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# PALAEOTOPOGRAPHY CONCERNING SEA LEVEL CHANGES TO RETHINK PAST HUMAN ACTIVITIES IN CENTRAL DALMATIAN ISLANDS AREA, ADRIATIC SEA

# PALEOTOPOGRAFIJA, UPOŠTEVAJOČ SPREMEMBE GLADINE MORJA ZA SPREMLJANJE PRETEKLIH ČLOVEKOVIH AKTIVNOSTI NA OTOKIH SREDNJE DALMACIJE

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## Abstract

Environmental conditions and access to natural resources are important factors for human behaviour and choices about where to make settlements. This important information must be understood and abstracted into appropriate spatial datasets, so as to be modelled in geographic information systems (GIS). The main objective is to design and realize a seamless integrated digital elevation model (DEM) from several data sources, including bathymetry. The important focus of this paper is to collect and interpret the sea level data for the Central Dalmatian islands over the past 15,000 years, describing the entire case study's implementation in terms of hydrology, landscape archaeology, geodesy, data quality assessment, and spatial analysis. The results demonstrate that the proposed model has the potential to rethink the archaeological theories of settlement patterns in the studied area. The limitation of the proposed study is a lower quality of bathymetric datasets, and the determination of the historical sea level due to a number of uncertain factors. The work has profound implications in terms of the developed GIS tools that make it possible to generate reliable datasets and simulate various scenarios, as well as for a non-destructive prediction of the past archaeological landscapes. The solution may help increase awareness about cultural heritage, environmental conservation, and climate change.

**Keywords:** sea level change, coastline model, palaeoenvironment, digital terrain model, bathymetric terrain model, GIS, spatial analyses, landscape archaeology.

## Izvleček

Okoljske razmere in dostop do naravnih virov so pomembni dejavniki človekovega vedenja in izbire lokacije bivanja. Po drugi strani je treba te pomembne informacije razumeti in formalizirati v ustrezne prostorske zbirke podatkov za modeliranje v geografskih informacijskih sistemih (GIS). Glavni cilj je oblikovati in uresničiti celovit digitalni model reliefa (DMR) iz različnih virov podatkov, ki vključujejo tudi batimetrijo. Pomemben poudarek tega prispevka je zbrati in interpretirati podatke o morski gladini za otoke Srednje Dalmacije za zadnjih 15.000 let ter izvedba študije v smislu hidrologije, krajinske arheologije, geodezije, ocene kakovosti podatkov in prostorskih analiz. Rezultati imajo potencial za učinkovit premislek o arheoloških teorijah o poselitvenih vzorcih na preučevanem območju. Omejitev predlagane študije je nižja

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kakovost batimetričnih podatkov in negotovost pri določanju pretekle gladine morja zaradi številnih dejavnikov. Glavna prednost so GIS-orodja, ki omogočajo ustvarjanje zanesljivih podatkov in simulacijo različnih scenarijev ter nedestruktivno napovedovanje preteklih arheoloških krajin. Glavna korist se pričakuje s povečano ozaveščenostjo o kulturni dediščini, ohranjanju naravnega okolja ter zavedanju o podnebnih spremembah.

**Ključne besede:** spreminjanje morske gladine, model obalne linije, paleookolje, digitalni model reliefa, batimetrični model reliefa, GIS, prostorske analize, krajinska arheologija.

## 1. Introduction

The Earth's topography is changing all the time due to human and natural influences. Long-term climate changes already caused various shifts in global flora, fauna, and human populations. The situation is even more pronounced over several centuries or millennia. However, our knowledge about environmental conditions decreases as temporal distance increased. One of the promising approaches is to generate palaeotopographical data as a base to elaborate a model of the environmental changes over a longer period.

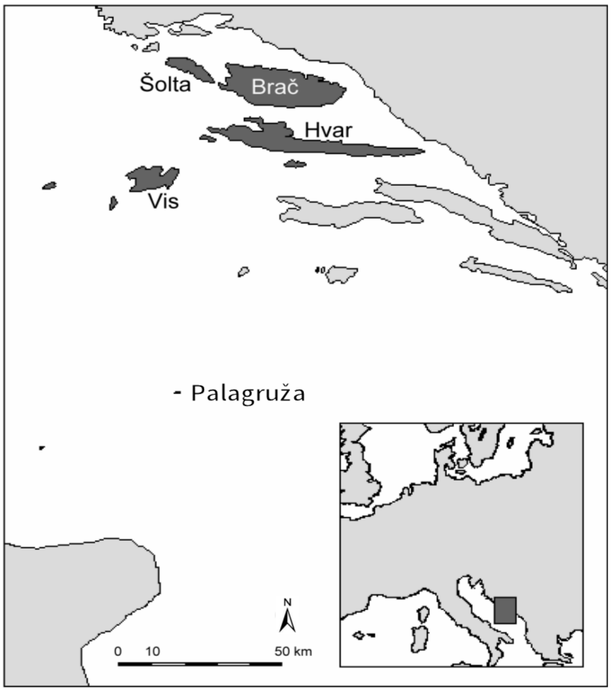

***Figure 1:*** *The study area.*

***Slika 1:*** *Študijsko območje.*

The Adriatic Sea occupies the foreland of the Apennine and Dinarides thrust belts, which originated in the collision of the African and the European plates, with a continental crust about 35 km thick. The contemporary Adriatic is a narrow epicontinental basin (with its extension of about 200 x 800 km). Its eastern shore, which features numerous islands, extends in the central part to the middle of the basin, while there are but few islands on the western shore.

An international team of archaeologists, historians, geographers and other specialists researched the Central Dalmatian islands in Croatia throughout the 1990s and beyond. The study area transacted the islands running from the mainland to the small island of Palagruža in the centre of Adriatic and incorporating islands Brač, Šolta, Hvar, Vis, and a number of smaller islands (Figure 1). As an important extension to our research of human activities in this region, the sea level changes and their potential impact on the archaeological theories are studied here.

## 2. Sea level dynamics

The study is focused on modelling the average sea level of the Mediterranean and Adriatic basin within different archaeological periods. The detailed sea dynamics theory is out of the scope of this paper and thus only basics are described to understand the complex changes. Sea level is a globally defined field that allows us to prescribe the complementary "sea level" over both continents and oceans (Mitrovica, 2003). In contrast, the "ocean height" only concerns the sea level prescription over oceans.

The Adriatic's main circulatory energy runs along the Croatian (NW direction) and Italian (SE direction) coasts. This energy depends on wind, sea density variance, tide oscillation, wave motion, inertial oscillation, pressure gradient, etc., with a maximum in autumn and winter, but it does not change the sea level significantly (Artegiani et al. 1997a, 1997b; Ursella et al., 2003).

### 2.1 Sea level evidence

Studies of sea level change are primarily concerned with variations in the quantities of the sea level and ocean height field, i.e. the changes to total water mass and its relocations at different times. Theories about sea level change encompass numerously interrelated global and local physical phenomena and processes (Mitrovica, 2003; Ridente and Trincardi, 2002). Computing changes must consider global ice history, ocean height change, rotation perturbation (Earth gravity field etc.), tectonics, shoreline migration, depositional cycles, and several local processes such as local seismic, tectonic deformation (subsidence), erosion formatting influence and sediment fluxing, storm surges and seiches, tides, etc. All these phenomena and many others act as a triggering condition to sea level bounding surfaces (i.e. the geoid and solid surface), and consequent water influx (water dumping) into the region concerned. It must be stressed that the accuracy of modelling highly depends on the completeness of the governing theory, its complexity, and the limits of reliability of the observational datasets. Therefore, the eustatic sea level values are rough estimates in general, but the shaping of the representative (calibrated) sea level curve is a fair representation of global sea level dynamics.

Research on relative sea level change in the Mediterranean area is rather limited. Sea level at the global scale is hydraulically controlled at the Strait of Gibraltar, limiting the amount of water flowing from the Atlantic Ocean (Sanchez-Roman et al. 2018). The palaeo sea level analysis for the area around Sicily and some other cases (Gargano, Italy) suggest the presence of a small anomaly with respect to other Mediterranean Sea level curves. The complex and interconnected mechanisms of eustatic sea rise, coastal rebound, and tectonic movements are becoming better understood in the Mediterranean (Antonioli et al., 2002, 2017).

Long-term sea level change analysis requires time-series of sea level heights over a period of several thousand years. Tide gauge stations provide records only over the last century that cannot be extended over a longer period associated with archaeological periods. Several more recent subsurface investigations suggest an overall glacio-eustatic control on sequence architecture in the Adriatic basin (Amorosi and Milli, 2001; Cattaneo et al., 2003; Antonioli et al., 2002). This means that general sea level dynamics in Adriatic basin were mostly qualified by global dynamics (global magnitudes of sea level high- and lowstands) and the regional tectonic impact was less significant and expressed at a certain deviation within global evolution. Similarly, information from younger deposits indicates that the cyclic stacking pattern of marginal marine and alluvial facies during the late Quaternary was formed under a predominantly glacio-eustatic and climatic control (Amorosi and Milli, 2001). Moreover, regional subsistence must have played a fundamental role in the accommodation space during the long phase of progressively lowering sea levels in the period of 125,000 years ago and onwards.

Despite holistic studies concerning sea level dynamics in the Adriatic basin along with its calibrations are not readily available; plenty of useful information can be obtained from specifically focused studies. A few studies investigate the importance and influence of sediment pathways evolution and fluvial supply fluctuations to sea level change but are mainly made for the western part of Adriatic basin (Cattaneo et al., 2003, Amorosi and Milli, 2001). The extent of weather and climatic determinants to relative (and more hazard) sea level oscillations in north-eastern Adriatic is shown through the investigation of storm surges in the last 100 years (Pasarić and Orlić, 2001). According to the authors, the seasonal variability triggered by storm surges may have a range up to 70 cm in sea level oscillations and thus the atmospheric disturbances may be understood as the ever-present contribution to the floods in the Adriatic coastal zones.

In terms of sea level variability also accompanying processes such as lowstand deposits, transgressive deposits and highstand deposits must be addressed, since these are main factors influencing sea floor thickness, and can reach from several meters up to dozens of meters in sediment cover, and therefore influence sea floor volume and consequently sea level height (Amorosi and Milli, 2001). Besides, the transition of thickness from several tens of meter of late Holocene mud to nil suggests the role of southward-flowing, bottom-hugging shelf currents in causing the redistribution of sediment along the Adriatic inner shelf (Cattaneo et al., 2003). In addition, subaqueous deltas (major river entering) in Adriatic basin (for example: Po delta fluvial supply in NW, Neretva fluvial supply in central east part) in more recent times play an important role in the basin dynamics as large amounts of sediment may be supplied to the shelf and prevent sedimentation in coastal settings. Simultaneously, such fluvial supply can exhibit extensive and laterally continuous mud-dominant regressive wedges up to several dozen meters in thickness at some distance from the coast (Cattaneo et al., 2003). Oceanic processes redistributing riverborne sediments alongside mud wedges barriers constitute the characteristics of basin-wide deposit, changing in time.

The Adriatic region is a wedge of continental lithosphere underlying the Italian peninsula, Sicily, and the Dinarides within the African-Eurasian (and Arabic) collision zone. Three microplates are found in the Eurasia-Arabia-Africa collision zone. One of them is the Adriatic (or Apulian or Apeninic-Adriatic) plate, whose promontory belongs to the African plate. The most accurate measurements were made with GNSS (GPS) for the geodetic system and mapping purposes. Locally, many accurate measurements have been taken around Venice, where a problem is the most perceptible and much influenced by anthropic factors. For Venice it is known that the physiologic rate of subsidence is around 0.4 mm/year (Valloni, 2000), resulting in almost 1 m in the last 2000 years For the Italian coast, meanwhile, sea level change has been studied for the past 10,000 years (Lambeck et al., 2004). We should also mention measurements for the Eastern Adriatic coast (Croatia) made with the C method$^{14}$ for the time around 10,000 BC (Surić et al., 2005). Kinematically, convergence between Eurasia and Africa is taking place in a north-south direction at a rate of 10 mm/year. The Adriatic lithosphere plate moves to the northeast with respect to Eurasia. The active deformation in the Adriatic region is highly variable. Velocities relative to the Eurasia plate decrease from the south (~5 mm/year) to the north (~2 mm/year; Battaglia et al., 2003). The general subsidence of the coast in Central Dalmatia is perceivable and it should be considered together with the sea level model (Baric et al. 2008).

These few examples only outline a small extent of the complexity of regional sea level parameters. To define how these often interrelated processes influence the sea level variation is not an easy task, and herein lies a reason why fine calibration for the Adriatic basin is ultimately lacking.

### 2.2 Sea level information synthesis

It has been noted that sea level modelling is rather complex. In spite of the mentioned difficulties, there is also lack of calibrations for regional basins. As a first estimate in this study, a model that contains relative changes was proposed and then its consequences to landscape changes were observed. The sea level model that we used combines global (eustatic) and local (tectonic) determinants and is calibrated for different parts of Earth, including the Mediterranean area. Existing techniques for natural fluctuation of sea level and global ice-volume change are based on the recent geological exploit of fossil coral-reef terraces or oxygen-isotope records from benthic foraminifera or on a combination of the two and different calibrations applied. The data used in this study is based on an improved technique using combined evidence of extreme high-salinity conditions in the glacial sea with a corresponding control model of water flow, adjacent to the fossil and isotope approach (Rohling et al., 1998). The model was primarily chosen because it can provide comparative and reasonable results together with other general information on sea level highstands and lowstands, and, furthermore, the results are associated with the last glacial-interglacial ice volume fluctuations of the order of today's

Greenland and West Antarctic ice-sheets. This method is also explored and tested on Red Sea data from Egypt (see Rohling et al., 1998).

The global sea level record (Table 1) has been developed on the calculation of parameters over the last 500,000 years. This is a time covering glacial and interglacial periods, so between 500,000 and 100,000 years before present sea level oscillations were cyclic and could have reached up to 140 m in range. The general error associated with the mentioned sea level lowstands is estimated to be about ±20 m. About 120,000 years ago the sea level reached its last highstand, and the situation was similar to today's. After that, slow but oscillating decrease happened and so, the last lowstand was just about 20,000 years, and the sea level at that time was about 120 m lower than today. From then on, the linear increase can be observed.

***Table 1:*** *Global sea level magnitude records calculated as an average of two methods' results. The first method was based on benthic isotopes and the second was based on coral reef terraces and benthic isotopes. Data regarding sea level estimates are interpreted according to Rohling et al. (1998). In bold the time slices corresponding to archaeological periods under investigation on Central Dalmatian islands are highlighted.*

***Preglednica 1:*** *Zapisi globalne ravni morja so izračunani kot povprečje rezultatov dveh metod. Prva metoda temelji na bentoških izotopih, druga pa na terasah koralnih grebenov in bentoških izotopih. Podatki o ocenah morske gladine so interpretirani glede na Rohling et al. (1998). V krepkem tisku so poudarjena časovna obdobja, ki ustrezajo arheološkim obdobjem v zvezi z raziskavami na srednjedalmatinskih otokih.*

| Date | Archaeological period | Average sea level [m] | Surić | Fairbanks |
|---|---|---|---|---|
| 2000 AD | Present | no data; level 0 | | |
| 700-800 AD | The Arrival and Era of the Slavs | no data; level 0 | | |
| **300 BC-200 AD** | **Roman colonisation**<br>**Greek colonisation** | **0** (**-1** in Adriatic) | | |
| | | linear increase | | |
| **1000 BC** | Iron Age | 7 | | ~ -2 |
| | | linear increase | | |
| **2200 BC** | Bronze Age | **8** | | **~ -5** |
| | | linear decrease | | |
| 4000 BC | The Neolithic | 5 | | |
| **6000 BC** | | **-6** | **-23** | |
| | | | -34 | |
| 8000 BC | **The Upper Palaeolithic** | -16 | (10500) -36 | ~ -38 |
| 10000 BC | | -31 | (13500) -38 | ~ -70 |
| **13000 BC** | | **-70** | | **~ -110** |
| 20000 BC | | -112 | | |
| 30000 BC | | -85 | | |
| 120000 BC | | ~0 | | |
| | | linear decrease | | |
| 135000 BC | Last glacial age | -120 | | |

However, our interest in this mapping is only for corresponding archaeological periods, i.e. for the last 15,000 years. Approximately 21,000 years ago the sea level (at last glacial maximum) was presumably around 120 m lower than today, whereas the northern Adriatic coast was that time located around 250 km more to the south according to today. After that sea level was rising continuously, refilling the Adriatic basin and reaching its peak ~4000 years ago, when sea level was around 8 m above today's sea level (this data is very uncertain). From that time onwards the sea level has been decreasing, reaching the situation of today.

The general sea level uncertainty constraint, with sparse indications on regional spatiotemporal dynamics and with a lack of sea level height evolution for the central Adriatic basin (our case study), forced us to use quite generalised data for our territorial analysis of the Dalmatian islands. Global (calibrated eustatic) sea levels were used to explore settlement's possible influence on islands. Because of the fact that some Roman Age sites are slightly under the present sea level (tectonics!), we suggested a sea level of –1 m instead of 0 m. Due to this estimation, the uncertainty is around one meter for the Roman Age and a few meters for the other older archaeological periods. For our model, the following sea level estimations according to the present situation are proposed:

- –1 m for Roman Age
- +8 m for Bronze Age
- –6 m for Neolithic, and
- –70 m for Upper Palaeolithic

Nevertheless, with the calculated and estimated data, we suppose that the proposed sea level modelling is a useful tool for the simulation of possible environmental situations in the studied historical period.

## 3. Central Dalmatia sea levels model implementation

A digital elevation model (DEM) is an appropriate dataset to model different sea levels. The traditional DEMs could be used only to model sea levels that are higher than the present sea level, such as for the Bronze Age (+8 m) for example. The sea floor data is needed to analyse all lower sea levels.

### 3.1 Integrated digital elevation model processing

The goal is to generate a seamless integrated DEM for elevations that are higher than the sea level, together with the bathymetry for the current sea floor. We employed the common horizontal coordinate reference system ETRS89 for all of the Central Dalmatia study area, with the geodetic datum of ellipsoid WGS84 and cartographic projection of UTM in zone 33T, which has a central meridian of 15° east. The grid cell size of 25 m was arbitrarily selected.

The used datasets reflected their availability in the time of the DEM processing at the beginning of the 2000s. They were available in three different coordinate systems. The first two groups of datasets were originally recorded in the old local Yugoslav systems and the third group in a global coordinate system. Topographic maps of the first group were produced based on a Gauss-Krüger map projection with a Bessel 1841 reference ellipsoid. A characteristic of this Cartesian coordinate system is its gross error in the fundamental point with a shift in latitude of around 1" and in longitude around 17". The other issue to be solved is that Central Dalmatia's topography was allocated into zones 5 and 6 according to the central meridians of 15° and 18° east. The second group of datasets according to the coordinate systems were the nautical maps. This coordinate system is similar to the first. The difference with respect to the first is only that the projection is Mercator with geographic coordinates. The third group of the datasets were recorded in geographical coordinates and not projected. These datasets are global.

The following datasets available in the three described coordinate systems were implemented for the integrated DEM generation. The assessment of their positional accuracy to "high", "medium", and "low", as indicated below, depends on the potential impact of the particular dataset on the seamless integrated DEM processing, and relevance of this final DEM for to the sea level dynamics analysis.

Primary datasets

- coastline: vectorised topographic maps 1:25,000: Gauss-Krüger projection on a Bessel 1841 ellipsoid; for most of the study area; positional accuracy is 13 m (relatively high)
- contour lines and spot heights: vectorised topographic maps 1:25,000: Gauss-Krüger projection on a Bessel 1841 ellipsoid; for most of the study area; vertical accuracy of 4 m, positional accuracy is low
- contour lines: vectorised topographic maps 1:5000: Gauss-Krüger projection on a Bessel 1841 ellipsoid; for a small area of island Hvar; vertical accuracy of 3.5 m, positional accuracy is medium
- contour lines: vectorisation of topographic maps 1:50,000: Gauss-Krüger projection on a Bessel 1841 ellipsoid; for islands Hvar and Vis; vertical accuracy of 7 m, positional accuracy is low
- sea floor spot heights; vectorisation of nautical maps 1:100.000; Mercator projection on a Bessel 1841 ellipsoid; vertical accuracy of 2 meters in flat areas and areas down to 10 m deep, otherwise around 10 m, positional accuracy is very low

Secondary datasets

- coastline: from global dataset – unprojected geographical coordinates; for lateral areas; positional accuracy of 100 m
- ETOPO5: unprojected geographical coordinates in 5’ grid of NGDC (ETOPO5, 2001); for lateral areas; very low accuracy
- GTOPO30: unprojected geographical coordinates in 30” grid of USGS (Hastings and Dunbar, 1998); for lateral areas; vertical accuracy of 25 m and very low positional accuracy

At first, the datasets from traditional analogue topographic maps (hard copy) were vectorised and attributed. All datasets were converted into a common coordinate system ETRS89 in UTM projection. The next step was data rasterization to a common raster cell size of 25 m. Different interpolation methods were used for dissimilar datasets: a spline interpolation for contour lines in scale 1:5000 and 1:25,000 and for the sea floor, a linear inverse distance interpolation for contour lines in scale 1:50,000, and a natural neighbour interpolation for ETOPO5 and GTOPO30. The resulted seamless integrated DEM surface was obtained using a weighted sum and geomorphological enhancement of singular elevation models.

The final model was better than any singular dataset at any location that was especially evaluated compared to the previously processed DEMs of islands Hvar and Brač, from vectorised contour lines of topographic maps in a scale of 1:25,000 and 1:50,000. The quality of the seamless integrated DEM is also proved with an analogy to the similar procedure and some similar datasets that were later applied on the national DTM with resolutions 12.5, 25, and 100 (Podobnikar, 2005; GURS, 2017). The final model is also geomorphologically correct without visible borders between different data sources. As we can see, all eight different datasets were efficiently integrated into a seamless DEM. The vertical accuracy and the geomorphological quality that varies from cell to cell were optimally balanced (Figure 2).

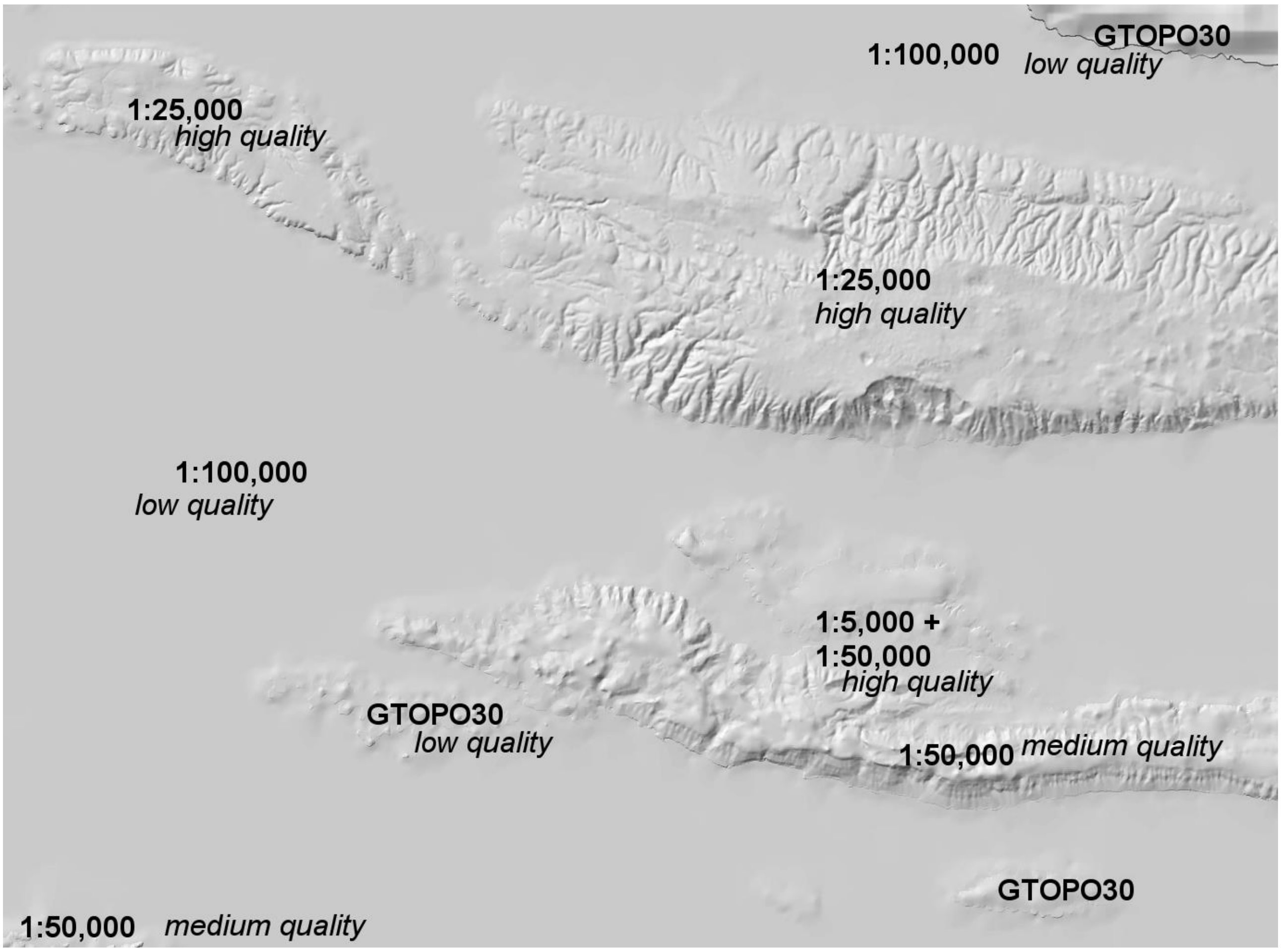

***Figure 2:*** *Variable quality of the integrated DEM as a product of conflation of different datasets using the weighted sum method on the part of the study area.*

***Slika 2:*** *Različna kakovost integriranega DEM kot produkta zlivanja različnih podatkovnih nizov z metodo tehtane vsote na delu študijskega območja.*

### 3.2 DEMs according to different coastlines

From the integrated DEM we calculated four singular contour lines that reflect proposed sea levels. These contour lines are actually simulated coastlines for different archaeological periods. Four DEMs with these new coastlines at 0 m elevation were then provided, reflecting various archaeological periods for the archaeological case study (Figure 3). The blue represents the areas below the sea and the visible surface is presented with shaded relief. Dark blue shades present the areas of the contemporary sea, where the sea floor data were not provided for this study. The most perceivable is the last simulation (Figure 3d) representing the Palaeolithic, where all the biggest islands are connected to the mainland. Only a few areas near the present coast remain as lakes. This situation, applying a static approach based on the rigid translation of the sea level over the present landscape morphology, is vague. Very probably, the lakes did not exist 15,000 years ago and they were modelled here as a result of the uncertain fluxes of sediments and the level of deposits of rivers Neretva and Cetina. The climate in the Palaeolithic was probably drier than today, the permeability of the ground is not known, etc. All these factors potentially contribute to a significant extent to coastal morphodynamics.

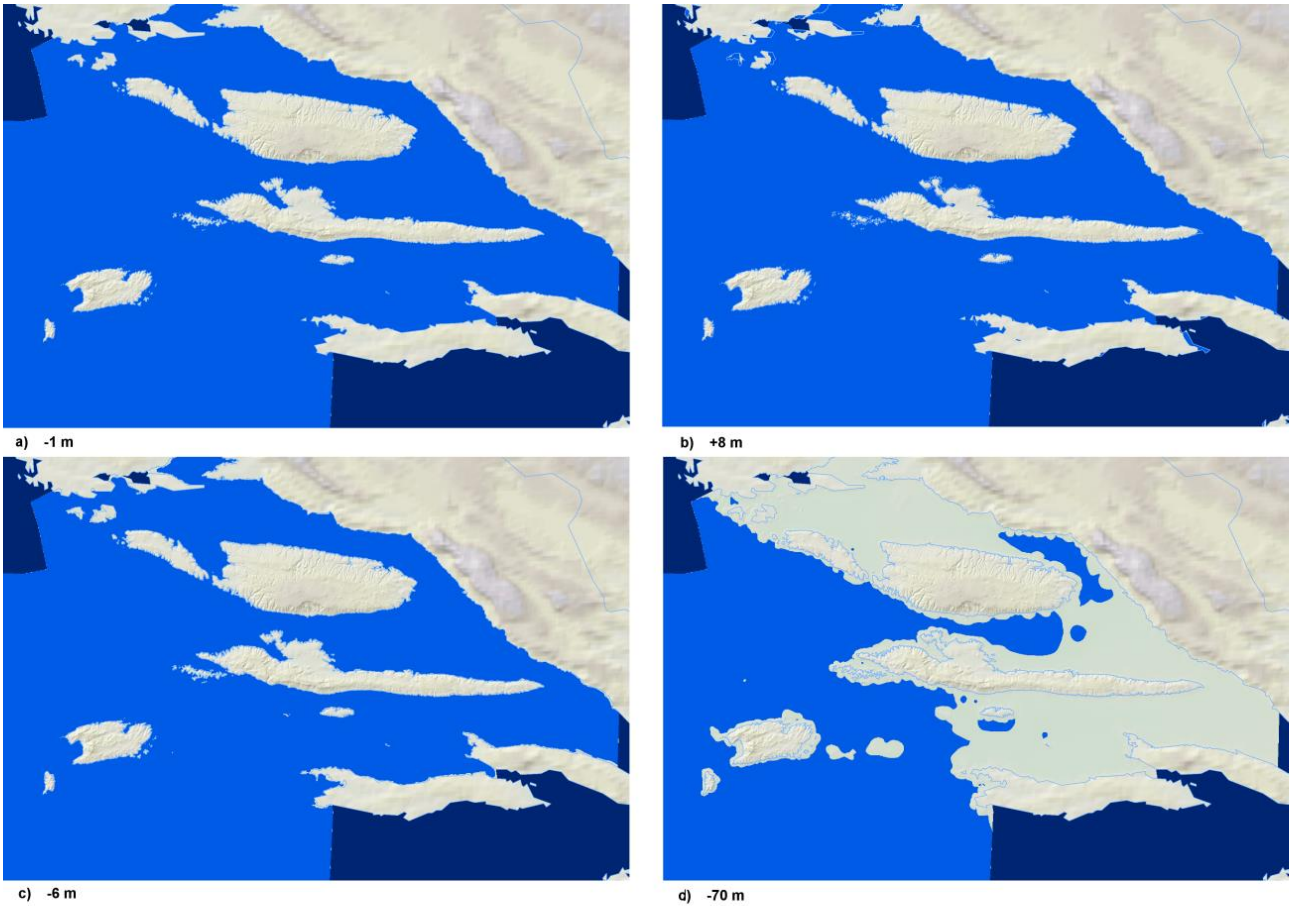

***Figure 3:*** *Simulated topography of the palaeolandscapes for Roman age (a), Bronze Age (b), Neolithic (c), and Palaeolithic (d) on the part of the study area.*

***Slika 3:*** *Simulirana topografija paleopokrajine za rimsko dobo (a), bronasto dobo (b), neolitik (c) in paleolitik (d) na delu študijskega območja.*

The results of the topography simulations in Figure 3a–c are less observable due to only a slight alteration in the sea level. Significance in the landscape's change is therefore highly dependent on both the sea level difference and the shore morphology. Figure 4 shows the simulated coastlines for the central part of the island of Hvar. It can clearly be seen that the contemporary one (blue, 0 m) is the most accurate with many details. All the others are less accurate, where the smoothness of the coastlines increases by increasing the depth of the contemporary sea. The most smooth (generalised) is the one for Palaeolithic (green, –70 m). The main reasons are in the inaccuracy of datasets, as well as in the later sediment deposits on the sea floor. It is also very possible that the ancient coast appearance was as much fractal (geomorphologically more branched) as the contemporary one due to the washed off sea surface dynamics. It is interesting that the Bronze Age contour line (violet, +8 m) is also very generalised. It was generated from relatively detailed datasets, at least as compared to the present sea level coastline. The reason for the surprisingly high inaccuracy of the contour lines higher than 0 m is in:

- the accuracy of contour lines vectorised from topographic maps is much lower than the accuracy of the coastline (it is much easier to recognise a clear border between sea and land than to construct a contour with a particular height)
- the coastline is vectorised at a scale of 1:25,000, the integrated DEM is produced mostly from contours in scales from 1:25,000 to 1:50,000 (rarely in scale 1:5000)

- contour lines on maps have contour interval from 5 to 50 m regarding the scale of source maps and slope that is low according to the detail level of a coastline
- positional accuracy of the integrated DEM diminishes when the slope is lower
- as indicated before, the area close to the coastline is eroded, not covered by soil and lacking vegetation, which causes some errors in photogrammetrically processed topography

Therefore, according to the DEM quality, we can conclude that the simulation of the coast would be good for general analysis in small scales at a regional level, but less suitable for the very fine large-scale, i.e. detailed analysis. Similar experiences with the DEM uncertainty simulation were provided by Gesch (2013) and Leon et al. (2014).

## 4. Archaeological case study

Archaeological evidence has shown that Adriatic islands played an important role in long-distance exchanges from prehistoric times. On the island of Palagruža, which is situated in the middle of the Adriatic, archaeological evidence from the Neolithic period emphasizes the existence of contacts over 8000 years ago. The pottery discovered at Vela Spila cave, within the island of Korčula, showed a strong relationship with the island of Hvar as well as the Adriatic coast and its hinterland during the Late Neolithic and Early Bronze Age (Čečuk and Radić, 2003). In addition, the presence of obsidian with Liparian origin, in the Neolithic station of Suzac, is a sign of trade (Della Casa and Bass, 2003; Tykot et al., 2001). From this period to Antiquity, the islands can be considered as a bridge between Mediterranean and Balkan cultural zones, and between the ancient cultures of Greece and Italy (Gaffney et al., 1997).

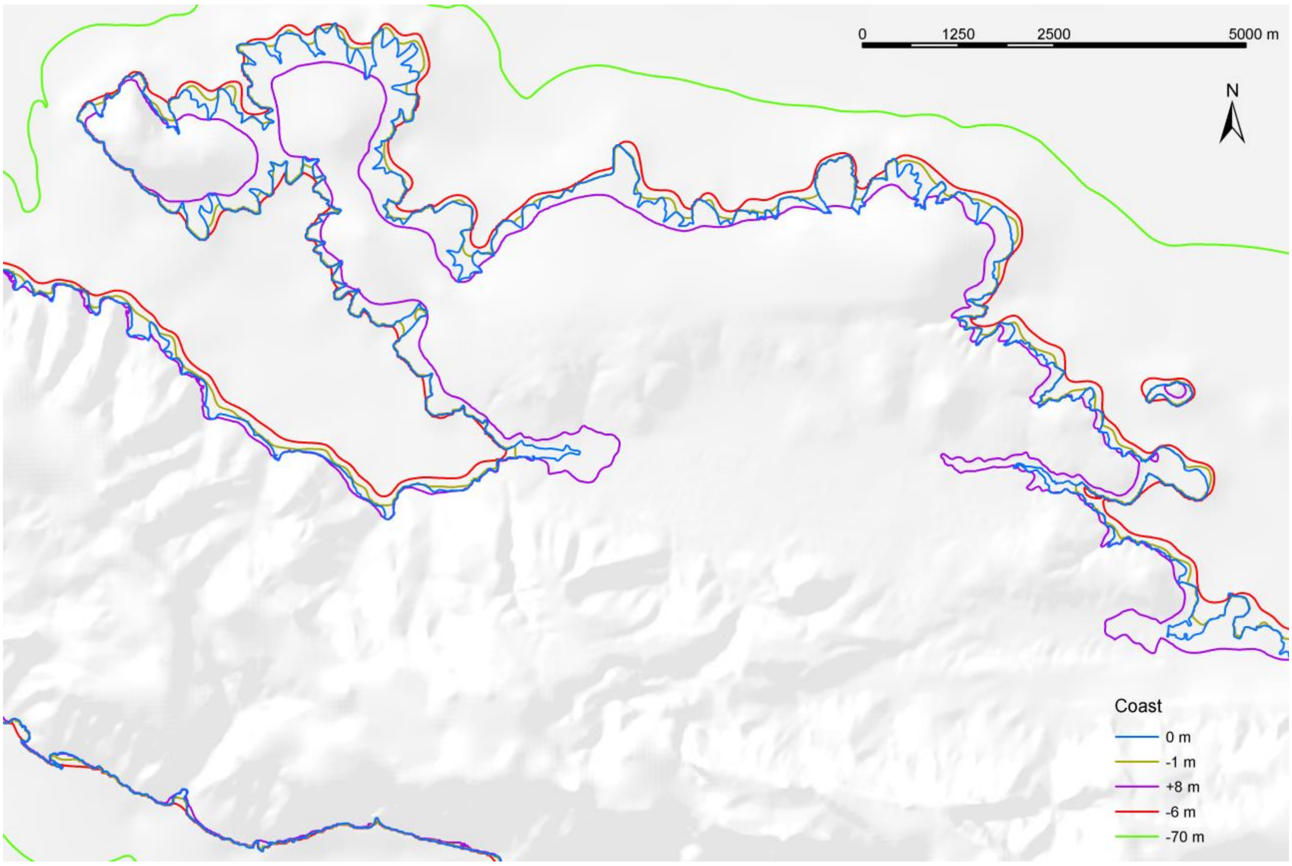

***Figure 4:*** *Comparison of coastlines of the different periods in the central part of the island of Hvar.*

***Slika 4:*** *Primerjava obalnih linij različnih obdobij za osrednji del otoka Hvara.*

We assume that sea level has an impact on settlement organisation. To illustrate this, the global sea level model indicates 14 m of difference between Neolithic (–6 m) and Bronze Age (+8 m on average). According to the present sea level, we can note variations from 1 and up to 8 m. With such amplitudes, we could expect substantial landscape modifications, which can alter our perception of territorial dynamics during past times.

Previous research used several relatively high-resolution thematic layers, such as digital elevation model (DEM), geology, pedology, hydrology acquired from topographic and thematic maps, and also satellite imagery. Simultaneously extensive data on archaeological sites and monuments were gathered using a variety of archaeological field survey techniques as well as archives and publication search. Many spatial analyses have been performed and interesting results were obtained (Gaffney and Stančič, 1991, Stančič and Kvamme, 1999). The analysis and the results were promising; nevertheless, these spatial analyses were all based on the current coastline. Distance and access to the settlement from the coast are measured on the same sea level reference, but the interpretation within the settlement organisation, including across and between periods, remains complex because of the weakly defined parameters.

Within this case study, the most important datasets have been modified and sea level dynamics have been considered according to the selected archaeological periods. The aim is twofold: (1) to observe settlement patterns regarding past sea levels, and (2) to verify regularity of spatial analyses to re-evaluate previous hypotheses regarding datasets that correspond to the recent environment and water source data. The settlement patterns were analysed for the entire case study area, while the regularity of the hypotheses was especially focused on the Stari Grad Plain on the island of Hvar, for the period between Bronze and Roman Ages. The result of the re-evaluation of the hypotheses is questionable because of the insufficient credibility of sea level data information for both periods, so it is not highlighted here.

Besides, it is our belief that with further spatial analysis and extensive study it would be possible to approach solving the question of whether environmental/climate change could have caused any shifts in native populations and culture in the central Adriatic Dalmatian islands.

### 4.1 Archaeological analyses considering sea level changes

An approach to our spatial analysis is demonstrated here. Accessibility from the coast should be considered as one of the main factors for the settlement pattern on islands. This accessibility can be evaluated using the cost distance from the coast. Then, the global distribution of settlements from the coast can be measured as time-distance, which can give, in some cases, qualitative information considering access. For instance, during the Bronze Age, for a hillfort position overhanging a 6 m cliff, the situation should be very different when the sea level was at +8 m. We developed the cost distance analysis with present and past coastlines for each period, the Bronze and Roman Age, in order to stress morphological changes and their influence regarding settlement organisation.

The cost distances were calculated with GIS tools based on the integrated DEM, described above, for each coastline. The least-cost distance algorithm is based on a calculation of friction surface regarding different slope. We considered metabolism and energy consumption of the human and its effect on moving speed. Then we applied a reclassification, which defined some accessibility steps:

- 0 to 5 minutes from the coast
- 5 to 15 minutes
- 15 to 30 minutes
- 30 to 60 minutes
- more than 1 hour

The example of the more complex results for the cost distance analysis for findspots from the Bronze and Iron Age (+8 m) show a significant difference (Figure 5).

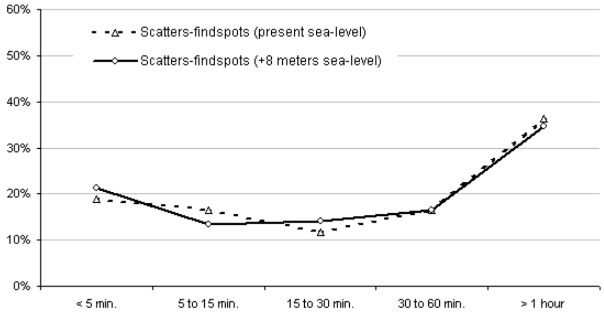

***Figure 5:*** *Cost distance analysis for Bronze and Iron Age sites for scatters and findspots.*

***Slika 5:*** *Analiza s stroškovnimi razdaljami za lokacije bronaste in železne dobe za razpršena najdišča.*

## 5. Conclusions

We have successfully produced an integrated DEM from eight data sources, applicable for palaeoenvironmental studies, and we also carried out relevant spatial analysis in GIS. The results for the case of the Central Dalmatian islands in the Adriatic Sea present an approach to improved archaeological models when higher-quality and usable datasets that consider palaeoenvironment are processed. Since the beginning of this study in 2003, many other studies, which try to consider the palaeoenvironment in archaeological research (e.g. van Heteren et al., 2014; Europe's Lost Frontiers, 2016) make this research even more relevant.

The main conclusions are the following: firstly, our approach facilitates possibly better imagination and insight into environmental characteristics over past times. Secondly, the palaeotopographic information should not be neglected for designing of appropriate spatial analyses for particular archaeological or other past periods. Thirdly, the data quality in this kind of spatial analysis is crucial for obtaining relevant results.

Besides the minor or notable level of the impact sea level might have on past settlement activities and location choice, the Adriatic Sea case study showed that palaeoenvironmental information should certainly not be neglected in archaeological studies. It has been once again proven that even the most sophisticated spatial models and GIS analysis cannot solve the problems if the information used is not adequate. For example, it would be even better to apply simple spatial analysis and spend more time on data selection, preparation, and evaluation.

The presented case study is an instructive example of real-time sea level simulation by means of a GIS-based spatial analysis, where one can simply change sea level height to get a visual impression and numerical values for any sea height or time series of them. Such a sea level simulation could be also a low-level basis for a complex virtual reality visualisation to demonstrate ancient living conditions. Simulating sea level dynamics can lead to thinking about other natural factors that better describe the environment. The other dataset that could considerably improve analysis is palaeovegetation – modelling that is several orders of magnitude more complex than that of elevations and sea levels (e.g. Podobnikar et al., 1998).

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