Fine-scale bathymetry assessment from LiDAR data: a practical tool for regional-scale hydraulic modelling

Évaluation de la bathymétrie à fine échelle à partir de données LiDAR : un outil pratique pour la modélisation hydraulique à l'échelle régionale

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RÉSUMÉ
L'acquisition de données bathymétriques pour les cours d'eau est une opération coûteuse, nécessitant des campagnes de relevés terrain intensives. Il s'agit cependant d'un élément essentiel pour la modélisation hydraulique. Une méthode novatrice permettant d'estimer la bathymétrie à partir de la surface de l'eau détectée sur des données LiDAR conventionnelles a été développée pour faciliter la modélisation hydraulique des cours d'eau à l'échelle des bassins versants. Utilisée en combinaison avec une estimation de la largeur des cours d'eau et des débits au moment de l'acquisition des données LiDAR, la surface de l'eau sur les données LiDAR permet de déduire l'élévation du lit en supposant une section bathymétrique rectangulaire, grâce à une modélisation hydraulique inverse. En intégrant cette solution dans une suite d'outils informatiques, il devient ainsi possible de cartographier les zones inondables à faible coût sur un vaste territoire avec une précision sans précédent. Cette approche permet de plus de réviser à moindre coût les cartes de zones inondables dans les rivières dynamiques, en plus d'ouvrir la voie à une caractérisation de l'habitat des cours d'eau sur de vastes territoires sur la base de profondeurs et de vitesses.

ABSTRACT
Acquiring bathymetric data for rivers is a costly operation, requiring intensive field surveys. However, it is essential for hydraulic modelling. An innovative method for estimating bathymetry from the water surface detected on conventional LiDAR data has been developed to facilitate hydraulic modelling of rivers at the watershed scale. Used in combination with an estimate of stream widths and discharge at the time of LiDAR data acquisition, the water surface on LiDAR data can be used to deduce bed elevation assuming a rectangular bathymetric cross-section, using inverse hydraulic modelling. By integrating this solution into a suite of IT tools, it becomes possible to map flood-prone areas at low cost over a vast territory with unprecedented accuracy. This approach also makes it possible to revise flood zone maps for dynamic rivers at lower cost, and opens up the possibility of characterising river habitats over large territories on the basis of depths and velocities.

KEYWORDS

Bassins-versants, bathymétrie, LiDAR, SIG (Systèmes d'Information Géographique), zones inondables

Bathymetry, flood zones, GIS (Geographical Information Systems), LiDAR, watershed

1 INTRODUCTION

Floods rank among the world's most frequent, hazardous, and damaging natural disasters (Bates, 2022). Traditional flood models, designed at the reach scale with cross-sectional river measurements, are in most cases not available at a national scale. Producing flood maps at this scale require shifting from reach-based models to automated global or regional models. Collecting bathymetric data over extensive areas is impractical in countries like Canada, where vast landscapes and river networks challenge effective flood management (Arnal et al., 2023). In response, low-complexity models often use simplified hydraulic geometry (Leopold and Maddock, 1953) to approximate complex river bathymetry at watershed scales (Follum et al., 2023; Garrote et al., 2021). While refined bathymetry estimation has been achieved at large scales (Neal et al., 2021), it typically relies on coarser resolutions (100 m to 2 km) or is limited to wide rivers in the case of SWOT (Surface Water and Ocean Topography) satellite data (Follum et al., 2023). Given the increasing availability of LiDAR surveys across large territories, a LiDAR-based methodology was developed to estimate bathymetry and to apply it in a GIS-automated 1D/2D hydraulic model (LISFLOOD-FP, Bates and De Roo, 2000) for efficient flood zone simulations across multiple watersheds.

2 BATHYMETRY ASSESSMENT PROCESS

2.1 Methodology

Bathymetry, absent from LiDAR data which do not penetrate water surface, is calculated using LiDAR water surface elevation, LiDAR channel width, and discharge at the time of LiDAR acquisition, and is estimated at cross-sections every 5 m along the river network. To the best of our knowledge, such a high spatial resolution exceeds that of all previous bathymetry assessment methods. Using automated Geographical Information System (GIS) tools, LiDAR water surface elevations are processed to address potential interpolation errors and noise, and are hydraulically corrected using quantile carving (Schwanghart and Scherler, 2017). Discharge data, derived from hydrological models or gauging stations, are spatially interpolated along the river network. Channel width is extracted from manually digitized wetted-area polygons visible in the LiDAR data.
An inverse 1D hydraulic solver, applying Manning's and Bernoulli's equations, computes bed elevations based on a rectangular channel bathymetry at each cross-section, eliminating the need for iterative adjustments (e.g., Choné et al., 2021; Neal et al., 2021). An innovative technique detects automatically abrupt changes in flow conditions, reducing the 5-m sampling interval when necessary.

2.2 Error assessment and sensitivity analysis

An uncertainty and sensitivity analysis (UA/SA), using the Sobol' (1991) method, was conducted for bathymetry estimation over a 767-km river network in the Saint-François watershed in Quebec, Canada. This analysis evaluated the uncertainty from four main input variables: Manning's n, water surface elevation, width, and LiDAR discharge. Additionally, bathymetry was validated by comparison with field-measured bathymetry at 1,163 cross-sections across various Quebec rivers, yielding a RMSE of 0.73 m. This global RMSE, however, conceals significant spatial variations, as revealed by UA/SA (Figure 1), with a high skewness in the uncertainty distribution.

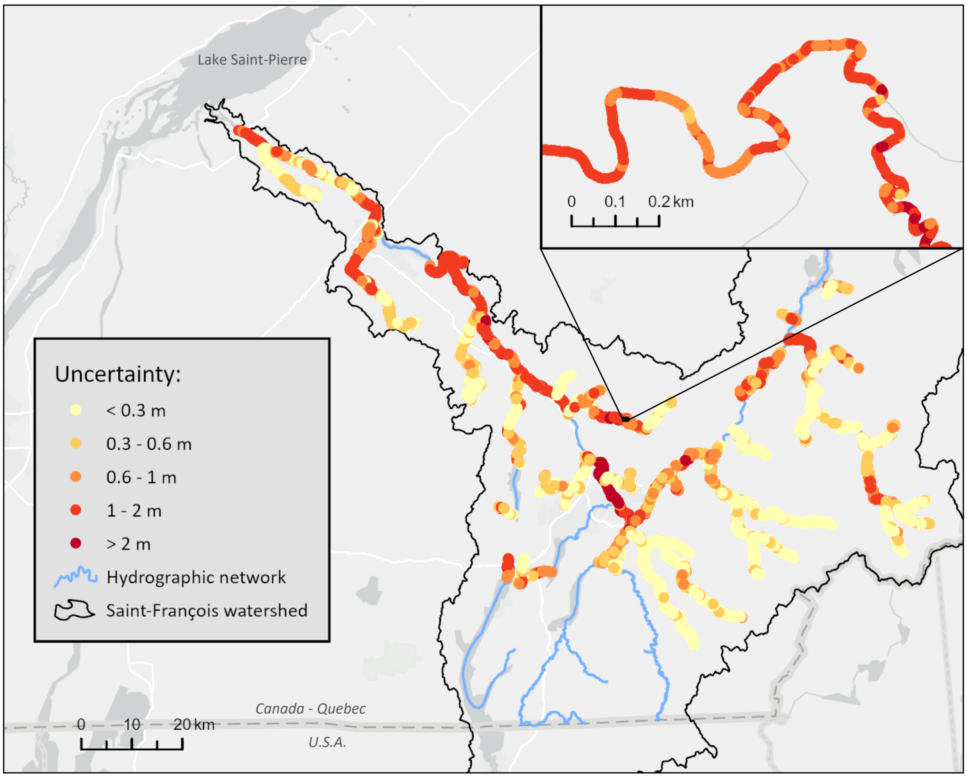

Figure 1: Bathymetry uncertainty over a 767 km river network in the Saint-François watershed (Quebec, Canada)

3 HYDRAULIC MODELLING WITH BATHYMETRY ASSESSMENT

3.1 Regional-scale hydraulic modelling

The estimated bathymetry can be used for a variety of purposes, including incorporation into hydraulic models. For regional-scale hydraulic modelling, a framework was developed using the LISFLOOD-FP hydrodynamic 1D/2D flood inundation model (Bates and De Roo, 2000; Bates et al., 2010; Choné et al., 2021; Choné et al., 2024; Neal et al., 2018). Operated in a steady-state flow mode, the model uses a constant channel Manning's n of 0.03, with variable floodplain Manning's n values based on land-use data. Data extraction and model setup are semi-automated within ArcGIS, enabling rapid hydraulic modelling over large territories (approximately 1 hour/km). A tiling system divides the river basin into multiple zones, allowing simulations to run individually within each zone, enhancing computational efficiency (Choné et al., 2021).

3.2 Applications

Hydraulic modelling with LISFLOOD-FP and the bathymetry estimates can simulate flood levels at watershed scales for various recurrence intervals, supporting the development of flood maps. This approach has been applied to more than 20 watersheds in Canada, mainly in Quebec, covering some 10,000 km of rivers. These models will aid Quebec's Government in producing regulatory flood maps for 20, 100, and 350-year recurrence intervals and in supporting a flood forecasting web portal for public access to predicted flooded areas. Validation of the regional-scale LISFLOOD hydraulic models with estimated bathymetry, by comparing simulated flood levels with water levels recorded in the field during historical high-flow events, showed a mean error of about 0.30 m. In Quebec, these models supplement conventional, reach-based hydraulic models used in areas considered at high risk, which rely on surveyed bathymetry and calibrated Manning's n. Future applications of this regional-scale modelling approach based on LiDAR estimated bathymetry may include in-stream habitat assessment based on simulated water depths and velocities. This approach can also account for morphological changes in river systems via repeated LiDAR surveys, a marked advantage over static bathymetric mapping for areas characterized by dynamic rivers. In addition, this method has been successfully applied to the River Severn (U.K.) using water surface elevation from from multiple SWOT swaths instead of LiDAR, and has highlighted some advantages over other available SWOT-based bathymetry assessment methods.

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