The influence of underwater dunes in spatiotemporal analysis of the hydrodynamic of the Saint-Lawrence River

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ABSTRACT: The Estuary of the Saint-Lawrence River is a high-energy fluvial sedimentary environment with the second largest annual discharge in North America (Hudon & Carignan, 2008). With the high dynamism in the Estuary, significant changes can be observed in the seafloor surface near Quebec City on a daily time scale. The hydrodynamics and the seafloor morphology of this complex section of the Saint-Lawrence is paradoxically poorly documented. In this paper, we present the results of a bathymetric survey in the vicinity of Quebec City, highlighting the sedimentary structures present there and their mobility.

1 INTRODUCTION

The data acquired from MultiBeam EchoSounder (MBES) surveys can be used for multiple applications. These datasets with high-resolution and accuracy are involved in the study of the seafloor morphology, the inspection of underwater structures and the safe navigation in navigation channels. In this context, the study of the dynamics related to underwater sedimentary structures such as underwater dunes has an important role. Such study can be an intricate task, starting with the extraction of these structures from Digital Bathymetric Models (DBM). Indeed, dunes are fuzzy objects, as many landforms. Therefore, their identification performed by human operators can be subjective, since the perception of the dunes varies from user to user depending on their background and experience.

Different approaches have been proposed in the literature to automatically segment and characterize dunes from the seafloor surface. Debese et al. (2016) and Ogor (2018) have proposed the identification of these structures from TIN (Triangulated Irregular Network). The first considered geodesic morphometry to extract the salient features of the dunes (i.e. crest line and troughs). The latter considered differential geometry to identify the crest lines of the dunes, which are used as seed regions to extract the whole structure. Di Stefano & Mayer (2018) and Cassol et al. (2021; 2022) have proposed approaches to segment dunes from a regular gridded DBM. Both performed a morphometric analysis of the DBM with the geomorphons algorithm (Jasiewicz & Stepinski, 2012). While the first work extracts the dunes through an aggregation of the DBM cells according to their geomorphon class, the latter considered an OBIA (Object-Based Image Analysis) approach, which shall be further discussed in this paper.

A spatiotemporal analysis of the dynamics associated to the dunes can be conducted once they have been extracted from multi temporal DBMs (i.e. DBM at different dates). Thibaud et al. (2013) have proposed a spatiotemporal analysis of dune migration through graph-based model. This approach considered two consecutive periods, as suggested by Del Mondo et al. (2010), with time being a discrete criterion associated to each survey. Duffy & Hughes Clarke (2005) considered a cross correlation method to study the process of dunes migration in marine context. Similar to the previous approach, they considered two consecutive datasets of the study area to observe the directional vector of dunes migration. Although there is some work in the literature on the spatiotemporal analysis of sedimentary structures, there is still a lack of knowledge on the features to extract and track to characterize the migration, especially in highly dynamic environments. Moreover, to our knowledge, there is no end-to-end automated approach to remove the operator from the process in order to provide greater objectivity and efficiency of analysis. This paper attempts to fill some of these knowledge gaps.

Based on a temporal bathymetric database, this paper proposes an analysis of the mobility of the dunes in the estuary of the Saint-Lawrence River. Such an analysis is crucial when proposing a new hydrodynamic model specific for the Saint-Lawrence River Estuary. Indeed, the mobility of these sedimentary structures on the seafloor is intimately related to the hydrodynamics and environmental factors as well as the characteristics of the dunes, as suggested by Kenyon (1970) and Le Bot (2001).

This paper is organized in three sections. The first section presents the methodology of extraction and spatiotemporal analysis of dunes from a DBM. The second section presents the results and discussion of the segmentation, characterization and spatiotemporal analysis of the dunes. The last section proposes some conclusion with prospects for future research related to the spatiotemporal evolution of dunes and hydrodynamic model.

2 SPATIOTEMPORAL ANALYSIS OF THE DUNES

This section described our proposed methodology to monitor the spatiotemporal mobility of underwater dunes. The first step addresses the determination of the relevant time scale for the acquisition of bathymetric data. This scale needs to be adjusted according to the environmental context and previous knowledge of the dynamism of the study area. Indeed, in marine environments the acquisition can be done with an interval of months or even years (Le Bot, 2001, Garlan, 2007), while in estuarine environments the acquisition of bathymetric data may be done daily, as further discussed in this paper.

Once the bathymetric data have been acquired and processed, a DBM is created from which the dunes are segmented using Cassol et al. (2021, 2022) method. Unlike existing methods in the literature, this approach does not involve any manual intervention to delineate landforms, which limits subjectivity, cumbersomeness and sources of error in the analysis of the surface as well as in the delimitation of the seafloor objects. The key principle relies on the formalization of the underwater dune object through a conceptual model that considers the underwater dunes can be identified on the seafloor by three salient features, namely, the crest line, the stoss trough and the lee trough. The crest line is the linear feature located in the higher zone of the dune. This feature is the upper bound of both sloping sides of the dune (i.e. stoss and lee sides). The stoss and lee troughs represent the boundary of the dune objects, being also represented by linear features. These troughs bound the stoss and lee sides, respectively.

Considering the formalized dune model, a morphometric analysis can be carried out on the DBM using the Geomorphon algorithm (Jasiewicz & Stepinski, 2012). This analysis aims to identify the three salient features previously mentioned. Then, the crest line of each dune on the DBM is matched with its corresponding lee and stoss troughs. This matching is done by searching the troughs nearest to the crest lines. The search is conducted in the orthogonal direction of the crest line orientation with a predefined range distance limit. Afterwards, the dune object is created by aggregating the pixels located in the area between the crest line and the troughs. Mathematical morphology and image processing are used to extract and better delineate the dune object. The result of is the dune object identified by the same label as its crest line.

Once the dunes have been segmented from the DBM, these structures can be characterized calculating a series of morphological descriptors. These descriptors consider the dune object segmented itself as well as its salient features. The main descriptors considered in the characterization are the dune orientation, depth, width, height, stoss and lee angles, stoss and lee widths and the symmetry index of the dunes. More details about the segmentation approach and the estimation of the morphological descriptors can be found in, respectively, Cassol et al. (2021) and Cassol et al. (2022).

A spatiotemporal analysis of the mobility of the dunes is performed once they have been extracted from the DBM. It consists of a manual extraction of several cross-sectional profiles through which the mobility of the dunes on the seafloor surface and their displacement can be observed and quantified. The dune objects, their related morphological descriptors as well migration scheme can be further integrated in a hydrodynamic model. Figure 1 synthetizes the steps of the proposed spatiotemporal analysis of underwater dunes.

3 RESULTS AND DISCUSSION

3.1 Saint-Lawrence Fluvial Estuary DBM

The Fluvial Estuary of the Saint-Lawrence River is a high-dynamic environment with a length of 400km with a width of a few kilometres in Quebec City and 70km downstream (i.e. Île aux Coudres). The seafloor depth ranges down to 60m. The dimensions are such that the conditions prevailing near Quebec city are highly complex. The tidal signal is asymmetric due to a strong competition between bottom friction and convergence effects. This region of the river is also characterized by a complex seafloor topography with different physical agents being responsible for the high dynamism, such as tide, waves, wind, ship waves, and ice (Drapeau, 1992). The studied area can be observed in Figure 2.

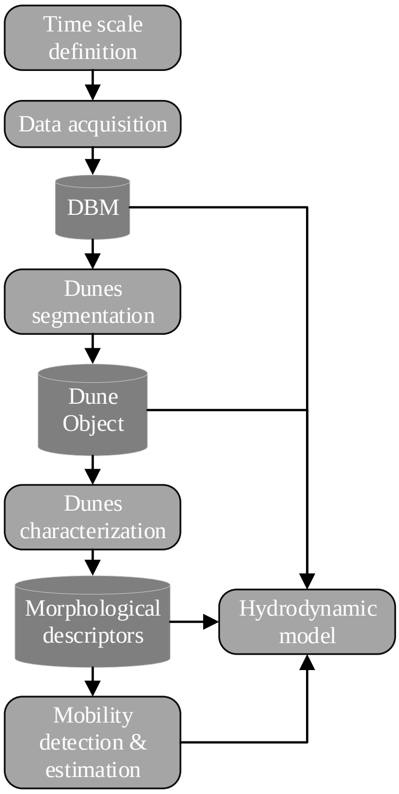

Figure 1. Approach for the spatiotemporal analysis of underwater dunes.

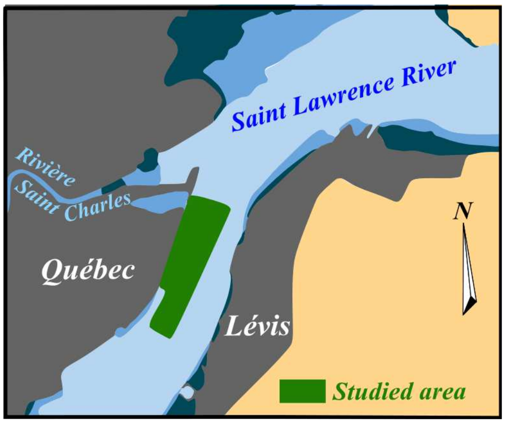

Figure 2. Study area of the Saint-Lawrence Estuary in Québec City. In green, the field of dunes surveyed. Maximum extension of 2.2km X 450m.

The MBES data used to generate the DBM considered in this paper was acquired from July 11th – July 14th, 2022. The data acquisition system consisted in a Kongsberg EM2040 MBES, an Applanix POS-MV320 and two GNSS antennas (Trimble GA830 and 540AP) embedded in the Louis-Edmond-Hamelin vessel. The field of dunes near Québec City was surveyed daily between 9:00 am and 12:00pm in the four days of acquisition. A DBM generated from the

MBES data acquired can be observed in Figure 3 with the crest lines of the dunes in red.

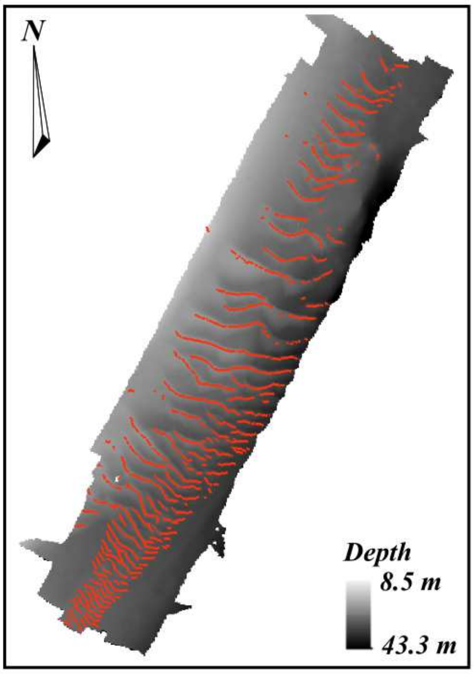

Figure 3 – DBM generated from July 13th MBES data with a resolution of 1m. In red, the crest line of dunes.

3.2 Dunes segmentation

The underwater dunes presented in the four DBM were segmented considering the approach described in the previous section. A total of 561 dunes were segmented over the four surfaces. Since the covered area of the survey was not exactly the same, 144 dunes were segmented in July 11th, 136 dunes in July 12th, 129 dunes in July 13th and 152 dunes in July 14th. An example of the dunes segmented can be observed in Figure 4. In this figure, we observe that larger dunes are located in the centre of the surveyed area while small dunes are observed in the north and south zones of the DBM. To analyse the performance of the segmentation of these sedimentary structures from acquired data, a ground truth was built manually segmenting dunes from each daily DBM. Therefore, three measures were computed to assess the performance, namely the true positive, false positive and false negative rate. A true positive is considered when a minimum of 50% of the segmented dune coincides with its area in the ground truth. A false positive is considered when the area of the segmented dune coincides less than 50% with the ground truth or when this structure does not have a related dune in the ground truth. A false negative is when the segmentation approach fails to segment a dune existing in the ground truth (adapted from Nguyen et al., 2020). The performance of the segmentation can be observed in Figure 5.

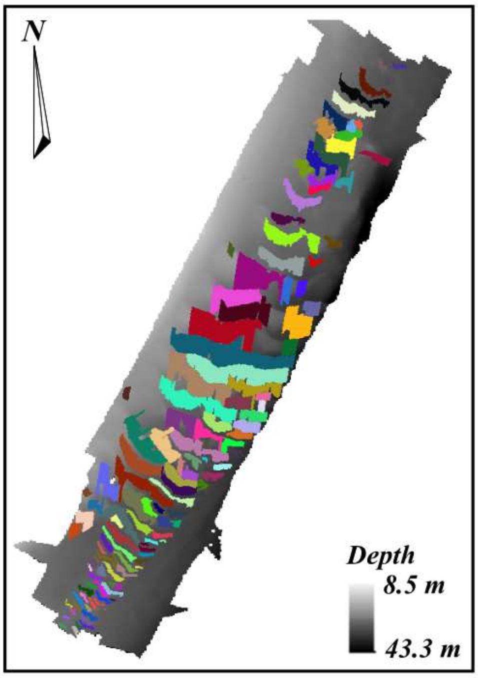

Figure 4 – Segmented dunes from the DBM. The dune objects are coloured on the DBM.

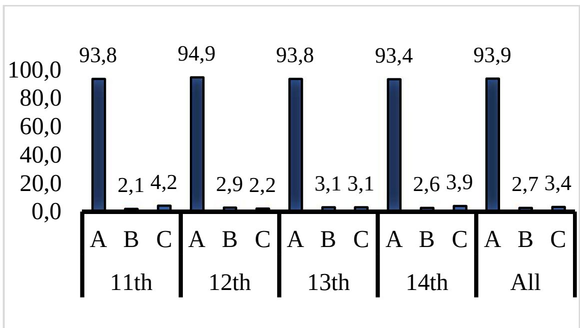

Figure 5 – Performance of the segmentation. A represents the true positive of each acquisition day, B the false positive and C the false negative. All considers the 561 segmented dunes overs the four days of acquisition.

The performance index over the four days of acquisition are similar to the overall performance considering the four days of acquisition. In the latter, 93.9% of the dunes were well segmented with 2.7% of false positive and 3.4% of false negative. The false positive is essentially associated with small dunes that the salient features are difficult to detect from the DBM due to its resolution of 1m. The false negative is essentially associated with dunes partially surveyed on the acquisition.

3.3 Dunes characterization

Once the dunes have been segmented from the DBM, they can be characterized using morphological descriptors. Their values are displayed as histograms in Figure 6 and 7.

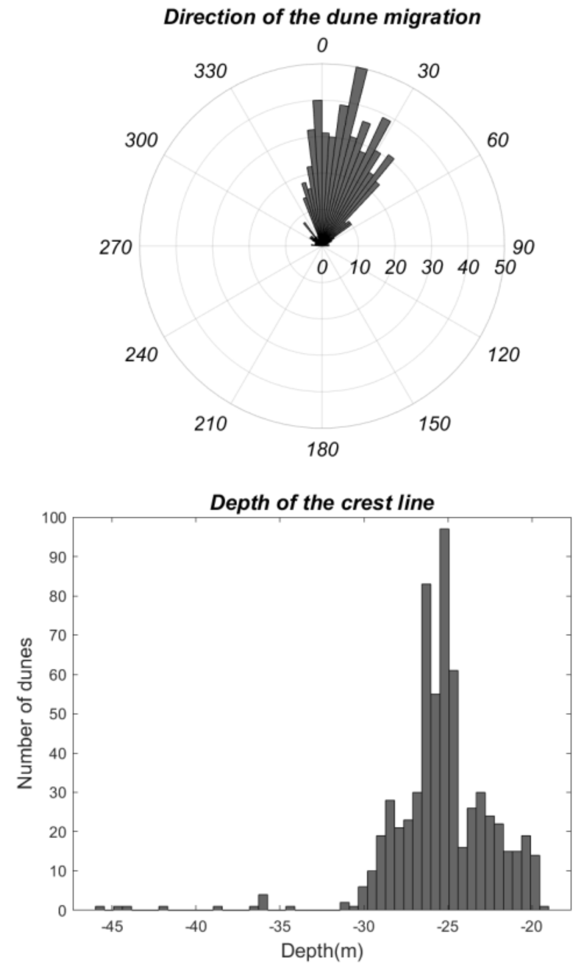

Figure 6 – Histograms of direction of dunes migration and depth.

According to the orientation of the dunes (cf. Fig. 6), their migration direction can be assessed as being approximatively 12.5° (i.e. median value), which is coincident with the main current of the Saint-Lawrence River in the study area. The dunes have a depth ranging from 19.5m to 45.7m (cf. Fig. 6), with a median depth value of 25.3m. The height of dunes ranges from 4cm up to 4.5m (cf. Fig. 7), with a median value of 0.77m. They have a width varying from 1.85m up to 100m (cf. Fig. 7) with a median value of 27m.

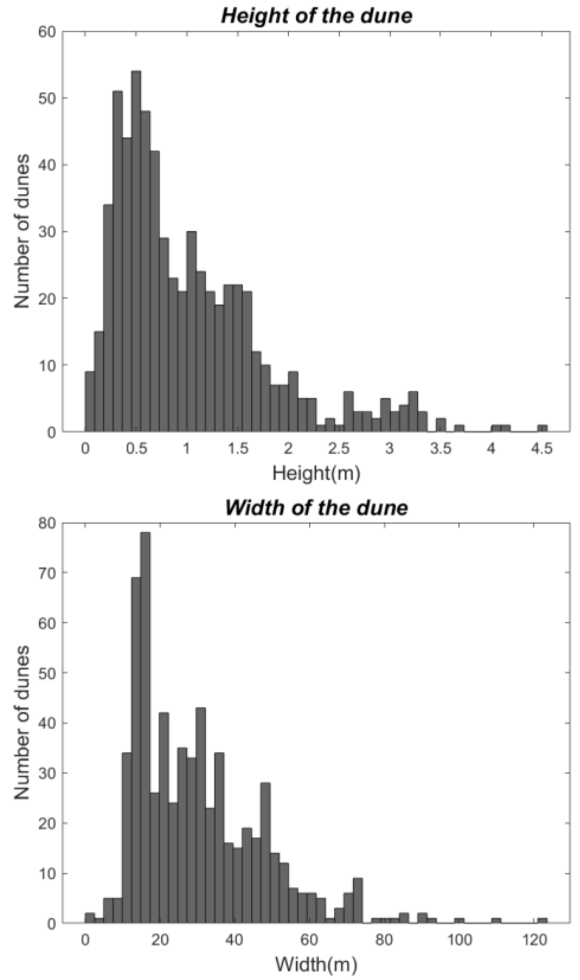

Figure 7 - Histograms of height and width of dunes.

We have also estimated the wavelength value (i.e. distance between the crest line of two consecutive dunes) and the density for this surveyed field of dunes. The median wavelength value, considering the four days of surveying, is 44m and the dunes density is up to 89% of the seafloor in this studied area. Considering these values for the morphological descriptors, the dunes of the study area are predominantly large dunes, as suggested by the dunes classification in Ashley (1990).

3.4 Spatiotemporal analysis of dunes

A spatiotemporal analysis of the mobility of the dunes in the Saint-Lawrence Estuary is proposed through different cross-section profiles. Figure 8 illustrates two profiles with underwater dunes present in DBM of July 11th and July 14th. We observe that the underwater dunes segmented in our study area are subjected to a migration rate up to 1m/day in different zones of the DBM. Indeed, the migration dynamic of large dunes differ from the small and medium dunes. The latter are located in the south region of our study zone (cf. Fig. 8 P1), migrated by traction on the seafloor, resulting in a difference up to 4m between July 11th and July 14th. A different dynamic can be observed in the centre of our study zone, with larger dunes migrating through an erosion-deposition regime (cf. Fig.8 P2).

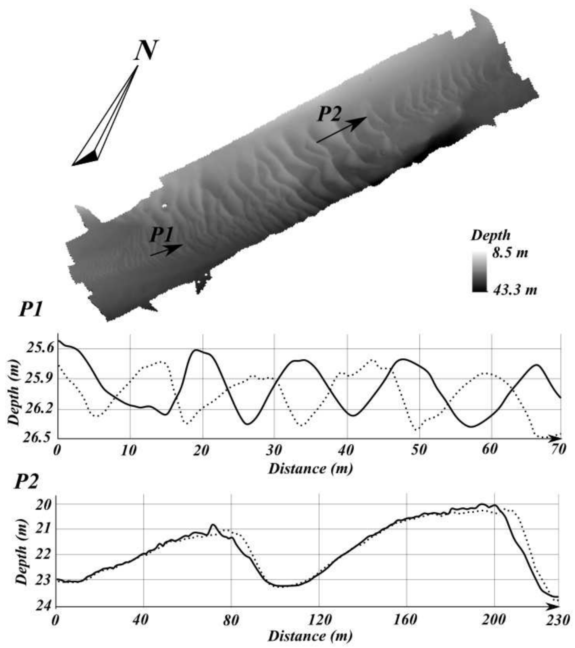

Figure 8 – DBM surface indicating profiles P1 and P2. The dotted line represents the profile from DBM generated with data acquired in July 11th and the black line data of July 14th.

4 CONCLUSION

This paper proposed a methodology to monitor the spatiotemporal mobility of underwater dunes in the Estuary of the Saint-Lawrence River. It consisted in the comparison of cross-sectional profiles through daily DBM in the same studied area. Two distinct types of displacement of dunes have been observed, the traction of small and medium dunes and erosion-deposition of larger dunes (cf. Fig. 8). This dynamic of migration is intimately related to hydrodynamic and environmental factors (e.g. current velocity, tidal information, grain size). Therefore, future works should consider a multisource approach to better analyse the mobility of dunes. Indeed, the information regarding these multiple factors may be helpful to better understand the dynamism of these structures on the seafloor surface.

Spatiotemporal information of underwater dune will be further analysed with respect to the tidal current. A 3D hydrodynamic model is under development yet. The model is based on the finite element method and will result on extension of an existing 2D depth integrated model which has been validated on field measurements (Matte et al. 2017a, 2017b). The newly developed 3D model will provide access to unmeasured flow velocities during the bathymetry investigation (i.e. July 2022) and complete information to better analyse the mobility of observed dunes (Hulscher, 1996). This information may be helpful to understand the correlation between the hydrodynamic and environmental factors with the morphological descriptors estimated for the dunes, as suggested by Kenyon (1970) and Le Bot (2001).

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