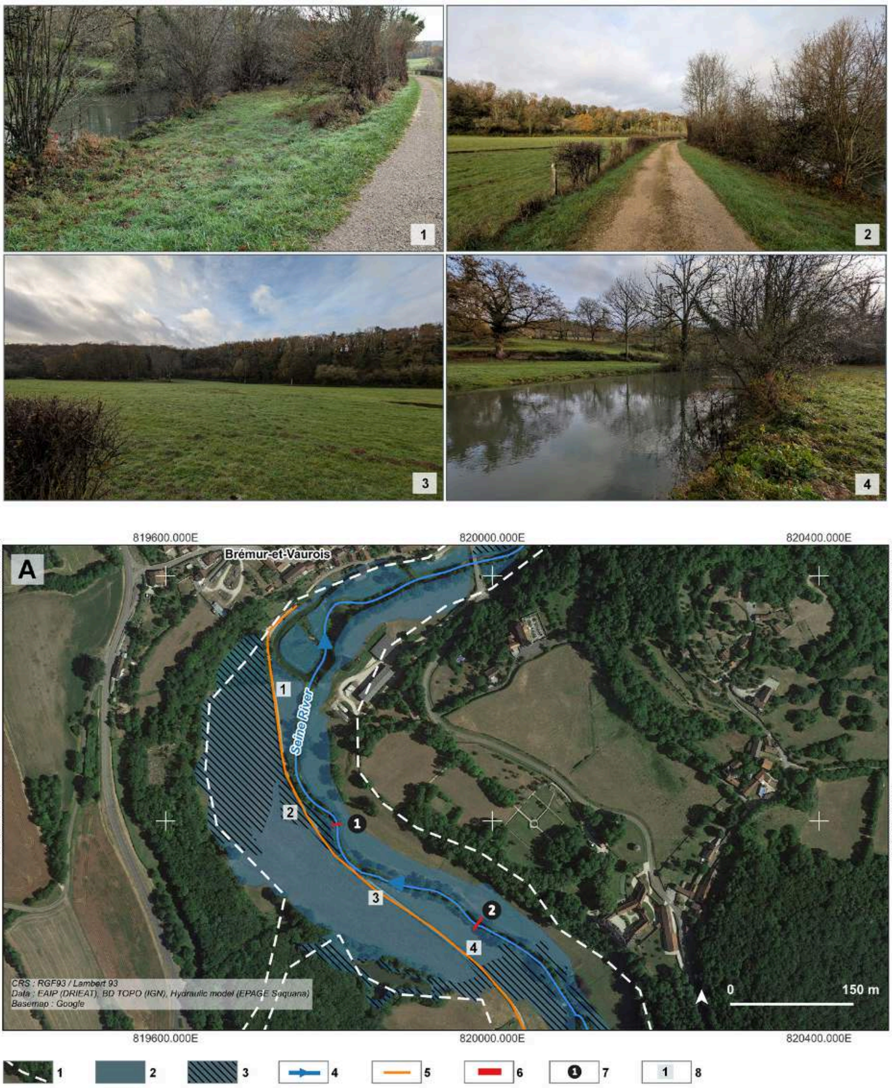
Regarding the automated mapping of levees, embankments and merlons, the tool tends to map non-existing objects yet did not fail to detect the existing ones. This can be attributed to an exaggeration of the low-pass filter. Further testing was conducted to refine the low-pass filter and eliminate artifacts; however, this could not be achieved without also removing existing objects, which was considered more critical. It should be noted that the current embankment detection does not account for the presence of internal erosion or culverts, and hence a potential hydraulic transparency of the embankment. This aspect is currently being tested for future integration. Overall, the tool's satisfying performance in detecting real features, alongside its ability to process large areas efficiently, makes it a valuable resource for floodplain management.

The characterization of river reaches could be enhanced by incorporating more nuanced criteria for deepening. The example of Brémur-et-Vaurois in the Châtillonnais illustrates that the current GIS tool does not distinguish between a flood expansion area that remains un-mobilized during a 10-year return flood and one that is un-mobilized during a 20-year return flood, as both are categorized as "altered". Introducing additional classes for the width-to-depth ratio may address this issue. Furthermore, accurately computing river depth from the DEM remains a challenge. Since the LiDAR DEM was not designed for bathymetric measurements, the actual stream depth derived from it is uncertain. The observed differences between the DEM data and the field measurements in terms of depth are not only influenced by the acquisition method, but also by the acquisition date and morphological changes that have occurred between these periods. As a result, the older DEM may not accurately reflect the current terrain and further reinforce discrepancies. In estimating river deepening, an unfavorable width-to-depth ratio indicates likely deepening. Conversely, reaches appearing natural might, in reality, be over-deepened but are not identified as such from the DEM. Due to the lack of bathymetric data across the entire EPTB Seine Grands Lacs territory and the high costs associated with producing such data, the depth calculated from the DEM, despite its uncertainties, remains the best approximation available.

Despite challenges, the tool demonstrates promises in river reach characterization and flood expansion area identification, with ongoing refinements expected to enhance its accuracy and validity in the upcoming updates.

5.2. The flood expansion areas in the Upper Seine River Basin

The study confirms that GIS-based LiDAR DEM analysis can contribute to understanding the hydrological dynamics of the Upper Seine River Basin and identify flood expansion areas.



B

	Width (*W*) in m	Depth (*D*) in m	W/D ratio	Sinuosity	Embankment	Characterization
Cross-section ❶	12.4	0.77	16.10	1.101	Yes – High impact	Altered
Cross-section ❷	15.24	1.38	11.04	1.101	Yes – Low impact	Altered

Fig. 9 – Flood expansion area identified as altered by the tool, compared to the hydraulic model of the EPAGE Sequana at Brémur et Vaurois, Côte d'Or department.

A: study-area mapping. The field photographs in Brémur show the footpath embankment, the unutilized expansion area and the width of the Seine River; B: comparison of bathymetric and geometric characteristics across two cross-sections at Brémur, Côte d'Or. These cross-sections were automatically generated by the tool and serve as a reference for assessing the functionality of the area.

1. Floodplain boundaries; 2. Flooded area for a 10-year return flood; 3. Flooded area for a 20-year return flood; 4. Channel and flow direction; 5. Footpath embankment; 6. Reference cross-sections computed by the tool; 7. Cross-section ID; 8. Photography location.

Fig. 9 – Zone d'expansion des crues identifiée comme altérée par l'outil, comparée à la modélisation hydraulique de l'EPAGE Sequana, Brémur et Vaurois, Côte d'Or.

A : cartographie de la zone d'étude. Les photographies prisent sur le terrain à Brémur montrent l'importance du chemin en remblais, la zone d'expansion des crues qui n'est plus mobilisée et la largeur de la Seine ; B : comparaison des caractéristiques bathymétriques et géométriques sur deux profils transversaux à Brémur, Côte d'Or. Ces profils ont été générés automatiquement par l'outil et servent de référence pour évaluer la fonctionnalité de la zone.

1. Limites du lit majeur ; 2. Zones inondées pour une crue de retour 10 ans ; 3. Zones inondées pour une crue de retour 20 ans. 4. Tronçon et sens d'écoulement du cours d'eau ; 5. Chemin en remblais ; 6. Profils obtenus par l'outil ; 7. Identifiant du profil ; 8. Localisation de la photographie.

Although local land managers are already aware that the basin has been heavily modified, the tool helps reveal the full extent of these alterations. It offers a reliable representation of the interactions between rivers and their floodplains, enabling the identification of flood expansion areas. By automatically analyzing parameters related to river channelization using open-source data, the GIS tool identifies areas where water can still naturally spread during a flood, as well as zones where overflows are no longer possible. Mapping potential restoration areas is not a new concept in GIS. Many studies have used GIS tools to identify restoration sites by analyzing statistical, historical, hydrological geomorphological, and remote sensing data (Thoms et al., 2018; Theiling et al., 2013; Xia et al., 2014). However, what sets this study apart from the previously cited work is its integration of a large-scale, automated floodplain analysis based on few data sources, using almost exclusively DEM data to assess a river reach's connectivity to its floodplain. Furthermore, the resulting maps can be interpreted at a detailed level.

While GIS was never intended to replace fieldwork, the maps produced can play an important role. By providing an initial database, they allow for the precise targeting of areas requiring more detailed investigations, thus optimizing resources and efforts. Additionally, the automated and standardized methodology ensures reproducibility and consistency, which can prove to be especially relevant for comparative studies and applications in other hydrologically or geomorphologically similar regions. The question of a coherent approach arises, for example, in the case of the Lower Seine basin, as a GIS-based initiative to identify priority restoration areas of wet meadows and flood expansion areas is already underway (Muntoni et al., 2023). The approach of the GIP Seine-Aval, responsible for the project, focuses more on identifying feasibility levers for potential projects. This raises the issue of integrating the various initiatives already started to achieve a comprehensive and coherent vision across the entire Seine axis.

The results obtained in this study can have direct implications for

B

	Width (*W*) in m	Depth (*D*) in m	W/D ratio	Sinuosity	Embankment	Characterization
Cross-section ❶	21.17	2.75	7.7	1.04	Yes – High impact	Heavily altered
Cross-section ❷	21.48	2.72	7.9	1.04	Yes – High impact	Heavily altered

Fig. 10 – Flood expansion area identified as heavily altered by the tool, compared to the hydraulic model of the SMBMA at Chanoy, Haute-Marne.

A: study-area mapping. The field photographs in Chanoy show the the Haute-Marne Canal and footpath embankments constraining the Marne River, the unutilized expansion area, and a straightened and deepened reach of the Marne River; B: comparison of bathymetric and geometric characteristics across two cross-sections at Chanoy, Haute-Marne department. These cross-sections were automatically generated by the tool and serve as a reference for assessing the functionality of the area.

1. Floodplain boundaries; 2. Non-flooded area for a 50-year return flood; 3. Non-flooded area for a 100-year return flood, identified as a priority restoration area by the hydraulic model; 4. Channel and flow direction; 5. Canal, railway and footpath embankment; 6. Reference cross-sections computed by the tool; 7. Cross-section ID; 8. Photography location.

Fig. 10 – Zone d'expansion des crues identifiée comme très altérée par l'outil, comparée à la modélisation hydraulique du SMBMA à Chanoy, Haute-Marne.

A : cartographie de la zone d'étude. Les photographies prisent sur le terrain à Chanoy montrent à quel point les remblais et particulièrement le Canal de la Haute-Marne contraignent latéralement la Marne. Ce tronçon de la Marne est particulièrement rectiligne et enfoncé. Toute une portion du lit majeur n'est plus mobilisable ; B : comparaison des caractéristiques bathymétriques et géométriques sur 2 profils transversaux à Chanoy, Haute-Marne. Ces profils ont été produits automatiquement par l'outil et servent de référence pour évaluer la fonctionnalité de la zone.

1. Limites du lit majeur ; 2. Zones non inondées pour des crues de retour 50 ans ; 3. Zones non-inondées pour une crue de retour 100 ans, identifiée comme zone de restauration prioritaire dans la modélisation hydraulique. 4. Tronçon et sens d'écoulement du cours d'eau ; 5. Chemin en remblais ; 6. Profils obtenus par l'outil ; 7. Identifiant du profil ; 8. Localisation de la photographie.

territorial management. Flood expansion areas act as natural buffers, reducing peak flows during flood events and limiting their impacts. Their integration is beneficial not only for major downstream cities like Paris but also for local communities. At the local level, the information produced allows land managers to integrate these key areas into their planning and avoid inappropriate developments based on a thorough understanding of natural dynamics.

While the results seem conclusive, the test was conducted on two geomorphologically similar territories. The local conditions may have influenced the automated analysis and the overall methodology will benefit from being tested and compared in areas further downstream.

6. Conclusions

The study demonstrates the valuable role of GIS in advancing flood management strategies in the Upper Seine River Basin, particularly in identifying flood expansion areas. By integrating open-source data, the tool provides a reliable pre-field analysis that helps identify where flood can still naturally spread, and areas necessitating restoration. The river's connectivity to its floodplain is inferred from the automated extraction of parameters from a LiDAR DEM: the reach's sinuosity, its width and depth, and the possible presence of embankments. The tool shows promising results, with comparisons to hydraulic modeling and field surveys producing satisfactory outcomes. While challenges related to the input data accuracy remain, ongoing refinements are expected to enhance the tool's capabilities and reliability. The ability to conduct large scale automated analyses offers a promising approach to addressing flood risk. In this context, GIS can serve as a bridge between hydrogeomorphological research and operational management. Its ability to deliver accurate spatial information makes it possible for more effective, resilient, and sustainable flood risk management practices at both local and basin-wide scales.

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Version française abrégée

Dans les décennies à venir, l'Europe sera confrontée à un risque inondation accru, résultant des effets combinés des changements climatiques et des activités humaines. Pour répondre à ces enjeux, l'Union européenne a adopté deux directives clés : la Directive-cadre sur l'eau (DCE) et la Directive inondation (DI), transposées en France à travers la loi sur l'eau et les milieux aquatiques de 2006 et la Loi d'Engagement National sur l'Environnement (LENE). Ces lois mettent l'accent sur la restauration des fonctions naturelles des plaines d'inondation, indispensables pour atténuer les crues. Sur le bassin amont de la Seine, l'EPTB Seine Grands Lacs a été chargé d'identifier les zones d'expansion des crues conformément aux objectifs définis par le Plan de Gestion des risques d'inondations (PGRI). Face aux limites liées au travail de terrain et à la taille du territoire à analyser, il est devenu nécessaire de concevoir une méthode automatisée basée sur les outils SIG et exploitant les bases de données numériques disponibles. Cette étude examine dans quelle mesure les données issues des MNT générés par le LiDAR sous SIG peuvent caractériser précisément les zones d'expansion des crues et propose une méthodologie adaptable à d'autres bassins hydrographiques similaires. Au sein du bassin amont de la Seine, deux territoires d'étude, gérés par des établissements publics, ont été identifiés : l'EPAGE Sequana, aux sources de la Seine dans le Châtillonais, et le Syndicat Mixte du Bassin de la Marne et de ses Affluents (SMBMA), qui couvre le bassin supérieur de la Marne. Ces zones ont été sélectionnées en raison de la disponibilité de modèles hydrauliques existants, capables d'identifier les zones d'expansion des crues telles que définies dans le PGRI, ainsi que de données de terrain fiables. Des relevés topographiques ont été effectués dans le Châtillonnais entre octobre 2023 et mai 2024, et en Haute-Marne en avril et octobre 2024. La méthodologie permet d'identifier et d'analyser automatiquement les zones d'expansion des crues en exploitant les avancées des outils SIG et l'amélioration de la qualité des MNT, en extrayant automatiquement des paramètres hydromorphologiques à partir des données LiDAR et vectorielles disponibles. En effet, au sein du lit majeur, il est essentiel de distinguer les zones d'expansion des crues fonctionnelles, qui sont mobilisées lors des plus petites crues, de celles qui sont déconnectées. Les formes naturelles des rivières, influencées par des variables de contrôle géologiques, climatiques etc. sont normalement façonnées par des crues morphogènes, comme celle de période de retour de 2 ans. Dans le bassin de la Seine, on s'attend à des cours d'eau sinueux, peu profonds et à chenal unique. Une déviation observée de ces formes peut indiquer des interventions humaines, telles que le recalibrage, l'élargissement, la rectification ou l'endiguement, ce qui perturbe la connectivité latérale entre lit majeur et rivière. Les autorités françaises ont produit des données LiDAR RGE Alti® 1 m à haute résolution pour cartographier les zones inondables, permettant une analyse détaillée des plaines alluviales. Cette étude utilise ces données pour estimer les changements dans la géométrie des chenaux, notamment en mesurant le rapport largeur/profondeur pour évaluer l'éventuelle altération des rivières et la connectivité avec le lit majeur. Les données LiDAR permettent également de cartographier automatiquement les digues, remblais et merlons de curage à partir d'anomalies topographiques. L'étude s'appuie aussi sur la base de données hydrologique BD TOPAGE® pour analyser la sinuosité des tronçons de rivières étudiés. En combinant ces paramètres, la méthode permet ainsi de distinguer les zones d'expansion des crues fonctionnelles, à préserver, des zones nécessitant des restaurations pour être mobilisées. Sur les zones d'étude choisies, les résultats se montrent satisfaisants, cohérents avec la réalité de terrain. La méthodologie automatisée de cartographie des remblais et merlons a détecté tous les objets souhaités, sur les deux zones d'études, bien qu'il ait légèrement surestimé la présence de merlons dans certaines zones. Ces artefacts n'ont pu être supprimés dans la méthodologie sans altérer la détection des éléments existants. Le calcul de la profondeur et de la largeur à plein bords du chenal, montre globalement une sous-estimation des profondeurs (de 0,7 m à plus de 3 m), ainsi que des largeurs à plein bords. Les largeurs à plein bords calculées correspondent à 92 % à 122 % des largeurs réelles observées. En revanche, la combinaison de ces paramètres, qui permet de mettre en avant si les débordements sont toujours possibles ou non, est cohérente avec les données issues de modélisation hydrauliques, des observations de terrain et des retours d'expériences des syndicats de rivière partenaires. Ainsi les secteurs repérés par le SIG comme altérés et leur degré d'altération semblent correspondre à une réalité de terrain. Des problèmes et imprécisions subsistent, notamment liées à la nature des données d'entrée, le MNT RGE Alti® 1m n'étant pas conçu pour récupérer des données bathymétriques. Des améliorations et ajouts, sur la notion d'élargissement du cours d'eau par exemple, sont déjà en cours et devraient renforcer les capacités et la fiabilité de l'outil. Dans ce contexte, la cartographie SIG sert de passerelle entre une analyse hydro-géomorphologique et une gestion opérationnelle. La possibilité de réaliser une analyse automatisée à grande échelle représente une approche prometteuse pour mieux considérer le risque inondation dans les pratiques d'aménagement et de gestion du risque.