Vulnerability of tidal morphologies to relative sea-level rise in the Venice lagoon (Italy)

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Abstract

Tidal morphologies in coastal lagoons are forced to keep pace with accelerated sea-level rise, and their survival relies on delicate feedbacks between surface and subsurface processes. Quantifying the vulnerability of tidal morphologies to relative sea-level rise should be one of the fundamental pieces of information for planning appropriate conservation strategies for lagoon areas. Most assessments of lagoon vulnerability to sea-level rise focus on intertidal environments, e.g., saltmarshes, and neglect the effects of sea-level rise on subtidal flats. This contribution proposes a vulnerability analysis of tidal morphologies in the Venice lagoon (Italy) to past, ongoing and future relative sea-level rise based on the concept that both intertidal and subtidal zones are sensitive to this process. Vulnerability is assessed by combining sensitivity and hazard maps properly generated from a series of indicators such as sea-level rise trends, land subsidence, morphological setting, and stratigraphic characteristics of Holocene deposits.

Introduction

Lagoons are part of unique wetland environments with both submerged and emerged morphologies that provide valuable ecosystem services worldwide (e.g., Barbier et al., 2011). Because their survival is strictly dependent on vertical elevation, there is broad consensus on the high susceptibility of tidal environments to the adverse effects of relative sea-level rise (RSLR), i.e. sea-level rise plus land subsidence, resulting in loss of morphological structure and consequently geo- and bio-diversity.

Despite the extreme fragility of tidal morphologies, quantification of their vulnerability to RSLR is still poorly developed, even though it is a fundamental starting point for guiding conservation and adaptation processes that will become increasingly critical in light of projected mean sea level rise by 2050. Most vulnerability assessments of lagoons and wetlands generally focus on the emerged sectors and neglect the potential effects that RSLR may also have on the submerged zones, especially the tidal flats that form a morphological continuum with saltmarsh platforms. Furthermore, these assessments rarely consider the heterogeneity of shallow deposits and the variability of land subsidence when calculating the RSLR.

This work aims at evaluating the vulnerability of tidal morphologies to RSLR in the Venice Lagoon, Italy (Figure 1). It provides a high spatial resolution analysis that downscales the framework proposed by Tosi et al. (2020), and combines relevant indicators describing the sensitivity and hazard status of tidal morphologies. Among the sensitivity indicators, the thickness of the main Holocene depositional units was considered because most of land subsidence in the Venice lagoon depends on the stratigraphic architecture of the shallow deposits (Tosi et al., 2009). Different hazard scenarios are used accounting for past, ongoing, and future SLR trends measured in the north Adriatic over the last decades and projected to 2050.

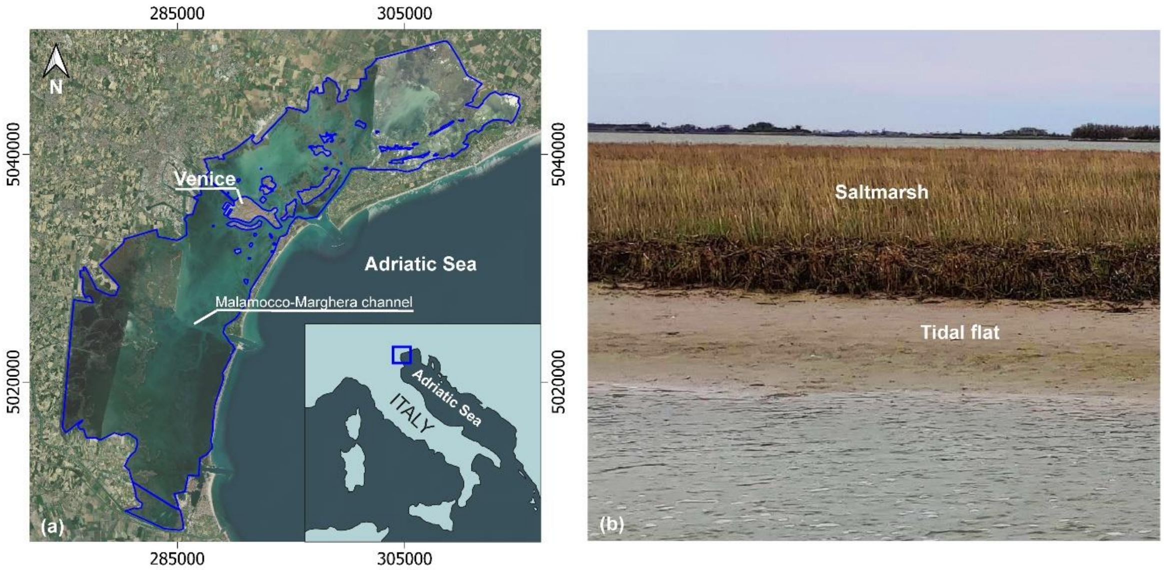

Figure 1. (a) Satellite image of the Venice lagoon facing the northern Adriatic Sea, Italy. (b) Typical tidal environment at low-tide condition with vegetated saltmarshes and bare tidal flats.

Methods

The vulnerability of tidal morphologies to RSLR was assessed according to an index-based model that combines the following indicators: land subsidence, sea-level rise, ground elevation of emerged and submerged areas, and stratigraphic architecture. Land subsidence was obtained from Sentinel-1 images acquired between 2015 and 2019 (Tosi et al., 2020) and processed using the Interferometric Point Target Analysis (IPTA) PSI chain. Three scenarios referred to the past (1990s), ongoing (2020s), and future (2050s) conditions were developed under different morphological settings and sea-level rise trends. The rates of past (1.5 mm/yr) and ongoing (3.5 mm/yr) sea-level rise were computed through time series analysis of the tide-gauge station located in Trieste, whose data are provided by Permanent Service for Mean Sea Level (https://www.psmsl.org/). The rate of projected sea-level rise (6.5 mm/yr) by 2050 was derived from the IPCC RCP8.5 scenario (Oppenheimer et al., 2019). The ground elevation indicator consists of a digital terrain model, which was obtained by merging three datasets to cover both the emerged and submerged lagoon areas. Specifically, LiDAR, bathymetric (https://idt2.regione.veneto.it/idt/downloader/download) and TanDEM-X data were properly homogenized and referred to the surface elevation conditions of the three scenarios. The stratigraphic architecture was derived from a simplified model of the Holocene depositional units mapped in Tosi et al. (2007a; b) and Fabbri et al. (2013). Specifically, three stratigraphic indicators were selected to account for the thickness of two muddy units with different degrees of consolidation, and the thickness of a sandy unit.

The index-based model approach followed these main steps: (i) set-up of the datasets related to each indicator (i.e., the thematic layers); (ii) classification of the thematic layers, i.e. each dataset was classified into 5 classes with scores ranging from 0 to 4 representing an increasing contribution to vulnerability; (iii) weighting of the sensitivity indicators; (iv) linear combination of sensitivity and hazard classified thematic layers to compute the vulnerability index.

Results

The result of the classification of the thematic layers is shown in Figure 2. All adopted sensitivity indicators show strong contributions of spatial variability to vulnerability.

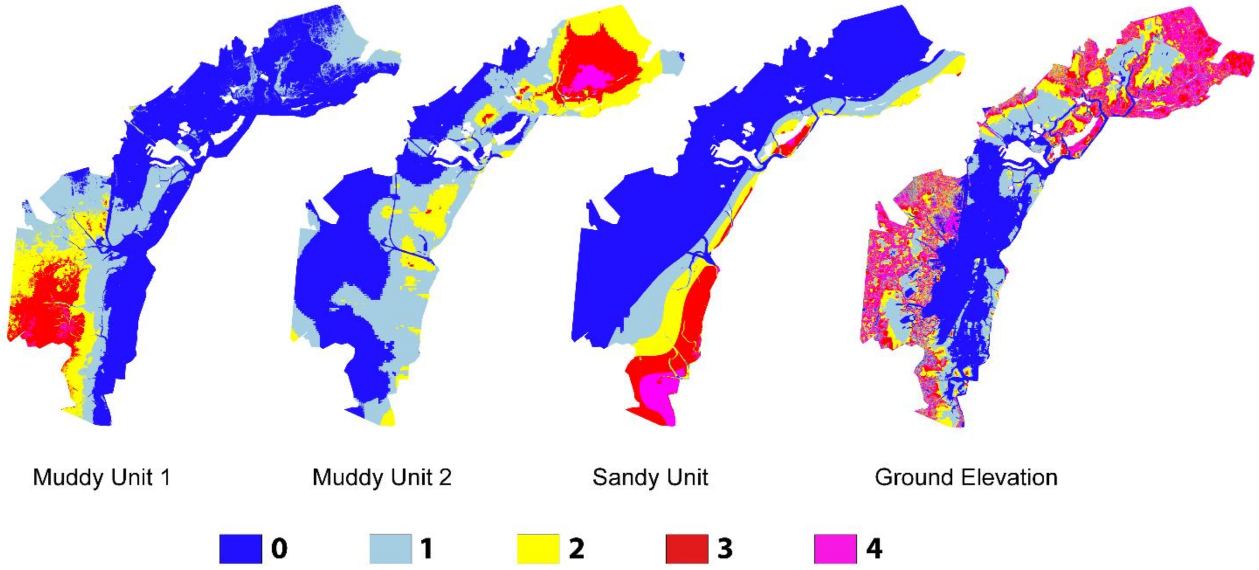

Figure 2. Classification of the thematic layers. Score from 0 to 4 identify low-to-high contributions to vulnerability.

The maps of the sensitivity, hazard, and vulnerability of lagoon morphologies (Figure 3) are provided here for the ongoing scenario as an example of the outcomes from this work.

The sensitivity map (Figure 3a) shows that tidal morphologies fall mostly in the negligible class (about 40%), while the marginal and moderate classes are rather similar at 35% and 25%, respectively. The hazard map (Figure 3b) highlights that 60% of the lagoon area is marginally threatened, whereas it is moderately and strongly threatened for 35 and 5 %, respectively.

The vulnerability map (Figure 3c), obtained from the appropriately weighted combination of sensitivity and hazard maps, depicts a large spatial heterogeneity, resulting from the variability of ground elevation of the emerged and submerged areas and the stratigraphic architecture associated with land subsidence and sea-level rise. Specifically, strong and moderate vulnerability affects nearly 30% of the lagoon basin, whereas marginal and negligible totals 70%.

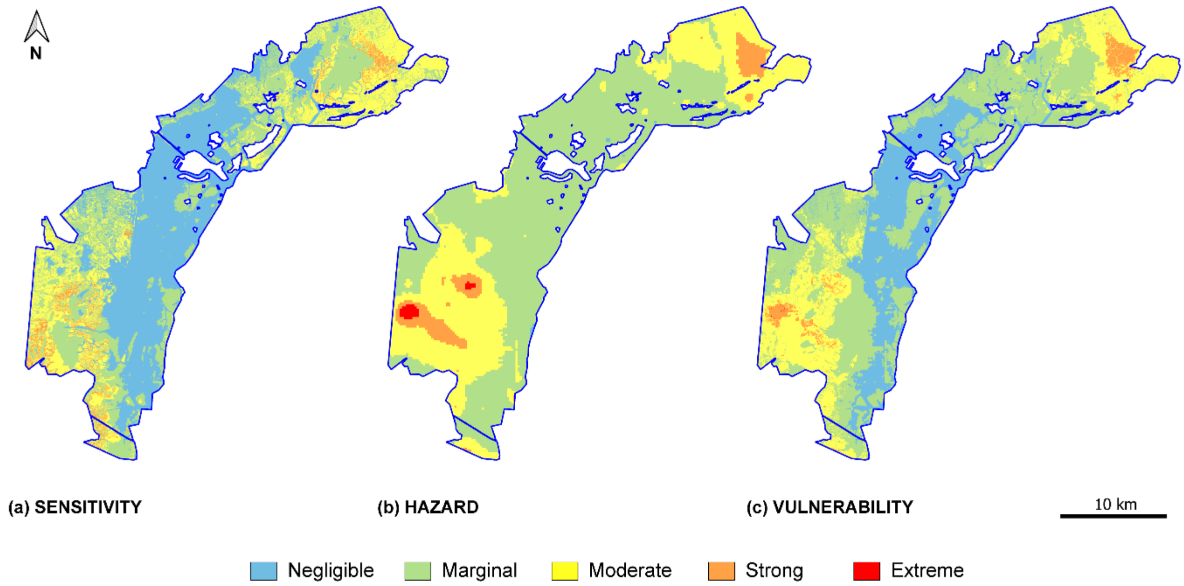

Figure 3. Maps of sensitivity, hazard, and vulnerability of tidal morphologies in the Venice lagoon under the ongoing scenario.

In general, there is a sharp increase in the vulnerability of emerged and submerged morphologies from past to future scenarios. The northeastern and the southwestern areas of the lagoon are the most threatened, while the central basin is relatively lower in vulnerability. In the 2050 scenario, 30% of the lagoon area is expected to be in strong and extreme vulnerability conditions.

Conclusion

The result of this work highlights the lagoon areas that need more attention. The worst ongoing conditions mainly affect saltmarshes in the northeastern and southwestern lagoon and reflect the occurrence of thicker fine-grained Holocene units and the higher land subsidence rates. Conversely, the relatively lower vulnerability classes refer to the central and southeastern lagoon areas where tidal flats and sandy unit prevail and sinking rates are lower. However, many of the present-day subtidal flats in these areas are the result of strong erosional and sinking processes caused by land subsidence due to groundwater exploitation in the industrial area (1950s-1960s) and the excavation of the Malamocco-Marghera navigation channel (1970s), which led to a transformation of lagoon morphologies from intertidal to subtidal. Therefore, in the ongoing scenario, the most vulnerable intertidal morphologies that occurred in the past have already disappeared.

It is expected that the vulnerability analysis will be a valuable aid to the management authorities in decision-making for the planning of measures aimed at safeguarding the Venice lagoon, among all, the reconstruction of the lost saltmarshes.

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