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Paleocoastline modelling – What a difference a few meters of sediment make?

Ana Novak

Geological Survey of Slovenia, Ljubljana, Slovenia

A R T I C L E I N F O

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A B S T R A C T

Paleoreconstructions of coastal and near-coastal areas have always served as a tool towards better understanding of past, present and future geological and geomorphological processes. The reliability of paleocoastline and sea-land extent modelling is controlled by input data. Here the difference between paleoreconstructions based on present-day bathymetry and a paleotopographic elevation model are examined on the example of the Gulf of Trieste (northern Adriatic sea) - a low-gradient submerged Last Glacial Maximum alluvial plain with fairly well-resolved bathymetry and pre-transgressional paleotopography. Results presented in this study show striking differences between the spatial extent of the two modelled sets of paleocoastlines which in places exceeds tens of kilometers. These results demonstrate the importance of using an appropriate geologically-supported elevation model for paleoreconstruction as unsuitable models can result in significant errors and unreliable reconstructions. This is especially noteworthy for low-gradient settings where even a slight variation in sea level can affect vast areas. Finally, the results of this study provide insight into the Early Holocene evolution of the present-day area of the Gulf of Trieste as an abrupt and predominant northeasterly oriented transgression direction is indicated from the paleocoastline reconstructions.

1. Introduction

Paleoreconstructions of past landscapes play an integral role in the effort to better understand past geological processes, environments and human-environment interactions. This particularly applies to coastal and nearshore areas which represent one of the most dynamic features of the physical landscape due to the constant pressure exerted by the variation of sea level and anthropogenic activity (Benjamin et al., 2017; Mattei et al., 2022; Rovere et al., 2016). Studies of past coastal and nearshore landscapes are particularly important in order to better understand the underlying processes related to sea-level changes and to better constrain and prepare for the future effects of sea-level rise on low-lying coastal areas prone to marine flooding (Carrasco et al., 2016; Cazenave et al., 2014; Chaumillon et al., 2017; Kopp et al., 2016; Milne et al., 2009; Nicholls and Cazenave, 2010; Rignot et al., 2011; Woodruff et al., 2013). In this sense reconstructions of past coastline positions contribute to our understanding of the land-sea dynamics especially during the Holocene transgression following the Last Glacial Maximum (hereafter LGM) and the resulting post-glacial sea-level rise.

The two main datasets used in the reconstruction of past coastlines and land-sea distribution are: 1) the sea-level curve providing a chronological constraint on the sea-level change and 2) the topographical (i.e. digital elevation) model onto which the sea-level variation is modelled. In the last decades several LGM-to-recent sea-level curves have been published and verified against different types of past sea-level indicators worldwide (Kaniewski et al., 2021; Khan et al., 2019, 2015 and references within; Lambeck et al., 2011; Mattei and Vacchi, 2023; Peltier, 2004; Peltier et al., 2015; Vacchi et al., 2018a, 2018b, 2016) thus allowing the user to use the most appropriate curve for their region of interest. Contrastingly, much less refined data is generally used for the paleotopography. Most commonly a model of the present-day bathymetry is used for the calculation of the land-sea distribution (Braje et al., 2019; Dean et al., 2022, 2020; Dixon and Monteleone, 2014; Hansson et al., 2018; Harff et al., 2005; Hetherington et al., 2004; Kolaiti and Mourtzas, 2023; Konikov et al., 2007; Lambeck, 1996; Leverington et al., 2002; Mourtzas and Kolaiti, 2013; Pollard, 2011; Quiñónez-Macías et al., 2023; Rick et al., 2013; Robles et al., 2015; Shaw et al., 2002; Shennan et al., 2000; Sikora et al., 2014; Sturt et al., 2013; etc.) with only rare examples accounting for nearshore sedimentation and/or erosion related to the sea-level change in the studied period (Hoebe et al., 2024; Oikonomidis et al., 2016; Robles-Montes et al., 2024; Sturt et al., 2013; Yao et al., 2009). While some studies have been

E-mail address: ana.novak@geo-zs.si.

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using alternative approaches for paleoshoreline reconstructions, such as: backstripping (Riddick et al., 2022; Westley et al., 2014), numerical modelling (Zhang et al., 2012) or consideration of archaeological, geological or geophysical indicators of past sea level (Aucelli et al., 2021, 2022; Deiana et al., 2021; Hijma et al., 2009; Kızıldağ et al., 2012; Liu et al., 2016; Lykousis, 2009; Nirgi et al., 2022; Rodrigues et al., 1991; Rosentau et al., 2020; Scardino et al., 2022; Wang et al., 2009), these still represent a relatively minor part of the published literature.

This study tries to evaluate the importance of using appropriate topographical input data for paleocoastline reconstructions. This is demonstrated on the example of the Gulf of Trieste in (northern Adriatic Sea) - a low-gradient submerged LGM alluvial plain with a fairly well-known bathymetry and pre-transgressional paleotopography. A comparison is made between the reconstructions using different paleotopograpical. The significance of the reliability of reconstructions are discussed along with the implications for understanding the Early Holocene evolution of the Gulf of Trieste.

2. Setting

The Gulf of Trieste is located in the northeastern corner of the Adriatic Sea between Italy, Slovenia and Croatia (Fig. 1). It is a relatively shallow gulf with depths averaging around 16 m and not exceeding 40 m (Trobec et al., 2018). Presently it is characterized by a relatively smooth bathymetric relief with depths generally decreasing towards the northwest (Fig. 1). The northern part of the gulf is characterized by sedimentary coasts of the Friuli plain which represent LGM-recent fluvial sediments (Fontana et al., 2019). The eastern rocky Karst coast is characterised by Mesozoic-Paleogene carbonates and Eocene Flysch (Jurkovšek et al., 2016). The southeastern coast is characterized by Istrian Eocene Flysch in parts covered by Quaternary fluvial sediments (Pleničar et al., 1969, 1973).

The Late Quaternary evolution of the Gulf of Trieste is intimately tied to the LGM and the subsequent global sea-level rise (Benjamin et al., 2017). During the LGM, the present-day area of the northern Adriatic was a vast low gradient alluvial plain of the Po river and its tributaries (Amorosi et al., 2016; Correggiari et al., 1996b; Kettner and Syvitski, 2008; Peresani et al., 2021). During that period the present-day area of the Gulf of Trieste was covered by the distal parts of the Isonzo (Soča in Slovenian) alluvial megafan (Fontana et al., 2008, 2014) and floodplain (Novak et al., 2020b; Ogorelec et al., 1991; Ronchi et al., 2023; Trobec et al., 2017). Following the post-glacial sea-level rise (Fig. 2; Lambeck et al., 2014) the northern Adriatic was relatively rapidly transgressed and submerged due to its low gradient (Chiocci et al., 2017; Correggiari et al., 1996b; Zecchin et al., 2015a). Consequentially, relatively few remnants of transgressional sedimentary bodies can be observed on the seafloor today as they were drowned, reworked or even completely eroded (Correggiari et al., 1996a; Moscon et al., 2015; Ronchi et al., 2018a, 2018b, 2019; Storms et al., 2008; Tosi et al., 2017; Trincardi et al., 2011a; Zecchin et al., 2015b). In fact, the transgressive and wave erosive action exposed and eroded large areas of the northern Adriatic alluvial plain which presently outcrops on the seafloor due to very low sedimentation rates away from the coast (Fig. 1; Amorosi et al., 2022; Correggiari et al., 1996a; Dalla Valle et al., 2024; Sherwood et al., 2004; Trincardi et al., 1994, 2011a, 2011b). In contrast, the pre-transgressional alluvial deposits in the Gulf of Trieste are remarkably well preserved, as documented by several seismic surveys (Novak et al., 2020b; Ronchi et al., 2023; see profile AA' in Trincardi et al., 2011b; Trobec et al., 2017; Zecchin et al., 2024), and covered by several meters of Holocene marine sediment which has been accumulating there for the last ca. 10,000 years since the onset of the submersion (Fig. 1; Gallmetzer et al., 2019; Ogorelec et al., 1991, 1997; Tomašových et al., 2019; Trobec et al., 2018). The depth of the boundary between continental and marine sediments was determined also in (a relatively small number of) offshore sediment cores and is located at approximately 25 m below sea level in the southern part of the gulf gradually shallowing

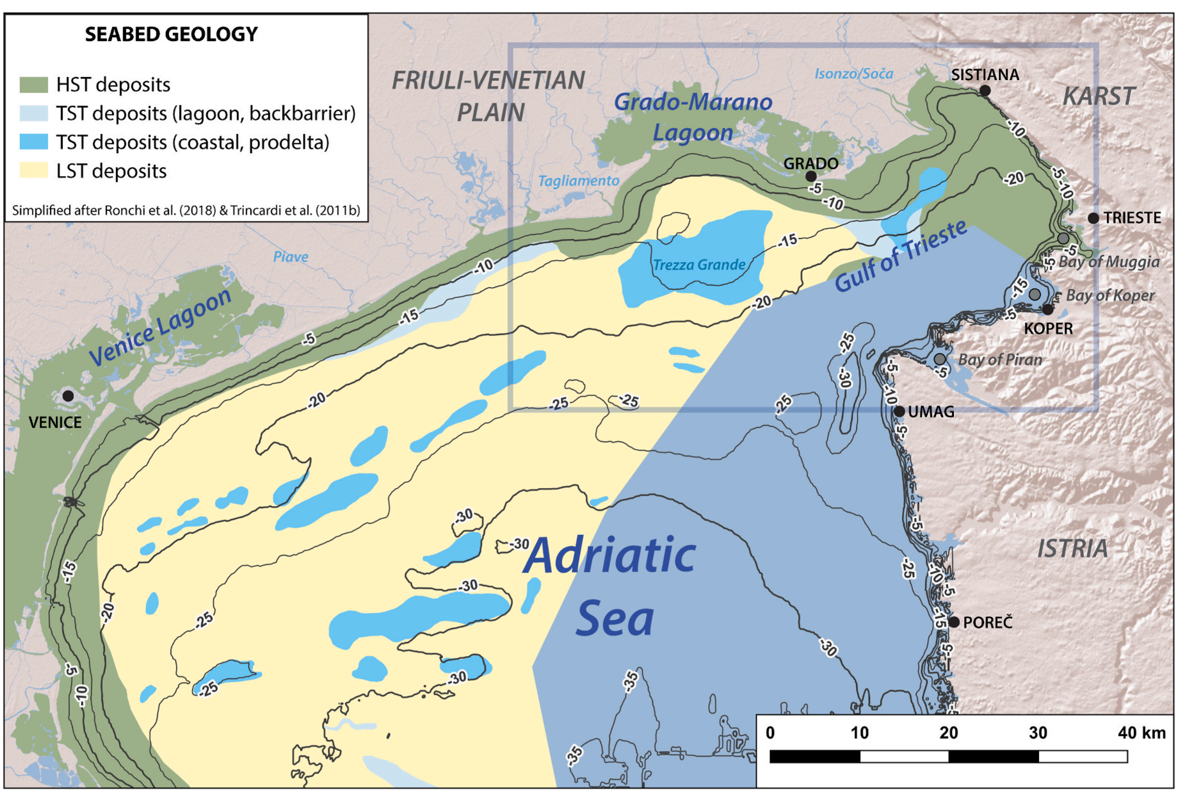

Fig. 1. Geographical location of the Gulf of Trieste (northern Adriatic Sea). The study area is indicated with a rectangle. Seabed geology is simplified after Ronchi et al. (2018a, b) and Trincardi et al. (2011a, b). HST, TST and LST are abbreviations for highstand, transgressive, and lowstand system tract. Depth contours are from EMODNET Bathymetry Consortium (2022).

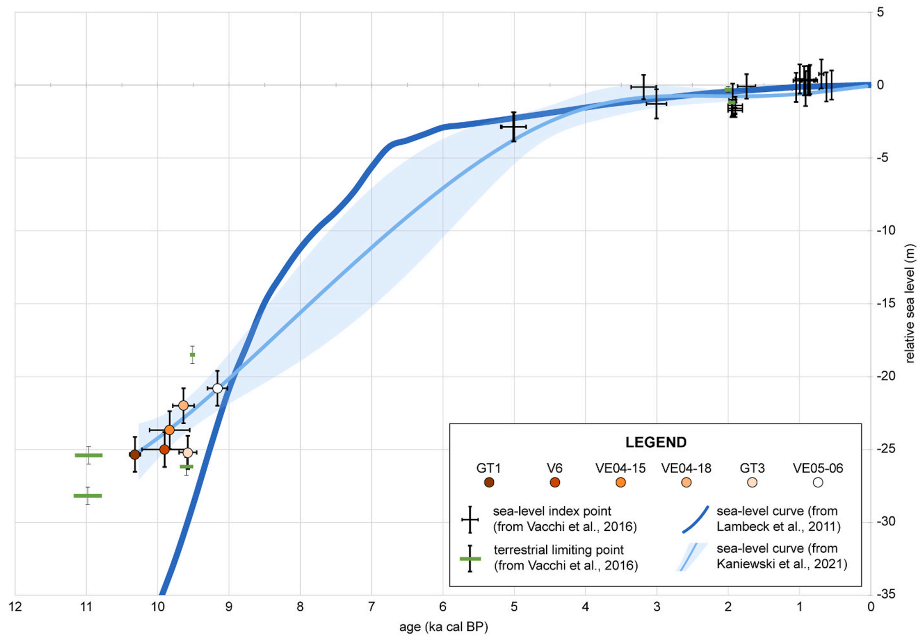

Fig. 2. Sea-level indicators and curves for the northern Adriatic Sea and the Gulf of Trieste. The sea-level curves are based on data published in Lambeck et al. (2011) and Kaniewski et al. (2021). The cores from the Gulf of Trieste are emphasized with circles and were originally published in Covelli et al. (2006), Ogorelec et al. (1991, 1981), and Trincardi et al. (2011a) and were later further analysed in Vacchi et al. (2016) and Kaniewski et al. (2021). The age and depth range of all sea-level points except GT1 are plotted based on data published in Vacchi et al. (2016). The age and depth range for GT1 is plotted according to the data published in Kaniewski et al. (2021).

towards the north (see Fig. 2 in Trobec et al., 2018). In the southern and central part of the Gulf of Trieste the alluvial sequences are also covered by very thin transgressive deposits which most commonly occur as channel fill of the pre-existing fluvial network and do not have a significant topographic expression (Ronchi et al., 2023; Trobec et al., 2017, 2018). The thickness of the transgressive deposits gradually increases towards the northern part of the Gulf of Trieste (Trincardi et al., 2011b).

The uppermost part of the Late Pleistocene-to-Holocene seabed stratigraphy and acoustic facies of the present-day area of the Gulf of Trieste is quite well-known due to several high-resolution geophysical surveys which have been conducted here in the last decades (Busetti et al., 2010; Gordini et al., 2004; Masoli et al., 2020; Novak et al., 2020a, 2020b; Ronchi et al., 2023; Trobec et al., 2017, 2018; Zecchin et al., 2015b, 2024). On geophysical profiles Holocene marine sediments are easily distinguishable from Late Pleistocene alluvial sediments (Novak et al., 2020b; Ronchi et al., 2023; Trobec et al., 2018; Zecchin et al., 2024). Towards the northern part of the gulf the marine sediments are in places deposited on transgressional sediments. They are usually represented by channel fill in the southern part of the gulf and develop significant thicknesses only towards the northern part of the gulf (Ronchi et al., 2023; Trincardi et al., 2011b; Trobec et al., 2017, 2018). In close proximity to the coast Holocene marine sediments can be deposited directly onto bedrock. The seabed stratigraphy of the general area is shown in Profile AA' in Trincardi et al. (2011b).

The well-defined acoustic facies characteristics and a dense network of high-resolution geophysical profiles of the upper few meters of the seabed allowed mapping of the thickness and the base of the Holocene marine sediments throughout the Gulf of Trieste (Trobec et al., 2018). As the Holocene marine sediment mostly overlies the LGM-Early Holocene alluvial sediments (especially in the southern and central parts of the gulf), the base of the Holocene from Trobec et al. (2018) can be considered as the pre-transgressional paleotopography and thus used as input data for paleoshoreline reconstructions (see Section 3). However, it should be noted that while the term pre-transgressional paleotopography is used in this paper for brevity, the thickness of transgressive deposits increases towards the northern part of the gulf where they already have a significant topographical expression (Trincardi et al., 2011b). In this sense, in the northern part of the gulf the surface of the base of the Holocene marine sediment from Trobec et al. (2018) overlies transgressive sedimentary deposits and is less representative of the pre-transgressional paleotopography. Still, for the southern and central parts of the present-day area of the Gulf of Trieste, which were most affected by the Early Holocene sea-level rise and are most important for this study, the base of the Holocene surface from Trobec et al. (2018) does in fact fairly well represent the pre-transgressional paleotopography. Hence, this term is used throughout this study. The mapping in Trobec et al. (2018) demonstrated that the modern bathymetry and the pre-transgressional topography significantly differ as the thickness of Holocene marine sediments deposited on the alluvial plain amounts to several meters, especially in the southern part of the gulf (Fig. 3).

The timing of the post-glacial sea-level rise in the northern Adriatic has been the topic of a number of studies (Antonioli et al., 2007, 2009; Furlani et al., 2011; Kaniewski et al., 2021; Lambeck et al., 2004, 2011; Vacchi et al., 2016). Several Early Holocene sea-level index points (hereafter SLIPs) and terrestrial limiting points for the Gulf of Trieste have been published so far (Covelli et al., 2006; Ogorelec et al., 1981, 1991; Trincardi et al., 2011a) and are summarized in Kaniewski et al. (2021) and Vacchi et al. (2016) and shown in Figs. 2 and 5. The latest sea-level curve for the Gulf of Trieste was published by Kaniewski et al. (2021). Compared to previously published sea-level curves (Lambeck et al., 2004, 2011; Vacchi et al., 2016) which demonstrate a mismatch with Early Holocene sea-level indicators with either overestimated either underestimated sea level, the sea-level curve from Kaniewski et al. (2021) shows a much better correlation between modelled and field data (Fig. 2). This probably results from the different methodological approaches used for the construction of the relative sea-level curves. While the curves from Lambeck et al. (2011, 2004) and Vacchi et al. (2016) are based on the glacial isostatic adjustment in response to the variability of the Late Pleistocene ice sheets, the sea-level from Kaniewski et al. (2021) is reconstructed based on dated sedimentary core (paleo)data following the approach introduced by Cahill et al. (2016). As there are two distinct clusters of SLIPs and terrestrial limiting points in the Gulf of Trieste at

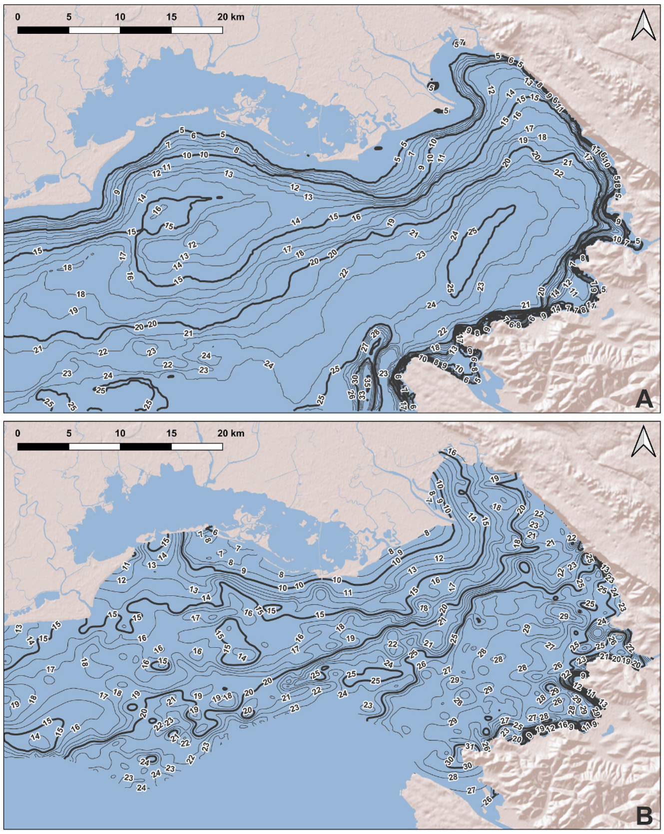

Fig. 3. Elevation models used for the reconstruction of past sea extent in the Gulf of Trieste. A) Present-day bathymetry (EMODNET Bathymetry Consortium, 2022). B) Pre-transgressional paleotopography (modified from Trobec et al., 2018).

approximately −25 m and −1 m with a gap between 9 ka cal BP and 5 ka cal BP (Fig. 2), the sea-level estimates are less confident during this gap interval.

3. Methods

The latest published sea-level curve for the Gulf of Trieste from Kaniewski et al. (2021) was used for the chronological constraint of the sea-level rise as it shows the best correlation with published sea-level indicators and terrestrial limiting points (see Section 2). The data for curve construction are available in the supplemental materials of Kaniewski et al. (2021).

Two openly available digital elevation datasets were used to simulate marine flooding of the study area during the Late Pleistocene-Holocene transition (Fig. 3). This was done in order to demonstrate the difference in obtained results when using modern bathymetry vs. geologically-based paleotopography. The first dataset was the present-day bathymetry published by the EMODnet Bathymetry Consortium (2022) which is a composite of different bathymetric datasets (Fig. 3A). Dataset download and more information regarding the source data and compilation is available on the dataset website (EMODNET Bathymetry Consortium, 2022). The second dataset was the topographical model of the base of the Holocene marine sediment published in Trobec et al. (2018) which represents the paleotopography of the research area before the post-glacial transgression (see Section 2; Fig. 3B). The dataset was created with the SKUA-GOCAD software by using geophysical, core and previously published cartographic data. For more details and data access refer to Trobec et al. (2018). For this study additional data points were added manually in the Bay of Piran in order to extend the paleotopographical model to the opening of the gulf towards the southwest. The datapoints were based on the depth of the base of the Holocene marine sediment from the southern part of the gulf (Trobec et al., 2018) and the depth of the marine-terrestrial sediment boundary from core V6 (Ogorelec et al., 1981, 1991). The datapoints were then extrapolated towards the edges of the bay in order to model a smooth paleotopographical surface. The extrapolated datapoints and the updated paleotopographical model was created by using the SKUA-GOCAD software.

Sedimentation was not considered when modelling the paleotopography in this study due to two reasons. Primarily, it is assumed that the sedimentary supply in the Gulf of Trieste was low in the initial phases of the transgression. The general current direction in the Adriatic is assumed to have followed a counterclockwise direction (Correggiari et al., 1996a; Razum et al., 2024) implying that the currents entering the Gulf of Trieste were sediment starved as no significant sedimentary input occurred along the eastern, mostly karstic, part of the Adriatic (Kettner and Syvitski, 2008). Secondly, the rate of sedimentation was likely significantly lower than the rate of sea-level rise. The average Holocene-recent sedimentation rate in the southern part of the gulf is approximately 2.5 mm/yr (Ogorelec et al., 1997) which is probably a relatively high value considering the proximity of the sampling location to the flysch coast presently providing terrigenous material. However, even if we assume this probably overestimated sedimentation rate, it is several times lower compared to the estimates of sea level rise between the studied interval between 10.000 and 9.000 cal BP (Kaniewski et al., 2021) which in some cases even exceed 10 mm/yr (Lambeck et al., 2014).

Marine flooding was simulated for both datasets at approximately 10,200 cal BP, 9650 cal BP, and at 8950 cal BP (Fig. 4) roughly corresponding to sea levels at −25, −23 and −20 m (Fig. 2; Kaniewski et al., 2021). The maximum modelled depth was constrained by the extent of

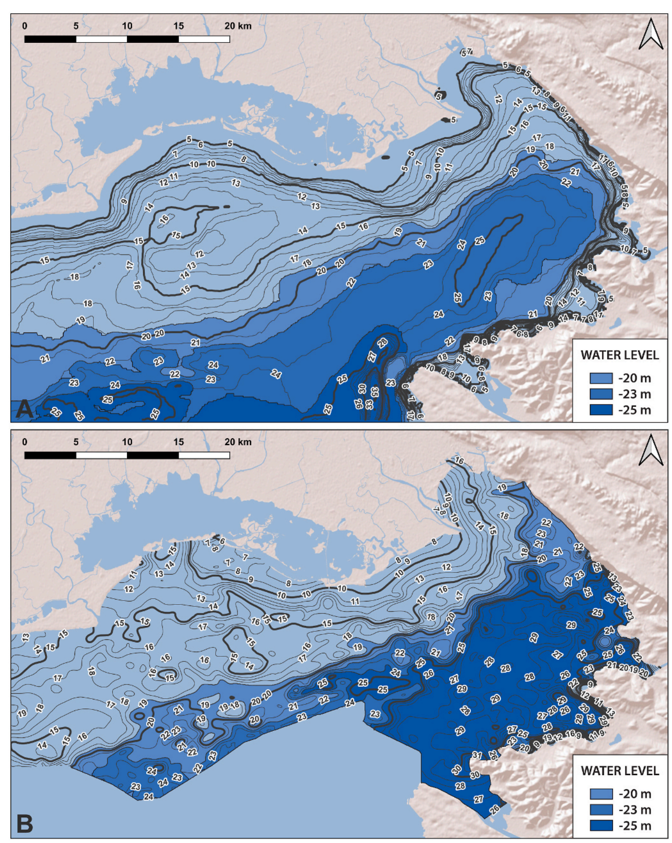

Fig. 4. Reconstructed sea extent in the Gulf of Trieste at water levels −25, −23, and −20 m roughly corresponding to 10200, 9650, and 8950 cal BP. A) Sea extent reconstructed by using present-day bathymetry. B) Sea extent reconstructed by using the pre-transgressional paleotopography.

the sea-level curve from Kaniewski et al. (2021). Shallower depths were modelled but are not presented here due to larger uncertainties related to the sea-level curve (see Section 2) and due to the increasing uncertainties regarding the pre-transgressional paleotopography related to the thickening of transgressive deposits towards the northwest of the gulf (Trincardi et al., 2011b; see also Section 2). Additional flooding simulations corresponding to sea level at −30, −29, −28, −27 and −26 m were done only on the paleotopographic model in order to spatially reconstruct the onset of transgression in the gulf (Fig. 5). The flooding was modelled with the "Simulate Water Level Rise/Flooding" tool contained within the Global Mapper GIS software. In order to account for higher sea-levels during storms and high tides, an additional increase (i.e. flood) of 1 m was added to the predetermined sea-levels. The readers can still refer to the depth contours if they want to disregard this increase. The resulting polygons were then extracted in the shapefile format and prepared for visualisation with the QGIS GIS software and are shown in Figs. 4 and 5.

4. Results

The results of paleocoastline modelling (i.e. flooding) are shown in Fig. 4 and clearly demonstrate the significant differences that can be observed in regard to the size of flooded i.e. transgressed areas for the two datasets.

When simulating water level at −25 m the sea barely enters the gulf when using present-day bathymetry (Fig. 4A). This is in striking contrast to the reconstruction based on the pre-transgressional topography where roughly half of the gulf is already flooded at this water level up to most parts of the present-day southern and eastern coasts (Fig. 4B). The northeastern maximum extent of the reconstructed shorelines differs for more than 25 km. Towards the northwest the distance between the city of Grado and the modelled shorelines is approx. 8 and 15 km for the paleotopographic and bathymetric model, respectively (Fig. 4).

Larger parts of the gulf become flooded when simulating water level −23 m on present-day bathymetry, but nearshore areas such as the present-day Bay of Piran, Bay of Koper, and Bay of Muggia are still land (Fig. 4A). The simulated sea extent on the paleotopographic model at this water level roughly corresponds to the extent at −25 m – the sea rarely extends more than 3 km northward at water level −23 m compared to the shoreline modelled at −25 m (Fig. 4B). The northeastern maximum extent of the reconstructed shorelines at water level −23 m now differs only for approximately 3 km. A similar discrepancy between the shorelines can be observed towards the northwest (Fig. 4).

When simulating water level −20 m on present-day bathymetry, roughly half of the gulf gets flooded excluding nearshore areas such as the present-day Bay of Piran, Bay of Koper, and Bay of Muggia. At its maximum northeastern extent, the shoreline is approximately 2 km from the present-day coast (Fig. 4A). The simulated sea extent on the paleotopographic model at this water level is comparable towards the northwest with its extent at −23 m – the difference is approximately less than 2 km. However, the sea does extend along the eastern coast approximately 10 km further northwest up to the town of Sistiana (Fig. 4B). When comparing the reconstructed shorelines from both datasets at −20 m the shorelines differ less than 2 km in their northwestern extent (Fig. 4).

Additional water levels corresponding to earlier sea-levels were simulated on the paleotopographical model in order to better understand the transgression in the Gulf of Trieste. The results of these reconstructions are shown in Fig. 5. These water levels cannot be chronologically constrained by the sea-level curve from Kaniewski et al. (2021) due to its shorter extent (Fig. 2). However, they can be tentatively constrained by the sea-level curve published by Lambeck et al. (2011) as follows: 26 m (9330 ka cal BP), −27 m (9400 ka cal BP) −28 m (9460 ka cal BP), −29 m (9520 ka cal BP), and −30 m (9590 ka cal BP). It should be emphasized, that for the Gulf of Trieste the sea-level curve from Lambeck et al. (2011) shows fairly large discrepancies with published geological data (Fig. 2; Section 2) therefore the provided ages are probably underestimated and are listed here only informatively. The sea extent for water levels between −25 and −27 m is fairly comparable and usually differs for less than 2 km. The maximum southeastern sea extent at water level −28 m is approximately 4 km less compared to the extent at the higher water levels. The sea extent simulated at water level −29 m only barely reaches the southwesternmost part of the gulf. At water level −30 m the modelled sea extent does not reach the southwesternmost part of the model (Fig. 5). Due to poor connectivity towards the southwest the modelled sea extent at −29 and −30 m is considered unreliable – most probably, the sea did not yet reach the present-day area of the Gulf of Trieste at these sea levels. For this reason, the sea extent at the deepest two levels is marked in grey in Fig. 5.

5. Discussion

5.1. Paleotopography vs. bathymetry for paleocoastline reconstructions

The results of the paleocoastline modelling presented in Section 4 demonstrate the striking difference between the land-sea distribution when using different topographical models for reconstructions. The coastline position in the presented study differs for several tens of kilometers which has significant implications for the reliability of paleoreconstructions and the understanding of the Early Holocene transgression in the Gulf of Trieste. This case study demonstrates the importance of using input data corresponding to the geological context of the studied area in order to obtain realistic estimates for the positions of past coastlines and the land-sea distribution.

Present-day bathymetry in paleocoastline modeling should be used very cautiously and only in settings where not much topographical variability is expected during the examined period of sea-level change. These include areas with neglible sedimentation/erosion, low sedimentary supply, and a predominantly rocky seafloor (e.g. karstic areas; Brunović et al., 2020, 2024; Hasan et al., 2020; Šolaja et al., 2022) or areas where very low sedimentation/erosion rates were previously confirmed by geological and/or geophysical investigations. Additionally, bathymetry can be cautiously used in areas with abundant past sea-level indicators, such as marine terraces, shore platforms, beach rock, archaeological remains, etc. (e.g. Aucelli et al., 2022, 2021; Caporizzo et al., 2021; Lebrec et al., 2022; Rosentau et al., 2020; Scardino et al., 2022) or where sedimentation and erosion rates or thickness are very well known and the paleotopography can be roughly estimated by subtraction or addition from/to the present-day bathymetry (Hoebe et al., 2024). Finally, the use of present-day bathymetry can be at least partially justified when reconstructing first-order approximations of the sea-land distribution during larger time periods (for example, during the LGM; Brunović et al., 2020; Kolaiti and Mourtzas, 2023; Micallef et al., 2013; Miccadei et al., 2011) or across larger regions (e.g. Brooks et al., 2011; Sturt et al., 2013) as the offshore geology and sedimentation/erosion rates or thickness are usually well defined only very close to the shore (often in proximity to important infrastructure) and not across a whole region.

In predominantly sedimentary coastal settings, the use of present-day bathymetric models for coastline reconstructions should be avoided. Especially in low-gradient settings (such as present-day coastal plains and continental shelves), the use of present-day bathymetry is prone to produce extremely misleading results as a slight variation in sea level can affect very large areas (e.g. Chiocci et al., 2017). In such settings, pre-trangressional topography based on geological data should be used, whenever possible. High-resolution shallow geophysical profiling is especially suited for determining paleotopography, as it allows relatively rapid and precise seabed subsurface mapping of large areas (e.g. Bellizia et al., 2022; Cotterill et al., 2017; Emery et al., 2020; Morelli et al., 2023; Ronchi et al., 2019, 2018b; Trobec et al., 2018; van Heteren et al., 2014). While core data can also be used for paleotopographic reconstructions, it requires very high data density (e.g. Morelli et al.,

2017) which is usually financially feasible only when conducting larger infrastructural projects.

5.2. Importance of realistic paleocoastal reconstructions

Realistic paleocoastal reconstructions are of great importance in past sea-level and archaeological studies. A more accurate delineation of past shorelines can help us better understand and estimate the spatial distribution of potential geological, geomorphological, and/or archaeological SLIPs. For example, in low-gradient settings without significant topographical variability the spatial distribution of potential SLIPs can be robustly estimated by comparing the paleotopography and sea-level curves. This is demonstrated in the low-gradient central and northern parts of the Adriatic Sea where the Late Pleistocene and Holocene transgressive deposits on the seafloor get progressively younger and shallower northwestward and generally correspond well with the sea-level curve (Amorosi et al., 2017; Moscon et al., 2015; Ronchi et al., 2018b, 2019; Trincardi et al., 2011a). For this example, the pre-transgressional paleotopography is similar to the present-day bathymetry due to sediment starvation away from the coastline (Dalla Valle et al., 2024) therefore the along-shelf spatial distribution (i.e. elevation range) and ages of the observed SLIPs correspond well to the modelled estimates. This would not be the case if the paleotopography was covered by thick post-transgressional deposits. In such circumstances, the use of bathymetry for paleocoastline reconstruction would result in paleoshorelines located too downward along the shelf - as is demonstrated in this paper for the Gulf of Trieste. Consequentially also the observed ages of potential SLIPs would be too young compared to the estimates from an unrealistic paleoreconstruction. This demonstrates the importance of using realistic paletopography for modelling past sea-land extent as it also allows us to more accurately predict the spatial distribution of potential SLIPs thus increasing the potential for successful discovery of geological, geomorphological, and/or archaeological SLIPs of an expected age in the field.

Another example to consider are areas with rugged terrain. When topography is varied enough to form isolated areas, we can observe hiatuses in the depositional record which also translates to the potential for SLIP formation - especially when the topography affects connectivity with the sea. In the Adriatic Sea such cases can be found across wide areas of the eastern part where the predominantly carbonate stratigraphy, high relief, and limited sediment availability result in a usually exposed rugged terrain with abundant rocky outcrops on the seafloor. In such settings, isolated basins are often formed, especially near the coast. Some recently published examples of these environments include Brunović et al. (2020, 2024) and Hasan et al., (2023, 2020). In such settings a SLIP can be formed only when the sea level exceeds the lowest point of the topographic barrier resulting in marine flooding of a previously isolated basin. Consequentially we can observe depositional hiatuses during times of isolation and formation of potential SLIPs (pending favourable conditions) at sea-level corresponding elevations when connectivity is (re)established. In tectonically-stable high-relief areas with very limited sedimentary supply and deposition (e.g. karst) the pre-transgressional/regressional topography and present-day bathymetry can be very much alike. In these cases the paleotopography starts to play a minor role and the connectivity of isolated basins becomes increasingly important in modelling paleo sea-land extent. Still, also in such instances valid paleotopographical data plays an important role in paleoreconstructions as it enables to determine the elevation of topographical barriers of isolated basins and, in absence of other chronological constraints, allows to build a robust chronology of marine-connectivity episodes when combined with a sea-level curve. A good understanding of both the connectivity of isolated basins and the distribution of past coastlines allows us to better predict the distribution and absence of potential SLIPs in areas of rough terrain.

Finally, realistic paleocoastal and landscape reconstructions are also of great importance for archaeological studies as they contribute to the understanding of the distribution of the archaeological record and the impact of sea-level change on past coastal communities. As these were strongly dependent on the sea and its resources, they were strongly affected even by minor changes in the sea-land extent. In this sense realistic paleoenvironmental reconstructions help in understanding not only the distribution of archaeological remains from a certain period but also provide some insight into the driving factors behind great societal changes (e.g. migration due to transgression). Furthermore, accurate delineation of past shorelines is an invaluable information for field-study planning as it enables and facilitates optimal site selection for archaeological studies.

5.3. Early Holocene transgression in the Gulf of Trieste

The results of paleocoastline modeling demonstrate that the sea started entering the area of the present-day Gulf of Trieste only after it elevated above water level of −29 m (Section 4, Figs. 2 and 5). This is also corroborated by all so far dated SLIPs in the gulf, which are all situated at shallower depths (Fig. 2; Covelli et al., 2006; Kaniewski et al., 2021; Ogorelec et al., 1981; Trincardi et al., 2011a; Vacchi et al., 2016). After the sea rose above −29 m almost half of the Gulf of Trieste was relatively abruptly flooded as demonstrated in Fig. 5. The reconstructions show the predominant flooding direction during Early Holocene was towards the northeast. Comparatively, the flooding towards the northwest was more gradual and occurred after the deepest parts of the basin were already filled (Figs. 4B and 5). This is also corroborated by the geological data – cores V6, GT3, GT1, and VE04-15 containing sea-level indicators at approx. 25-24 m below sea level are located within areas flooded at water levels between −28 and −26 m, while the youngest and northwesternmost cores VE04-18 and VE05-06 are located in areas flooded at water levels between −23 and −20 m (Figs. 4B and 5). Abrupt flooding of a large part of the gulf is also evidenced by core GT1 which contains the oldest dated Early Holocene SLIP at approximately 25 m and is located far towards the northeastern part of the present-day Gulf of Trieste. During the Middle and Late Holocene the predominant flooding direction turned towards the northeast as deeper parts of the basin were already flooded.

During the post-LGM and Early Holocene sea-level rise the sea advanced towards the northwest on the northern Adriatic alluvial plain (Correggiari et al., 1996b; Trincardi et al., 1994). This is in stark contrast to the observations presented in this study where the predominant transgression direction in the Early Holocene is towards the northeast. The peculiar spatial dynamic of the transgression in the present-day area of the Gulf of Trieste is intimately related to the pre-transgressional paleotopography, namely the general topography of the area mainly controlled by the morphology of the Torre and Isonzo megafan system after the LGM and the presence of the rocky coasts of Istria and Karst in the eastern and southern parts of the gulf (Fig. 1; Ronchi et al., 2023). The eastern portion of the megafan system extended towards and into the present-day area of the Gulf of Trieste (Fontana et al., 2014; Ronchi et al., 2023). As the sea advanced along the northern Adriatic, topographically higher parts of the megafan in the northeastern part of the Adriatic plain hypothetically located west of the Gulf of Trieste possibly acted as a barrier initially hindering entry of the sea in the present-day area of the gulf. Over time the ongoing sea-level rise overstepped the proposed sedimentary topographical high and then the sea instantaneously flooded large parts of the present-day area of the gulf. The predominant flooding direction was towards the northeast as this direction was perpendicular to the longitudinal direction of the Isonzo megafan (Fontana et al., 2014; Ronchi et al., 2023). The abrupt nature and evidence of the Early Holocene transgression in the gulf was already partially discussed in the previous paragraph. Another indirect

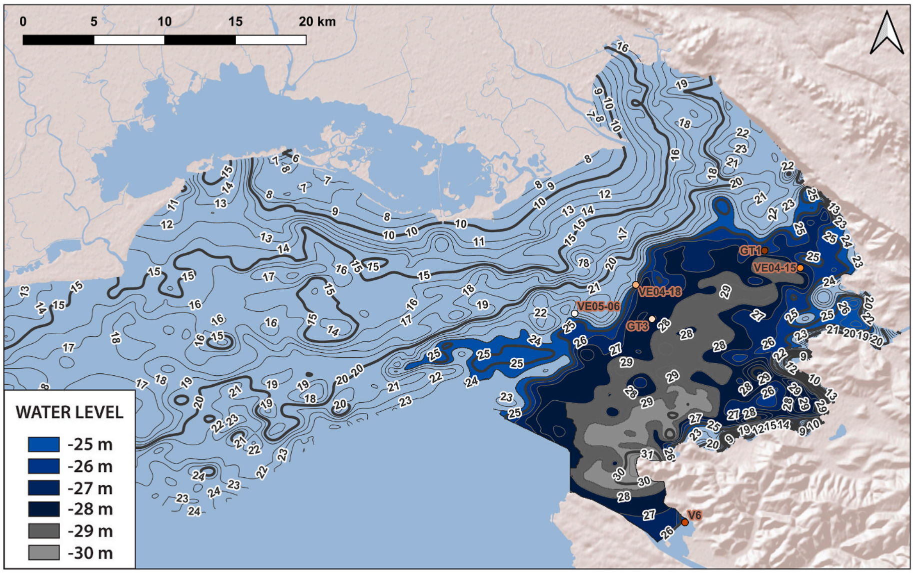

Fig. 5. Reconstructed sea extent at water levels between −30 and −25 m and cores containing Early Holocene sea level index points in the Gulf of Trieste. The extent at water levels −30 and −29 m is plotted in grey as it is considered unreliable (see Section 4). The cores were published in Covelli et al. (2006), Ogorelec et al. (1981, 1991), and Trincardi et al. (2011a). For the ages and depths of the sea level index points refer to Fig. 2.

indication of the sudden inundation is the exceptional preservation of Late Pleistocene fluvial features which were subsequently buried by Holocene marine sediment but are presently still clearly visible in the seabed morphology and in high-resolution geophysical profiles (Novak et al., 2020b, 2023; Ronchi et al., 2023; Trincardi et al., 2011b; Trobec et al., 2017, 2018; Zecchin et al., 2024). Evidently and contrary to the northern Adriatic (Ronchi et al., 2018b; Trincardi et al., 2011a, 2011b), the area of the present-day Gulf of Trieste did not experience significant erosion of the LGM-Early Holocene sedimentary record due to transgression and related wave action (Zecchin et al., 2024). While the gulf is well protected from all directions except the northwest, at least partial erosion of the pre-transgressional fluvial drainage network would be expected. For this reason, sudden inundation of a large part of the gulf coupled with a potential sedimentary barrier acting as a geological wave breaker could favour the observed preservation of the pre-transgressional deposits. However, it should be clearly noted that, to the author's knowledge, no evidence of such a sedimentary body has yet been found and its presence is here only hypothesized. There is, however, an observable change in the orientation of the northeastern part of the northernmost front of transgressive deposits (Trincardi et al., 2011b) south of the Tagliamento river and the Trezza Grande sedimentary body (Zecchin et al., 2015b) that could indicate elevated topography towards the northeast (Fig. 1). An additional factor favouring the preservation of the fluvial stratigraphy during transgression could be the predominantly fine-grained composition of the top part of the fluvial sediments (Novak et al., 2020b; Zecchin et al., 2024) resulting in lower erodibility compared to less cohesive sediments containing higher proportions of sand particles (de Smit et al., 2021; Wu et al., 2018).

Finally, the reconstructions shown in this work also have implications for understanding the archaeological record in the Gulf of Trieste. Based on bathymetry-derived paleoenvironmental reconstructions it was previously believed that the earliest Neolithic sites in the northern Adriatic are situated in the present-day area of the Gulf of Trieste. Only when the difference between the pre-transgressional paleotopography and the present-day bathymetry was considered it became apparent that most of the area of the present-day gulf was flooded long before the Neolithic (Benjamin and Bonsall, 2009). The results from this study corroborate the assumption of Benjamin and Bonsall (2009) and provide additional insight into the extent of the flooded areas of the Gulf of Trieste in different time periods.

6. Conclusions

This study demonstrates the importance of using appropriate input data for paleoreconstructions of past shorelines and sea-land extent. Using bathymetry instead of a paleotopographic elevation model can result in significant errors resulting in unrealistic reconstructions and should be avoided whenever possible. Instead, paleotopographic elevation models based on geological data should be used in order to generate more reliable and evidence-based reconstructions. These findings are especially important for reconstructions in predominantly sedimentary low-gradient continental shelf and coastal areas where even relatively small sea-level variation can affect vast expanses of the low-gradient area.

Paleocoastal modeling for the Gulf of Trieste in this study demonstrated that the post-glacial transgression in the present-day area of the gulf was controlled by the pre-existing topography of the broader area. The flooding of the gulf was relatively abrupt and initially in a predominantly northeasterly direction perpendicular to the longitudinal direction of the Isonzo megafan. After the deepest parts of the basin were filled flooding gradually advanced towards the higher northwestern areas. These findings provide new insights into the Early Holocene evolution of the present-day area of the Gulf of Trieste.

Data availability

Data used in this study is available at EMODnet Bathymetry Consortium (2022; https://doi.org/10.12770/ff3aff8a-cff1-44a3-a2c8-1910bf109f85) and Trobec et al. (2018; https://doi.org/10.5194/essd-10-1077-2018).

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CRediT authorship contribution statement

Ana Novak: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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