TECHNICAL REPORT ON SEDIMENT STOCKS IN THE ALLUVIAL COASTAL SYSTEMS

Activity 3.2

Task 3.2.2

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PROJECT CHANGE WE CARE

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Activity:	3.2 Geological and geomorphological setting and recent history
Phase Leader:	Veneto Region
Deliverable:	3.2.2 Technical report on sediment stocks in the alluvial coastal systems.

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1. INTRODUCTION

1.1. Climate change in the Adriatic region

According to the Intergovernmental Panel on Climate Change (IPCC), at the current rate global warming is likely to reach 1.5° C between 2030 and 2052 (IPCC, 2019). One main consequence of this near-future temperature increase will be a rise in sea level together with other severe environmental alterations, which will expose small islands, low-lying coastal areas, and delta regions to multiple risks.

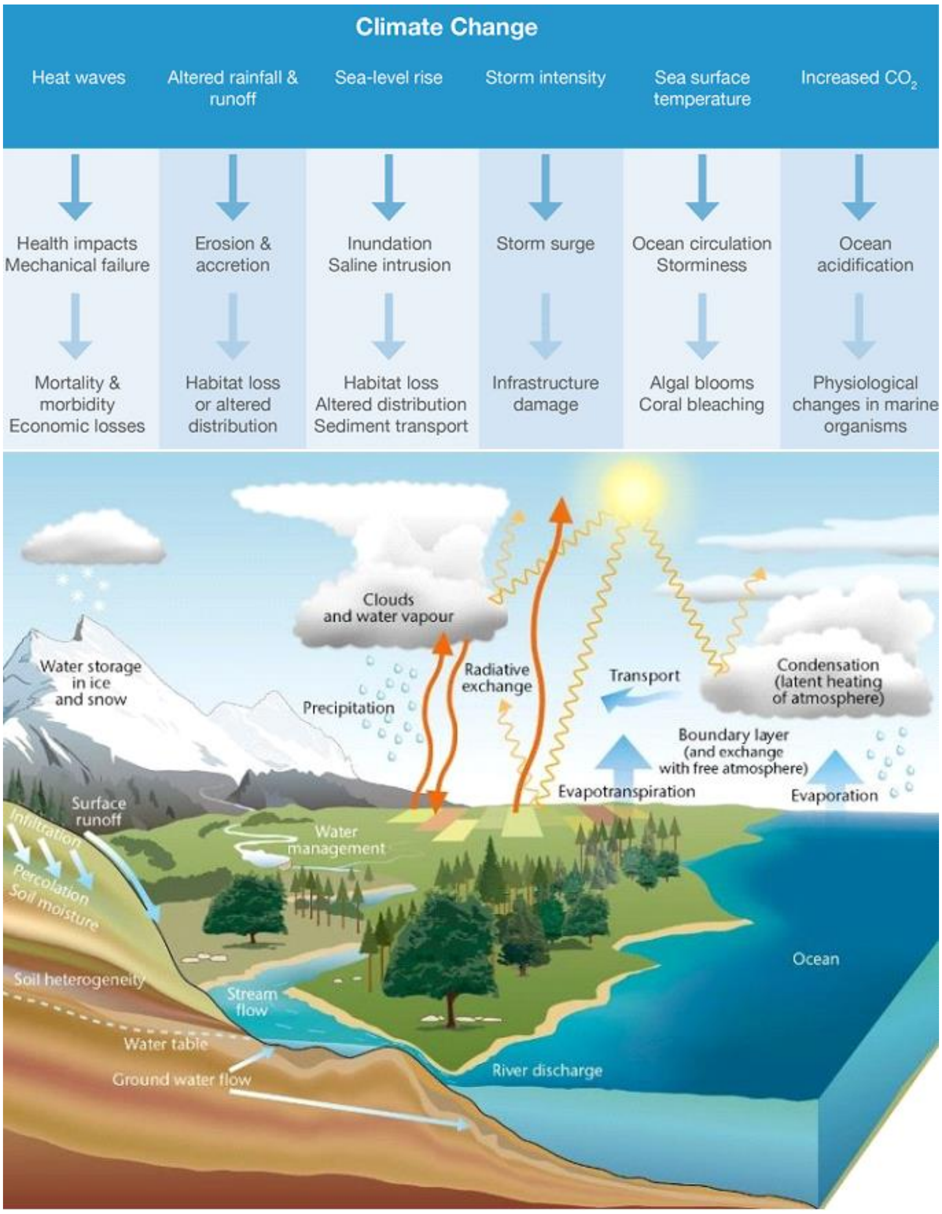


Figure 1-1: Climate change impacts on the coastal areas

Besides the increase in intensity and frequency of floods and storm surges, coastal settlements and ecological systems are susceptible to several perils exacerbated by the global warming, including increased saltwater intrusion, loss of coastal resources and reduction of the productivity of fisheries and aquaculture.

In particular, it is likely that the coastal regions will be affected by changes in: a) water chemistry (i.e. salinity, pollutants); 2) biocenosis (distribution, composition, population dynamics of animal and vegetable species); 3) geomorphology (solid transport, coastal line, delta shape, sediment composition; 4) soil characteristics and land use (Figure 1-1).

The Adriatic Sea is particularly prone to the impacts of the sea-level increase, due its conformation characterized by a low depth, a long and close shape, and anticlockwise currents. Moreover, distinct morphological, biological, and economic features characterize this densely populated area, leading to a differentiation in the expected response of the system to the future changes.

In normal conditions, the coasts in the northern Adriatic Sea are subject to higher tides, river floods, and salt intrusion compared to other Adriatic areas. Additionally, large sectors are generally subsident and susceptible to erosion. The climate change is very likely to interfere with the aforementioned natural processes and to worsen all these negative effects.

1.2. The project Change We Care

1.2.1. Project structure

This project aims at planning adaptation measures to address the most probable climate change scenarios in the coastal areas of the Adriatic region. This goal would be achieved through a harmonized planning system, based on the assessment of the different drivers affecting the future trends in the area. Overall, the project development includes **five work packages (WPs)**, excluding the first preparatory step:

0. project preparation
1. project management and coordination of activities
2. communication activities
3. **knowledge base improvement**
4. evolution dynamics under climate change
5. Pilot sites: adaptation strategies

1.2.2. WP3: knowledge on status and recent trends of the processes

The objective of this specific Work Package (WP) is to improve the knowledge about the status and recent trends of coastal and transitional system processes. Six activities took place in this WP to evaluate the following aspects:

- 3.1- Hydrological, thermohaline physical and weather-marine climate setting
- **3.2- Geological and geomorphological setting and recent history**
- 3.3-Characterization of water and sediment fluxes from the mainland
- 3.4-Habitats and biodiversity mapping and aquatic ecological quality elements: status and trend
- 3.5-Relationship between hydro-morphological factors and intertidal and transitional habitats
- 3.6-Integrated observational and modelling strategies for filling identified knowledge gaps

1.2.3. WP 3.2 activity

The Veneto Region is responsible for the activities 3.2.

"The activity 3.2 draws the state-of the-art on geological and geomorphological settings and recent evolution in the coastal areas, in particular in the selected Pilot Sites. A general description is based on available information and elaboration of historical maps, aerial photos and satellite images and topographic surveys. Where required for specific needs in relation to WP5 activities "Adaptation strategies in the pilot sites", the update of the current morphological framework would be achieved by specific campaigns, e.g. using low cost new airborne methods for assessing subaerial coastal morphology, bathymetric surveys on coastal and transitional zones, with some focus on coastal defenses. The identification of shoreline trends and sediment budget estimates deriving from sediment fluxes estimate (A3.3) permits to evaluate and interpret the erosion/depositional styles also in the framework of climate change and sediment transport drivers".

The Activity 3.2 produces three deliverables:

3.2.1 - Pilot areas geomorphological maps (report)

3.2.2 - Technical report on sediment stocks in the alluvial coastal systems (report)

3.2.3 - Data set on geomorphological and sedimentological assessment (data collection file)

The present Report, concerning the activity 3.2.2 "*Sediment stocks in the alluvial coastal systems*", has been drawn up with the contribution of the partners. This deliverable provides information on sediment characteristics and a base for the identification of the extent and fate of sediments delivered from the mainland.

The analysis considers the whole Adriatic region and the following pilot areas:

1. Neretva River
2. Jadro River
3. Nature Park Vransko Jezero
4. Banco di Mula di Muggia
5. Po River Delta, with a focus on Sacca del Canarin and Sacca di Goro

Figure 1-2: Location of the pilot sites of the project Change We Care

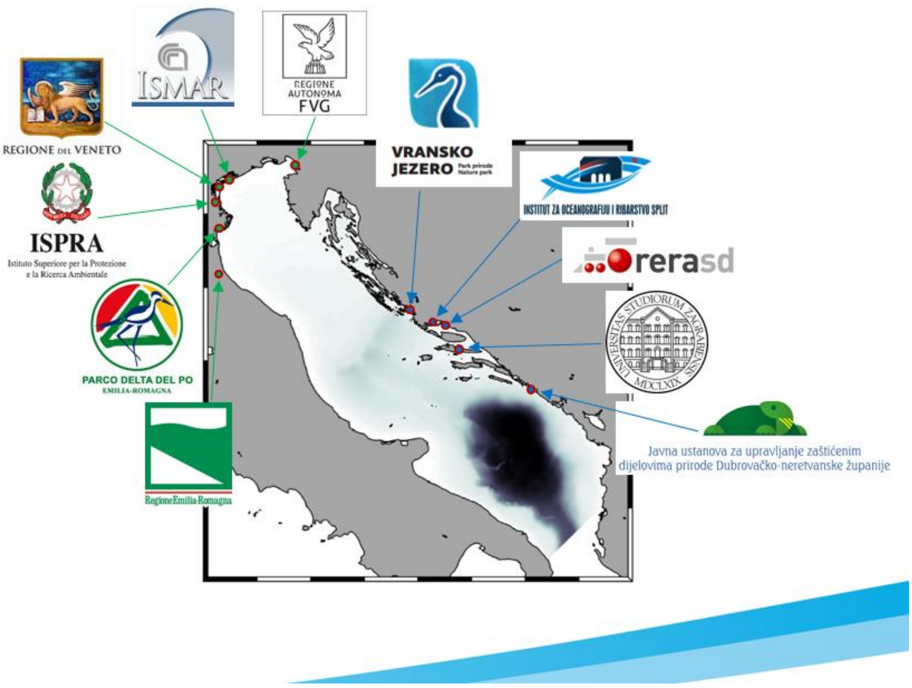


Figure 1-3: Partners involved in the Change We Care project

1.2.4. Data collection methodology

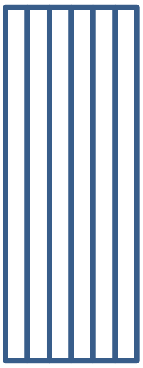
First, all the available data were collected, selecting the information useful for the preparation of the three planned reports.

The data set was obtained through the implementation of an input table that was shared with all the partners, who filled the document with the data regarding different environmental issues. A table in excel has been developed, with the structure described below

1.2.4.1. Available data collection – Table filled by each partner:

In Column:

CATEGORY TYPOLOGY (printed data, IT. data: .shp, .dwg, .tiff format, etc.)
DESCRIPTION
REFERENCE AREA (Adriatic or Local and partial or total)
DATA COLLECTED (by actual land measurements or by models)
YEARS/REFERENCE PERIOD (years, monitoring frequency)
AVAILABILITY OF THE DATA (institution, contact person, e-mail)
NOTES (regarding the maps, scale)
RELEVANT FOR (Activity/Deliverable)



In Row:

HYDROLOGICAL AND HYDRODYNAMIC PARAMETERS

- Hydroperiod
- Residence/transit time
- Water surface free level
- Flow rate
- Stress at the (river, sea, lagoon) bottom
- River flow
- Studies of special interest

GEOMORPHOLOGICAL PARAMETERS

- Bathymetry (rivers, lagoons, coastal areas)
- Topography (national, regional, and/or local cartography, GPS surveys)
- Aerial and satellite images
- Geomorphological maps
- Geological maps
- High resolution DTM
- Land Use maps
- Shorelines (e.g. photogrammetry, remote sensing, or site surveys)
- Information on evolutionary trends (eg. Coastal erosion maps, subsidence trends, etc.)
- Hydraulic Defense Works
- Hydraulic works (sump pumps, pumping stations, navigation basins, etc.)
- Maps of lithology, maps of sediment
- Hydraulic hazard maps, hydraulic risk maps
- Studies of special interest

SEDIMENTOLOGICAL PARAMETERS

- Maps of sediments/granulometry (rivers, lagoons, coastal areas)
- Suspended solid transport
- Solid transport at the (river, sea, lagoon) bottom
- River flow data
- Sedimentation rates: canals and shallow waters
- Sedimentation rates: sandbar/sand marshes
- Nourishment and dredging (data, volumes, etc.)
- Studies of special interest

PHYSICAL-CHEMICAL PARAMETERS

- Water temperature
- Water salinity
- Concentration N, P, C: water
- Concentration N, P, C sediment: channels, shallow waters sandbar, sand marshes
- Oxygenation
- Sediment salinity (sandbar/sand marshes)
- Studies of special interest

BIOLOGICAL PARAMETERS

- Maps of different habitats
- Phytoplankton
- Macroalgae
- Phanerogam
- Clams

MODELLING DATA – RIVER, METEO, OPEN BOUNDARY, LAGOONS

- Water flow (daily or better hourly), 3D flow
- Water level, sea level
- Water temperature, salinity
- Wind (hourly or at least three hours)
- Atmospheric pressure
- Humidity
- Solar radiation
- Air temperature at 2 m
- Cloud cover

ADDITIONAL DATA

- Specific measures defined in SIC and ZPS areas
- Aquaculture (Location and extension of the areas)
- Aquaculture (Clam - Location and extension of the areas)

- Aquaculture (Mussels - Location and extension of the areas)
- Minor fishery (macrobenthic fauna in the lagoon, eg: corbola, etc.)
- Location and extension of the areas

1.2.4.2. Preparation of the data set for the WP 3.2

Afterwards, the data collection for WP 3.2 was carried out in four steps:

1- elaboration of summary tables (geomorphological and sedimentological parameters) for each pilot site
2- submission of summary tables (geomorphological and sedimentological parameters) to each partner for data set controlling and completion (Figure 1-4)
3- analysis of data received and summary in a single simplified table
4- **Integration with additional data collected by the Veneto Region**

Then the data were reorganized, by selecting the most useful ones and considering the most significant studies for the **reports** regarding the **geomorphological and sedimentological evolution of the Adriatic region and pilot sites.**

WP3 - AVAILABLE DATA - GEOMORPHOLOGICAL PARAMETERS — 3.2.1 Report: Pilot areas geomorphological maps

	CATEGORY	TYPOLOGY (printed data, IT. data: .shp, .dwg, .tiff format, etc.)	DESCRIPTION	REFERENCE AREA Adriatic or Local (Pilot Areas- from 5.1 to 5.6), and partial or total.	DATA COLLECTED - by actual land measurements or by models	YEARS / REFERENCE PERIOD (and, if known, indicate the monitoring frequency)	AVAILABILITY of the data (institution, contact person, e-mail)
PILOT SITE 4: BANCO MULA DI MUGGIA - RFVG							
RFVG	Bathimetry Rivers						
RFVG	Bathimetry Lagoons						
RFVG	Bathimetry Coastal areas	shp -point, GeoTiff	Bathimetric data along transects collected by Consiglio Nazionale delle Ricerche, Gruppo di Studio dei Litorali; digitalization and DTM by Costal Group UniTS	originally 54 bathimetric sections between Timavo and Tagliamento, 15 section in the Pilot area Mula di Muggia	Bathimetric surveys along transects	1968	Servizio Geologico Regione FVG (Antonio Bratus) Università degli Stud di Trieste Dipartimento di Matematica e Geoscienze (Giorgio Fontolan)
		shp -point, GeoTiff	Bathimetric data from Regione Autonoma Friuli Venezia Giulia, 1979 - Studio dell'assetto fluviale e costiero della Regione Friuli – Venezia Giulia. ELC – Electroconsult, Studio Volta s.n.c., 161 pp.); digitalization by Costal Group UniTS	originally 28 bathimetric sections (until 10 m depht) between Timavo and Tagliamento, 8 section in the Pilot area Mula di Muggia	Bathimetric surveys along transects	1978	Servizio Geologico Regione FVG (Antonio Bratus) Università degli Stud di Trieste Dipartimento di Matematica e Geoscienze (Giorgio Fontolan)
		shp -point, GeoTiff	Bathimetric data from Regione Autonoma Friuli Venezia Giulia, 1985. Studio sedimentologico e marittimo costiero per il dei litorali del Friuli Venezia Giulia, ipotesi di intervento per il recupero ambientale e la valorizzazione della fascia costiera. A cura di A. Brambati, Regione Autonoma Friul	35 bathimetric sections (until -6m) between Grado and Primero, Pilot area Mula di Muggia	Bathimetric surveys along transects	1985	Servizio Geologico Regione FVG (Antonio Bratus) Università degli Stud di Trieste Dipartimento di Matematica e Geoscienze (Giorgio Fontolan)

WP3 - AVAILABLE DATA - SEDIMENTOLOGICAL PARAMETERS — 3.2.2 Report: Technical report on sediment stocks in the alluvial coastal systems

	CATEGORY	TYPOLOGY (printed data, IT. data: .shp, .dwg, .tiff format, etc.)	DESCRIPTION	REFERENCE AREA Adriatic or Local (Pilot Areas- from 5.1 to 5.6), and partial or total.	DATA COLLECTED - by actual land measurements or by models	YEARS / REFERENCE PERIOD (and, if known, indicate the monitoring frequency)	AVAILABILITY of the data (institution, contact person, e-mail)
PILOT SITE 4: MULA DI MUGGIA - RFVG							
RFVG	Maps of sediments/ granulometry rivers						
RFVG	Maps of sediments/ granulometry Lagoons						
RFVG	Maps of sediments/ granulometry Coastal areas	geotiff	Sedimentological map of MZ (phi) from Regione Autonoma Friuli Venezia Giulia, 1985. Studio sedimentologico e marittimo costiero dei litorali del Friuli Venezia Giulia, ipotesi di intervento per il recupero ambientale e la valorizzazione della fascia costiera. A cura di A. Brambati. Regione Autonoma Friuli Venezia Giulia, Direzione Regionale dei lavori Pubblici, Servizio dell'Idraulica, Trieste: 67 pp., 161 pp.); digitalization and geotiff by Costal Group UniTS	Pilot area Mula di Muggia	derived from sedimen sampling and analysis	1985	Servizio Geologico Regione FVG (Antonio Bratus) Università degli Studi di Trieste Dipartimento di Matematica e Geoscienze (Giorgio Fontolan)
		.pdf	Morpho-sedimentological map from GORDINI E., CARESSA S., MAROCCO R., 2003. Nuova carta morfo-sedimentologica del Golfo di Trieste (Da Punta Tagliamento alla foce dell'Isonzo). Gortania. Atti Museo Friul. di Storia Nat., 5-29.	Gulf of Trieste			
RFVG	Suspended solid transport						

PO RIVER DELTA | VRANSKO JEZERO | JADRO RIVER | B MULA DI MUGGIA | NERETVA

Figure 1-4: Summary tables for each pilot site reorganized by the Veneto Region

2. RECENT SEDIMENTOLOGICAL PROCESSES IN THE ADRIATIC COASTAL SYSTEM

2.1. General description

The Adriatic Sea is located in the eastern sector of the Mediterranean Sea, at its northernmost latitude. It separates the Italian Peninsula from the Balkans, stretching in the NW-SE direction from the gulf of Trieste to the Strait of Otranto. Clockwise from the north, it is bounded by Italy, Slovenia, Croatia, Bosnia and Herzegovina, Montenegro, and Albania, while southwards it is connected to the Mediterranean Sea through the Ionic Sea.

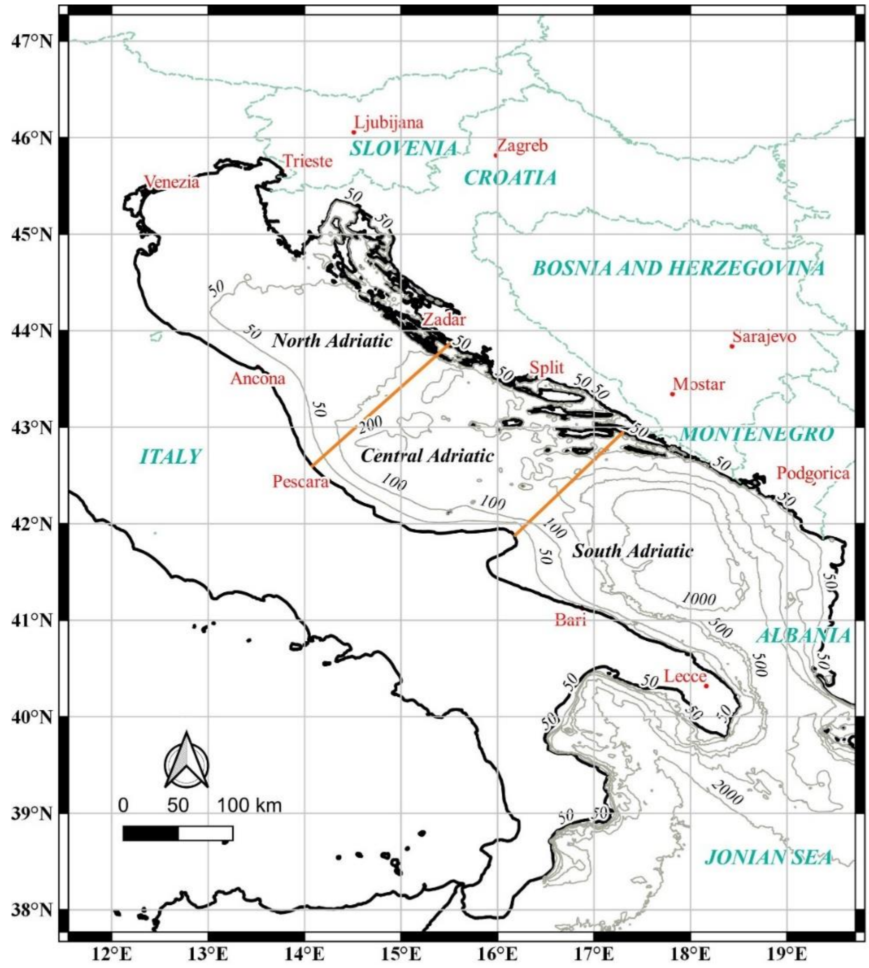


Figure 2-1: Adriatic basin configuration: boundaries and bathymetry in the three sub-basins. (Bathymetric data from EMODnet Geology)

The basin is over 800 km long and around 150–200 km wide, with a surface of about 138,600 km^2 and a volume of roughly 35,000 km^3 (McKinney, 2007). Its bathymetry shows strong transversal and longitudinal asymmetries.

Based on its morphology, the Adriatic basin can be divided into three main sub-basins, with increasing depth from north to south (Figure 2-1):

- The northern section, which is bounded to the south by the transect approximately at 43.5°N). It reaches an average bottom depth of about 35 m and it gently slopes part in south-eastern direction down to around 100 m depth.
- The central Adriatic, which elongates to the transect joining the Gargano Peninsula to the Croatian coast, with an average depth of 130-150 m. This part is also characterized by the presence of a complex transverse depression, reaching the depth of 240-270 m. South of it is the morphological elevation known.
- The southern area, which reaches the Otranto Strait, and it shows a wide depression (Meso-Adriatic Depression-MAD) 1218-1225 m deep, characterized by a regular morphology and the absence of marine relieves.

The Change We Care project involves the northern sub-basin, where the two Italian sites are located, and the central and southern sub-basin, which hosts the three Croatian pilot sites.

Close to the shoreline the seabed slope is largely influenced by the morphological features of the coast, which are highly indented and rocky in the eastern part and along the Apulian coast.

2.1.1. Ocean circulation affecting sediment dispersion

The Adriatic surface circulation is cyclonic (counterclockwise) with a northwest flow along the eastern coast and a return southeast flow along the western coast. Local cyclonic gyres develop in the three sub-basins and they have significant seasonal variations (Figure 2-2). They disappear in winter when only the north Adriatic current (NAd) and the southern Adriatic current (E-Sad) are active, while they are quite strong during the other seasons, when they are associated to the west coastal currents of the central and south Adriatic sub-basins (W-MAd e W-SAd).

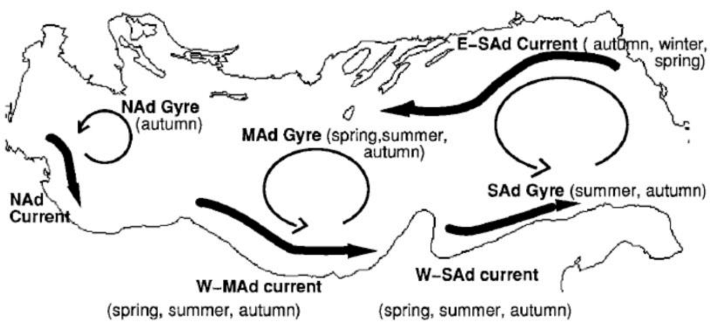


Figure 2-2: Schematic reproduction of the Adriatic Surface Water, from Artegiani et al. 1997

The general circulation is quite complex and influenced by different by factors:

1. Tidal excursions, which are relevant in the Adriatic Sea compared to other Italian seas, reaching 1 m at Venice. Fluxes and refluxes due the tides lead to strong coastal currents close to estuaries, straits and canals.

2. Wind shear forcing, which also causes drift currents through the combined action of the shear stress at the seabed and the pressure gradient along the water vertical column. The typical winds Bora and Sirocco blow along the eastern coast of the Adriatic Sea especially during cold months, while during the warmer season, sea and land breezes are frequent. Annual winds are generally NNW-SSE in the South Adriatic Basin.

3. Gradients due to the irregular distribution of surface pressure, temperature or salinity. They are responsible for the thermohaline circulation in the Adriatic Sea and for the flow of deep-water masses. In the North Adriatic Sea, along the western coast, the density and the salinity of the water is generally low because of the local climate conditions, rainfall, and fresh-water inflows from the rivers, especially from the Po River. This condition leads to an important circulation within the Mediterranean Sea, although with seasonal variations. In Summer denser and saltier water masses flow northwards from the Eastern Mediterranean Sea through the Otranto Strait, at the a depth of almost 400 m. On the contrary, in autumn-winter, the northern waters cool down and become denser. Therefore, a thermohaline current flows southwards across the continental shelf into the Ionian Sea, to the depths of the Taranto Canyon (WACC, western coastal current).

Surface and deep circulation has important implications for sediment transport. When the northern waters cool down sinking in the continental shelf, downwelling results in vertical mixing and straining of the cross-shore gradients, which in turn bring to enhanced down-coast fluxes of sediments.

The Adriatic Sea is the major source of the densest water in the eastern Mediterranean and the eastern Mediterranean deep water. Moreover, it takes in up to one-third of the freshwater flow received by the entire Mediterranean. Its entire volume is exchanged into the Mediterranean Sea through the Strait of Otranto every 3–4 years, a very short period, likely due to the combined contribution of rivers and submarine groundwater discharge.

2.2. Geological description

The Adriatic region can be considered as an independent microplate within the Africa - Eurasia collision zone. This Adriatic Plate is a small tectonic plate carrying primarily continental crust that broke away from the African plate along a large transform fault in the Cretaceous period. The name Adriatic Plate is usually used when referring to the northern part of the plate. This part of the plate was deformed during the Alpine orogeny, when the Adriatic/Apulian Plate collided with the Eurasian plate.

The Adriatic Plate is thought to still move independently of the Eurasian Plate in NNE direction with a small component of counter-clockwise rotation [1].

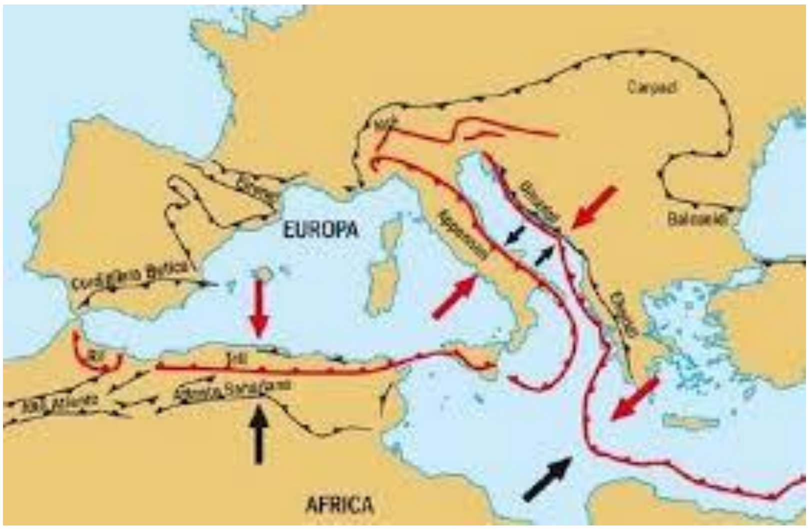


Figure 2-3: Tectonic movements in the Mediterranean area. From Devoti et al, 2002

From a geological point of view, the Adriatic basin represents the foreland of the Apennines and the Dinaric chains and it is characterized by a continental crust 30-32 km thick, which reduces to 24 km towards south.

2.2.1. Geological evolution

The Adriatic shelf is a shallow semi-enclosed basin that corresponds to the most recent (post-Miocene) Apennine foreland (Ori et al., 1986). The western part of the north-central Adriatic is occupied by a Plio-quaternary foredeep basin. The present foredeep is located in the Po Valley and in the Adriatic Sea and its filling consists of Pliocene-Quaternary age clastic sediments, with thicknesses up to 6000 m.

The Quaternary clastic deposits of the Po Valley, between the Apennine chain to the south and Alpine to the north, have thicknesses up to 1000-1500 meters. During the middle Pleistocene, the Po Plain progradation caused the complete filling of the foreland basin (Pieri&Groppi, 1981; Dondi *et al.*, 1982; Ricci Lucchi, 1986; Ghielmi et al., 2013).

During the last part of the Quaternary, the rapid succession of glacial and temperate conditions led to repeated fluctuations in the sea level, which had a significant impact on the sedimentation of the continental margins, causing the repeated passage from depositional conditions (favorable to sedimentation) under erosive conditions (subaerial exposure). All these fluctuations have been characterized by prolonged phases of sea level fall, and simultaneous growth of the ice sheets, separated by intervals of rapid rise and melting of the ice sheets. The interval following the last glacial

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[1] *R. Devoti; C. Ferraro; E. Gueguen; R. Lanotte; V. Luceri; A. Nardi; R. Pacione; P. Rutigliano; C. Sciarretta; F. Vespe (2002). "Geodetic control on recent tectonic movements in the central Mediterranean area". Tectonophysics.* ***346*** *(3–4): 151–167.*

and low stationing of sea level was characterized by a significant and generalized change in the structure of the continental margins.

The sea level has indeed risen by about 120 m in about 14-15,000 years submerging large areas of the continental shelf previously subaerial.

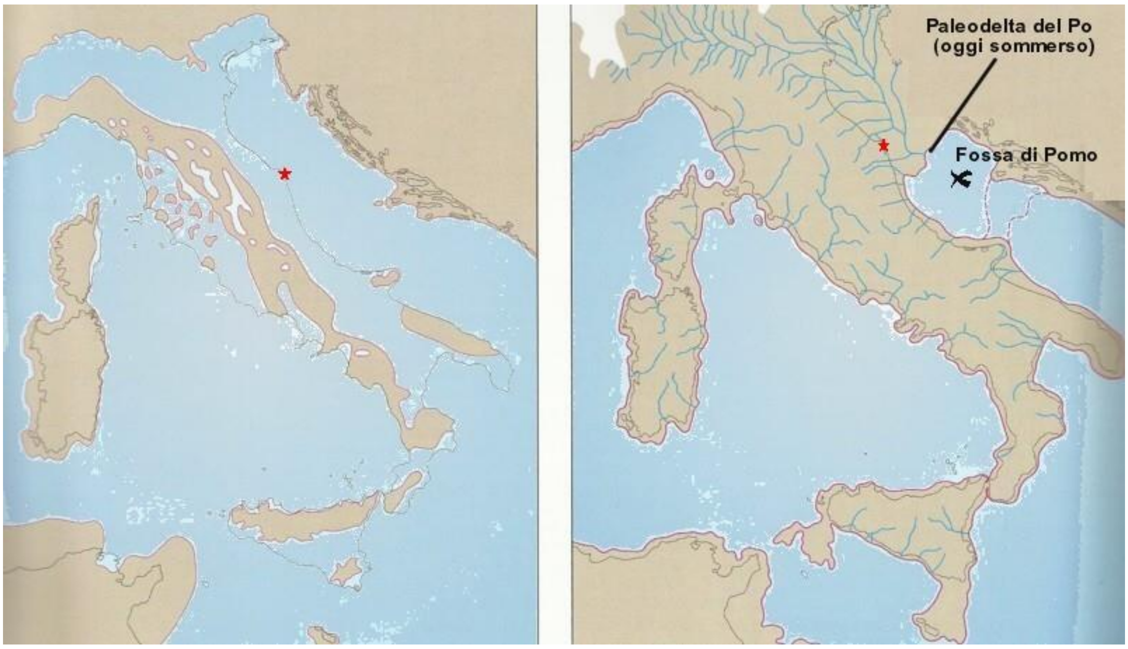

Figure 2-4: Extension of the Adriatic sea in Early Pliocene (right) and in Pleistocene (left – glacial maximum c. 18.000 y BP), the red asterisk indicates the previous position of the Po Delta

ISMAR-CNR has conducted several research projects on the Italian side of the Adriatic Sea over more than 20 years, collecting bathymetric, geophysical and sediment core data.

The goal was to perform multidisciplinary studies of modern sediment dynamics, and of past environmental changes during the last eustatic cycle. It was produced the surficial geological map of the Adriatic Sea as part of the "Geological Mapping of the Italian Seas" at the scale 1:250.000, sponsored by the Italian Geologic Survey (SGI), now part of ISPRA (Figure 2-5and Figure 2-6). The chart of the deeper geological structure focuses on the geological setting and Meso-Cenozoic evolution of the area.

The six geological charts of the subcrop contain the thickness of the Plio-Quaternary unit, and all the tectonic features, and are referred to the base of the Plio-Quaternary unit. Inside each sheet, seismic reflection profiles crossing the area and stratigraphic sketches are presented, they show the long time geological evolution and the tectonic context of the Adriatic Sea.

The geological map of the Adriatic Sea is the first cartographic project in Italy giving a synthetic representation of the distribution of genetic composition of the Adriatic shelf and margin and the tectonic and stratigraphic characteristics of the Adriatic Sea. The charts of the seafloor and subsurface represents geological bodies outcropping at the seafloor or lying in the immediate subsurface, and contains information on their stratigraphy, internal geometry, geomorphology, sedimentologic characters and geochronological significance in the context of the late-Quaternary sea-level fluctuation.

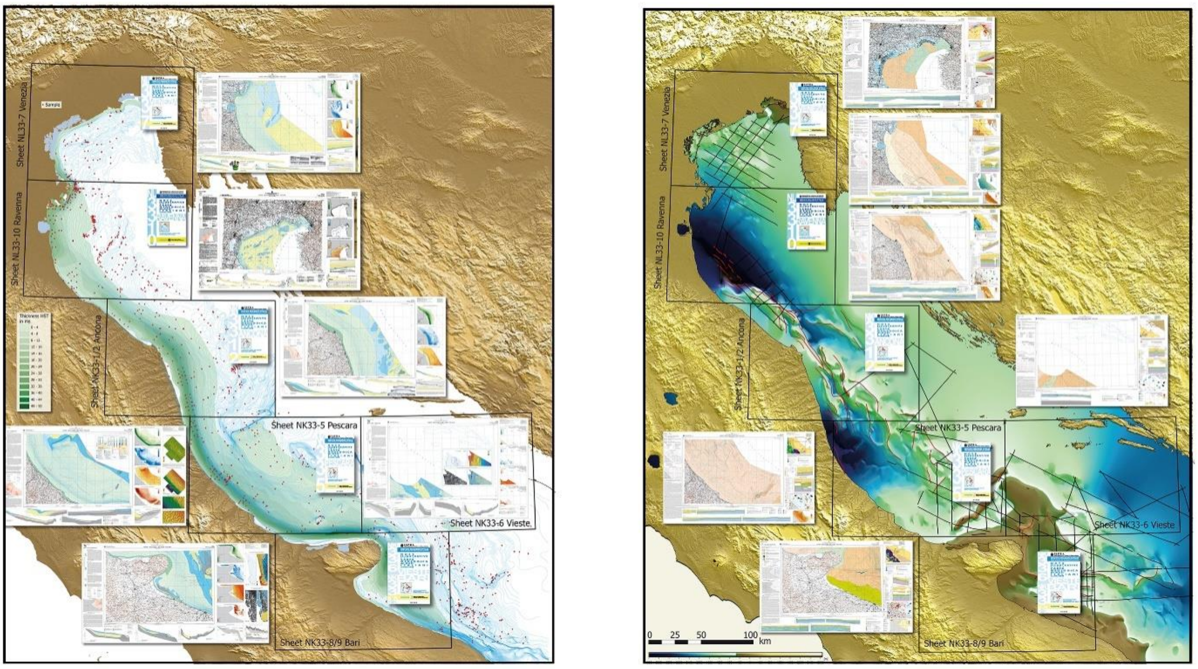

Figure 2-5: Marine Geological map of the entire Adriatic,left superficial geology and right referred to the base of the Plio-Quaternary,published in "Geological Mapping of the Italian Seas" at the scale 1:250.000, sponsored by the Italian Geologic Survey (SGI, now part of ISPRA) (online: https://www.isprambiente.gov.it/Media/carg/index_marine.html)* [2]

The six geological maps together with their explanatory notes contain the late Quaternary deposits representing the depositional sequence of the last glacial cycle:

1. **HST High stand System Tract (last ca. 5.000 years Before Present)**
2. **TST Trasgressive System Tract (18.000-5.000 years Before Present)**
3. **LST Low Stand System Tract (25.000-18.000 years Before Present)**
4. **FST Fallings System Tract (125.000-25.000 years Before Present)**

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[2] **F. Trincardi, A. Argnani, A. Correggiari 2012 Geological mapping of the Italian seafloors: the Adriatic Project 7th EUREGEO, Bologna Italy June 12-15th 2012 390-391 Proceedings vol. 1, and Geological mapping of the Italian seafloors: the Adriatic Project* F Trincardi, A Cattaneo, A Correggiari, D Penitenti - Mapping Geology in Italy (APAT). S. EL. CA, Firenze, 2004*

The surficial geological map represents the deposits formed during the last glacio-eustatic fluctuation corresponding to three main stages (according to the sequence stratigraphy terminology: Low Stand System LST, Trasgressive System TST, High Stand Sytem HST).

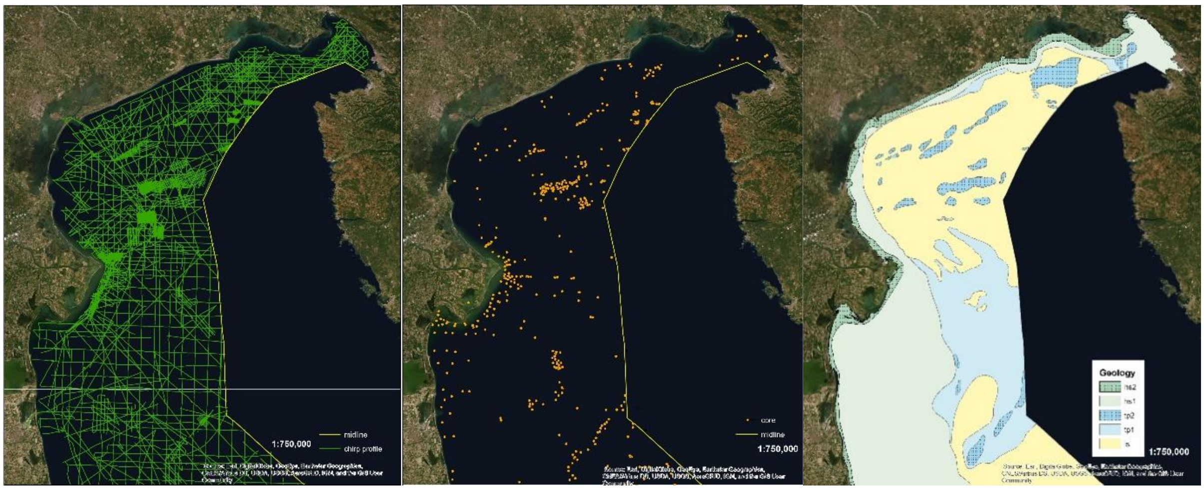

*Figure 2-6 -**Left**, chirp: tracklines of the seismic profile owned by ISMAR-CNR used for mapping the seafloor of the Adriatic Sea. **Center:** location of the core acquired by ISMAR-CNR used to study the seafloor. **Right**, Marine Geological map published in "Geological Mapping of the Italian Seas" at the scale 1:250.000, sponsored by the Italian Geologic Survey (SGI, now part of ISPRA). Foglio Venezia NL-33-7 and Foglio Ravenna NL 33-10. The surface map of the seafloor of the Adriatic represents with different colors the deposits of the fall and low stand system tract (LST) in yellow, transgressive system tract (TST-tp1,tp2) in light blue and high stand system tract (HST-hs1,hs2) tract in green.*

During the Last Glacial Maximum (LGM .ca 25.000-18.000 years Before Present, Figure 2-7) most of the area of the Adriatic basin was in subaerial conditions with exception of the Mid Adriatic Depression (MAD). The Po River and tributaries reached the central Adriatic basin, feeding thick progradational deltaic wedges from NW, while the north Adriatic was covered by an extensive alluvial plain and the eastern part of the basin was occupied by shallow carbonate formations subject to karstic erosion.

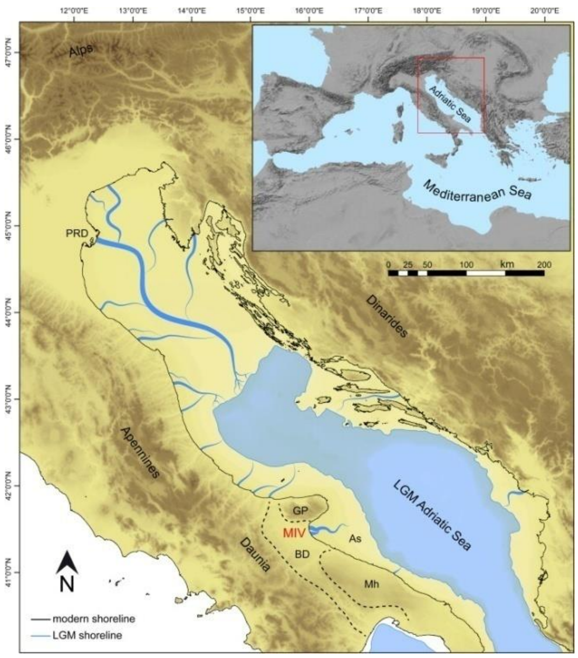

Figure 2-7: Last Glacial Maximum (LGM .ca 25.000-18.000 years Before Present)

Due to the relative sea-level rise that took place afterwards, the former glacial alluvial plain was flooded progressively, and the basin became 7 times wider. At the time of maximum marine transgression, the shoreline in the Po Delta was .ca 30 km inland with respect to its present location. A sea-level high stand conditions established, and new depositional processes took places.

The **low stand deposits (LST)** are mainly alluvial deposit made up of overconsolidated clays and fluvial sands containing typical continental faunas.

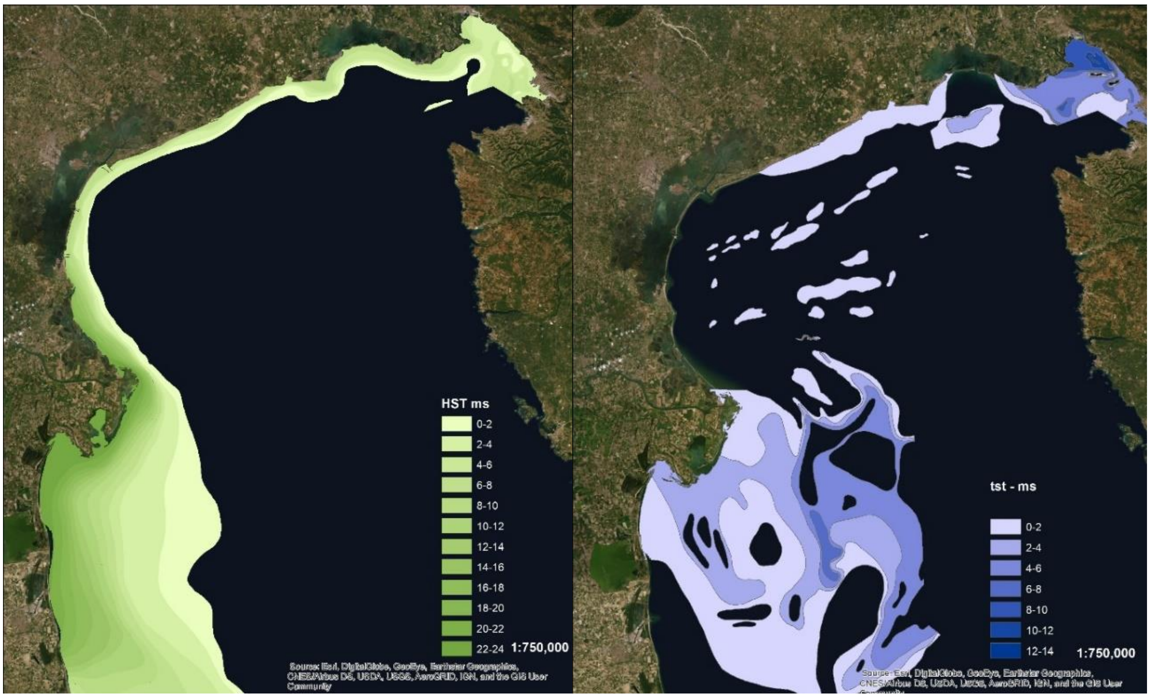

*Figure 2-8: **Left,** map of the thickness (in millisecond,10 millisecond=7.5 m) of the high stand system tract (HST). **Right**,map of the thickness (in millisecond, 10 millisecond=7.5 m) of the transgressive system tract (TST). Transgressive deposits in north Adriatic emerge in limited and discontinuous areas between about 10 m and 36 m at the bathymetric limit of the midline, while the Highstand deposits consist in a mud progradational unit with prodelta facies.*

The **transgressive deposits (TST,** Figure 2-8 right**)** emerge in limited and discontinuous areas between about 10 m and 36 m at the bathymetric limit of the sheet. The TST are present in continental (*tc*) and paralic (*tp*) facies, eroded by a diachronous surface of transgressive ravinement marine surface (*rs*). The transgressive base unit is represented by a transgression surface (*ts*) that marks the beginning of the sea level rising. The top of this unit is the surface corresponding to maximum flooding surface (*mfs*). In the northern Adriatic the *tp1* unit consisting of mud and sandy mud, containing horizons of peat associated with molluscs of brackish environment. The *tp2* unit consists of fine to medium sands grain size, well sorted, distributed in lentiform bodies buried in complex system.

Two morphological areas evolved distinctly in the Adriatic basin, a western part where the fluvial sediments led to the formation of a thick mud prism along the coast of the Italian shelf, and an eastern part, dominated by karst formations. Here, the marine transgression drowned the karst reliefs causing the formation of an archipelago of islands and islets and generating one of the most indented coasts in Europe (Figure 2-9).

The late-Holocene Adriatic **Highstand Systems Tract (HST)** (5,5000 years ago to present) includes three genetically-related depocenters: 1) the Po delta and Prodelta, 2) the central Adriatic prodelta wedge, fed from the Po and coalescing Apennine rivers, and 3) the Gargano subaqueous delta nourished by shore-parallel sediment advection, 600 km south of the Po Delta (Figure 2-10)

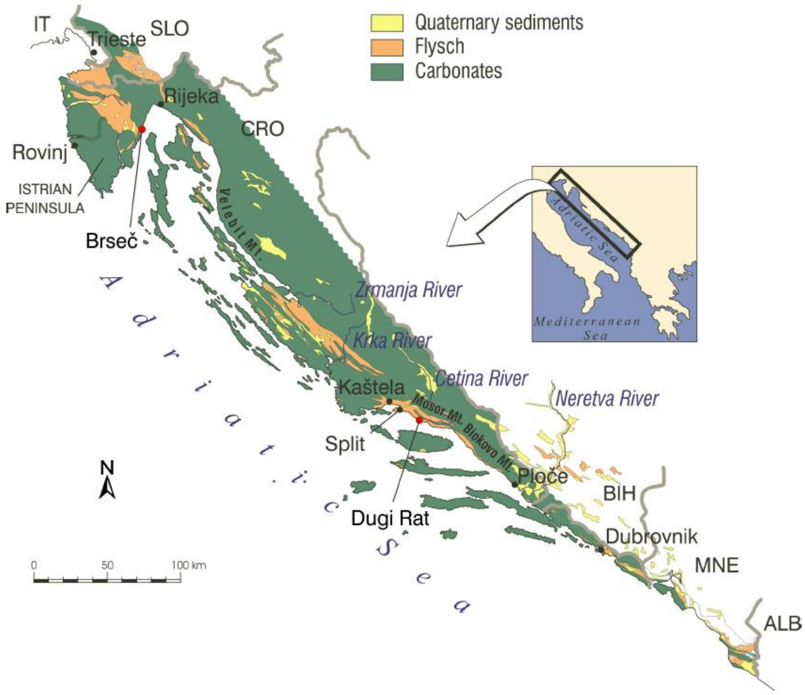

Figure 2-9: Geological setting along the Croatian coast (from Pikelj et al. 2016)

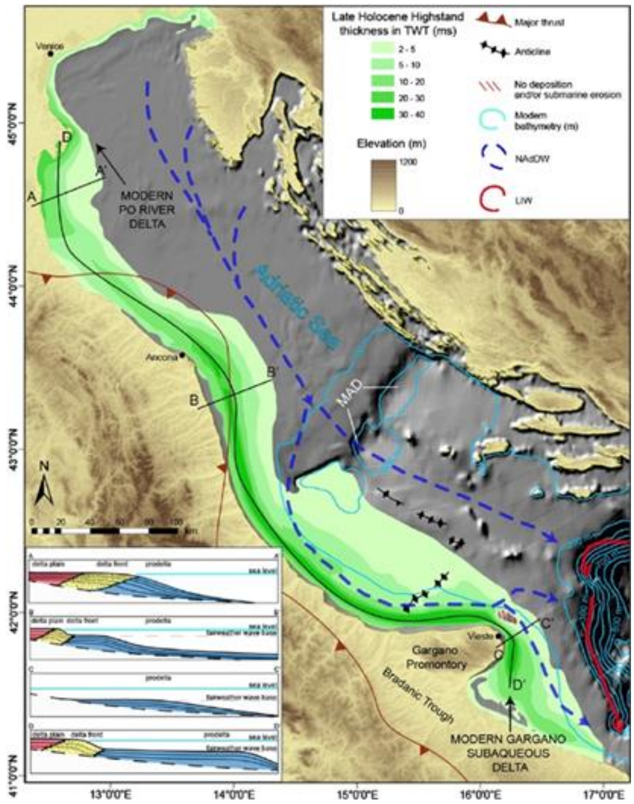

Figure 2-10: Thickness distribution of the Late-Holocene HST wedge (from Pellegrini et al. 2015; Cattaneo et al., 2007)

2.2.1.1. Granulometric classes.

The granulometric classes of surficial sediments in the basin of the entire Adriatic are represented using the data found in the literature and collected in the EMODnet portal, Geology. The data do not have a homogeneous distribution (Figure 2-11, left). Data D50 (mean diameter) values were interpolated using the Kriging method (simple), available in the ArcGIS Geostatistical Analysis module.

The choice to use the classification to 7 Folk classes (Figure 2-12) has allowed the identification of areas with fine surface sediments which in the western part of the Adriatic basin are the most common, due to the fine grain solid transport of the Po river and the Apennine rivers (Cattaneo et al 2003).

Maps of the grain size maps are available on the portal EMODNET, section “Seabed Substrate”.

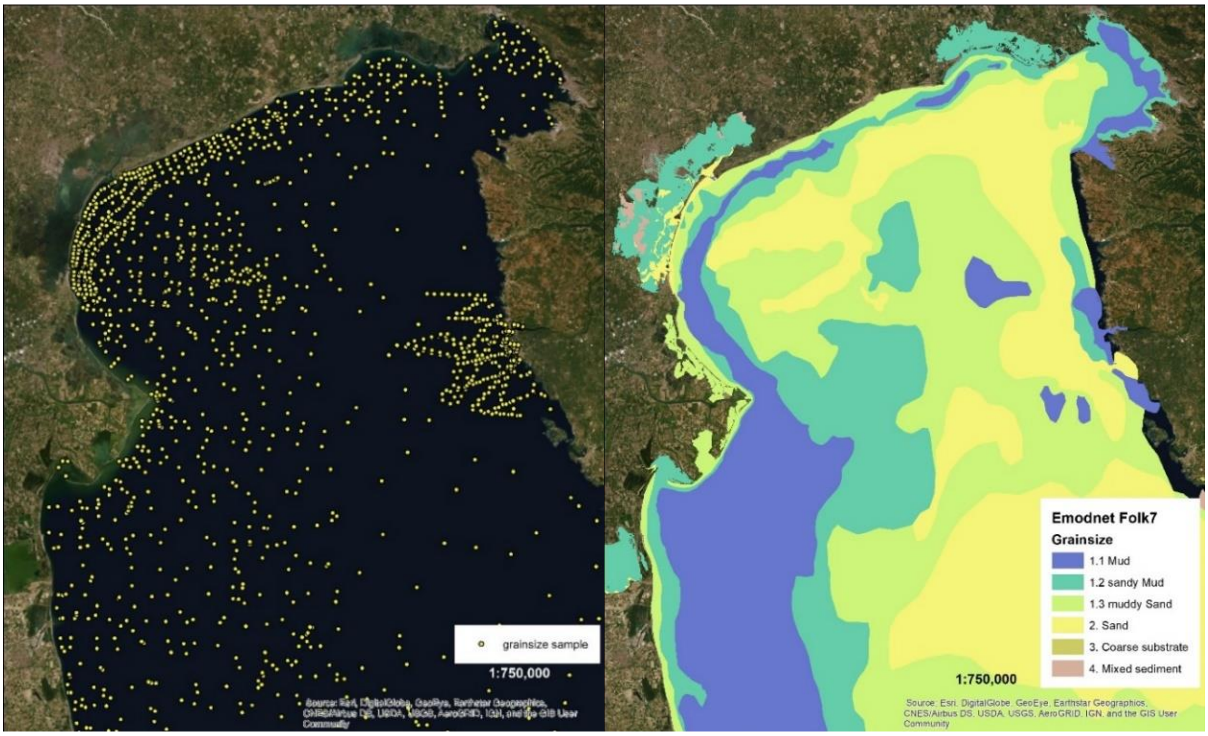

Figure 2-11: Left: samples used for create the classification of the grainsize presented on EMODnet Geology. Right: classification of grain size in north Adriatic according to Folk 7 classes from Seabed Substrate of EMODnet Geology. The seventh additional class, rock & boulders, is not present in the study area.

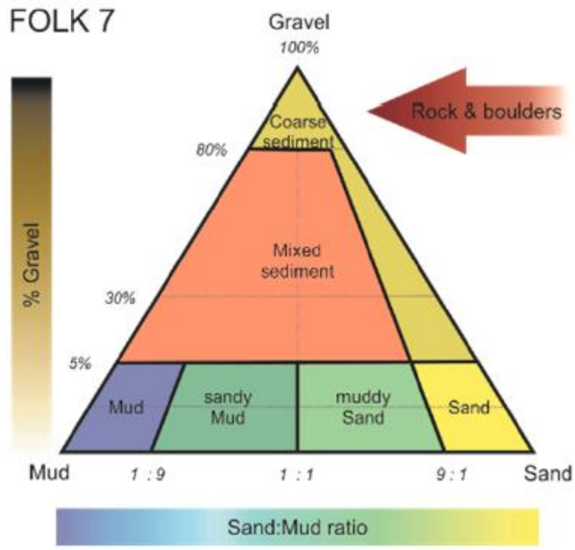

Figure 2-12: Folk classification. The original diagram is supplemented with an additional class, rock & boulders, having grain-size larger than gravel

2.3. Status and trend of sediment stocks

2.3.1. North Adriatic bathymetry

The bathymorphological map of the Northern Adriatic including the lagoons of Venice, Grado and Marano, result of a technical-scientific collaboration between various agencies, including the CNR and the IIM (Military Hydrographic Institute), has been recently published (http://doi.org/10.5281/zenodo.3754625, Foglini et al. 2020) under the patronage of the Veneto and Emilia Romagna Regions. The map consists of a main chart that illustrates the seabed elevation model (200 m resolution) derived from the integration of all the data acquired with single-beam echo sounders with a vertical exaggeration of 30x, necessary for highlight the main geomorphological characteristics of the low gradient North Adriatic platform.

The bathymetric chart includes a series of blue polygons (key map) that illustrate the coverage of the higher resolution data collected with multibeam echo sounder acquired by CNR ISMAR, IGAG (nstitute of Environmental Geology and Geoengineering)and IIM, both along the northern coast and in the open sea, since 2005 to 2016.

Six high resolution bathymetric maps have been created together with the main map (Figure 2-14), highlighting the multibeam surveys conducted in several sites:

- in the port of Ravenna,
- **at the mouth of the Po river (Po di Pila),**
- in the Venice Lagoons (North Lagoon and mouth of the port of Chioggia),
- in the port of Trieste,

- in the Ravenna off-shore area (relict sand deposits attributed to transgressive deposits).

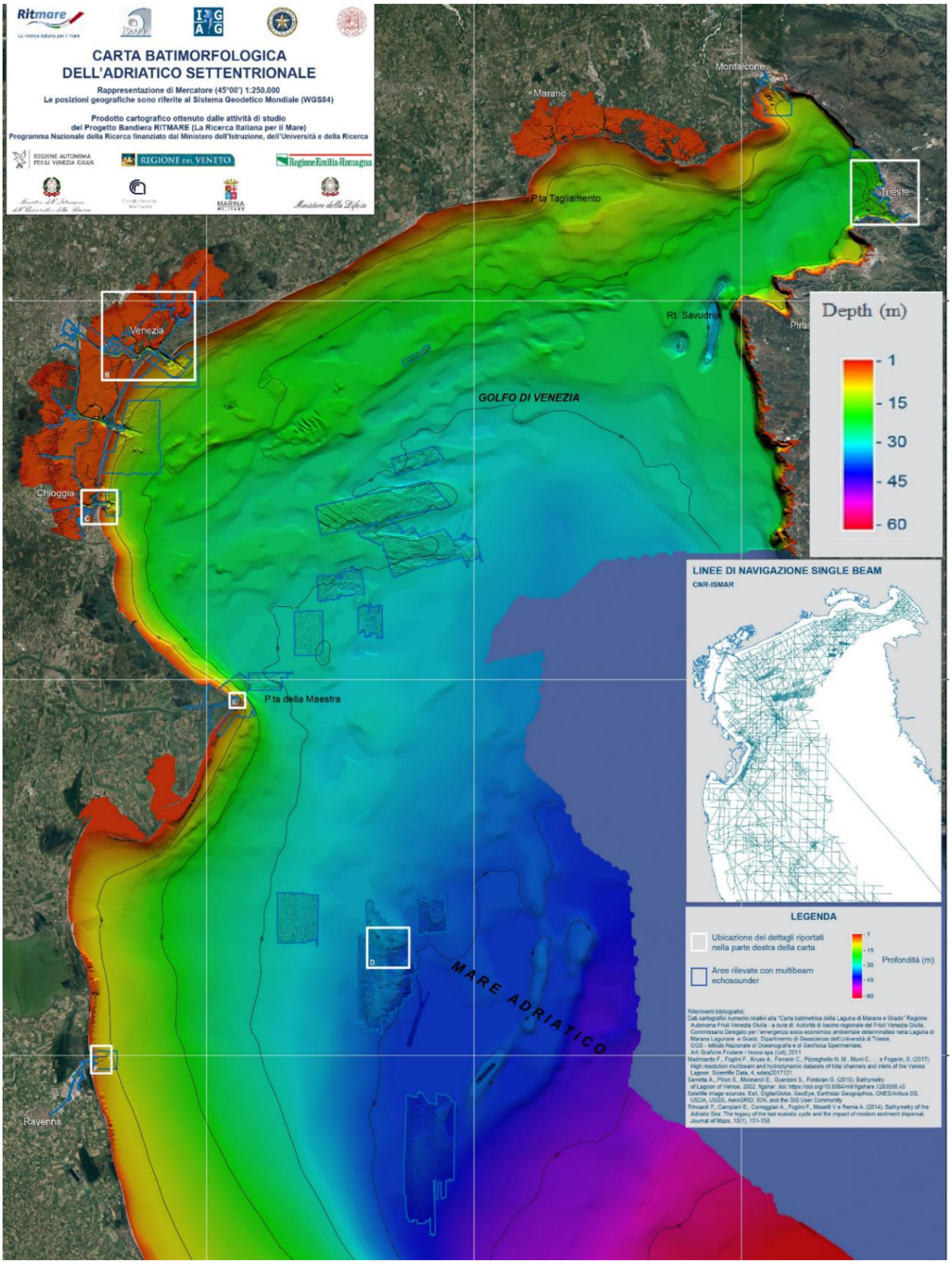

Figure 2-13: Morfobathymetric map of the northern Adriatic Sea, Modified map of the left panel of the high resolution bathymetric maps (http://doi.org/10.5281/zenodo.3754625)

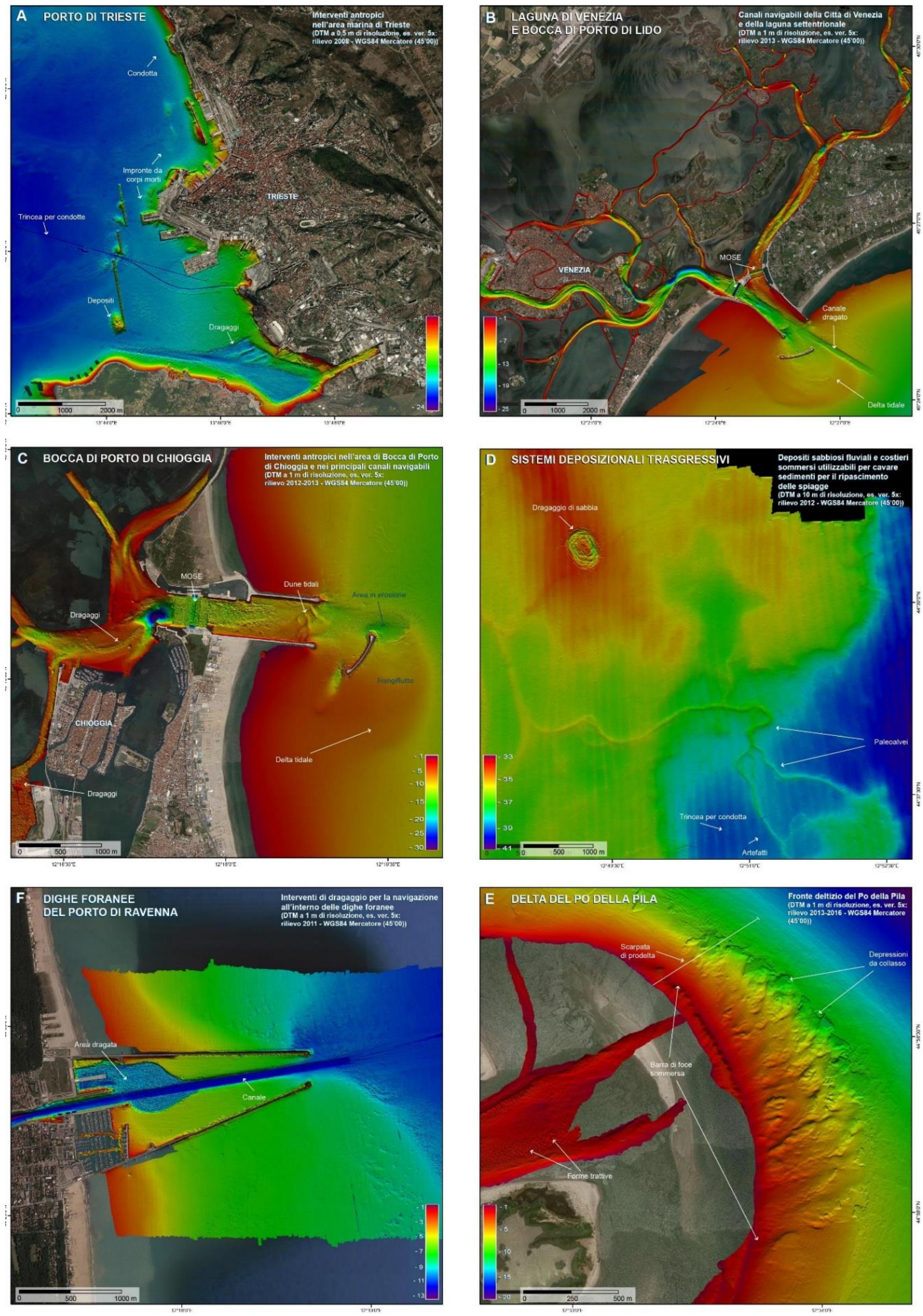

Figure 2-14: Six high-resolution bathymetric maps

3. SEDIMENTOLOGICAL PROCESSES AT PILOT SITES

3.1. Neretva river delta

3.1.1. General site description

Neretva River and its delta is the major and dominating geomorphological feature in the area. Delta area is composed of three geomorphological parts that are generally tectonically predisposed: Čapljina area in Bosnia and Herzegovina, Metković and Opuzen areas in Croatia (Figure 3-1). The Dinaric Karst bedrock has been incised by the paleo-Neretva River during the last glacial period, and Neretva Delta took current form during Holocene, when the Adriatic Sea rose to the present-day levels (Juračić, 1998).

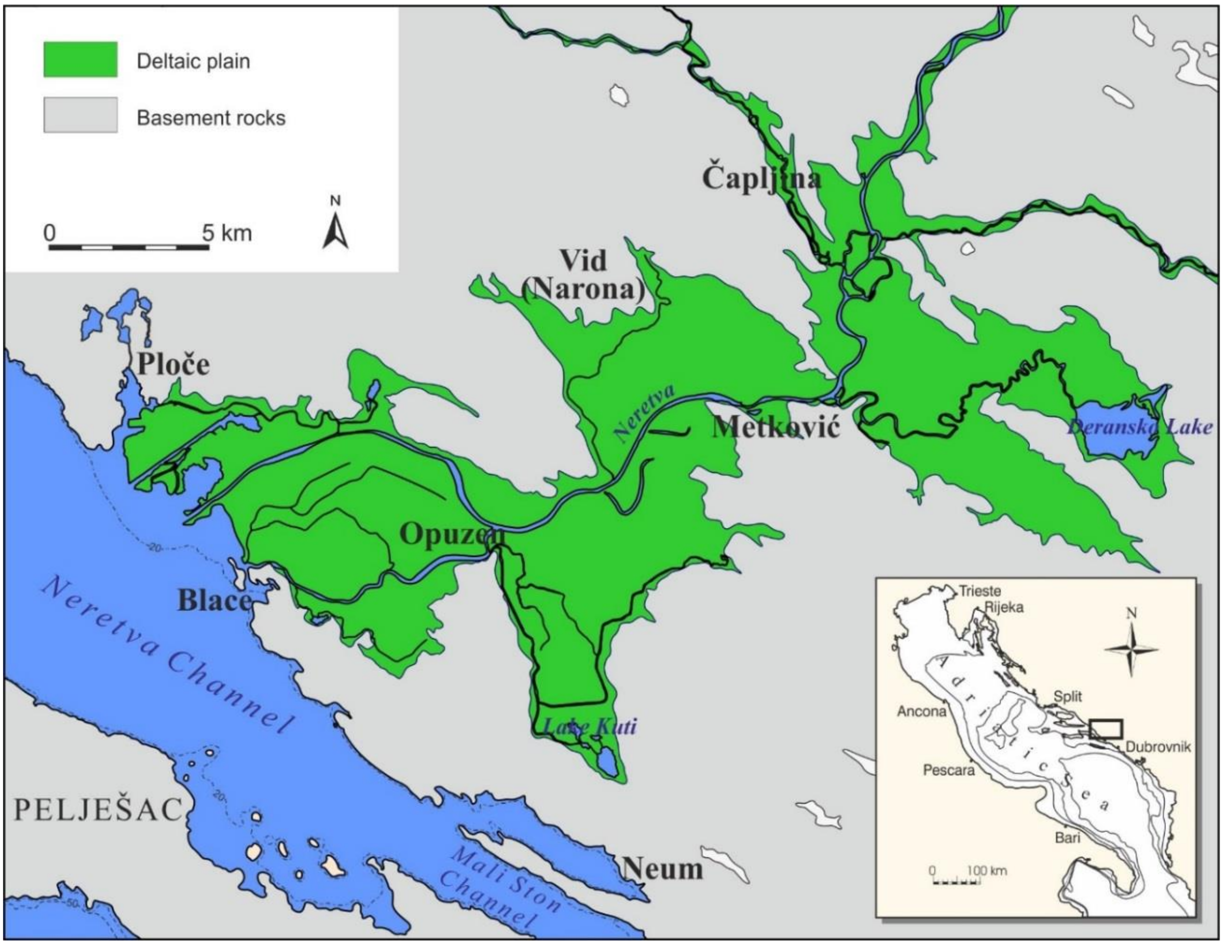

Figure 3-1: Neretva River Delta (deltaic plane) is a major geomorphological feature in the southern part of the Dinaric Karst that is built predominantly by the carbonate rocks (basement (bedrock) of the delta). Source: http://geol.pmf.hr

Mesozoic carbonate rocks that make up the karst bedrock and the wider perimeter of the delta were deposited on the former Adriatic carbonate platform (Vlahović et al., 2005). Overlying Paleogene carbonates and clastics were deposited during the orogenesis of the Dinarides, and the Neretva Delta in general geotectonic subdivision is situated in the External Dinarides that are characterized predominantly by highly deformed succession of the carbonate and clastic rocks (Korbar, 2009). Karst bedrock is characterized by a dissected relief, numerous caves and sinkholes within the fractured carbonate rocks. The oldest rocks are the Upper Triassic dolomites that are overlaing by a zone of Jurassic carbonates, both outcropping along the NW-SE striking zone in the basement of the river mouth and along the coastal area. Cretaceous limestones and dolomites predominate in the area but there are also structurally constrained narrow and elongated NW-SE striking (Dinaric strike) zones of the Paleogene carbonates and clastics.

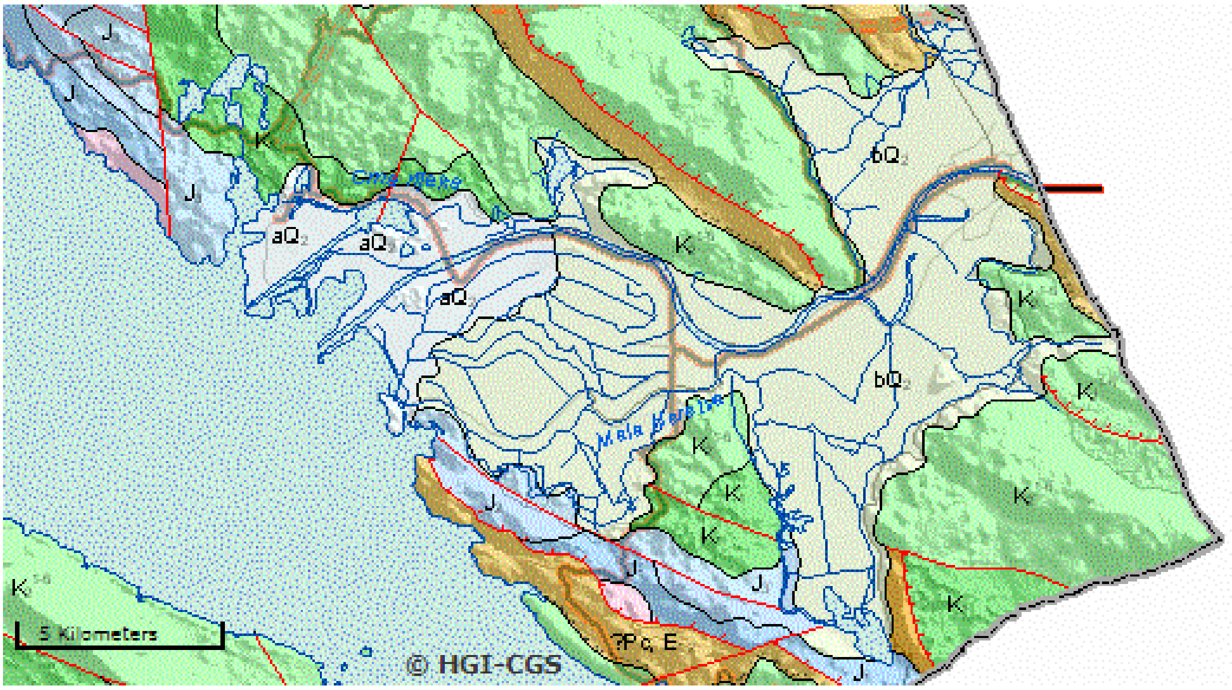

Figure 3-2: Crop of the Overview geological map of the Neretva delta area in Croatia. ***Grey*** *- delta sediments (aQ2 – alluvial, bQ2 – palustrine),* ***Orange*** *– Cenozoic carbonates and some clastic rocks (Pc, E),* ***Green*** *– Cretaceous carbonates (K),* ***Blue*** *– Jurassic carbonates (J),* ***Purple*** *– Triassic carbonates (T). Source: HGI-CGS: http://webgis.hgi-cgs.hr/gk300/default.aspx*

There are three general morphological units of Neretva Delta area: the karst hinterland, lowland area of the delta and the coastal strip (Nature Park Neretva Delta, 2007). Within the regional geomorphological and geological framework, the karst basement of the delta can be simply defined as a flattened bedrock area along the lower river channel covered by superficial Quaternary loose sediments deposited by the river during Quaternary that resulted with the present-day shape of the delta (Juračić, 1998). Southwest of Metković the topmost Quaternary sediments are characterized mostly by palustrine sediments (organic rich swamp mud), while west of Opuzen and down to the river mouth are represented by delta sediments: sand, gravel and sand - clay material. It can be assumed that the beginning of the creation of the present-day delta fall in the age of sea level rise, roughly before 8000-6000 years (Juračić, 1998).

Neretva originates southeast of Zelengora at an altitude of 1095 m, mainly flows through Bosnia and Herzegovina, and flows into the Adriatic Sea south of Ploče. It is about 218 km long, out of which in

Croatia ~22 km. In the upper and middle part of the Neretva river is representing a typical mountain passing narrow valleys with steep slopes. Downstream of Počitelj, Neretva leaves canyon and flows through the valley of the meander-nut (Ljubenko and Vranješ, 2012). The stream base forms a main stream that is navigable to Metković and Mala Neretva, which is separated from the main flow on the left from Opuzen. Watercourses of the left hinterland of Neretva river are Mislina and Jezerača with a source in the lake Kuti. Both after the composition passes in Prunjak that flows into Mala Neretva near Opuzen. Watercourses are right waterside Glibuša, Norin, Nut, Desanka and Crna rivers. Desne are a pit that is spring zone of the upper horizons (Vrgorac field and Rastoka). A series of springs is located on the contact of the valley with karst, most notably the Modro oko.

The whole basin is collected in the central part of the valley in lake Desne, and from there it flows into the Neretva river through Desanka and the port of Ploče (Lake Vranjak) through the Black River. A new port of Ploče channel reduced the flow of the Black River, which is now much less refreshing the lake Birina, beside which flows into the sea.

The regulation works in the course of the Neretva towards the end of 20th century and contemporary land reclamation significantly changed the number and spatial distribution of the lakes. Lakes area in the Croatian part of the delta before reclamation totaled 1,404 ha, followed by reclamation it decreased to 635 ha. The most important lakes before reclamation were: Modrič, Glogačko lake, Životina, Dragače, Timenica and Palinić. Today there are still Desne lake, Lake Vlaška, Parila and Kuti. Modro oko and source of the Norin in Prud are most important springs capped for water supply of the village. Outside the alluvial plains are Baćina lakes. Baćina lakes are cryptodepression, consisting of five connected lakes: Lake Plitko, Podgora, Očuša, Sladinca, Crniševa and separate lake Vrbnika. The largest is Lake Očuša (55.4 ha) and the maximum depth was measured in Crniševo (31 m). Despite the sea and permeable karst terrain lakes are filled with fresh water (County Development Strategy 2016-2020).

River has many tributaries that flow into the main water stream directly or indirectly underground karst flows (Margeta and Fistanić, 2000). Large amounts of water come in the delta area through springs that are located along the perimeter of the alluvial plain, which are especially generous in the rainy part of the year. Those additional quantities of water from areas outside orographic basin (Juračić, 1998) come through karst underground.

Most of the rainfall occurs in the winter period (November), while the least rainfall is in the summer, so the middle summers are sometimes with no precipitation, and the annual evaporation is 500-900 mm. The mean annual flow of the river is 269 m^3 / s, the minimum is 44 m^3 / s (probability 0.05), and the largest 2,179 m^3 / s (probability 0.01). Runoff coefficient is about 0.871. The flow is measured at 21 measuring station for more than 30 years.

Water quality is mostly satisfactory, except in parts of the river with large settlements and downstream from them (Margeta and Fistanić, 2000). In the dry summer period, due to the reduced flow of fresh water from the basin, intrusion of the sea water into the interior of the basin increases through the riverbed and underground through fracture karst system and through alluvial valley (Ljubenko and Vranješ, 2012). Moreover, the entire valley main inflow of salt water (sea) occurs in the deep layers of the alluvium (Vranješ et al., 2013). In this way, water in surface watercourses becomes very saline, particularly in the bed of the Neretva, as well as ground water. In summer, sea water wedge penetrates through the Neretva river bed upstream up to Gabela. Under the influence of freshwater wedge is pushed downstream until it is fully ejected out of the river bed (Ljubenko and Vranjes, 2012).

The process of salinization all over the valley at the present time is quite pronounced, and the water regime of the river is completely changed compared to the natural state, due to the construction of the hydropower system in Bosnia and Herzegovina. So far in the Neretva river basin there is nine hydroelectric power plants constructed, and two more are planned. In the basin of the Trebišnjica there are seven already built, with three planned in the system called “The Upper horizons”. Also, five reservoirs and lakes are already built, and five more in the expansion plan.

Changes in the basin that will occur due to further construction of hydropower systems are cross-border issue of Croatia and Bosnia and Herzegovina. The consequences of the activities will be felt in the Neretva delta, Mali Ston and the Župa Bay, and water sources in the Dubrovnik coast (Vranješ et al., 2013). The consequences of changes in the water regime are most noticeable in the area of Lower Neretva. A direct consequence of reduced water regime is salinization. Also, amount of river sediment deposit coming from the basin is reduced, which is causing elution of Neretva riverbed in the area of Lower Neretva during the flood waters, especially near the mouth.

3.1.1.1. Location (site map, study domain, access routes, cities, etc.)

The Neretva Delta is a valley in the south of the Croatian Adriatic coast, formed at its mouth by the Neretva River itself. The Delta covers an area of 12,000 acres. The Neretva Delta from Metković to the estuary from the north and northeast is bounded by the branches of the Dinaric mountains, and from the south by the Podgradina-Slivno hills.

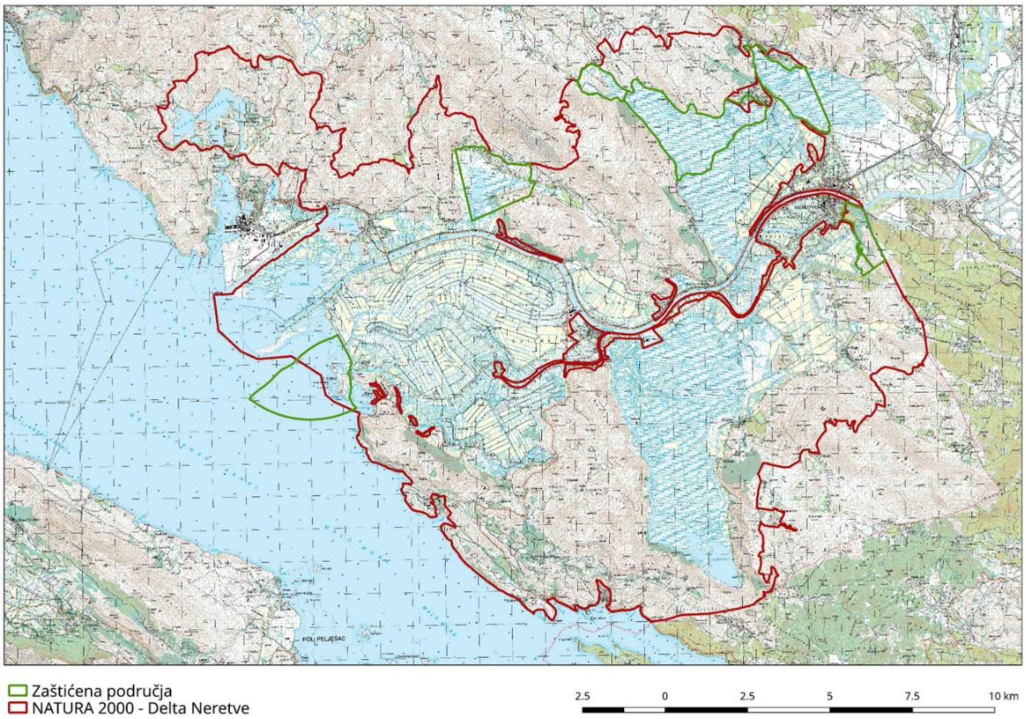

*Figure 3-3: Protected areas (**green color frame**) and NATURA 2000 site Neretva Delta (r**ed color frame**)*

Figure 3-4: Orthophoto image of the Neretva River mouth (source DGU: https://geoportal.dgu.hr/)

3.1.1.2. Physical and environmental features (synthesis)

The area has Mediterranean climate with mild, rainy winters and hot, dry summers. Here are some basic climate characteristics according to data of the Meteorological and Hydrological Service of Croatia. The air temperature has an average value of 14-15 °C. The coldest is December – February period with average temperature of ~7°C, although temperatures can go down to -5°C or even below. The temperatures are highest in July (average ~25°C) and August and can go over 40°C. Average annual precipitation ranges from 1,250-1,500 mm. December is the rainiest month while July is the driest one with less than 200 mm. Humidity is highest in September, December and January (average 72%) and the lowest in July and August (average 54%).

Neretva River is dominant watercourse of the area. Its main characteristics in this final section are: average annual water level of 91±13 cm (range 65-124 cm); average annual water flow of 269 m³/s (range 44– 2,179 m³/s); average annual water temperature near Metković being 11.9 °C (range 0 -26 °C). River has a high water level in winter, while during summer there is a lack of water. This is partly due to several hydropower plants upstream in Bosnia and Herzegovina, which hold the most of Neretva waters with dams. In such situations when Neretva has a very small flow downstream of the dams, marine waters enter the river, spreading its influence upstream all the way to Metković (border with Bosnia and Herzegovina).

Hydromorphic soils prevail in Neretva Delta. Narrow zones along watercourses are covered with alluvial soils (fluvisol). Amphigley soils are represented in wider area, receiving water from rainfall as well as from underground water. Surrounding carbonate hills are covered mostly with calcicambisol ('brown' soil on carbonates) and mould ('black' soil).

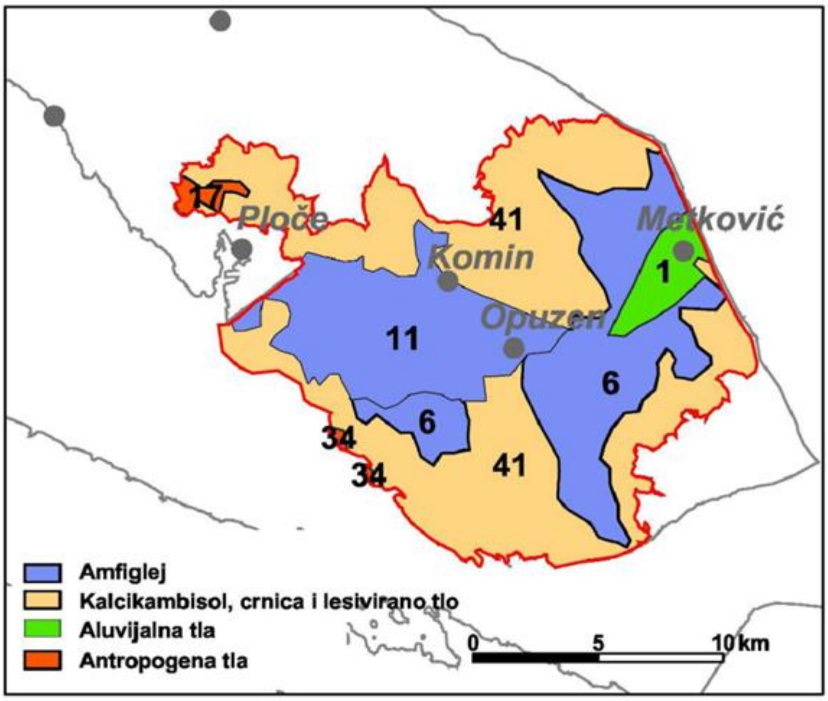

Figure 3-5: Soil map of Neretva Delta River (Source: Soil map of Republic of Croatia, Martinović, 2000

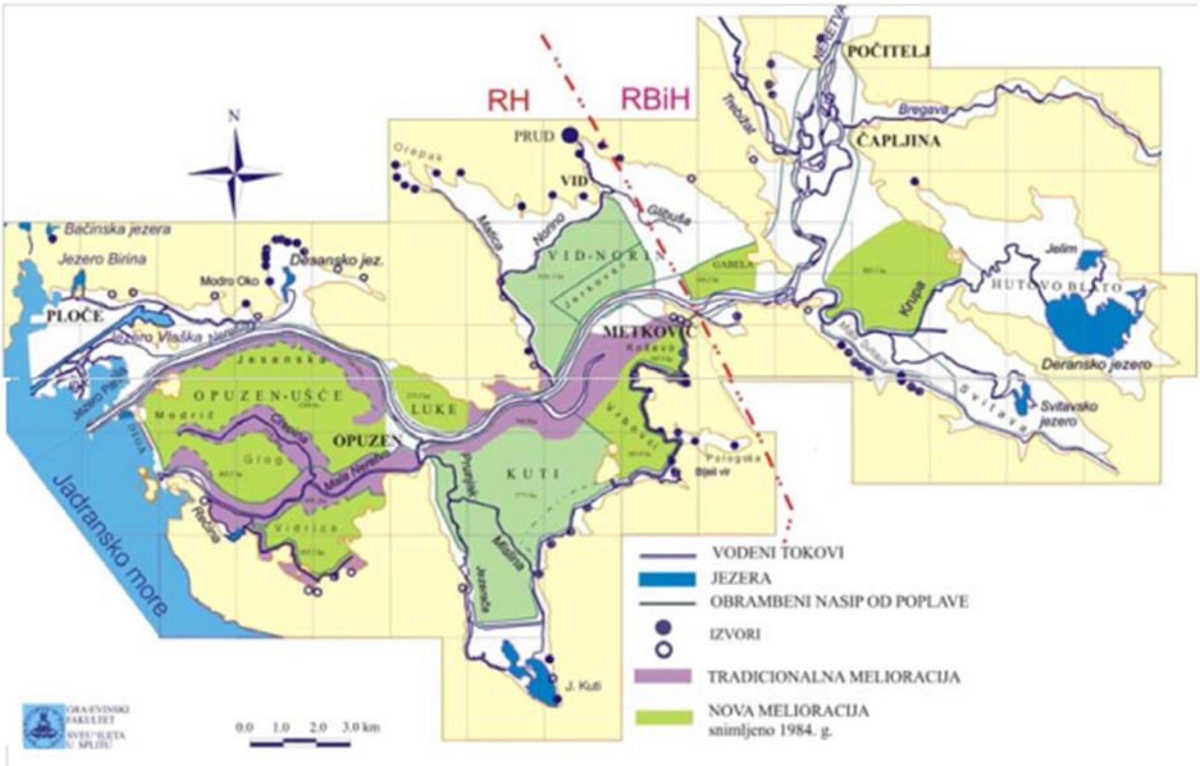

Figure 3-6: Hydrological status in Lower part of Neretva today (Source: Vranješ et al., 2013)

3.1.1.3. Administration, main economic activities, recent development, land use

The Neretva Delta area is very densely populated with about 35,600 inhabitants (2011), with the majority of the population living in the cities of Metković (16,788), Ploče (10,135) and Opuzen (3,254) situated in the westernmost part of the Dubrovnik-Neretva County (Croatia).

People are present in Neretva Delta for thousands of years, turning wetland into arable land and establishing transportation routes towards the hinterland. Locals use the delta area mainly for agricultural purposes, but also for activities such as hunting, fishing and aquaculture.

With the beginning of the first land reclamation and changes in the course of the Neretva river, especially contemporary interventions in the last 50 years, the man began to change significantly the natural characteristics of the delta and thus dictate the economic orientation and the location and form of settlement. Until then local community lived on fisheries, hunting and agriculture which depended on traditional way of land reclamation called "jendečenje". That is traditional way of creating land parcels in the marsh (digging channels and putting excavated soil aside, thus making small land plots). These traditional channels are called "jendeci" and form unique, specific landscape in Europe. Land ownership is one of the most significant issues related to land use and management in Neretva Delta. Situation with property rights in the area is very complex and the status of the most of agricultural land is not clear (state vs. private ownership). A part of the State-owned agricultural land is being leased to local people.

The population is also increasingly turning to tourism. In recent years, the tourist offer has been supplemented by activities such as photo safari trips, kitesurfing, windsurfing, cycling, agritourism and gastronomy. The main visual identity of the area is the reclaimed agricultural landscape with many irrigation channels.

It is important to highlight the specific geographic location of the Neretva delta which created precondition for forming important traffic intersections of main roads, rail and maritime transport. The important part of local economy in area is cargo seaport in Ploče, second in Croatia by the amount of transshipment, a multi-purpose port for transshipment of almost all kinds of commodities represented in international maritime transport. An integral part of the port of Ploče is Metković port which is located 20 km upstream on the river Neretva.

3.1.1.4. Main problems and management objectives

The most prominent factors in the past that adversely affected ecological character of Neretva Delta were connected to water management, including land reclamation activities with the purpose of turning wetland into agricultural land. Today the largest threats are also connected to issues of water management and agriculture sectors. As the consequence of water regulation activities in surrounding area of Croatia in Bosnia and Herzegovina, there is a trend of decrease of water level and quantity in Neretva Delta that adversely affect not only wetland habitats and biological diversity of Delta but also agriculture. The less water in Neretva and its tributaries in Delta, the stronger influence of the sea and salinization of water and soil can be expected. There are different water management plans and projects currently going on in Neretva Delta. They deal with solving the problem of salinization; irrigation of agricultural land; flood control, treatment of sewage water of the town Metković and other activities. There are even plans for further meliorations of remained wetland areas.

Other problems and threats to ecological character of the Neretva Delta include: expansion and intensification of agriculture; excessive use of pesticides and fertilizers; fragmentation of wetland habitats; spreading of urban zones on account of wetland; water pollution with non-purified urban and industrial waters; unsolved land property rights; illegal taking of state owned agricultural land, including marshes; non-regulated recreational and touristic activities, especially on the river mouth, illegal hunting and fishing; frequent fires in reedbeds.

In the surrounding area especially problematic are issues related to transboundary water management and numerous water regulations in catchment area of the Neretva and neighboring Trebišnjica River in Bosnia and Herzegovina. Watersheds of these two rivers are connected through karst underground. Re-direction of waters from so called Upper horizons ("Gornji horizonti") of Trebišnjica River into the area of Lower horizons ("Donji horizonti") with three existing hydropower plants results in loss of water in lower Neretva area, lower summer water level, drying out of water springs and strengthening of influence of the sea. There are plans to increase these activities and to take the most of available water for additional use of hydropower plants in eastern Herzegovina.

3.1.2. Available sedimentological data, studies, maps

According to the Basic geological maps of the area (Marinčić et al., 1972; Raić et al., 1976, 1980; summarized in webgis map of Croatian Geological Survey - HGI-CGS) the Neretva River deltaic plain is built of Quaternary alluvial and palustrine deposits. Although the map shows only generic subdivision, in the explanatory notes (Magaš et al., 1979; Raić and Papeš, 1977; 1982). There are general indications on the Quaternary sediments that consist mainly of peat and clay (organic swamp deposits), which underlain by clayey sands, sands of variable grain size, sandy clay, gravelly sands, sandy gravel and Holocene gravels (alluvial sediments), as well as Pleistocene conglomerates. The Neretva Channel is a microtidal, low-wave energy environment characterised by river-dominated sedimentation processes (Jurina et al., 2010). Sedimentation rates at the mouth are estimated by Jurina et al (2013), while Jurina et al. (2015) reported on surface sediments from Neretva river and its tributaries. Generally, the surface alluvial sediment is mostly sand and silt, while mud dominates in the cultivated swamp (Kralj et al., 2016).

3.1.3. Acquisition of new in-situ data to complete knowledge

There were no new in-situ measurements within the ChangeWeCare project. However, the data on the amount of sediment in suspension and the bedload of the Neretva River stream is important for future projections of the trends in sediment accumulation.

3.1.4. Current status (qualitative, quantitative) of the site sediment stocks

The lowland part of the Neretva River is only 36 km long and flows through Quaternary alluvial deposits**.** The Neretva River discharges its water and sediment load into the semi-enclosed microtidal environment of the Neretva Channel. The Neretva River profile consists of 7 sampling stations (N1–N7); 6 in the river itself (N2–N7) and one in front of the river mouth (N1). Additional sampling of the delta plain sediments included the Mala Neretva distributary (N11–N13), the Norin River (N14–N18) and other local tributaries (N8 and N10), the Lake Kuti (N9), and the intact wetland area (N19). At additional 31 locations in the Neretva Channel (stations C1–C31) surface sediments (uppermost 5 cm) were collected.

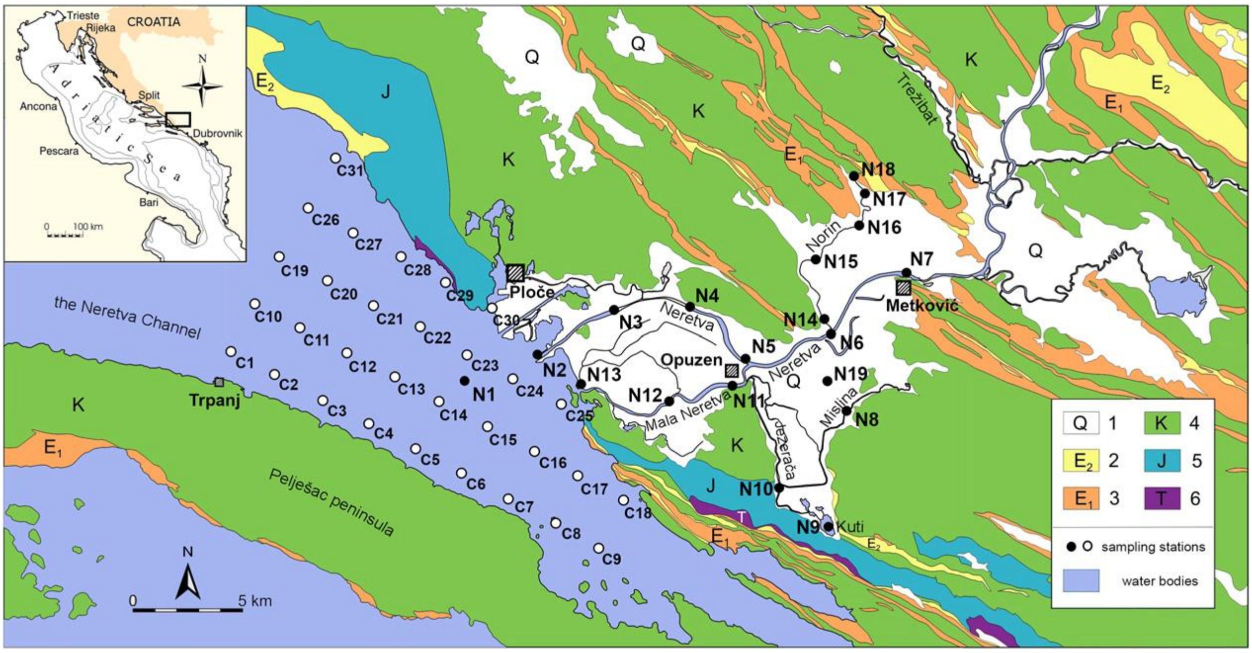

Figure 3-7: Geological map of the Neretva River delta and the Neretva Channel showing the investigated area and sampling stations (N1–N19 and 31 stations in the channel). Legend: ***1*** *— Quaternary alluvial deposits (Q);* ***2*** *— Eocene flysch (E2);* ***3*** *— Eocene limestones (E1);* ***4*** *— Cretaceous limestones and dolomites (K);* ***5*** *— Jurassic limestones and dolomites (J);* ***6*** *— Triassic limestones (T). Source: Jurina et. al. (2015)*

According to Jurina et al (2015), most of the surface sediments (uppermost 50 cm) from the Neretva River delta plain were classified as sandy silts. Only in the Neretva River, at stations N2, N5 and N6, were sediments classified as silty sand due to the higher content of the sand fraction (up to 65%). The surface sediments from the Mala Neretva distributary channel (stations N11–N13) were somewhat finer than sediments from the Neretva River. A significant content of sand (35%) was found only at the river mouth (station N13), and sediment from station N12 was classified as silt. Regarding the remaining delta plain surface sediments, only the sediment from the intact wetland area (station N19) was classified as silt. Surface sediments from the Neretva Channel were mostly classified as clayey silts. The sand fraction was generally low (0–10%), with the exception of one sample collected near a small islet (station C8) where 64% of sand fraction was found. The dominant sediment fraction in all other samples was silt (62–78%). In the central and innermost parts of the Neretva Channel, high proportions of claysized particles were found (25–33%), while sediments closer to the river mouth contained more silt and sand. The mineral composition of investigated surface sediments was similar.

The dominant phases in the delta plain sediments and subaqueous deltaic deposits were quartz, calcite and clay minerals, with secondary appearance of plagioclase and dolomite. Only exception is the surface sediment from the Lake Kuti (station N9) where surprisingly high carbonate content (73%) was found, while XRD analysis revealed only presence of calcite. A significant difference in the distribution of clay minerals and carbonate content was observed along the Neretva River profile (stations N1–N7). A higher carbonate content was found in the surface sediments from the Neretva River (N2–N7, 40–45%) than in the Neretva Channel (N1, 30–35%).

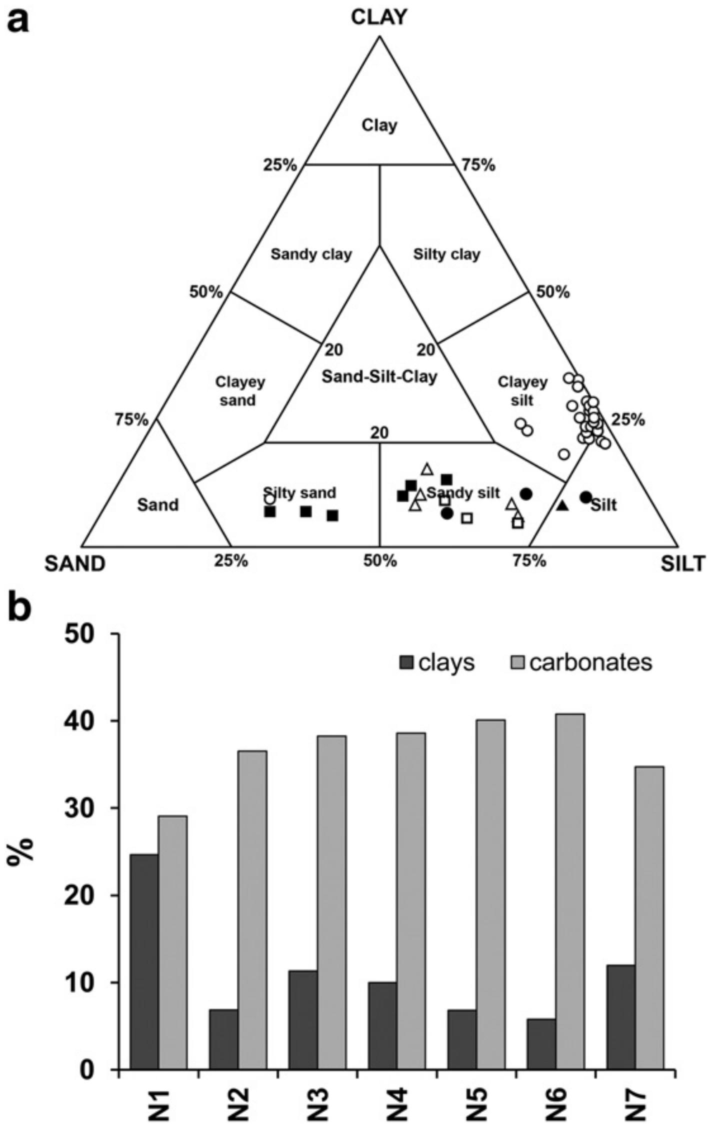

*Figure 3-8: **(a)** Ternary diagram for classification of sediments with surface samples from the investigated area denoted on the basis of their sand/silt/clay ratios (■— the Neretva River; ●— the Mala Neretva; □— the Mislina River, the Jezerača River and the Lake Kuti; Δ—theNorin River; ▲—the intactwetland;○—theNeretva Channel). **(b)** The ratio between carbonate and clay mineral fractions in surface sediments along the Neretva River profile. Source: Jurina et. al. (2015).*

3.1.5. Analysis of recent trends of the sediment stocks

The Eocene flysch deposits (marls and sandstones) which predominate in the upper part of the river catchment in Bosnia and Herzegovina, provided large amounts of sedimentary material during Quaternary (Juračić, 1998). However, as a consequence of the hydropower plants in upper stream of the Neretva River in Bosnia and Herzegovina, the delta is during the last few decades not supplied with the large volumes of sediment.

Neretva river trough is widened for 2-3 m near Komin and Rogotin bridges. Carried material is deposited at the river mouth in the sandbar Škanj. Deposition of suspended sediment which is restoring a valley is stopped by flood control measures. The result is a subsidence along the entire valley, in places and over a meter (Vranješ et al., 2013).

Most of the relatively coarser grained material (fine grained sand) was deposited at the river mouth and along the circular sandbar Škanj that is the main natural barrier for the direct influence of the sea into the Neretva Delta.

Considering low sediment input during the last decades, the bar is under the strong influence of the rising sea, and it is expected that the waves and currents could strongly affect the bar in future.

There are no available studies on the present day sediment dynamics around the mouth of Neretva River. Especially interesting would be the analyses of sediment dynamics along the circular sandbar Škanj that should be planned for future studies. Thus, sedimentological studies and precise geodetic monitoring along the river mouth is needed in the area for the analyses of the evolutionary trends.

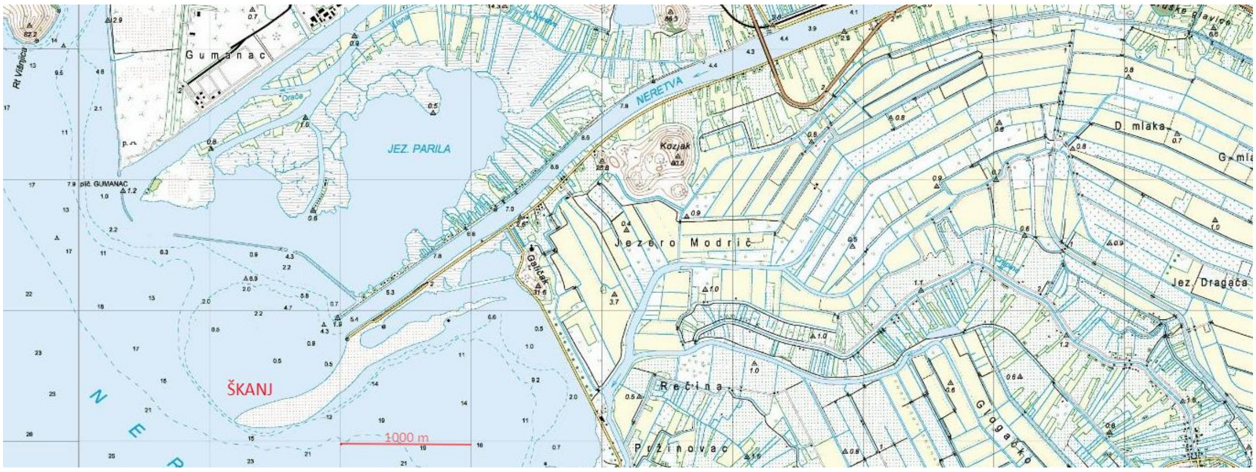

Figure 3-9: Topographic map of the Neretva River mouth. A few kilometers long narrow sandbar Škanj that has a kilometer wide circular shape at the mouth is marked. (Source: DGU: https://geoportal.dgu.hr/). Coordinate grid is 1 km

Sediment accumulation rates of the fine-grained sediment (clayey silt), estimated from the distribution of 137Cs in core sediments, were approximately 6 mm y^{-1} in front of the Neretva River mouth and 4 mm y^{-1} in the channel area (Jurina et al., 2013).

3.1.6. Conclusion

1) The Neretva River deposited sediment from suspension mostly along the riverbed, in the deltaic plain and to the semi-enclosed microtidal environment of the Neretva Channel (Adriatic Sea).

2) Most of the relatively coarser grained material (sand) was deposited at the river mouth, along the circular sandbar Škanj that is the main natural barrier for the direct influence of the sea into the Neretva Delta.

3) Because of the construction of the hydropower system in Bosnia and Herzegovina during the last decades (the system called "The Upper horizons"), there is a significant change in the water regime, that is most noticeable in the area of Lower Neretva (delta area).

4) A direct consequence of reduced water regime is salinization and reduction of sediment in suspension, which is causing elution of Neretva riverbed in the area of Lower Neretva during the flood waters, especially near the mouth.

5) Neretva river trough is widened during the last decades for 2-3 m near Komin and Rogotin bridges, and the carried material is deposited at the river mouth in the sandbar Škanj.

6) The surface alluvial sediment (the uppermost 50 cm) from the Neretva River delta plain is mostly silt and sand, while mud dominates in the surrounding cultivated swamp. Seabed sediments from the Neretva Channel (Adriatic Sea) were mostly classified as clayey silts.

7) Sediment accumulation rates are approximately 6 mm y^{-1} in front of the Neretva River mouth and 4 mm y^{-1} in the channel area.

8) Quartz, calcite and clay minerals predominate in the delta plain sediments, with secondary appearance of plagioclase and dolomite.

9) Higher carbonate content was found in the surface sediments from the Neretva River than in the Neretva Channel (Adriatic Sea).

10) The sandbar Škanj is under the strong influence of both, the river during the rainy season and the rising sea, and it is expected that the waves and currents could strongly affect the sediment stocks along the bar in future.

3.2. Jadro River

3.2.1. General site description

3.2.1.1. <u>Location (site map, study domain, access routes, cities, etc.)</u>

Jadro River is located in the central Dalmatia (Croatia), in the central part of the eastern Adriatic coast (Figure 3-10 and Figure 3-11).

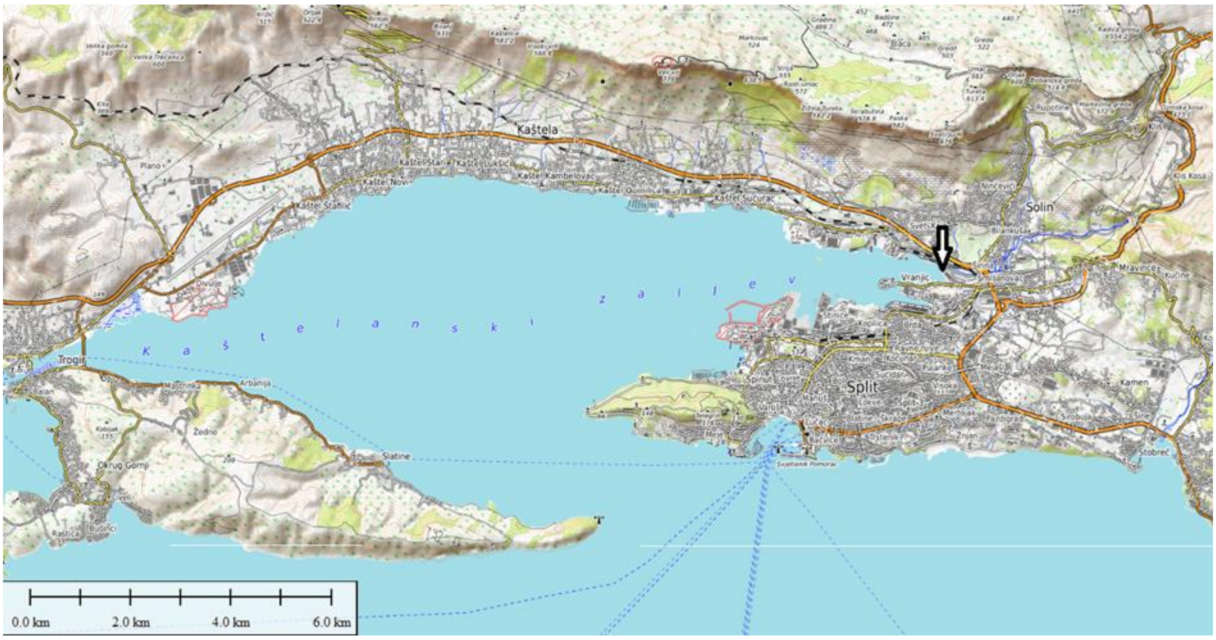

Figure 3-10: Location map of Jadro River (mouth is marked by arrow) at the easternmost tip of Kaštela Bay (Kaštelanski zaljev) in the town of Solin - ancient Roman Salona (Source: Open Topo Map).

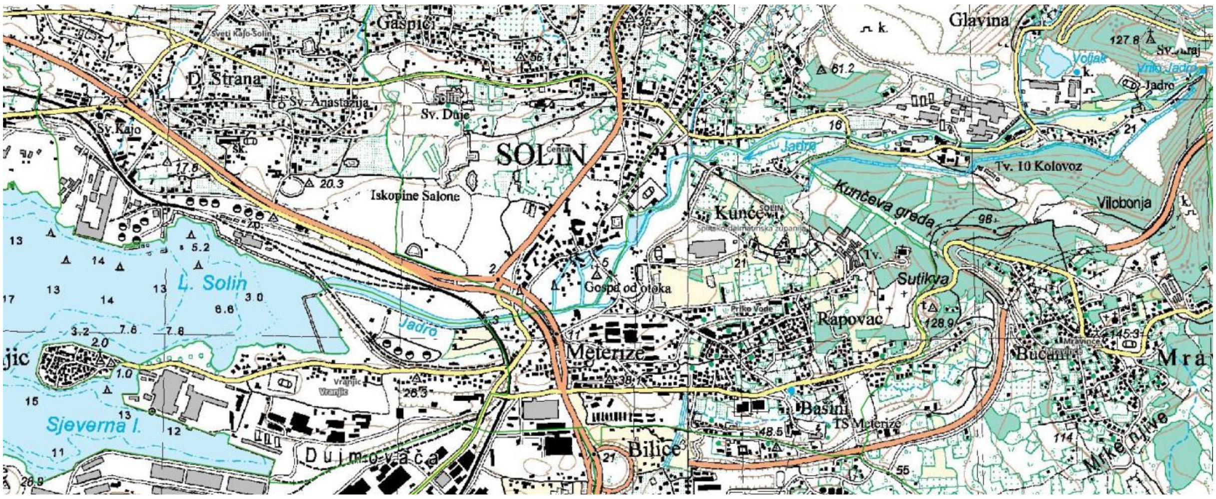

Figure 3-11: Location map of Jadro on the official topographic map (Source: DGU: https://geoportal.dgu.hr/). Coordinate grid is 1 km.

The area is situated in the close hinterland of the regional capital - city of Split. Most of the short River and the mouth itself are administratively situated within the town of Solin. The mouth is situated in Vranjic Bay - the easternmost tip of the larger Kaštela Bay.

The Kaštela Bay is a semi-enclosed oval-shaped embayment of the Adriatic Sea, bordered by the Kozjak Mountain from the north, by Split peninsula from the southeast, and the island of Čiovo from the southwest. The northern part of Kaštela Bay belongs to the town of Kaštela, while the town of Trogir is situated on the western tip.

3.2.1.2. Physical and environmental features

Geomorphologically, Jadro River is situated on the easternmost part of a lowland area called Split-Kaštela basin. The basin is elongated east-west and bordered by Dinaric mountain range from the north, and partly covered by shallow Adriatic Sea in the present-day Kaštela Bay (Kaštelanski zaljev) that is characterized by maximal depth of 43 m in the central part of the Bay.

Geologically, the Split-Kaštela basin is predominantly built of highly deformed and eroded Eocene flysch deposits (marls and sandstones), while the underlying and surrounding karstified and highly fractured Cretaceous to Eocene carbonate rocks (mostly limestones and dolomites) outcrop on the mountains and the islands (MARINČIĆ et al., 1971; Figure 3-12). The wider area is referred to the typical Dinaric karst or the External Dinarides, developed in the latest stage of the Alpine orogenesis in the region (KORBAR, 2009). The basin is situated between the High Karst Zone in the northern hinterland and the Adriatic Zone on the south, both charaterized mainly by carbonate rocks (http://webgis.hgi-cgs.hr/gk300/default.aspx).

The Jadro spring is located in the hinterland of Split, in the common foothills of the Mosor Mt (1339 m. a.s.l) on the northeast, and Kozjak Mt (676 m. a.s.l) on the northwest. The spring is situated at the contact of karstified and permeable carbonates and impermeable flysch rocks. The Jadro River flows from its source through a narrow alluvial valley underlain completely by impermeable rocks (predominantly flysch marls), and eventually debouches in the Adriatic Sea at the mouth in the Vranjic Bay on the easternmost tip of the Bay of Kaštela (Kaštelanski zaljev, Figure 3-12). The coastal plain is almost completely covered by settlements and agricultural areas or vegetation on the soil, while steeper mountain slopes have completely denuded karst surfaces without any soil.

The catchment area of Jadro spring is more than 400 km^2 that is characterized predominantly by karstified carbonate rocks (Mesozoic limestone and dolomites) in the wider hinterland. Thus, Jadro River spring is part of the largest aquifer systems in Dalmatia (FRITZ & KAPELJ, 1998).

*Figure 3-12: Basic geological map (crop from MARINČIĆ et al., 1981) showing Split-Kaštela basin and location of Jadro River mouth (**black arrow**). **White** color (al) marks Jadro River alluvial deposits. In **yellow** (E2,3) are areas of impermeable Eocene flysch deposits. **Orange** and **green** colors mark permeable carbonate rocks. Coordinate grid is 5 km.*

3.2.1.3. Administration, main economic activities, recent development, land use

The Kaštela Bay and Split basin represents an economic and territorial unity, with the city of Split as the dominating centre. The city of Split is the second largest city of Croatia and the administrative centre of the County of Split-Dalmatia. According to MARGETA (2002), total population of the narrow coastal area has tripled over the past half of 20th century, reaching 284,000 inhabitants in the year 1991.

The estimated population for the year 2015 is 355,000, which represents about 6% of the total population of the Republic of Croatia, while the surface area represents less than 2% of the national territory. Split is the second largest town of Croatia. Its population is about 192,000 inhabitants in accordance with population census from 2001. The town of Solin is located in the eastern part of the Bay, in the area of the ancient Roman town of Salona. The medieval town of Trogir is located in the westernmost part of the study area. Between these two towns, along the northern coast of the Bay, the town of Kaštela unites the past seven separate villages. The Jadro spring is used for the potable water supply of Split, surrounding settlements and the towns of Solin, Kaštela and Trogir (approximately 350.000 people).

According to MARGETA (2002), the fast population growth was accompanied by the development of tourism, industry, traffic and trade. The all industrial activity is concentrated at the north-eastern coast of the Bay, between the towns of Solin and Kaštela and on the north-eastern coast of the Split peninsula. The main industries are a shipyard, a brewery, food processing, and soft drinks production. Tourism in the area is mostly of a summer-season character, despite the fact that the area is rich in ancient and mediaeval monuments and beautiful nature in the hinterland and on the nearby islands.

The principal tourist facilities are located in Trogir and Kaštela area, and in the fastly growing tourist center – the City of Split. The area represents an important traffic crossing point on the central Adriatic coast. The Split harbor is connected with the national railroad net. Regional roads running along the coast, and the main Croatian highway (A1) is situated in the close hinterland. The passenger port is the single connecting point for the central-Adriatic islands with the mainland, as well as with other major Adriatic towns of Croatia, Italy and Greece. The Split airport, located between the towns of Kaštela and Trogir, is open for domestic and international traffic. It is important for the transfer of foreign tourists. The coastal plain along the northern coast of the Kaštela Bay has always been important for the production of early fruits, while in the past 50 years a rather high green-house capacity for vegetable and flower production has been constructed in the western part of the area.

The Jadro River area land use is shown on Figure 3-13 and Figure 3-14.

The lower stream is marked as natural (dashed green) area, settlement (yellow) and industrial (orange) zones. Estuarine part of Jadro and the mouth is marked as a public water and a harbor (light blue), while south of the mouth there is an area planned for nautical marine (dark blue). Coastal belt north and south of Jadro River esturay is planned for mixed public and social purposes (walking trails, local boat harbor etc.), while a part of it is a protected historical place (Roman Salona; dashed white). North and south of the Vranjic Bay (that is under influence of Jadro River) is planned for industrial and settlement purposes, with the exception of small peninsula in the central-southern coast that is marked as a green park.

The upper stream and the spring are planned to be green zones protected as a special ihtiological reserve (http://www.dalmatian-nature.hr).

Figure 3-13: Overview of the land use in the area of Jadro river (Source: DGU: https://geoportal.dgu.hr/).

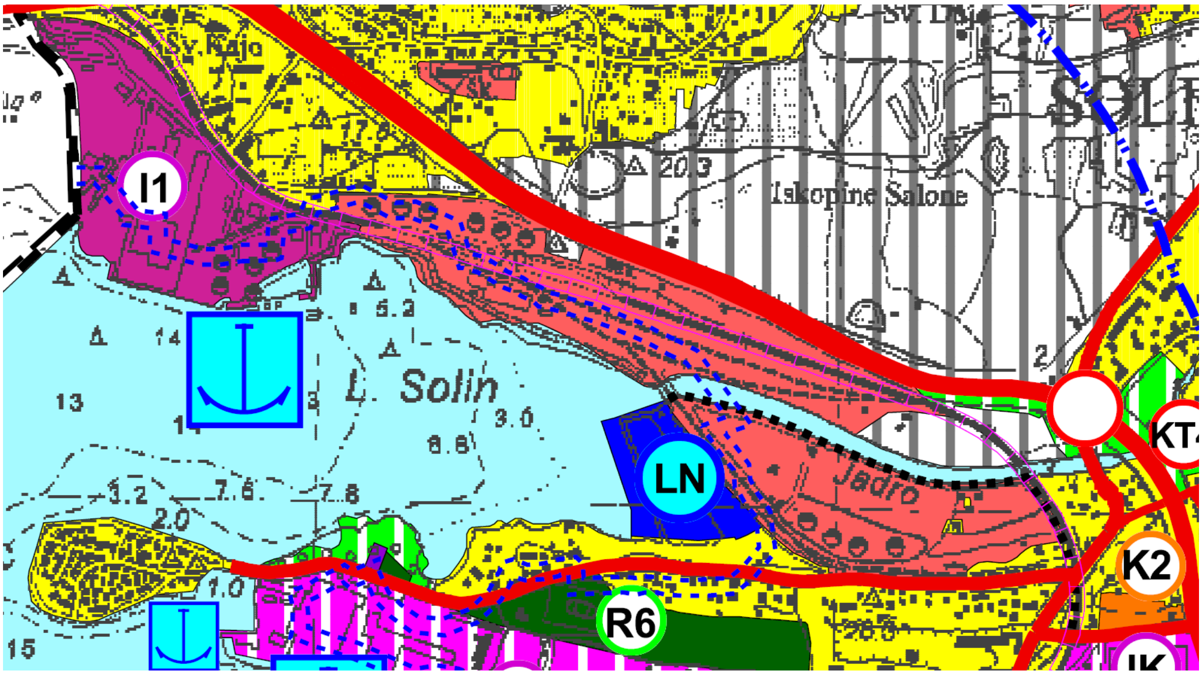

Figure 3-14: The town of Solin land use map in the area of Jadro estuary and the mouth (ZZPU-SDZ, 2017).

3.2.1.4. Main problems and management objectives

The area of the Kaštela Bay was known as one of the most polluted areas of the eastern coast of the Adriatic. The environmental pollution was a consequence of fast industrialization and urbanization without development of appropriate urban infrastructure, in particular of a waste water collection and disposal system. The main conflicts because of that are between industry and tourism, industry and housing, and waste water discharge and tourism (MARGETA, 2002).

After the latest war in Croatia that ended in 1995, the activities on infrastructure development have been clearly indicated as the first area for the projects implementation. The Croatian Government, as well as the local governments of the Bay's surrounding municipalities has given the approval for the action to be taken with development banks. The World Bank and EBRD have approved large loans for the construction of sewage systems (MARGETA & BARID, 1996).

In 2004, the sewage system was completed, comprising a network of pipelines, pumping stations, a tunnel, treatment plants and offshore submarine outfalls. Consequently, sewage discharge into Vranjic Basin suddenly stopped (BULJAC et al., 2016 and refernces therein). The monitoring program of sanitary quality of sea in Kaštela Bay (October 2008 - May 2009) indicates a significant improvement in the sanitary quality of sea Vranjic after years of extremely high concentrations of faecal pollution indicators in this area (The Integral Project of Kaštela Bay Protection - ECO Kaštela Project).

3.2.2. Available sedimentological data, studies, maps

Most of the sediment deposited in the Jadro alluvial plain and in the Vranjic Bay has been brought before the urbanization and industrial development in the area. Urbanization in the area of Jadro River mouth became in Roman time, and various modifications in Jadro River watercourse have been made during the last two millennia.

The topographic catchment of the Jadro is relatively small and covers about 22 km^2 (LJUBENKOV, 2015). The upper stream is under the influence of a substantial discharge (Act. 3.2.1. report) and relatively high topographical gradient, while the lower stream is characterized by estuarine circulation. Several smaller streams and two larger tributaries contribute to the flowing discharge. However, the tributaries have in general a torrential character and, hence, feed the Jadro occasionally, during the rainy season, bringing significant amounts of sediment. In the summer period, the streams are mostly dry.

3.2.3. Acquisition of new in-situ data to complete knowledge

There are no available more precise data on the amount of sediment in suspension of the Jadro River stream. That is why the suspended sediment should be measured within act. 3.3.

Recent studies on the present day sediment stocks are not available neither for the riverbed and the seabed nor for Jadro River mouth and the eastern part of Kaštela Bay (Vranjic Bay). Acquisition of new data is needed (sub-bottom profiler, systematic coring of the sediment etc.).

3.2.4. Current status (qualitative, quantitative) of the site sediment stocks

Although the amount of eroded material is crucial information for understanding of weathering processes in softer rock masses (flysch marls), there are no previous studies on erosion of flysch in Jadro River topographic catchment. Besides, only few previous analyses of the sedimentological processes on the pilot-site Jadro River and Vranjic Bay have been done. BULJAC et al. (2015) sampled and analyzed the uppermost 10 cm of seabed sediment at a few sites across the Kaštela Bay.

The easternmost site (site S2) is located in the central part of Vranjic Bay on the coordinates ϕ (N) 43° 31´ 57" and λ (E) 16° 27´ 15" at the sea depth of 18 meters. The analysis revealed that the sediment in the uppermost 10 cm at the site S2 is mud (silty clay or clayey silt) characterized by approx. 50% of siliciclastic material and 40 % of carbonates with some 9% of organic matter. The portion of mud in sediment is decreasing to the west on other sampled sites across the whole Kaštela Bay, implying that Jadro River supply mostly with fine-grained material (silt and clay).

3.2.5. Analysis of recent trends of the sediment stocks

Recent trends in the sediment stock are poorly known for the Jadro River mouth and the Vranjic Bay. Based on the analyses of the 137Cs distribution in sediment in the Kaštela Bay, LOVRENČID-MIKELID et al. (2017) observed temporal and spatial sedimentation rate variations between three studied periods: 1954–2005, 1963–2005/2006, and 1986–2005/2006. Sedimentation rates were in the following ranges: 0.29–0.49 cm/yr for the 1954–2005 period, 0.58–0.95 cm/yr for the 1963–2005/2006 period, and 0.50–1.32 cm/yr for the 1986–2005/2006 period. The average total sedimentation rates for three periods were 0.41 cm/yr, 0.81 cm/yr, and 0.61 cm/yr, respectively.

Long-term sedimentation rate increase in the whole Kaštela Bay was observed and clearly connected to the industrialization and urbanization processes in the coastal area. LOVRENČID-MIKELID et al. (2017) concluded that intensive anthropogenic activities in the coastal area are reflected in the whole bay depending on the amount of the discharged sediment material, topography of the sea bottom, and water currents, and that some localized areas of sediment accumulation may form.

The Jadro River topographic water catchment is mostly covered with soil and vegetation or cultivated fields that reduce the erosion of the flysch marls that characterize the bedrock in the upper stream catchment area (Figure 3-15).

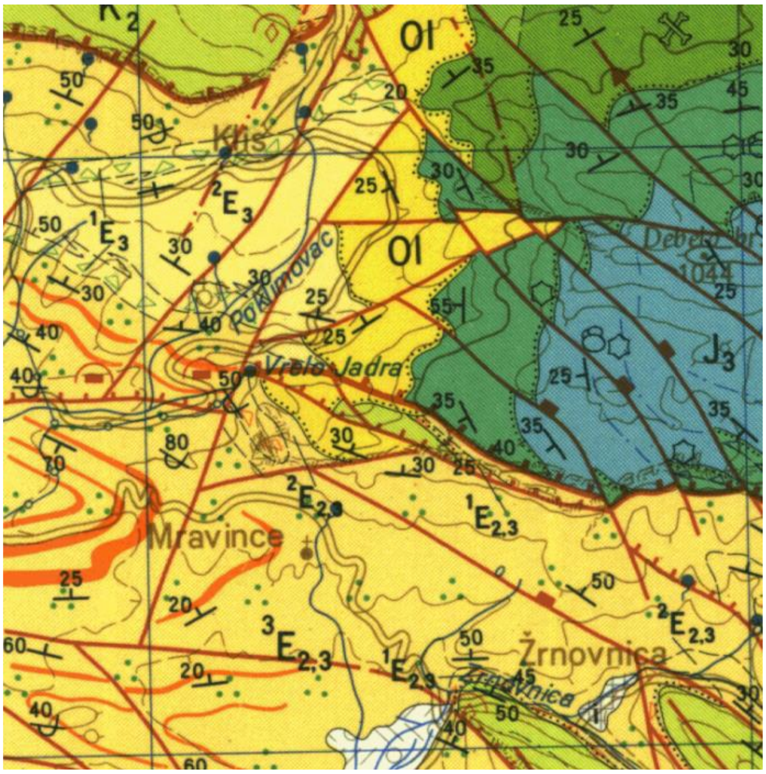

Figure 3-15: Basic geological map (crop from MARINČIĆ et al., 1976) showing impermeable Eocene flysch deposits (in yellow, $E_{2,3}$) in the Jadro River upper stream topographic catchment. Note two quarries north of the Jadro River. Coordinate grid is 5 km.

The soil and vegetation along with the agricultural fields are protecting underlaying flysch marls from erosion. The agricultural land use has not been changed significantly during last 50 years. However, the western part of the topographic catchment is characterized by urbanisation (Figure 3-14) that probably contribute to the flysch erosion downstream of the impervious areas.

However, probable major cause of the increased erosion of the flysch and related increased sediment deposition in the Vranjic Bay could be the quarring activities in the Jadro River upper stream area (Figure 3-16).

The analyses of the badlands in flysch terrains in central Istria (Croatia) revealed that the sediment production from the badland erosion is 8000 times higher than in vegetated areas (GULAM et al., 2014).

The only badlands in the Jadro River topographic catchment area are quarries (Figure 3-16). Thus, further research is needed for reliable estimation of the rate of flysch erosion in the area, but it is out of scope of the Change We Care project. However, the measurements of the sediment in suspension of the Jadro River lower stream should be done at the entrance to the estuary during the rainy season when the expected erosion of flysch marls is probably the highest.

The recent trends of the sediment supply by Jadro River could be evaluated in Act. 3.3. Furthermore, various climate change scenarios could significantly affect erosion and sediment supply to the Jadro River mouth, and should be evaluated in Act. 4.1

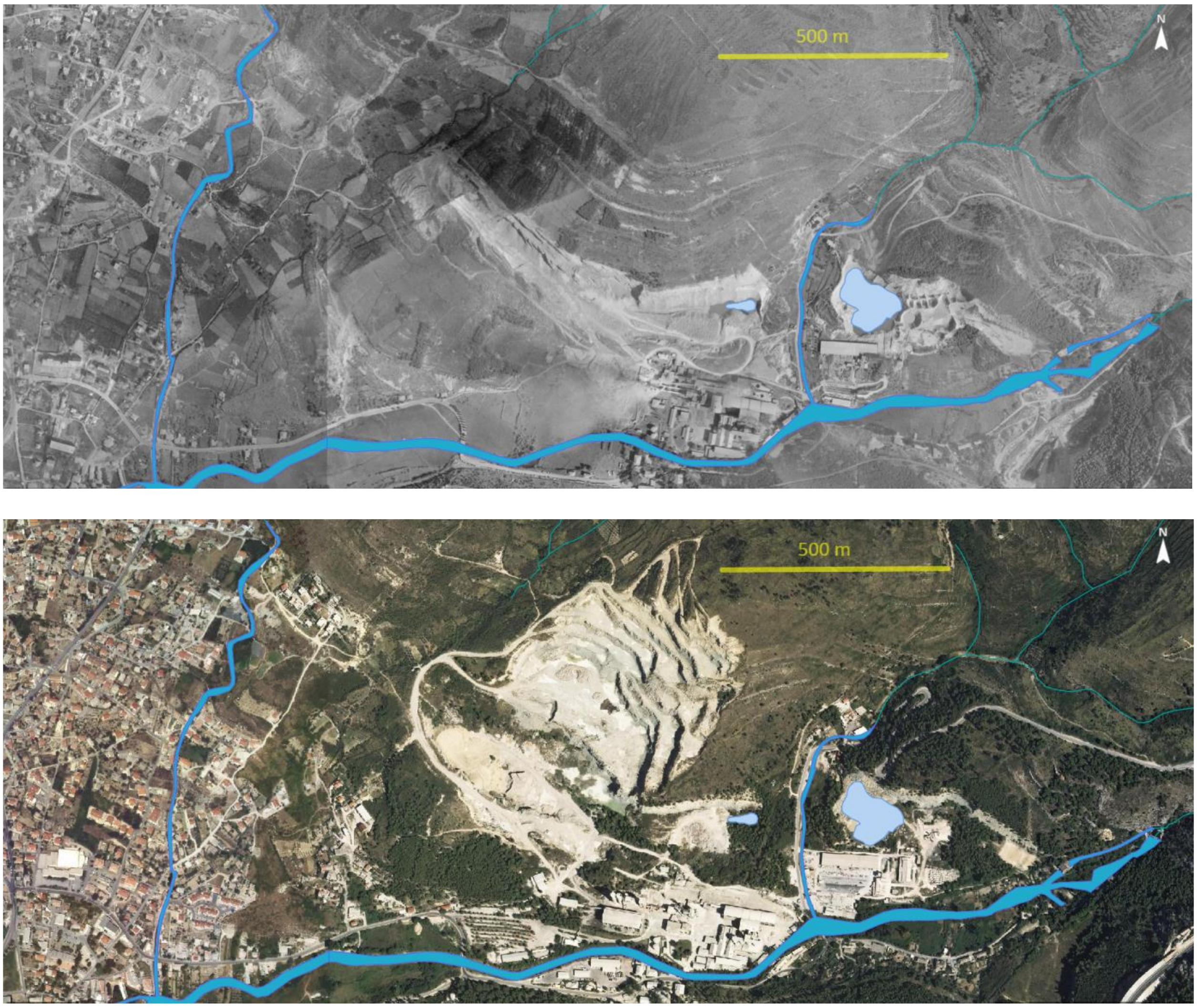

Figure 3-16:Comparision of orthophoto images of Jadro River mouth taken in 1968 (upper image) and in 2017 (lower image). Note a huge quarry developed in flysch marls in the central part of the image. Source: DGU (https://geoportal.dgu.hr/).

3.2.6. Conclusion

3.2.6.1. Results of the activities and discussion

1) The Jadro River spring is located in the contact zone of two major geological units in the area: the karstified and permeable carbonate sedimentary rocks (predominantly limestones and dolomites) that characterize the catchment area in the hinterland, and impermeable coastal flysch belt (predominantly marls) that characterizes Split-Kaštela Basin;

2) Several smaller streams and two larger tributaries have in general a torrential character and that is why an unknown amount of sediment is probably eroded from the topographic catchment during the rainy season.

3) The erosion of flysch marls from the quarries situated along the upper stream resulted with the substantial quantities of mud (silt and clay) that is brought by Jadro to the sea during the last 50 years.

4) Most of the sediment is deposited on the sea bed of the eastern part of Kaštela Bay, i.e. in the small and shallow Vranjic Bay.

5) Long-term sedimentation rate increase in the whole Kaštela Bay was observed and clearly connected to the industrialization and urbanization processes in the coastal area.

6) Comparision of available orthophoto images revealed that increased urbanisation and quarring activities in the Jadro River topographic catchment area during last 50 years probably significantly contributed to the surface erosion and related sediment supply of mud to the mouth.

7) Further research is needed to estimate the rate of erosion in the area.

8) Measurements of the sediment in suspension of the Jadro River lower stream should be done during the rainy season when the expected erosion of flysch marls is probably the highest (Act. 3.3.).

9) Various climate change scenarios could significantly affect erosion and sediment supply to the Jadro River mouth, which should be evaluated in Act. 4.1.

3.2.6.2. Problems and solutions

Generally, the sediment stocks on the pilot-site Jadro River mouth is under strong anthropogenic influence and thus should be under control of the local and regional spatial planners.

3.2.6.3. Analysis of data quality

Data quality is low and for any further more sophisticated analyses, new data acquisition should be performed.

3.3. Nature Park Vransko Jezero

3.3.1. General site description

3.3.1.1. Location (site map, study domain, access routes, cities, etc.)

The area of Vransko Lake and Jasen is located on the eastern coast of the Adriatic Sea in the northern part of the Dalmatian region (Figure 3-17). It is well connected by land, air and sea, which includes the A1 motorway, Zadar and Split airports, marinas and ports, as well as the railway in the immediate vicinity.

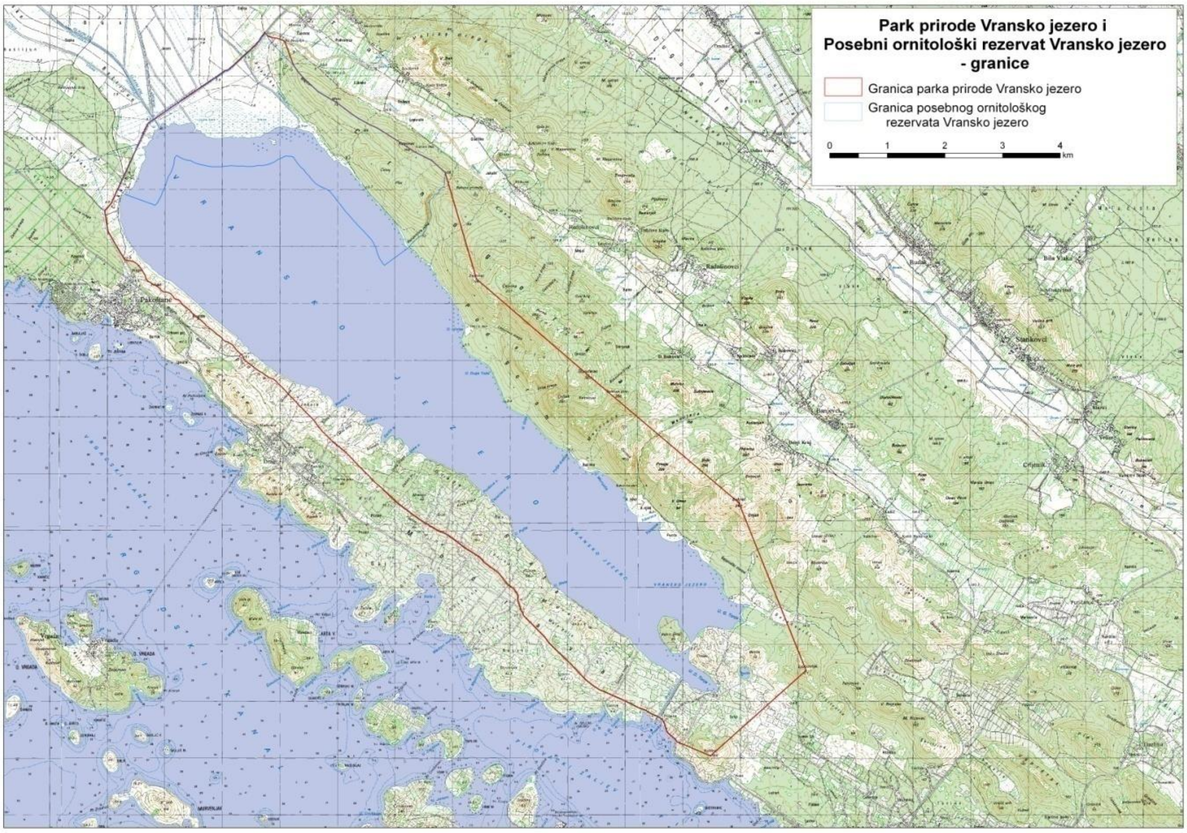

Figure 3-17: Area of Nature Park Vransko lake, Nature park borders-red line and special ornithological reserve -blue line.

Vransko Lake Nature Park is located on the east longitude 15 30 '53 "to 15 39' 36", and in the northern latitude 43 50 '52 "to 43 56' 18". (Figure 3-18) is within two Croatian counties, with 42 km² (74%) in the area of Zadar County and 15 km² (26%) of the area in Šibenik-Knin County. The entire surface of the Vransko Lake water belongs administratively to Zadar County. The distance from the city of Zadar is 30 km and from the town of Šibenik is 24 km.

At the local government level, the area is mostly located within the municipality of Pakoštane, and includes parts of the municipalities of Stankovci, Pirovac and Tisno and the town of Benkovac. At the administrative level of the settlement, parts of the settlements of Pakoštane, Draga, Vrana, Radašinovci, Banjevci, Kašić, Betina and Murter are included, although most of the populated areas are 1-3 km outside the boundaries of the Nature Park (Figure 3-19). Several smaller parts of the inhabited areas are located within the boundaries of the Park: part of Vrana (Majdan), part of Betina (Prosika) and part of Pakoštane (southern lake shore).

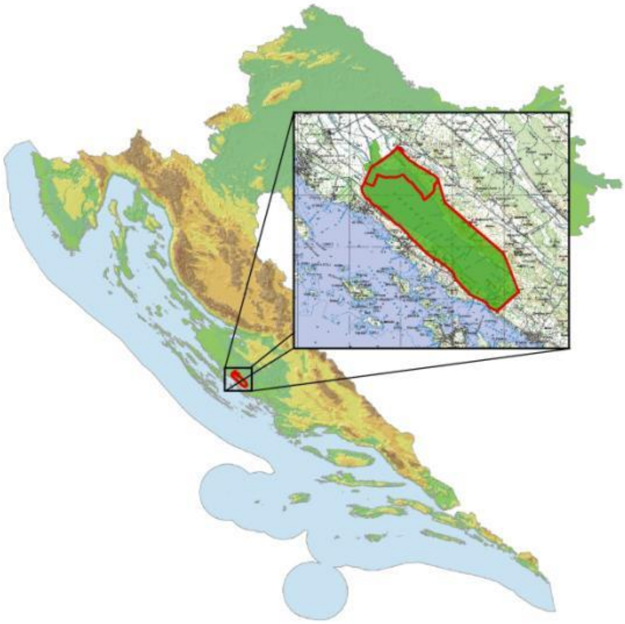

Figure 3-18: Location of Vransko lake Nature park in Croatia.

Figure 3-19: Counties and settlements in the Nature Park area. In green Jasen floodplain NATURA 2000 site

3.3.1.2. Physical and environmental features

Vransko lake is the largest lake in Croatia and one of only two large wetlands in the Mediterranean part of Croatia. The area of the Vrana Lake Nature Park, together with the adjacent Jasen floodplain, is a unique natural and hydrogeological phenomenon. Due to its unique natural values, Vransko Lake with its surrounding area, total area of 57 km², was declared a Nature park on July 8, 1999.

Due to wildlife biodiversity, especially birds, an 8.65 km^2 area in the northwestern part of Lake Vrana, was declared an Ornithological Reserve by the Municipality of Biograd na Moru on February 22, 1983. This area is one of the most ornithologically significant in Croatia and is included in the list of important ornithological areas in Europe (Important Bird Areas in Europe). Extreme geological activity in the past has created a diversity of terrestrial forms and geochemical composition of rocks in a small area, resulting in different soil types that support numerous habitats and species.

The Vransko Lake and Jasen area is along the Neretva River delta, Lonjsko polje and Kopački rit, one of the most valuable wetland habitats in Croatia. It is the last breeding ground for several species of herons in the Croatian coast and an important wintering ground for many species of waterfowl at European level. The lake is located at the intersection of intercontinental migratory routes, and is therefore an indispensable resting place for a large number of migratory species traveling from northern Europe or western Siberia to their wintering grounds. During the period of intensive migration, there can be between 800,000 and 1,000,000 birds at a time in the Nature Park, and more than 200,000 birds regularly use Vransko Lake as a wintering area. A great natural value of the Nature Park is the community of freshwater and wetland ecosystems, especially in the area of flood meadows and reeds. The richness of the flora and fauna (indigenous and introduced), together with the freshwater reservoir, further enhance the ecological significance of the area.

The lake is situated in a shallow karst bed and separated from the Adriatic Sea by a narrow karst ridge. Significant seasonal variations in water level and changes in salinity due to intrusion of sea water through permeable karst, create conditions for development of very specific habitats. The shallowest northwest part of the Ramsar site proclaimed in 2013 is characterized by reedbeds, floodplain and seasonally flooded arable land; the hills lining the eastern coast are covered by typical Mediterranean macchia and garrigue, while the lower western coast gives a more rocky appearance. Vransko lake marsh habitats is a remaining of what used to be a much larger Vrana swamp, drained by melioration canals in 18th century.

3.3.1.3. Administration, main economic activities, recent development, land use

The Nature Park, the Ornithological Reserve and the areas of the ecological network within the boundaries of the Nature Park are managed by the Public Institution Vransko Jezero Nature Park. The activity of a public institution includes the protection, maintenance and promotion of an area with the aim of protecting and preserving the authenticity of nature and ensuring the smooth running of natural processes and the sustainable use of natural resources, as well as monitoring the implementation of conditions and measures of nature protection. Most of the total area of the Nature Park and the entire area of Jasen are owned by the Republic of Croatia.

In addition to the Public Institution of the Nature Park, on behalf of the state as the owner, state-owned enterprises of the Croatian Waters and the Croatian Forest manage 80% of the surface of the Nature Park. Croatian Waters are responsible for the water pump at the exit of the Main Channel (Kotarka) into the lake, which monitors the water level in the Jasen area. Croatian Waters is also responsible for maintaining canals in the lake area and for measuring water levels, watercourses and water quality in and around the Nature Park. Around 10 ha of olive groves are privately owned mostly by inhabitants of Murter island, agricultural land in the Reserve and on the southwest corner of the Park are owned by inhabitants of Pakoštane municipality. Most of the flooded meadows and marsh area are owned by the state. Combination of state (mostly "Croatian Forests") or municipality owned, with smaller privately owned particles (mostly for agriculture). Drained fields of Jasen (natural part of flood zone) in the catchment are being used as agriculture land by a single private company.

Vransko Lake is the biggest reservoir of fresh water in this region of Croatia. In 1970-ties there have been plans for building accumulation of fresh water in Vransko Jezero Lake and its usage for water supply, but the idea was abandoned due to problem of salinization. Springs from Vransko jezero's catchment (Kakma, Biba, Škorobić, Turanjsko jezero, Kutijin stan) are, however, regularly exploited for water supply, and Begovača seasonally. Springs Tinj, Mali Stabanj, Veliki Stabanj, Pećina are used for irrigation of arable land. During rainy season Vransko Jezero's marsh prevents high waters from destroying the dikes and intruding the fields outside of the flood zone. The reedbeds are excellent in purifying waters that enter the lake through melioration canals, carrying fertilizers that could enhance lake eutrophication. The land in the catchment area is mostly used for intensive agriculture on medium-size plots. As the land is not very fertile due to salinization, it is not cultivated regularly, which is in favor of maintaining good water quality of the lake.

In the park's area there are three visitors' centers managed by the public institution: Prosika harbor with the info point, souvenir shop, refreshment point, observation hide, educational trails; Kamenjak sightseeing point with the info point, souvenir shop, refreshment point and an educational trail and Crkvine info center with souvenir shop and an educational trail with watchtowers for experiencing bird biodiveristy. In the year of 2019, 48155 visitors have been recorded in the Nature Park.

Within the boundaries of the Nature Park, intensive agricultural production is taking place on the peripheral parts of the ornithological reserve, in which several crops are harvested annually. Mainly hybrid varieties are grown using agro-technical measures to achieve the best possible yield with the use of fertilizers and chemical plant protection products. The same type of agriculture takes place on private estates along the border of the ornithological reserve and in a large part of the catchment area of the Škorobić and Pećina streams.

Extensive agriculture is taking place in other parts of the Park without major adverse effects on the ecosystem. Cattle-breeding is becoming increasingly scarce, so the number of small-toothed cattle has fallen dramatically in recent decades, while large-toothed cattle have almost disappeared from these areas. In the rural hinterland, several dozen families raising sheep and goat herds have been maintained and are used by state-owned pastures in the Nature Park area. The two families have their own herds and stables in the Nature Park area, which should definitely be monitored and supported.

3.3.1.4. Main problems and management objectives

Interventions in the past in the catchment area affected significantly the ecological character of the Nature park. The first human interventions were construction of the Prosika canal and other melioration canals starting in the 18th century, which resulted in drainage of a large part of the wetland northeast of the lake. Out of 570 ha of former Vrana Swamp as much as 410 ha has been meliorated, while only 160 ha remained in the natural flooding regime.

Out of 31 karst springs in the catchment, 5 are used for public water supply, 7 for irrigation of agricultural fields, and 4 are used locally (for water supply or individual field irrigation). In addition to this, illegal landfills have been made in the agricultural fields, from which the land owners pump the water out.

The total annual pumping estimates amount 1.9×10^6 m^3 for water supply and about 1.0×10^6 m^3 for melioration. These anthropogenic influences are worsened by the climatic change factor. Recent trends in rise of the sea level for 0.13 mm/year (detected for the period since 1969), combined with the regional decrease in rainfall and increase in water uptake, cause salinization of Vransko Jezero Lake and subsequent change in habitats. Potential risk lies in the County's plans for advanced irrigation in the catchment area.

The main management objectives are adapting to long-term drought periods with low water levels, intrusion of the sea water and salinization up to 10‰, eutrophication processes during drought periods, alochtonous fish species without population control (Prussian carp), avoiding planned golf courses in the catchment and further water uptake for irrigation in the catchment area.

3.3.2. Available sedimentological data, studies, maps

3.3.2.1. Geological history and processes

Vransko Jezero Lake is a shallow flooded alluvial plain, formed in Cretaceous, partly covered with eocenic nummulitic limestone and quaternary sediments (Figure 3-20). The lake bottom is covered in thick limestone mud, which is continuously sedimenting. Lake's bottom is at -3 m, sand reaches down to -13 m, clay is sedimentated between -13 m and -23 m, clay with gravel prevails between -23 m and -30 m, and below -30 m is rocky substratum.

In this area, there are no deposits of Neogene age, but only the youngest, mostly unconsolidated Quaternary sediments (Q) are present. In periods of high sea levels, karst depressions inland were filled with water, and lake and marsh sediments (j) were deposited, while in periods of low sea levels they partially or completely dried out. The progress of the karstification process in the terrain composed of carbonate rocks resulted in the gradual lowering of the water level during the geological past.

In the last 300 years, major changes in the natural regime of the depositional environments were caused by anthropogenic impact due to implementation of land reclamation and the perforation of drainage canals (Prosika Canal) and tunnels (Nadinsko blato), which significantly reduced the extent of the flooded areas in the Field of Vrana.

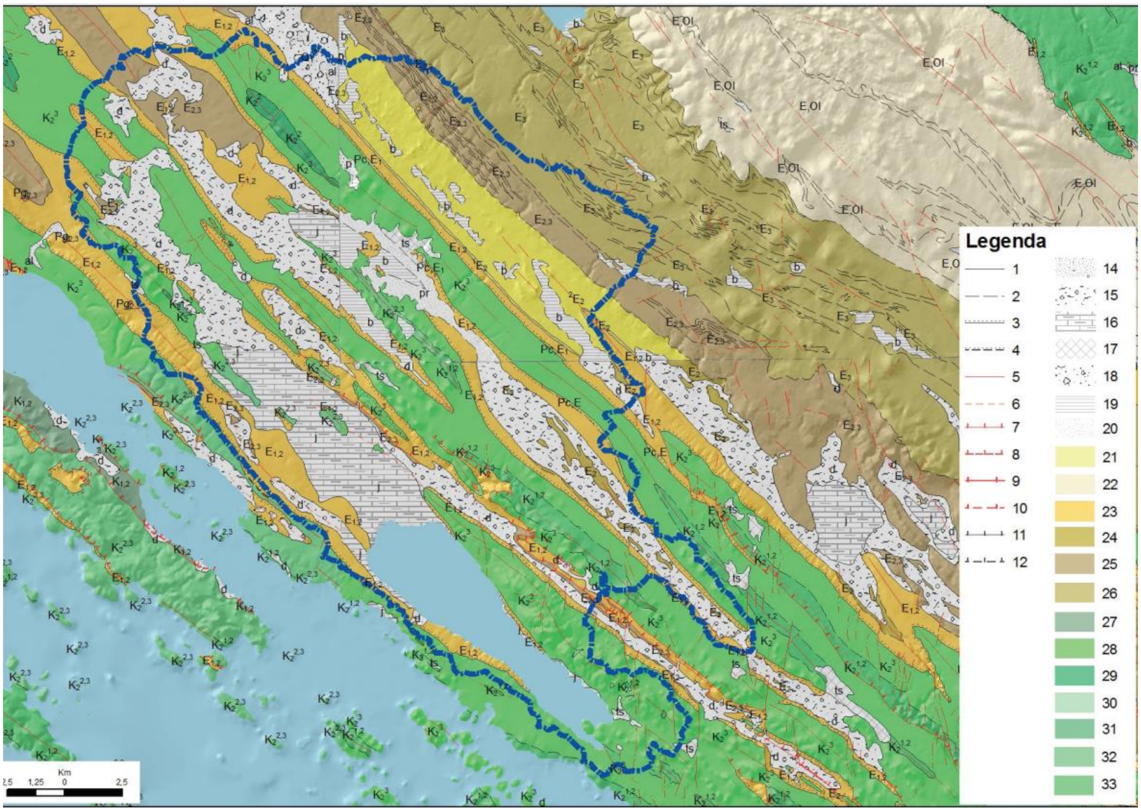

Figure 3-20: Geological map of Lake Vrana and its catchment (Mamužić & Nedela-Devide, 1971; Mamužić & Nedela-Devide, 1973; Mamužić, 1966; Mamužić, 1975; Majcen et al., 1970; Majcen & Korolija, 1973). The orographic catchment was determined with ArcGIS (ESRI, 1999-2009) and marked with dark blue line. Legend: 1) Geological boundary; 2) Proposed geological boundary; 3) Erosional-discordant boundary; 4) Proposed erosional-discordant boundary; 5) Fault; 6) Proposed fault; 7) Reverse fault; 8) Proposed reverse fault; 9) Thrust fault; 10) Proposed thrust fault; 11) Transgression; 12) Proposed transgression; 14) al Alluvial sediments; 15) d Diluvial sediments; 16) j Lake sediments; 17) ts Terra rossa; 18) Q13 Sandy clays; 19) pr Proluvial sed.; 20) Pond deposits; 21) 2E2 Limestones, marls and clastites; 22) E, Ol Platy limestones; 23) E1,2 Foraminiferal limestones; 24) E2 Flysch; 25) E2,3 Flysch and conglomerates; 26) E3 Conglomerates and limestones; 27) K1,2 Dolomites; 28) K23 Rudist limestones; 29) K22 Stratified limestone; 30) K21 Dolomite and limestone; 31) K22+3 Limestone and dolomite; 32) K22,3 Dolomite and dolomitic limestone; 33) K21,2 Limestone and dolomites with chondrodonts.

3.3.2.2. Paleolimnological study

A paleolimnological reconstruction of the Lake Vrana near Biograd was done by Ilijanić (2014) based on the dated sediment core over a length of 11 m (only 8 m of the core was dated), divided into several intervals that indicate different sedimentological deposits and environments over the lake's history. Chronology of the lake sediment sequence was based on five radiocarbon dates on freshwater shells, corrected for hard water reservoir effect. Zone 1 (Figure 3-21) is probably of Late Pleistocene age, while zone 2 (Figure 3-22) is then early Holocene and divided into three intervals. Zones 1 and 2 are characterized by a higher content of siliciclastic detrital materials, which indicate intensive erosion from the catchment and thus a flood plain environment in Lake Vrana, similar to karst poljes. In the middle Holocene, zone 3 (Figure 3-23), the lake was formed, and divided into two intervals with very high carbonate content, the latter showing a gradual increase of marine influence. The present conditions in Lake Vrana were established in the late Holocene, zone 4 (Figure 3-21).

In zone 4/3 (13-6 cm; 0.1-0.03 ka cal BP), there is a sudden increase in the sand fraction, and the average particle size is 229 µm. This period could correspond to the cold conditions of the Little Ice Age (LIA, 400-100 BP; 1550-1850 AD). Additionally, this sandy layer could be related to the construction of Prosika Canal in 1770 AD for the drainage of the wetlands in the Field of Vrana, which caused the lowering of Lake Vrana's level by approximately 3 m. In this period, sediments and materials from other parts of the lake have been mixed. Placing of such resuspended sand material can be attributed to this intervention. For a more detailed description see the Deliverable 3.2.1.

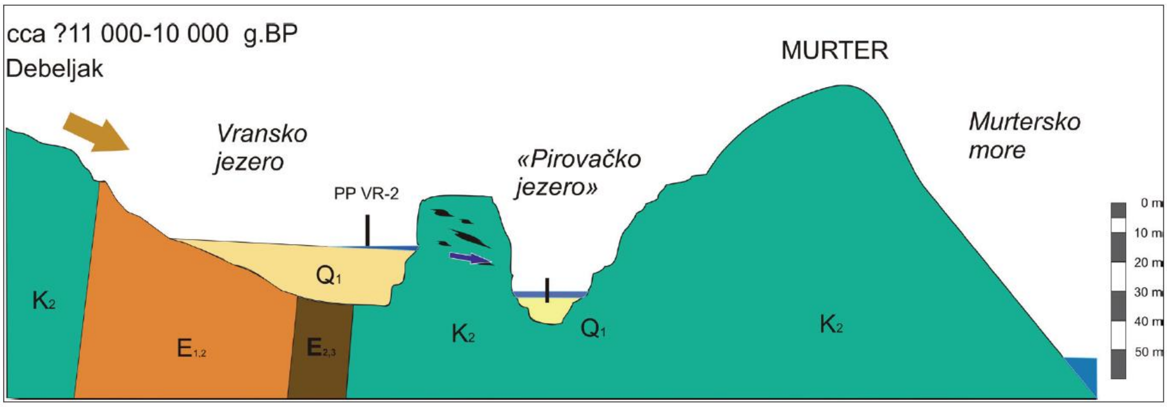

Figure 3-21: Reconstruction of Lake Vrana near Biograd in the Early Holocene; Lake Vrana existed as a floodplain with streams and the occasional formation of ponds.

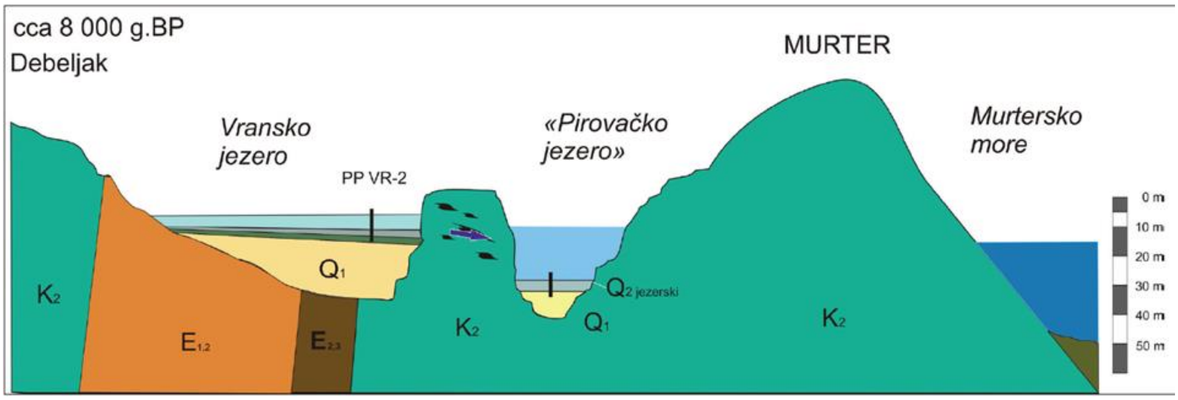

Figure 3-22: Reconstruction of Lake Vrana near Biograd in the period ca. 8,000 years BP; Lake Vrana is formed as a result of blocked water outflow into Pirovac Bay ('Lake'), which was filled with water due to sea-level rise.

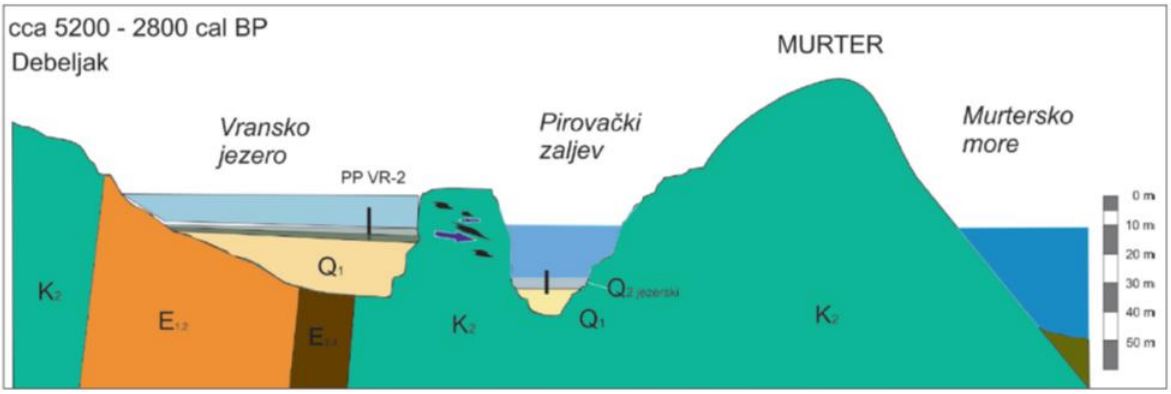

Figure 3-23: Reconstruction of Lake Vrana near Biograd in the period between 5,200 and 2,800 years BP; increasing influence of seawater on Lake Vrana.

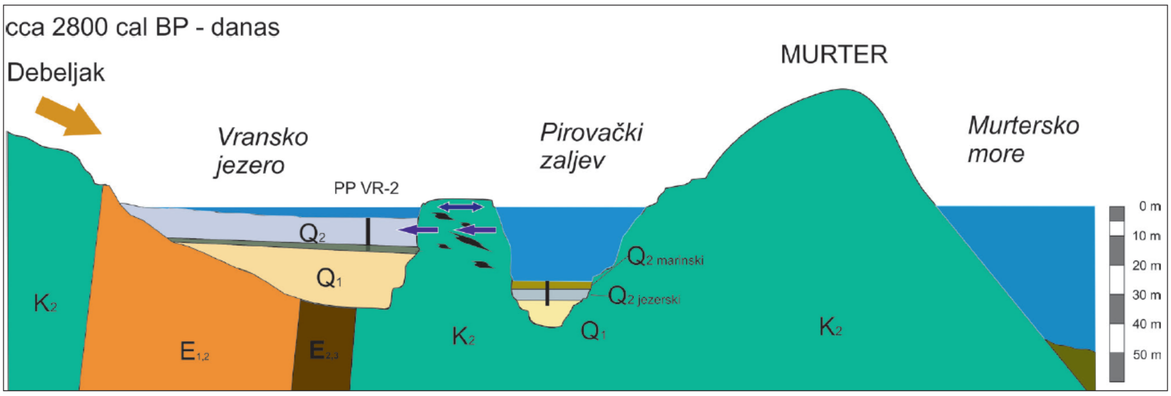

Figure 3-24: Reconstruction of Lake Vrana near Biograd in the period from 2,800 to today; present conditions in Lake Vrana are established, with seasonal fluctuations in more and less brackish environments.

3.3.3. Acquisition of new in-situ data to complete knowledge

No new in situ data was acquired to complete the knowledge.

3.3.4. Current status (qualitative, quantitative) of the site sediment stocks

According to Ilijanić (2014) the sedimentation rate in Vransko lake in the last 2 700 years is 0.04 cm per year, which means that 4 mm of sediment precipitates in 10 years. The edge of the lake, especially in the northern part, where the depth varies from 1 to 2 m, could pass from the lake phase to the marsh, just as there is a swamp in the far northwest. Increased anthropogenic nutrient intake origin could lead to disruption of the current state, with eutrophication and increase sedimentation. The current sedimentation process in the lake is dominantly the carbonate sedimentation, resulting from the sedimentation of the biota in the lake water column as explained after.

The majority of the groundwater flow and the lake watershed are from the direction of Ravni Kotari situated NW of the Vransko Lake and it is presumed to be the main source of terrigenic material to the lake. The sediments in the lake were analyzed by Fajković et al 2010 and the mineral phase analysis showed the presence of calcite, quartz, micas, and pyrite in all three composite samples indicating the same source material for the whole lake. Sedimentation environment in the Vransko Lake is considered as the low– to medium–energy environment. It is likely that the anoxic conditions occur in the lake sediments.

Sediment composition depends on the geological composition of the surrounding source rocks consisting mainly of limestones, lacustrine deposits, and flysch. Carbonate component predominates in the sediment composition. Sedimentation rates are higher in the NW part of the lake in all three studied periods (i.e. 1954–1964, 1964–1986, and 1986–2010) probably due to the more pronounced watershed influence. Sedimentation rates showed the same patterns of the temporal variations and a general decrease after the 1964 at both studied sampling stations.

3.3.5. Analysis of recent trends of the sediment stocks

The yield of terrigenous sediment via watercourses that flow into the lake from the Vransko Polje can be estimated approximately on the basis of available flow monitoring, concentrations and sediment transport from October 1995 to June 1997, conducted by DHMZ at the Vrana - Lateral Channel station (Figure 3-25).

It is evident that relatively significant daily drifts (in the order of magnitude above 1 tons per day) occur during more pronounced water periods, especially when larger waters occur after a longer drought period.

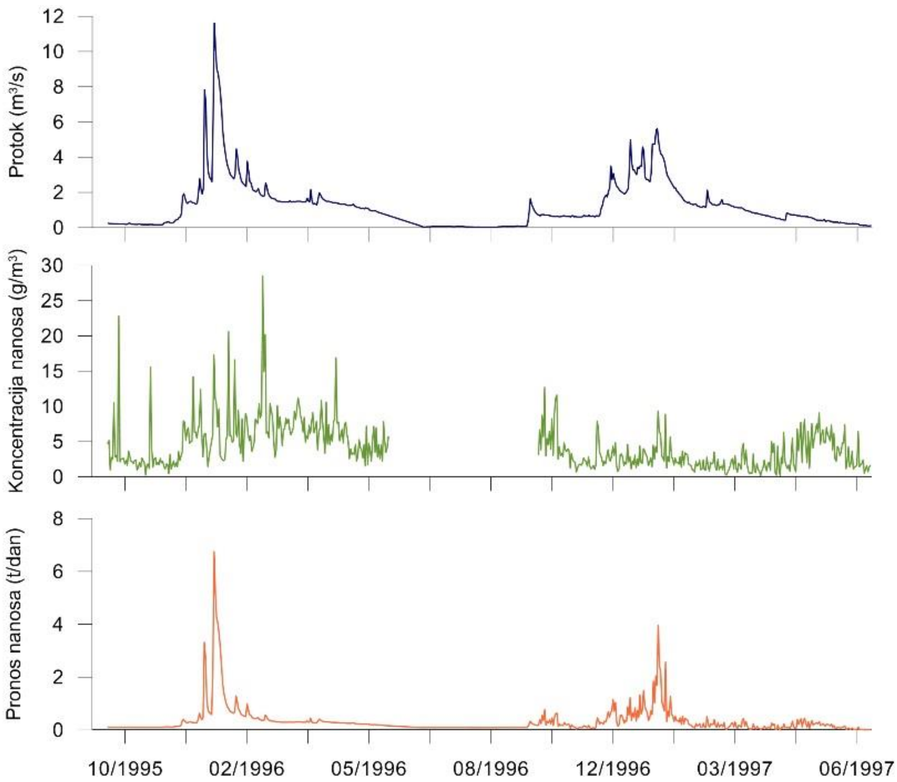

Figure 3-25: Flow rate (m³/s), concentration (g/m³) and sediment flow (t/day) rate at Vrana Station - Lateral Canal (10.1995-1.1997) lack of data supplemented by a regression model

3.3.6. Conclusion

3.3.6.1. Results of the activities and discussion

Lake Vrana near Biograd na Moru is the largest freshwater lake system in Croatia, receiving most of its water through its tributaries from the Vransko polje. It is a shallow lake of 31.12 km^2 at an average water level of 0.82 m.a.s.l.. The lake is dynamically balanced with inflows from the basin and fluctuations in sea level, and sedimentation processes play a very important role in maintaining the lake as a predominantly freshwater system. They occur in the lake in such a way that the lake system is characterized by dominant autigenous calcite deposition processes (Ilijanić, 2014) with a relatively small direct yield of terrigenous material that reaches its lake tributaries as well as occasional aeolian erosion yields. Calcite is excreted from the waters of the lake itself and precipitated by organisms that build skeletons from calcite, and by their extinction, fossil fragments accumulate to form biogenic limestone. The action of bacteria, and in particular cyanobacteria, is a major mechanism for the formation of recent carbonate deposits in freshwater environments (Thompson and Ferris, 1990). The process of calcite precipitation depends on the pH of the water, the temperature and the concentration of the nutrients. Higher amounts of nutrients during bacterial growth result in faster growth and higher amounts of precipitated calcite.

The conducted studies determined the sedimentation rate in different parts of the lake system. The work of Ilijanić (2014) discusses the processes of sedimentation over a longer geologically historical period. Fajković (2014) considers the dynamics of sedimentation during the recent historical period (1954-2010), for which the average sedimentation rate is estimated to be 5.5 mm/yr in the northwestern part of the lake and 3.4 mm/yr in the southeast. If taken as an average value of 4.45 mm/year, it would appear that about 140,000 m^3 of sediment is deposited at the mid-lake level per year.

3.3.6.2. Problems and solutions

Sedimentation processes are extremely important for preserving the survival of cryptodepression lakes in coastal karst areas, and in general for protecting coastal karst aquifers from salinization. Specifically, in the presence of the effects of climate change reflected in rising sea levels, the equilibrium between groundwater in the aquifer and the sea also rises to higher levels where fissure systems are more open.

However, rising sea levels also cause a slowdown in flow through coastal karst aquifers. When sea level rise is more intense than the mentioned processes of sedimentation within coastal karst aquifers, which is happening in recent times, hydrological connections of the sea and groundwater, and in the case of the lake system, intensify and the risks of salinization are more pronounced, especially due to at the same time, there is a decrease in inflow.

3.3.6.3. Analysis of data quality

Data quality is sufficient but more interdisciplinary research between geologists, hydrologist, biologist are needed to answer the questions about the influence of climate change the Vransko lake Nature park ecosystem.

3.4. Banco Mula di Muggia

3.4.1. General site description

3.4.1.1. <u>Location (site map, study domain, access routes, cities, etc.)</u>

The Banco Mula di Muggia is located in Friuli Venezia Giulia Autonomous Region (Figure 3-26). It is entirely included in the Municipality of Grado (province of Gorizia GO, Italy), on the northern coast of the Adriatic Sea, located between the Grado inlet and the mouth of the Isonzo River. The coordinates are between 13°24’36” and 13°28’15” East and between 45°21’17” and 45°39’30” North.

It is part of the system of low sandy beaches of the Friuli Venezia Giulia, limited to the west by the mouth of the Tagliamento and to the east by that of the Timavo, where the high rocky coast begins.The coastline has undergone significant changes in historical times due to natural processes but also to anthropic actions i.e. land reclamation and tourism development.

Grado is a touristic island at the eastern part of the Marano and Grado Lagoon (Figure 3-27). The town has about 8.000 inhabitants but during the summer season this number increases at least three times; statistic data say that 1.355.334 is the number of presences in the accommodation facilities for the whole 2017.

Figure 3-26: Overview of the study area.

The area is well connected by land, air and also sea. Two regional routes connect Grado to the highway A4 and Trieste is about 1 hour of trip by car. The Trieste airport is about 20 km and railway stations are at the same distance. A seasonal service connects by boat Grado to Trieste and an efficient cycling network connects the site to the mainland.

Figure 3-27: Location of Grado (www.viamichelin.com).

3.4.1.2. Physical and environmental features

The Banco Mula di Muggia is a barrier-island system of relict sand banks, extends up to 2 km seawards. The barrier-islands are elongate accumulations of unconsolidated sediment that separate the open sea from a landward restricted basin (Figure 3-28).

Figure 3-28: Arial view of the Banco Mula di Muggia.

The main sediment source is the Isonzo River, which represent the eastern limit of the study area.

The system is very sensitive to sea-level rise and storm patterns, thus providing clues to process changes through time. The tidal magnitude is unusual for the Mediterranean Sea, with semidiurnal mean and spring tidal ranges of 65 and 105 cm respectively. The passage of atmospheric low pressure systems is able to amplify tidal water levels up to 160 cm: the so called “acqua alta”. Climate is temperate, influenced by ENE (Bora) and SE (Scirocco) winds.

External sandy bars tend to migrate toward south-west, following the littoral drift generated by waves. On the western terminus, the bathymetric contours curve abruptly, thus inducing bars to shift landward toward the touristic beaches. Therein, sediment tends to accumulate over time, and the area is currently a sediment sink for the whole up-drift sector (Figure 3-30).

The succession of sandy bars (between -2 m and -5 m), arranged in the form of an arc, represents the outer limit of a wide muddy intertidal zone partially covered by seagrass (Figure 3-28-Figure 3-29).

Laminated and filamentous microbial mats develop on intertidal flats. The barrier present higher-energy conditions and rippled sand and shell debris is locally abundant. It is commonly assumed to represent the remnants of the former Isonzo river delta having formed during the Middle Ages.

Figure 3-29: The western part of the Banco Mula di Muggia: the sandy bars and the muddy intertidal zone are visible.

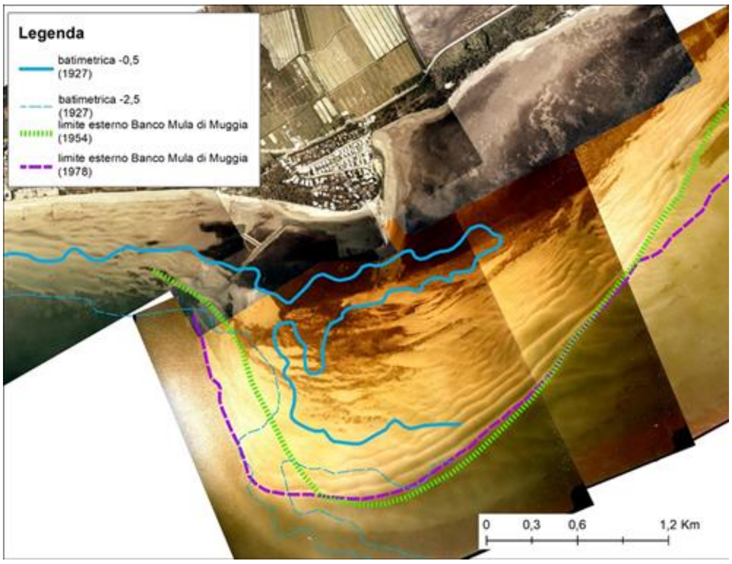

Figure 3-30: Bathymetric contours v/s years in the western part of the Banco Mula di Muggia.

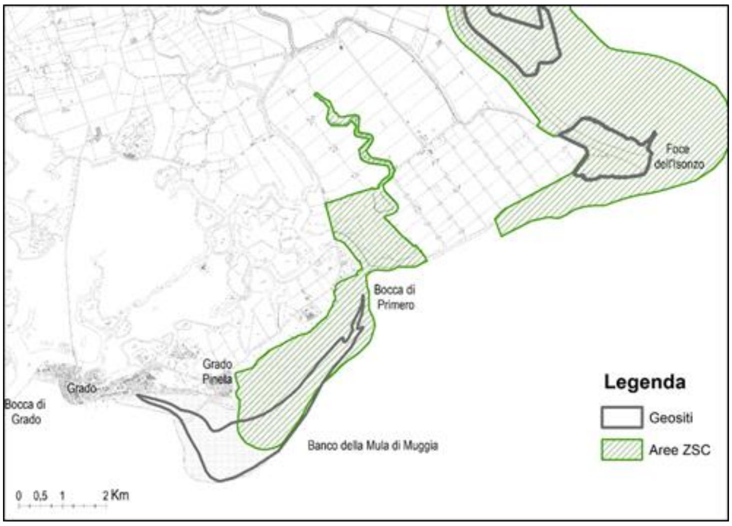

Figure 3-31: Site of Community Importance (ZSC, in Italian) and geosite perimeter.

The Isonzo delta consists of a delta structure stretched out along the mouth of Sdobba, which became the only distributary channel after the occlusion of the Quarantia branch in 1937. It has a typical river-dominated form, with a single elongate distributary, about 1300 m wide at the base, and 700 m wide at the mouth, extending ca. 1 km in NNW-SSE direction.

The delta plain is formed by herbaceous bogs and reed thickets (Fragmites) which leave the place towards the sea at tidal plains, with the typical sandy-pelitic sediment cover, extending for about 700 m from the shoreline (Banco Spigolo and Banco del Becco). A series of bare bars characterize the delta front.

The area of Banco Mula di Muggia is recognized for its outstanding biodiversity: it is a geosite and it is part of the Special Area of Conservation IT 3330006 (Figure 3-31). Habitat 1110, Sandbanks, which are slightly covered by sea water all the time and Habitat 1140, Mudflats and sandflats not covered by seawater at low tide, are its features.

3.4.1.3. Administration, main economic activities, recent development, land use

The Special Area of Conservation IT 3330006 is managed by the Region (Regional Low 07/2008). The entire area is state-owned, just a small part of beach is under concession to private individuals. The Regional Law 11/2015 confirms to the Region the soil protection function for the realization of the defense and conservation interventions of the coasts with the exception of the inhabited centers. The Municipalities carry out the defense of coastal towns, as well as the beach nourishment interventions.

On the edge of the protected area, many touristic activities are present; they are mainly seasonal activities, linked to seaside tourism. Four big camping-resorts with fully equipped beaches are located in the eastern part. Grado Pineta is a touristic district of Grado having several hotels, restaurants and second houses; a small marina is present too. The territory of the municipality of Grado has a touristic offer of 23.791 beds (2016). Most of the beaches are equipped, with services for tourists such as bars, and beach equipment, while the Banco Mula di Muggia area, thanks to its environmental peculiarities, has low anthropic pressures because shallow waters and silty sediments are not a tourist attraction.

The CORINE Land Cover (CLC) inventory defines three different classes of land use for the area (Figure 3-32): Code 331 (beaches, dunes, sand), Code 112 (discontinuous urban fabric) and Code 311 (broad-leaved forest). The information is not sufficient for the definition of the area where the tourist settlements are present, because part of the camping and touristic villages are classified as code 311. The imperviousness products of the Copernicus land service (Figure 3-32) capture the percentage of soil sealing and it is an important information about the anthropogenic pressure. Built-up areas are characterized by the substitution of the original (semi-) natural land cover or water surface with an artificial, often impervious cover.

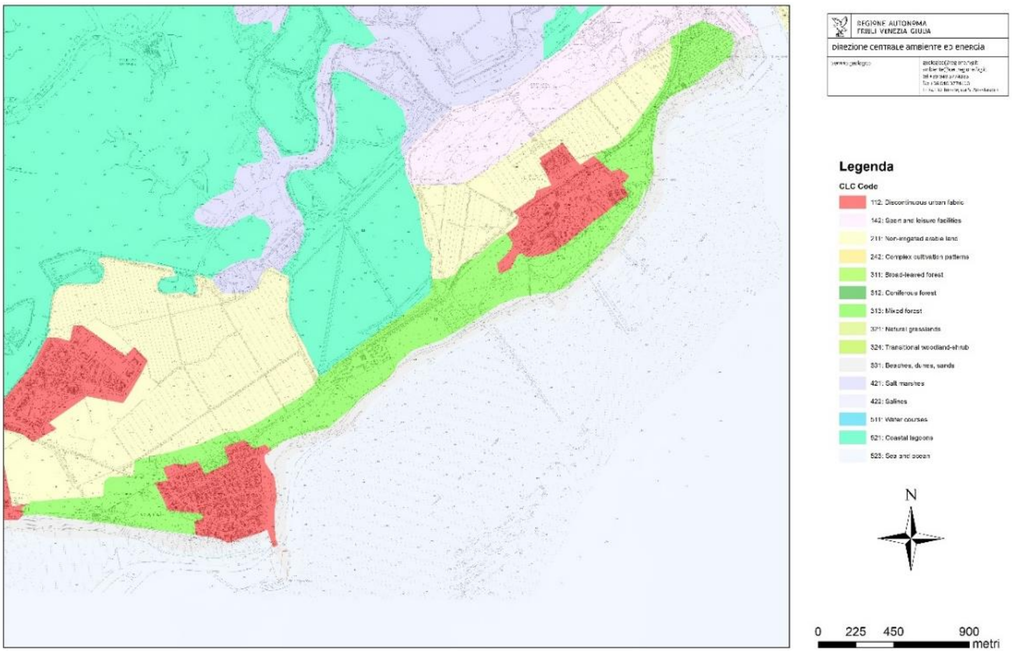

Figure 3-32: Map of land use from CORINE Land Cover (CLC) inventory (land.copernicus.eu).

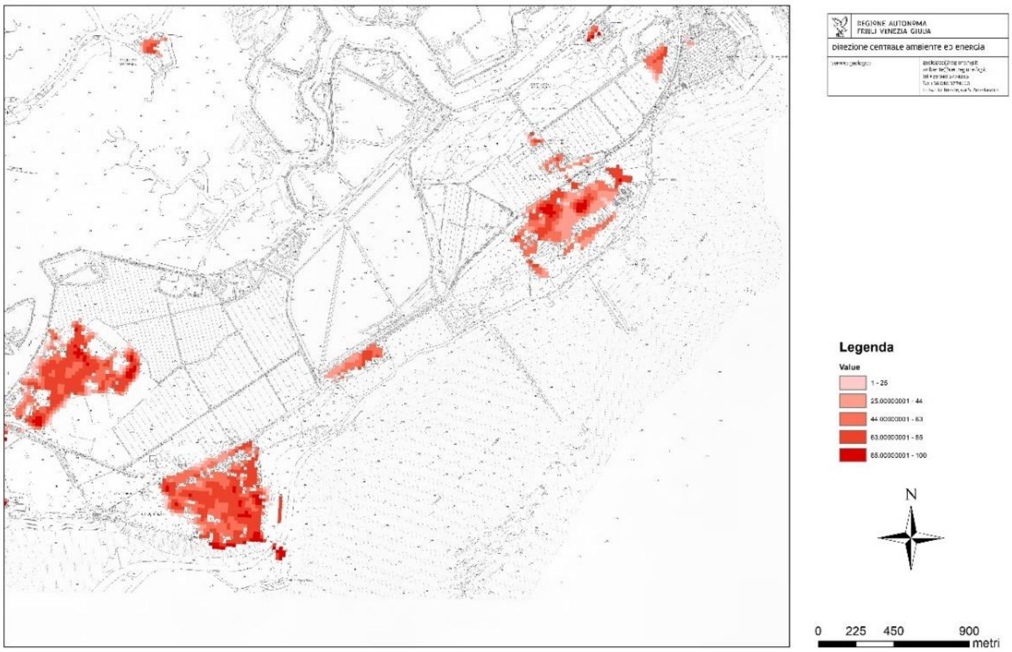

Figure 3-33: Imperviousness map (land.copernicus.eu)

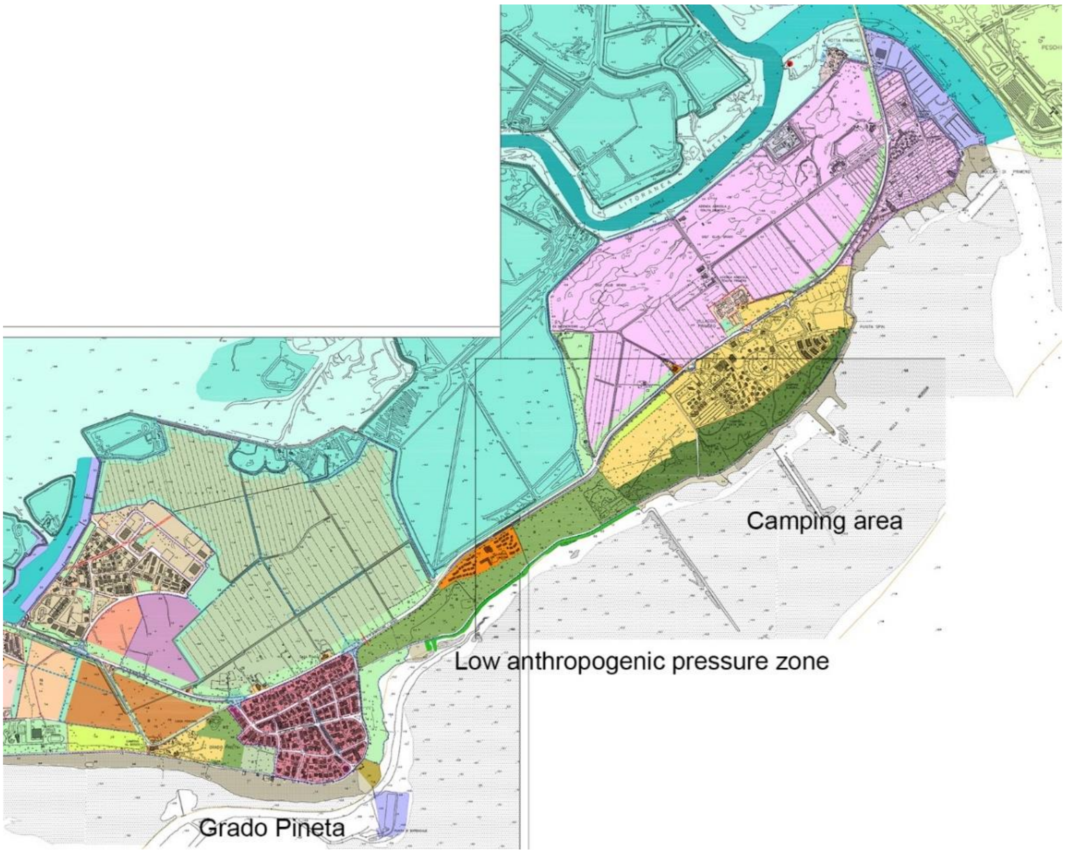

Figure 3-34: Extract from the Municipal Master Plan of Grado, the three different pressure zone are visible; from left, can be distinguished the Grado Pineta district, the low pressure wooded area and the camping area. (Municipality of Grado)

The Municipal Master Plan of Grado define the whole inland as area for marine tourism development, but the wooded area between Camping and Grado Pineta has a lover anthropic pressure and this part of beach is identified as an ecological corridor (Figure 3-34)

3.4.1.4. Main problems and management objectives

The main problem is the conflict between the tourism development and nature protection. Two contrasting elements, such as an area for marine tourism development and a Natura 2000 site, coexist in the same area. Although the Banco Mula di Muggia is a wildness area for its geomorphological peculiarities, the onshore area is densely populated, especially in summer.

The management of the camping and touristic villages ask for sandy beaches for their guests, but actually their businesses look onto the wide muddy intertidal zone partially covered by seagrass protected by the succession of sandy bars. This is the result of a wrong urban planning of the sixties of the last century, when seaside tourist activities were setup in a paleo lagoon area.

The other problem is the external sandy bars that tend to migrate toward south-west causing the loss of quality of the main touristic beach of Grado, the seabed becomes lower and the muddy component prevails.

It is problematic, especially because the economy of the Municipality of Grado is based on seaside tourism. During the eighties of the last century administrator looked for a solution: a canal was dug in the area of Grado Pineta, changing the coast line too, but it wasn't a successful operation.

On the other side, the system of banco Mula di Muggia is very sensitive to sea-level rise and storm patterns, as well as the entire urbanized part of the city of Grado.

The management objective for the Banco Mula di Muggia aims at the harmonization of tourism development and the protection of coastal geomorphological features according to the rules of the Special Area of Conservation IT 3330006. The rapid dynamics of the sand banks and the erosional/depositional pattern characterized based on WPs 3 and 4 results, as well as the vulnerability zoning are the key driver for defining the correct way to use a"living with nature" approach.

Therefore, a solution must be driven by natural trends, as a fundamental guideline for a correct human use, thus forcing us to a responsible and sustainable development- This permits to limit possible impacts of definitive choices, as those following hard engineering philosophy. Configuration regimes aimed at beach nourishment or morphological reshaping could be possible options.

3.4.2. Available sedimentological data, studies, maps

3.4.2.1. Role of the pilot site in the regional sedimentary setting

At regional level, the coastal sedimentary prism consists of a wedge-shaped body that connects to the seabed about 13-15 m deep. This sedimentary body is the result of erosive and depositional processes that have affected coastal deposits in the last 5000 years (late Holocene), since the highstand phase of the sea level (whose seismic marker is the highstand systems tract - HST: cfr. Trincardi et al. 2011, Carta geologica dei mari italiani - Foglio Venezia).

The seabed of the Gulf of Trieste can be divided into two parts (Brambati, 1985; Marocco, 1989; Gordini et al., 2003):

- A sandy area, up to 4-5 m (upper shoreface), influenced by the waves and currents; the most dynamic part of this system is the closest to the coast, where elongated systems of bars and troughs develop. Here the maximum longshore transport occurs, that is responsible for transport of the sand from the sedimentary sources (river mouths) along the adjacent beaches.
- A deeper zone, up to 13-15 m, defined by smooth bottoms with a constant slope and characterized by fine sediments (silty or muddy). The sediments of this area are moved only during heavy storms. Soft sediments, fine material carried by the rivers as suspended load, usually form the lower limit of this zone. In the pilot area at these depths, there is also the presence of relict sedimentary bodies.

At greater depths, residual sedimentary structures are related to the geological history of the basin (Trincardi et al., 2011; Trobec et al., 2017).

The -5 m isobath is in general parallel to the shoreline in the northern Adriatic, but isobath protrusions are present and are currently related to the presence of tidal inlets and river mouths that tend to generate sedimentary bodies of lobed shape such as ebb-tidal deltas and river deltas.

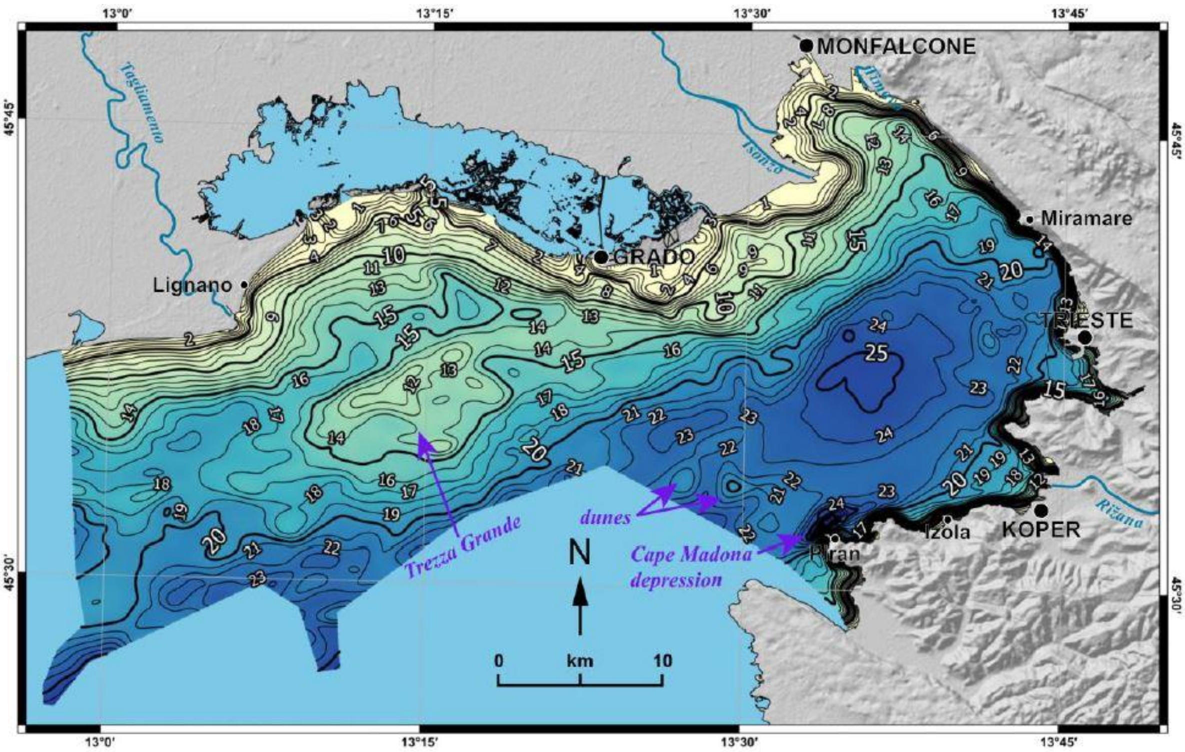

Figure 3-35: Bathymetric map of the Golfo di Trieste (da Trobec et al., 2017).

The area of the pilot site is characterized by the presence of an isobath protrusion due to the Banco della Mula di Muggia and the delta of the Isonzo River (Figure 3-35), where the Holocene sediment thickness reaches the 8 m (Trobec et al., 2017, Figure 3-36). The Isonzo River represents a current sediment source, whereas the Banco della Mula di Muggia is not directly linked to a sedimentary source and represent an important anomaly, probably related to ancient river systems (Marocco, 2009).

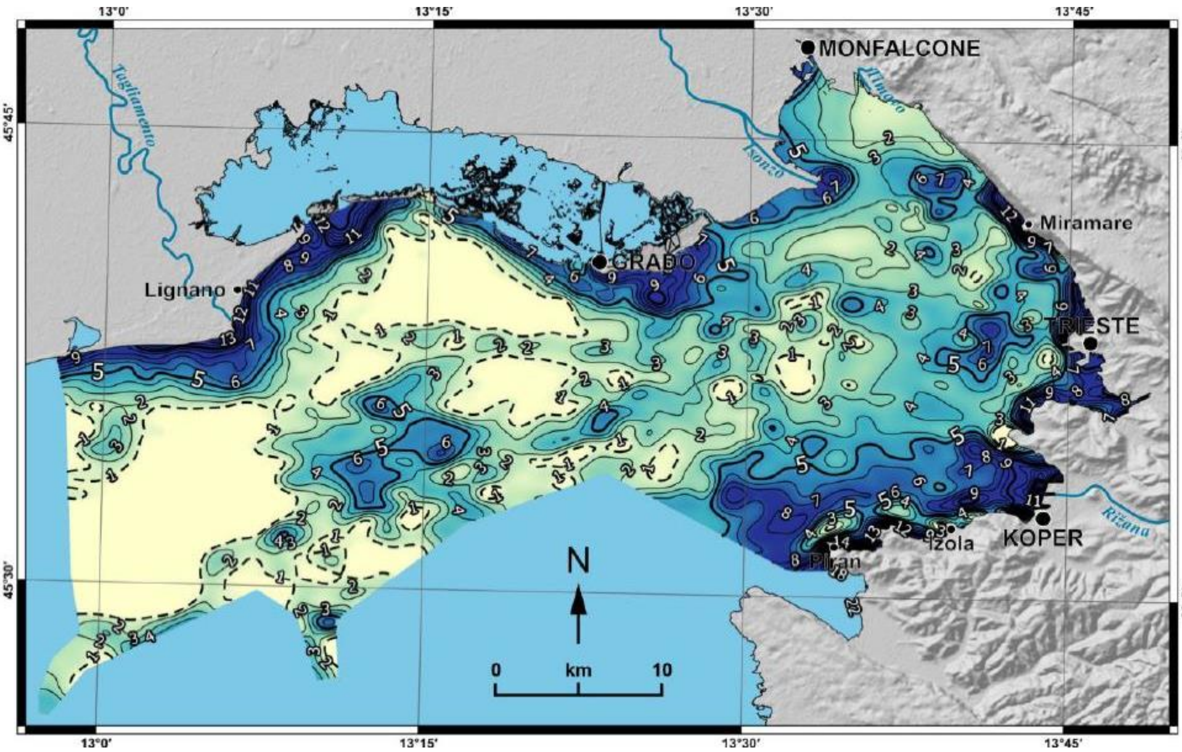

Figure 3-36: The thickness of Holocene marine sediment in the Gulf of Trieste (in meters) (da Trobec et al., 2017).

3.4.2.2. Sedimentology inthe study area

A bunch of detailed sedimentological maps from 1985 (Brambati) reports the distribution of **mean size values (Mz)** expressed in ϕ classes[3]**,** and the percentages of sand, of clay, of silt in the pilot site area. They are based on samples from 1985 and from 1972-73 (by the CNR survey).

These are the most complete and updated dataset for the area. The maps representing the distribution of the **mean size values (MZ)** and **sand percentage** has been digitized and are shown in Figure 3-37 and Figure 3-38.

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[3] The phi unit is a logarithmic transformation of millimeters into whole integers, according to the formula: , where d = grain diameter in millimeters

Despite the irregular distribution of the samples, the maps allow to have a sedimentological framework of the site and to highlight some evidences.

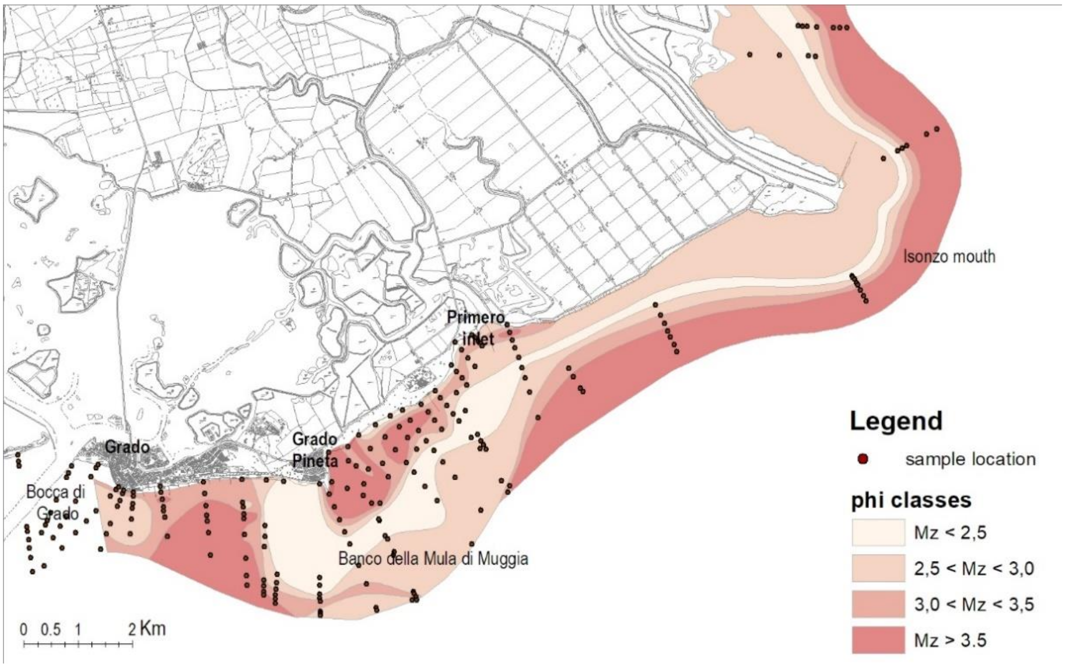


Figure 3-37: MZ values distribution and sample location in the pilot site (after Brambati 1985, modified).

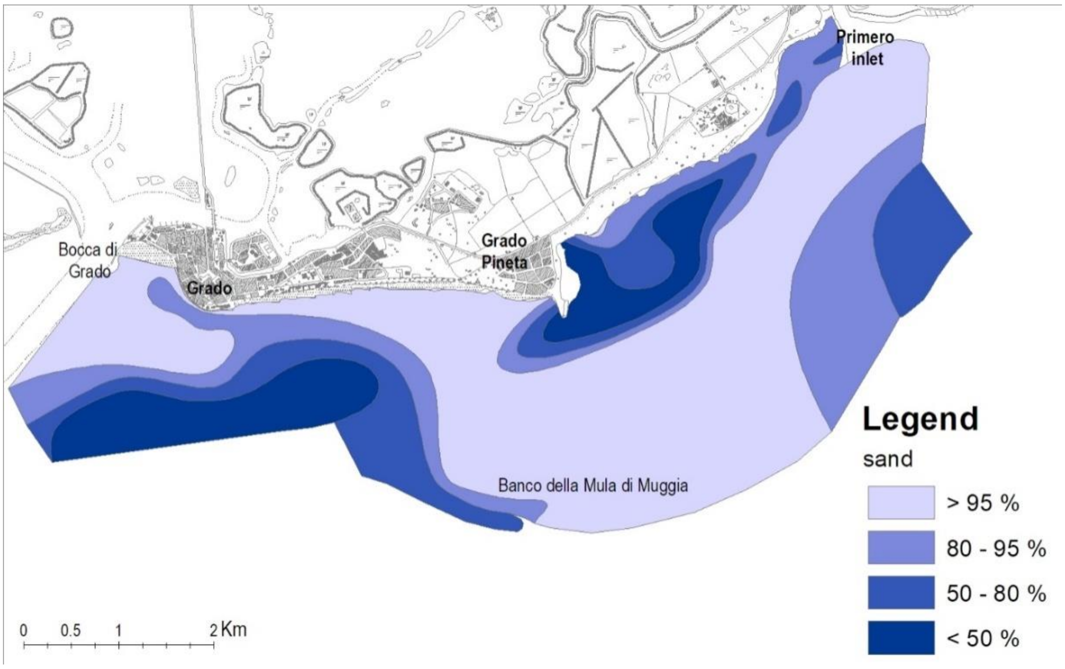


Figure 3-38: Sand percentage distribution in the pilot site (after Brambati 1985, modified).

In order to describe the relationship between the sedimentology and geomorphology of the area, the map in Figure 3-39 overlays some morphological elements derived from the geomorphological map (Deliverable 3.2.1) to the sedimentological map of Brambati (1985).

Evidences can be summarized as:

- There is an inversion of the normal trend of the MZ and sand content from the shoreline to seaward in the coastal stretch between Grado Pineta and the Isonzo mouth. Here the finest sediments (3 and 3.5 phi values) cover the shallow water facing the shoreline, confirming the back barrier characteristics of the area.
- The zone with the coarsest MZ (2.5 phi classified as fine sand) is distanced from the shoreline and indicatively follows the outer limit of the bank identifying this zone as the most dynamic.
- The lack of samples in the area of shallow water in front of Grado Pineta does not allow describing this part from the sedimentological point of view. The attribution of the coarsest MZ values and the maximum sand content is probably incorrect.

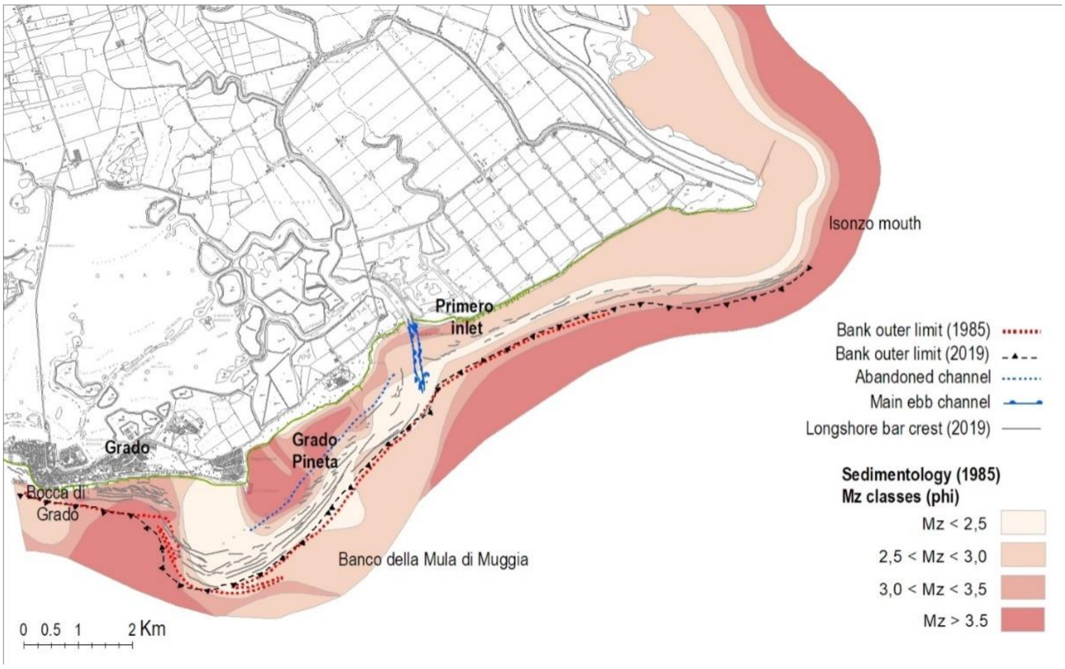


Figure 3-39: Overlay of some morphological elements derived from the geomorphological map (Derivable 3.2.1) to the sedimentological map of Brambati (1985).

A focus of the area of the Primero delta was carried out by Cirilli (1999) based on a sediment sampling on the Primero main channel and on the intertidal area on the sides. More than half of the samples were classified as sand, while the remainder were classified as sandy pelites and very sandy pelites.

From the relative areal distribution of the MZ (Figure 3-40) some remarks can be derived:

- The data are in general agreement with the previous data of Brambati (1985).
- The tidal flats to East of the channel is characterized by the coarsest sediments (MZ 2.50 phi fine sand), very well sorted (σ < 0.35 phi). The sediment characteristics indicate this area as the most dynamic, exposed to the wave action on shallow water. Here the western longshore drift acts and bar and toughs are the dominant landforms.

- The values of 2.50 phi are also distributed along a wide strip situated to East of the channel and oriented about N-S which correspond to the morphology of the channel margin linear bar, as well as in two isolated zones to West. This strip interests also the last part of the Primero channel, up to the bathymetric -3 m. Near the closure of the channel to sea, this strip shrinks, bending towards West and connecting with the Banco della Mula di Muggia. This pattern highlights the presence of a by-pass corridor, which convey the sand from East to West.

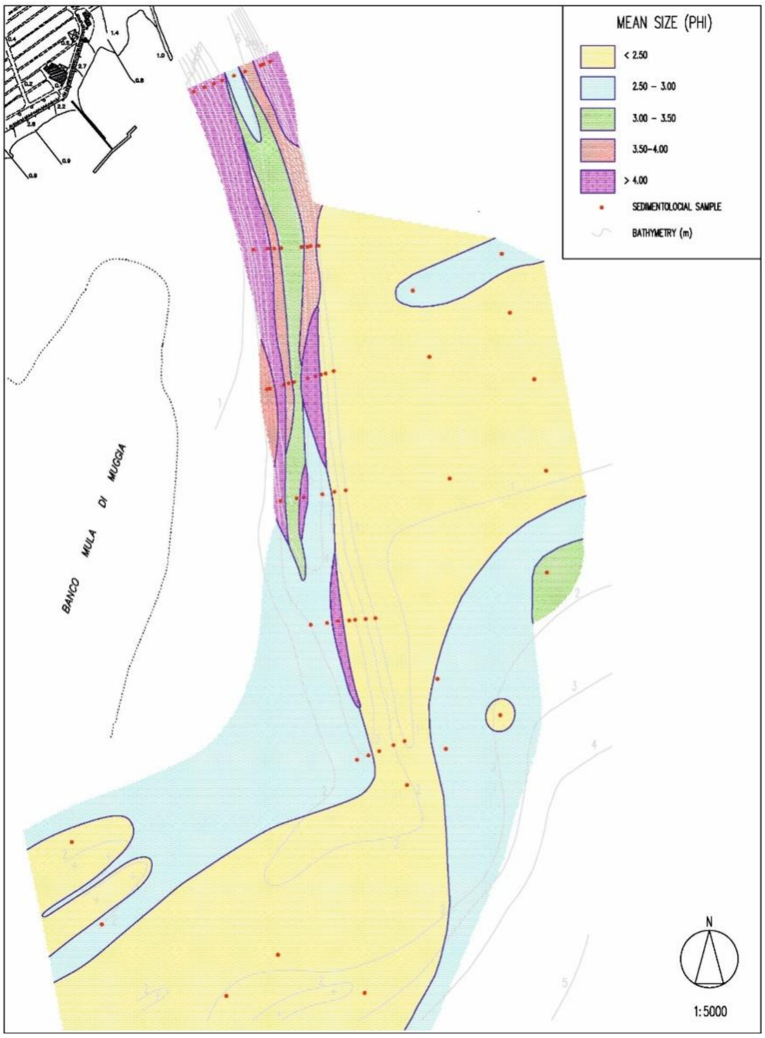


Figure 3-40: Distribution of MZ (phi) of sediment (from Cirilli, 1999).

3.4.3. Acquisition of new in-situ data to complete knowledge

In order to update the sedimentology dataset of the pilot site, a focused sampling activity was planned (Figure 3-41).

As can be seen from Figure 3-41, the criteria used for the sampling plan are as follows:

1. Sampling for the profiles: this basic mode was chosen in order to have a representation of the variation on a profile of the sediment type, especially depending on the depth and to better compare this data with the previous from Brambati (1985).

2. Sampling aimed at the morphodynamic purposes: the samples were concentrated beyond a certain depth, in sandy most dynamic zone, with the aim to understand the paths of sand and therefore the origin of the transported sediment.

3. Focused on the morphological features: it has been expected that some samples will be collected in correspondence of particular deep morphologies (see elongated deep bars) to study their sedimentological composition and contribute to investigate their origin.

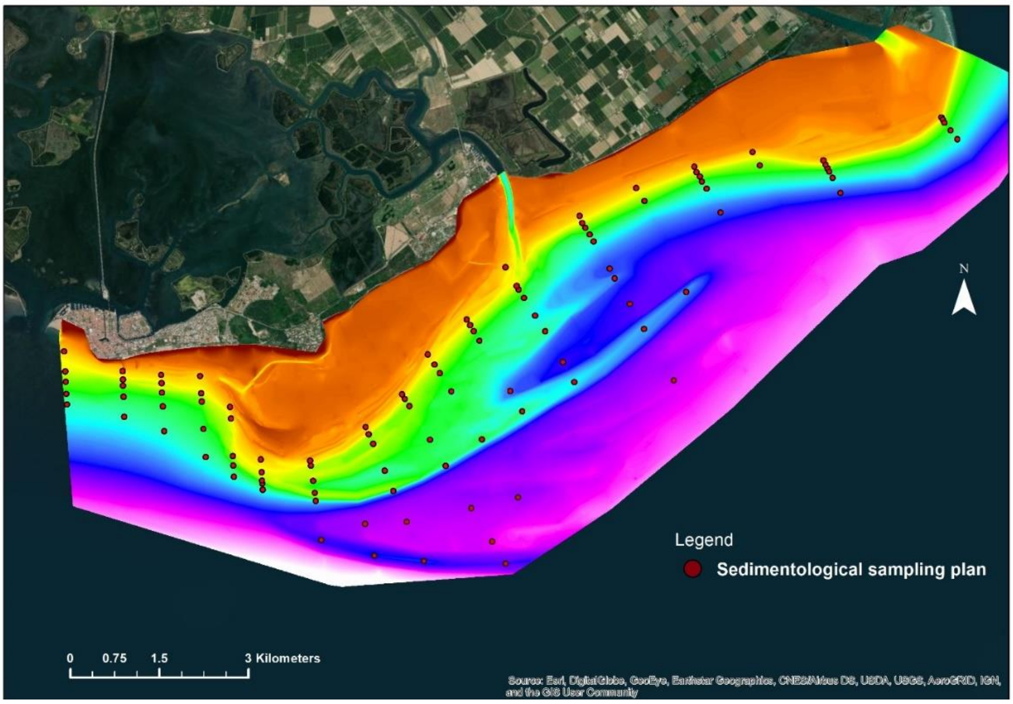


Figure 3-41: Map describing the sedimentological sampling plan. In the background, the DTM 2019 highlights the morphological features.

However, the sampling plan could not yet be implemented for several reasons. In the first place, there were problems with authorization because of the stricter rules adopted by the Port Authorities for this type of work at sea. In addition, the area is logistically difficult to manage, ideal weather and tidal conditions are necessary. Finally, the current pandemic conditions related to Covid-19 have further extended the start of the survey.

3.4.4. Current status (qualitative, quantitative) of the site sediment stocks

In order to evaluate the sedimentary processes (accumulation/erosion), to determine the sediment paths and quantify the sediment budget within the pilot site area, two different methods were applied:

1. The comparison between bathymetric profiles of the different years.
2. The comparison between areal sectors (cells geometric or specifically designed) starting from the bathymetric maps (DTM) of the different years.

The basis of this analysis is represented by the topo-bathymetric profiles described at Deliverable 3.2.1, that includes the surveys from 1968, 1985, 2007 and 2019 and the relative DTM (Digital Terrain Model) (Figure 3-42).

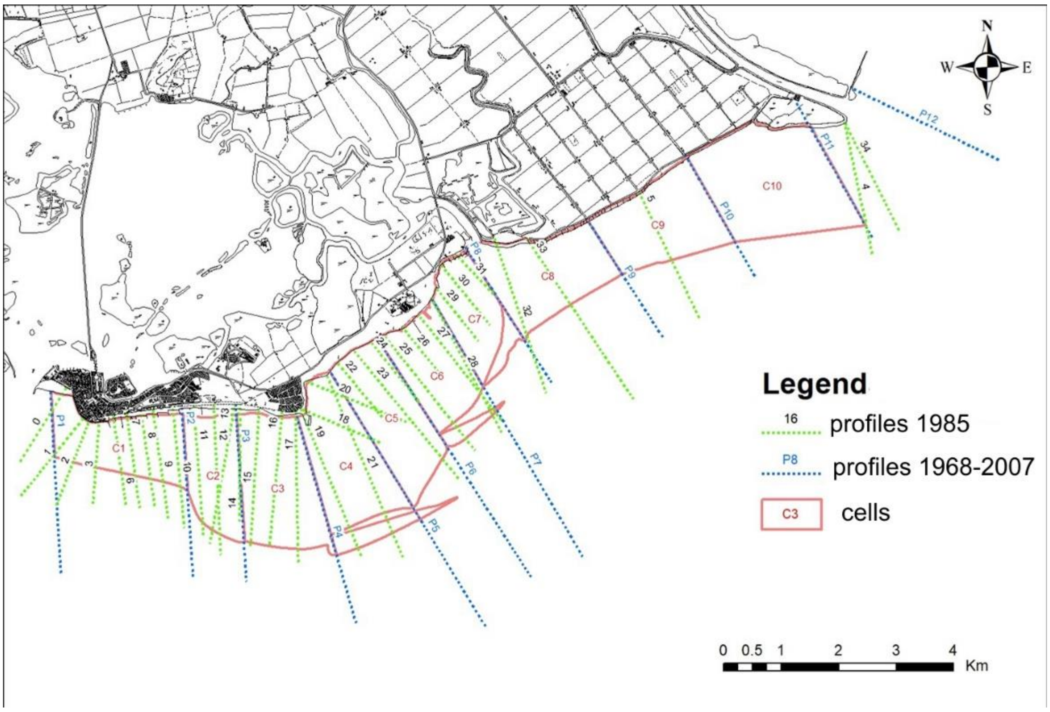


Figure 3-42: Location of the bathymetric profiles from 1985 and 1968 - 2007 and of the geometric cells used for computation.

(1) The topographical profiles have been extracted from the DTMs so that they coincide as closely as possible with the position of the surveys, to maintain a high degree of reliability. The extraction was performed using the profile extraction tool "Stack Profile" in Arcgis. The resulting sedimentation/erosion rate shows different behavior along the coastal area as highlighted by the graph in (Figure 3-43).

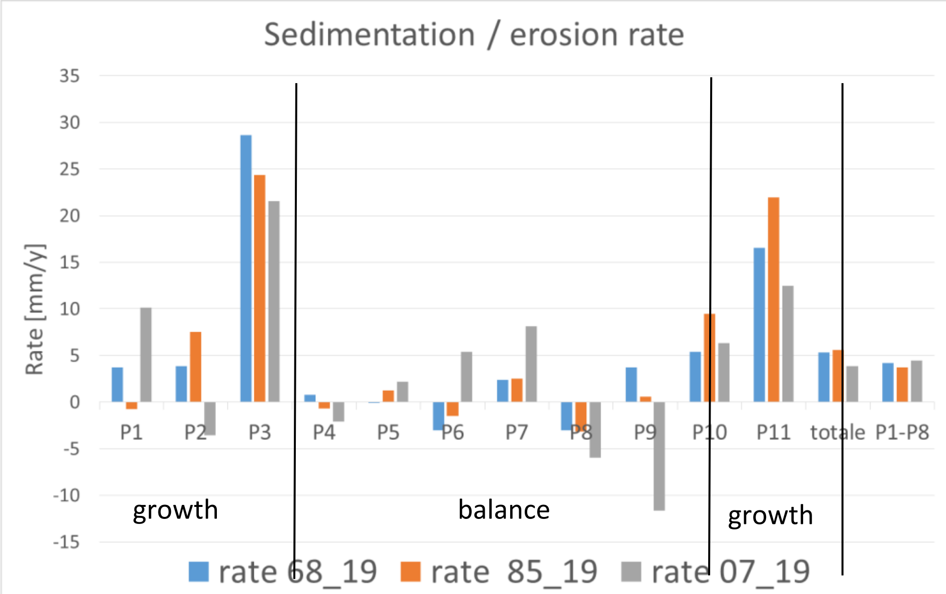


Figure 3-43:Summary chart of the trends identified on sedimentation rates from the 2007 sections.

(2) Starting from the available DTM for the area (1968, 1985, 2007 and 2019), the "Raster calculator" instrument of Arcgis was used to calculate the difference between the DTM of the year 2019 and the older DTM. The result of this procedure is a new raster containing the values of the topographic differences (Figure 3-44), which conceptually represent the deposited thickness for the positive values and the eroded thickness (or autocompaction) for the negative values.

In order to evaluate the sediment stocks status in the area, the 1968 and 2019 situation was chosen, the other difference maps were used for evaluating the trend of sedimentary processes.

The application of the method of geometric cells was considered not entirely satisfactory, because of an important difference in the sedimentation rate along the profiles. For this reason, the construction of specific cells were adopted as represented in Figure 3-44.

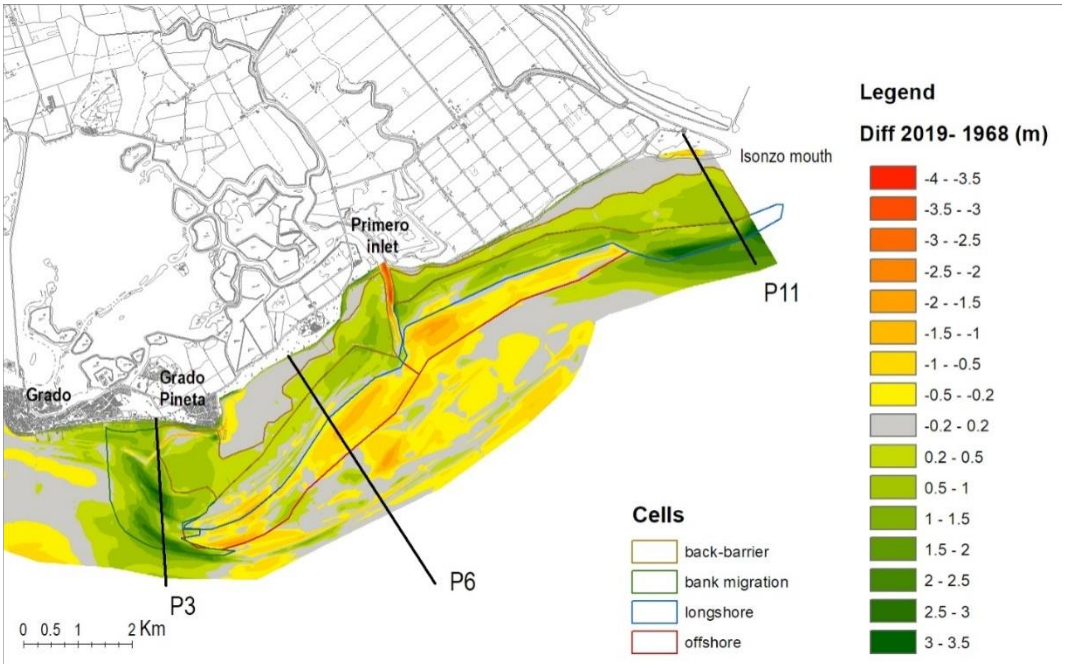


Figure 3-44: Map of the altimetry differences and sub division of the coastal area in cells with different sediment budget and dynamic processes. Some profiles are reported in black line.

The sedimentary accumulation/erosion rate computed on the cells, is shown in Figure 3-45. In this context, the wave and tide climate and the location of the sedimentary source (Isonzo river) provide important elements for evaluating sedimentary transport vectors and understanding the dynamic of the area:

0. The back-barrier cell: this area is characterized by accumulation. The presence of fine material and seagrasses indicate the low dynamism of the environment, where the decantation of fine sediments dominates due to the combined effect with the tide. The here applied methods aren’t valuable to determine sedimentation rates for this environment type.
1. The longshore cell between Isonzo mouth and Primero inlet: it includes the area of the delta lobe and the bar and trough zone within the depth range -0.3-2.7 m from the delta area to the Primero channel. High sedimentary accumulation rates characterize the cell (41000 66000mc/year) corresponding to sedimentation rate of 8-13 mm/y (Diagram 1, Figure 3-45).The topo-bathymetric surveys confirm the progradation of the delta lobe.
2. The longshore cell from the Primero channel to the apex of the Banco. This area is substantially balanced from the point of view of the sedimentary budget. Morphological evidence points out a strong longshore transport from east to west induced by the effective incidence orientation of the Bora wind (Diagram 2, Figure 3-45).
3. The bank accumulation cell: this area shows strong sedimentary accumulation with values of 43000-53000 m^3/year, corresponding to sedimentation rates of 13-16mm/y. The high rate is also identifiable by the morphologies present in the area. In contrast to the trend of rising sea level the formation of the emerged bank indicates a significant sedimentary flow conveyed towards the western side of the Mula di Muggia. From the point of view of the distribution of

accumulation rates, the area is not homogeneous: most of the accumulation takes place in the emerged bank area, while the accumulation rates towards the inlet of Grado are gradually lower (Diagram 3, Figure 3-45).

4. The offshore cell: includes the area from the outer limit of the bank to the closure depth within the range -2/-2.5m and -5.4 m; it appears interested by erosion processes. From the morphological point of view, it coincides, at the level of the Banco, with a finger bars area. The finger bar morphology suggests that the transport is directed towards N-E, that is, opposite to the direction of migration of the Banco (Diagram 4, Figure 3-45).

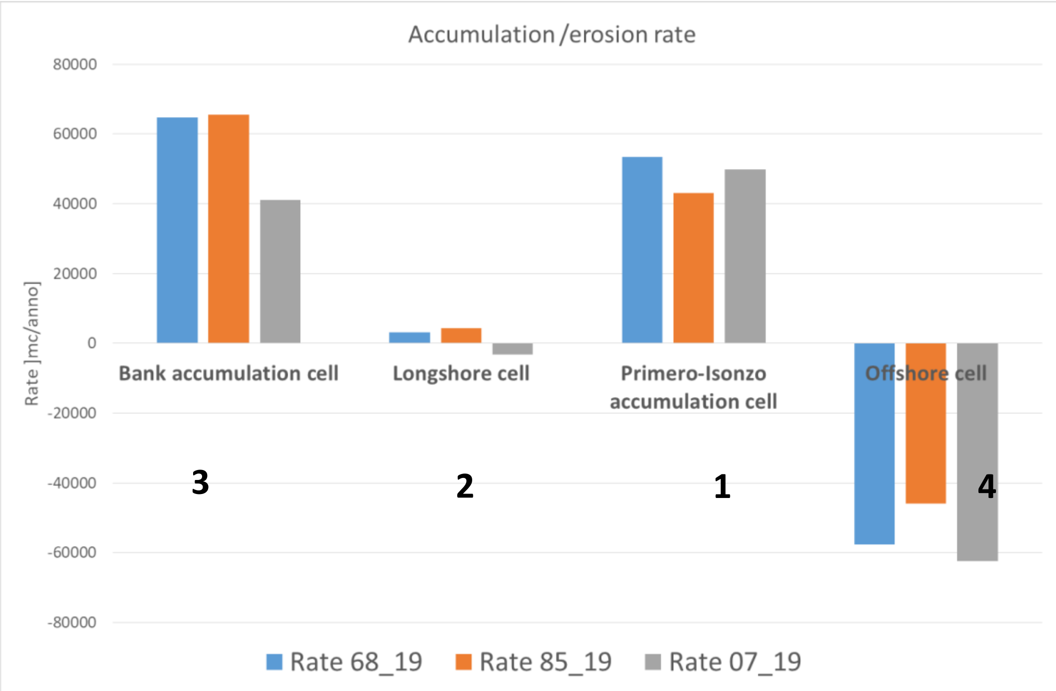


Figure 3-45: The sedimentary accumulation/erosion rate in the four situation investigated

Figure 3-46, Figure 3-47and Figure 3-48 describe the evolution along some of the topo - bathymetric profiles mapped in Figure 3-44. Data from 2019, 2007 and 1968 surveys are presented.

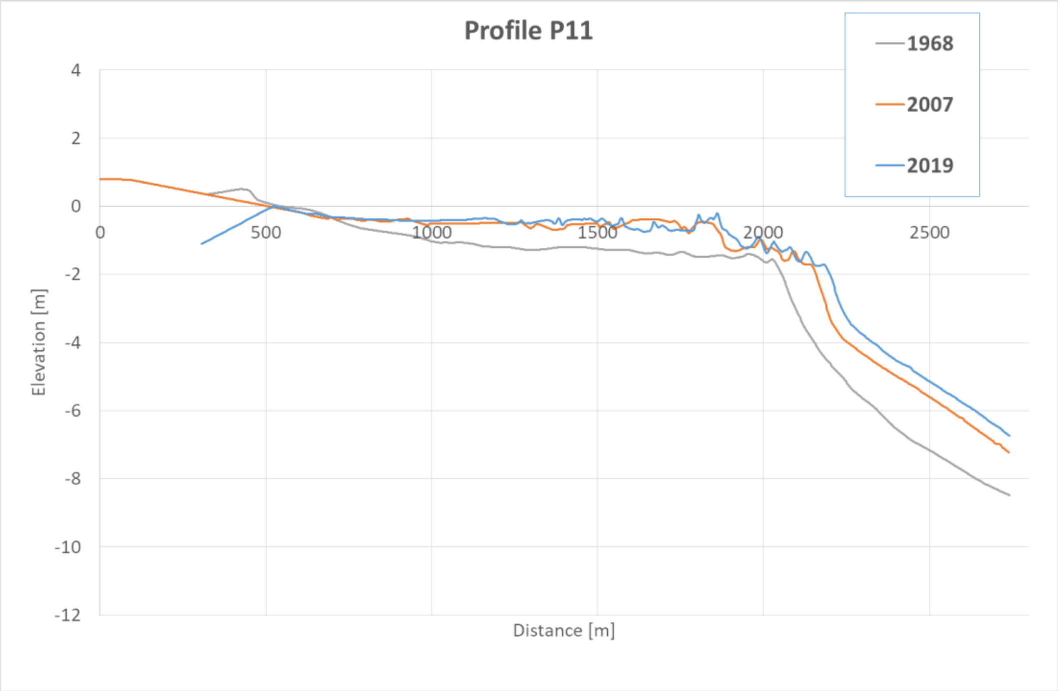


Figure 3-46: Topo- bathymetric profile P11.

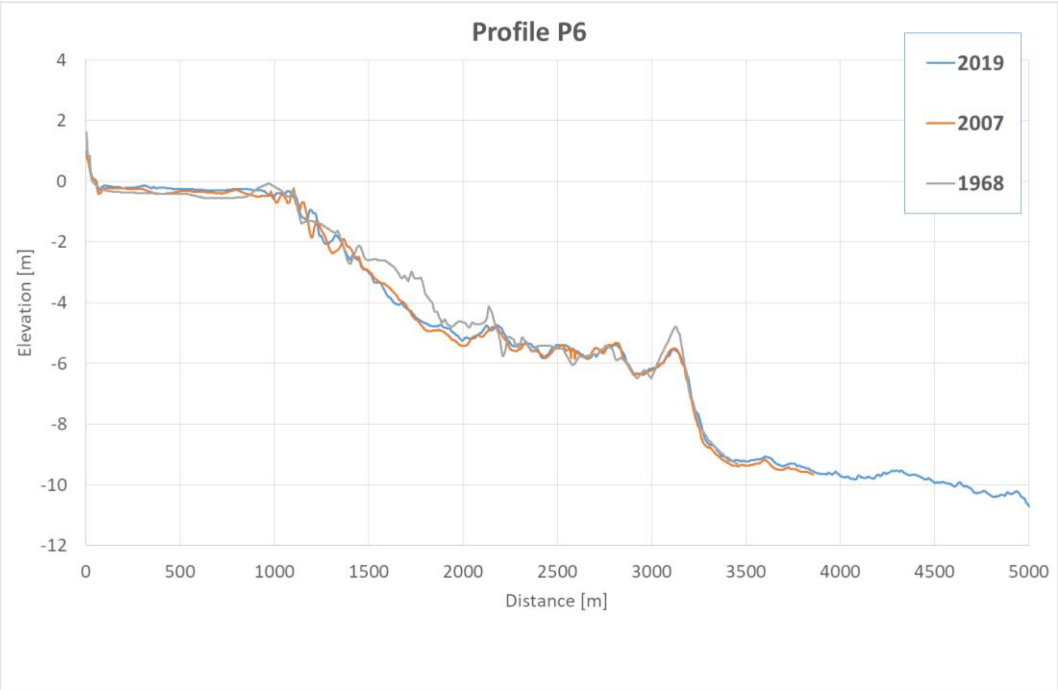


Figure 3-47: Topo- bathymetric profile P6.

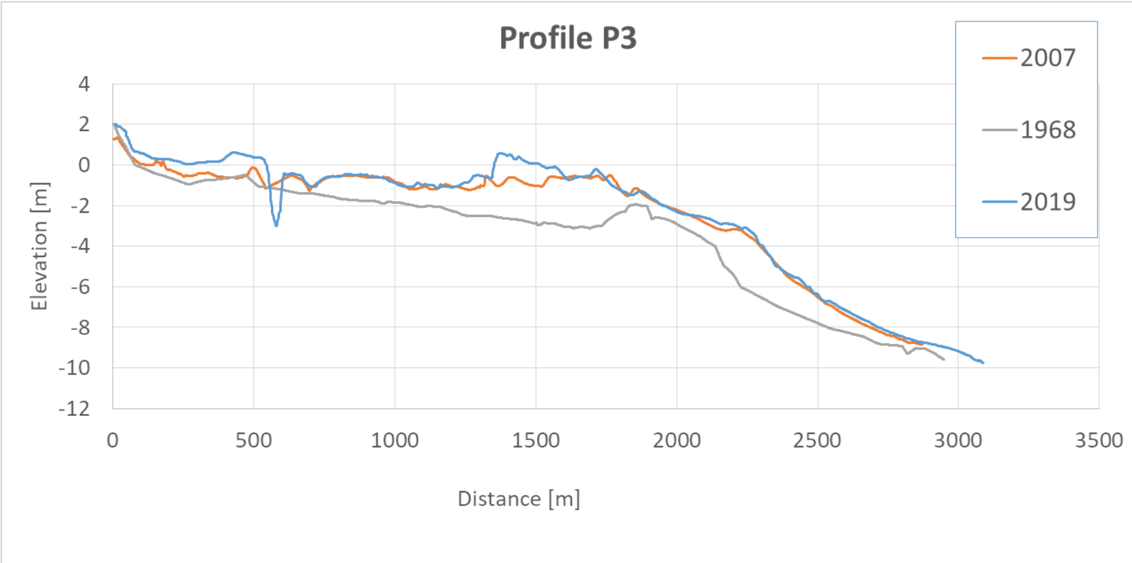


Figure 3-48: Topo - bathymetric profile P3 represents the area of the maximum sediment accumulation.

A model of sediment circulation, that indicates the solid transport of the river Isonzo as the main sedimentary source, can be assumed. The sediments, entering the system from the mouth of the Isonzo River, are transported westward by the wave motion driven by Bora wind and tidal currents. A part of the sand deposits in the area close to the mouth of the Isonzo River, while a great part passes along the stretch of coast between the first and the protrusion of the Banco.

The area with the maximum protrusion, the emerged bank and all the coastline up to the mouth of Grado, acts as a trap for the sediments transported longshore. The causes of the high sedimentation in this area are still unclear and therefore only hypotheses can be made. It could be caused by morphology: the presence of an important longshore drift and the waves coming from SSO, change abruptly the relationships between the marine external forces in this area with generation of high sedimentation rates leading to a sudden accumulation of sediments. Finally, part of the sediments accumulated on the top of the Banco della Mula di Muggia are transported to the coast of Grado, feeding part of the coast up to the Grado inlet.

Finally, it is assumed that on the deepest part of the shoreface (between 2.5 and 5m) the sediments undergo a reverse drift and suffer erosion by the long period waves originated by the winds of Scirocco (Figure 3-49).

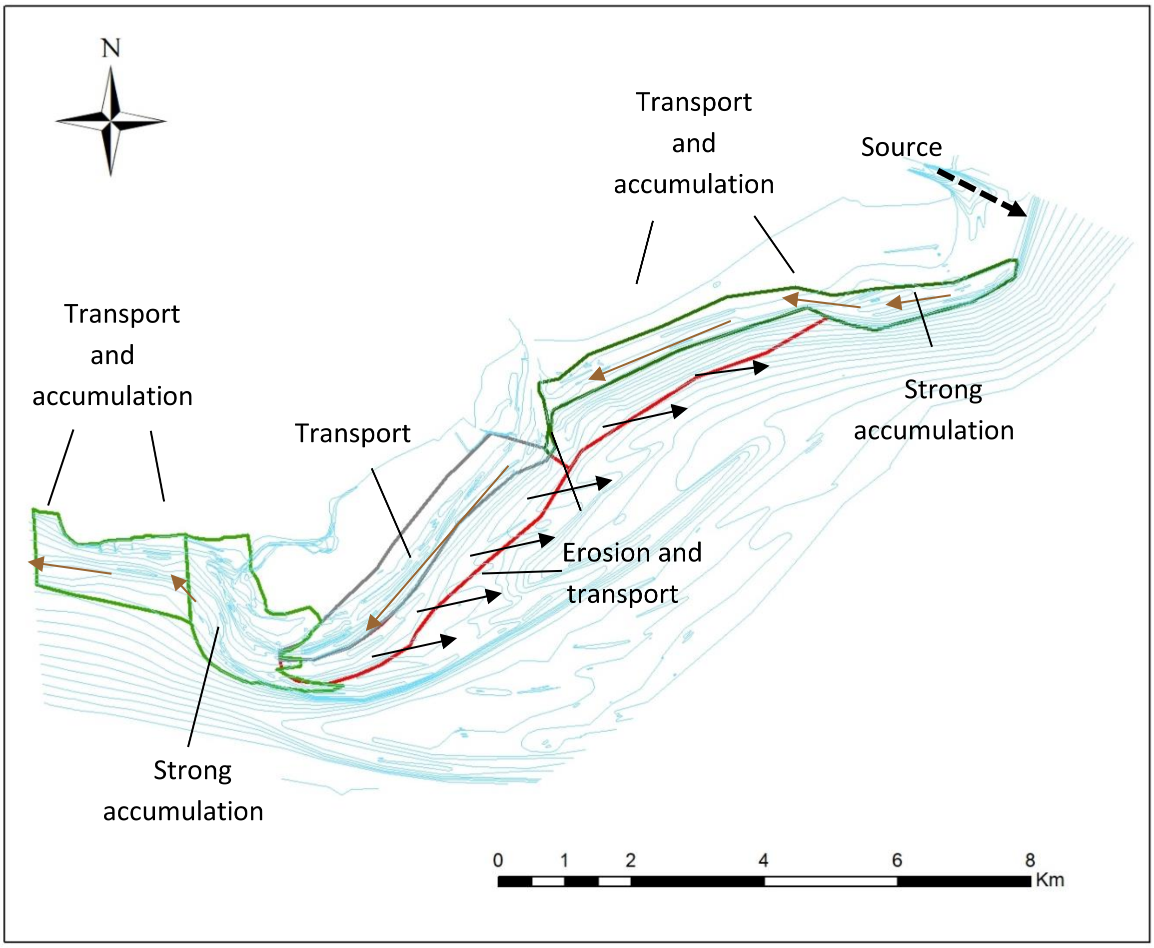


Figure 3-49: Representation of the sandy sediment dynamics in the study area.

3.4.5. Analysis of recent trends of the sediment stocks

The study area shows a depositional trend in the zone of low depths, within the -2m. In particular, the accumulation area, such as the emerged bank and the whole coast to the West, up to the Grado inlet, presents high sedimentation rates. The collected and processed data do not show a unique trend: some data describe a decrease in the sedimentation rate over time (e.g. from the P3 profile, Figure 3-48) while from others there is a continuity in trends (integrative cell analysis).

In recent years, it is important to consider the increase of the sea level in the evolution of a littoral assessment: it is possible that an accumulating coastline retreats because the sedimentation rate is inferior to the increase of the sea level.

Comparing the rate of sea level rise, which since 1990 is +4.44mm/y, and the sedimentation rates obtained for the computation in the area of the Banco della Mula di Muggia (profile P1-P8 = +4.16mm/y for 1968-2019, +3.69mm/y for 1985-2019 and +4.46mm/y for 2007-2019), the sea transgression effect and the sedimentary accumulation are almost balanced.

Considering the accumulation rates in the cells of Figure 3-44, the average sedimentation rates could be estimated (Table 3-1).

Table 3-1 Sedimentation rates calculated on supplementary cells (values are in mm/y)

cell		Sedim rate 68_19	Sedim rate 85_19	Sedim rate 07_19
1	accumulation Primero-Isonzo	15.95	12.86	14.88
2	longshore transport	1.07	1.53	-1.14
3	accumulation Mula di Muggia	12.56	12.74	7.98
4	area offshore	-11.04	-8.80	-11.96

The data of Table 3-1 and the context of sea level rise allow some considerations about the morphodynamic evolution.

In purely sandy sediment accumulation areas, accumulation rates exceed the sea level rise rate by at least twice as much: it is probable that deposition areas will remain so, even considering the maintenance or increase of sea-level rise rates. The long-shore transport corridor present a deficit of sediments if compared to the sea level rise and tend to deepen: a probably morphological response could be a landward shifting of the bar and troughs area. In this case the Banco della Mula di Muggia could shrink or could be tightened as consequence of a typical roll-over process.

3.4.6. Conclusion

3.4.6.1. Results of the activities and discussion

The analysis and evaluation of the sedimentology and the sedimentary budget for the area between the inlet of Grado and the mouth of the Isonzo River is the target of the activity. The DTM generated from the 2019 topographic and bathymetric survey was compared to the older 1968, 1985 and 2007 DTM.

The new sedimentological data are still not available, but the 1985 data describe the MZ and the sand percentage distribution, confirming the morphological features of a barrier/back barrier configuration for the area (cfr Deliverable 3.2.1).

Referring to the sedimentary budget and to the morphological evidences, the coasts of Grado, which includes the Banco della Mula di Muggia, could be subdivided into sectors with different characteristics of sedimentary dynamics.

The longshore sectors near the delta apex and the western part of the Banco show the highest sediment accumulation rates. The central sector of the Banco is characterized by an extended area of bars and troughs up to the depth of 2-2.5 m, with a balanced sedimentary budget.

The lower part of the upper shoreface, (here indicated as offshore cell) between about -2m and -5,4m, is in strong erosion and is characterized by the presence of finger bars, rhythmic structures indicating vectors of sedimentary transport towards NE, that is, opposite to the prevalent regional longshore drift.

Results confirm that the direction of longshore transport is directed towards SSO. The sediments conveyed to the mouth by the Isonzo River are transported by the dominant wave regime (Bora and Levante) towards Grado, at first by-passing the Primero inlet and the whole central body of the Banco, to deposit at its western end, which acts as a sedimentary trap. Results confirm a surplus of sediments.

3.4.6.2. Problems and solutions

The presence of the Banco della Mula di Muggia and the shallow seabed area adjacent to the mouth of the Isonzo River has as consequence that the real dynamic part of the coast profile is translated seaward and the seabed and the beach are protected from wave action. For this reason, their appearance is abnormal if compared to other Adriatic beaches: seabed is shallow and sediment has a significant fine component.

The morphodynamics of the area includes complex aspects that need to be analyzed. They are linked to the sedimentary resilience, which derives from a sedimentary circulation governed by alternating force and from a river sedimentary source whose contributions are still indeterminate.

The Banco Mula di Muggia survives and evolves migrating, occupying spaces now dedicated to seaside tourism. It constitutes an important sandy reservoir that should be considered strategic for the coast's conservation, regarding the diffused coast's erosive crisis and the increment of the extreme events.

It should therefore not be considered as an enemy to be fought but rather as a good to be preserved, an adaptation need in order to live with the climate change in progress, avoiding implementing solutions that lead to an ephemeral benefit.

3.4.6.3. Analysis of data quality

The collection of historical data and their GIS comparison develops an appropriate scientific process, basis for an appropriate coastal planning.

The sedimentological data available for the area are not updated but their good quality allows to have a good morphodynamic framework in order to understand the coastal processes, if combined with the morphological data. In fact, the data of 1985 offers a good coverage of the area with the exception of the tidal flat facing Grado Pineta and the methods used for granulometric analysis (sieving on ½ phi) furnish sufficient quality for the computation of the parameters (MZ, % of sand and sorting). The agreement with the sedimentological data from 1999 for the area of Primero is a good indication for the quality of the data. The update and improvement of the sedimentological knowledge through the planned sampling shall be conducted in such a way as to be consistent with the previous data.

The budget calculation depicts a general delicate aspect in coastal studies. Some critical aspect that were considered during the analysis process are:

- The different coverage and distribution of the original topo – bathymetric data.
- The peculiar configuration of the Banco with significant changes in orientation, which determine as consequence a low lateral continuity of the surveyed landforms.

- The great extent of shallow water and seagrass, which could affect the reliability of the bathymetric data.

In order to minimize the inaccuracy of the results, different methods were applied to compute sediment budgets and the data were corrected according to an error estimation. The consistent values of the sedimentary budget, obtained comparing the different time intervals and the different methods, represent a good test of the robustness of the results.

3.5. Po River Delta and focus sites Sacca di Goro and Sacca del Canarin

3.5.1. General site description

The Po Delta represents the final sub-basin subtending the entire Po River catchment, and it develops as a flat region with a surface that overs 1.6 % of the total Po catchment, which is almost completely below the sea level (Piano di gestione del distretto idrografico del Fiume Po, Stato delle risorse idriche, 2016).

The Po River is the longest river in Italy and it receives most of its water supply from several watercourses, which originate from the Alps and Apennines and join the Po River after crossing the Padan plain. Therefore, its drainage area includes large territories in the western and central part of Northern Italy (Figure 3-50, left), and it extends until the Adriatic Sea where the delta develops.

3.5.1.1. <u>Location (site map, study domain, access routes, cities, etc.)</u>

The Po River Delta is located in Northern Italy, between the provinces of Venice and Ferrara. The main access route is the Strada Statale Romea, n. 309, which connects Venezia to Ravenna, following the Adriatic coastline and crossing the Po branches. Other provincial routes start from SS 309 spreading towards east in the territory of the Delta. The surface of active Po Delta falls entirely in the province of Rovigo (Veneto Region), or Polesine, beyond Po di Goro. The area of the historical delta includes a part of the province of Ferrara (Emilia Romagna Region).

*Figure 3-50: **left**, Po River catchment and main tributaries. **right**, location and access routes. The grey line represents the boundary between the Emilia Romagna (south) and Veneto Region (north), where the active part of the Po Delta is located.*

The focus area of **Sacca del Canarin** is located in the municipality of Porto Tolle, under the jurisdiction of Veneto Region. It has a surface of almost 6.5 km^2 and it extends between two of the Po mouths, Busa di Scirocco in the north and Busa Bastimento in the south.

The focus area of **Sacca di Goro** is located in the southernmost part of territory of the Po Delta, under the jurisdiction of Emilia Romagna Region. The lagoon has a total area of 26 km^2 and falls within the administrative borders of the Municipality of Goro and of the Province of Ferrara.

3.5.1.2. Physical and environmental features

The Po River Delta is the result of natural and anthropogenic processes that have affected the mouth of the Po River for centuries, leading to its typical cuspid shape. In this region the Po River is divided into different branches: Po di Levante, Po di Maistra, Po di Pila (the easternmost mouth that subdivides in turn in three branches, Busa di Tramontana, Busa Dritta and Busa di Scirocco), Po di Tolle, Po di Gnocca, and Po di Goro.

Between these deltaic branches there are both territories surrounded by fresh water and called islands ("*isole*"), and bodies of water that are connected in different measure to the sea, comprising valleys, lagoons and *sacche*. Among them are the two focus areas of Sacca del Canarin and Sacca di Goro.

The active part of the Po Delta develops in the NS direction ranging between the Adige mouth and Po di Goro, while in the past the territory between Po di Goro and the Reno River represented the main Delta. Today this area is hydraulically disconnected from the Po River and regulated by hydraulic works. The historical evolution of the Delta has been widely described in report 3.2.1 and here briefly reported in paragraph 3.5.1.5.

The Delta is a transitional environment between fresh and salt water. With exception of embankments and dunes, most of the delta plain is completely below the mean sea level, mostly because of subsidence processes, with maximum depths of -4 m in some points. The morphology is controlled by the interaction between sediments and water, as well as among depositional processes, stabilizing action of the vegetation and destructive power of the flood surges.

As a result, the Po delta shows all morphological features of transitional environment like *velme*, *barene* and *scanni*, and it hosts high level of biodiversity. Most of the coastline is characterized by sandy beaches and mouth bars (*scanni*), except for some rigid hydraulic works along the coastline that are built to regulate some of the lagoon and fluvial mouths.

From an environmental point of view, the Po Delta, with its interconnection of aquatic and land habitats, of fresh and salt water, represents a particularly important environmental and ecological system. It is an extensive wetland area for rest, wintering and reproduction along the migratory routes. Thanks to the variety of its environments, several protected areas have been established in the last decades:

In 1999 the Po Delta was included among the Italian World Heritage Sites by UNESCO. Furthermore, since 2015, it has been part of the natural reserves designated by the MaB UNESCO (Man and Biosphere), which is a world network of Biosphere Reserves including internationally recognized terrestrial, marine and coastal ecosystems.

Figure 3-51: Po Delta Park of the Veneto Region (green) and Po Delta Park of Emilia Romagna (red). SCI-SAC and SPA are highlighted with a dashed pattern. Location of the two focus sites of Canarin and Goro (Regional webgis)

The MaB reserve of the Po Delta is a large area covering territories of the Veneto and Emilia Romagna Regions, with a total surface of 138,000 ha, of which 30% are located in Emilia Romagna and 70 % in Veneto. From an administrative point of view, the territory is divided between the Veneto and Emilia Romagna Regions, which manage independently the parts under their jurisdiction.

The area is one of the most important ecosystem in Europe, with 31 Sites of Community Importance (SCI), 22 Special Protection Areas (SPA) and 13 Natural Reserves, where over 450 species of resident and migratory birds live or breed. It also hosts over than 40 species of mammals, while the flora of the area includes almost 979 species of plants (Natereg project).

The Po Delta of the Veneto Region represents a unique large Site of Community Importance and Special Protection Area. It includes 22 protected habitats, (of which six are priority habitats), and 102 protected species (of which four are priority). The Special Protection Area overlap partially the SCI, distinguishing from this one for its minor extension along the main branch of the Po River (until Papozze), for the inclusion of all the secondary branches of the Po (enclosing Po di Levante) and for the dune system in Ariano nel Polesine.

Besides the delta system, this territory comprises the coastal dune systems, the valleys, the sandy spits and the fluvial islands as well as the floodplains and oxbows. Halophisous and psammophilous plants colonize the singular sand formations at the fluvial mouths and along the margins of the lagoons. In addition, remnants of ancient forests are present in some parts too. The valley part is characterized by the presence of a large complex of reeds, sandbanks, canals and marshes. The natural landscape includes water bodies with submerged Macrophyte vegetation and wide flat islands that host halophilous types and syntypes. The priority habitat "coastal lagoon" is the most representative one due to its coverage (45%), and it is largely present in the focus area of this report Sacca del Canarin.

The Sacca di Goro belongs to the SCI "Sacca di Goro, Po di Goro, Valle Dindona, Foce del Po di Volano" and it develops as a large marine lagoon that is partially isolated from the seas by the sand spits at the Po river mouths. 20 Habitats of Community Importance (of which three of priority importance) cover 78% of the surface of the entire Site. These encompass: sandbanks, estuaries, lagoons, annual vegetation on the marine depositions such as Salicornia and vegetation in the muddy and sandy parts, such as Spartina grass, Mediterranean inundated pastures, mobile embryo dunes and white dunes (of the littoral sandbar), dunes with forests of Pinus pinea, Mediterranean wet meadows with high herbaceous plants and reed, gallery forests of Salix alba and Populus alba, Hydrophilous tall herb fringe communities of plains. The focus area of Goro includes the wide reeds of Gorino at the mouth of Po di Goro and Po di Volano.

- **Sacca del Canarin**

The Sacca del Canarin is a lagoon located in the eastern area of the Po Delta, among the branches of Po di Pila in the north, Busa di Scirocco in the northeast and Busa del Bastimento (Po di Tolle) in the south. It is part of a vast complex of brackish lagoons formed by the continuous reworking of the shoreline.

It has a recent formation, as it is located in the apical part of the Delta, in the portion of territory that has developed in the last centuries. Therefore, in comparison to Sacca di Goro that is a more ancient gulf, Sacca del Canarin is relatively young.

From an environmental point of view, but also considering its history, Sacca del Canarin belongs to the system of "Basson-Canarin". An artificial embankment built during the '70s and that connects the riverbanks to the sand spits seawards disjoints the internal circulations of the two lagoons. Canarin receives salt water from the sea at the mouth near the "*Scanno* del Canarin", while fresh water derives from different points: in the north, through a floodgate located in the embankment; in the south through Busa del Bastimento and in the west, through the pump system of the remediation consortium.

This is a marsh area with high level of salinity, and it is characterized by the absence of islands and reeds, possessing only few submerged bedforms. Its current configurations is the result of several anthropic interventions carried out in the past decades with different ambitions, first to reclaim land for agricultural purposes (Figure 3-53) and then to protect the inland territories from the sea ingression.

Figure 3-52: the main Pila mouth of the Po River and the inlet to Sacca del Canarin. On the background the Enel power station is visible (not working anymore). Figure taken from the website agrinsieme

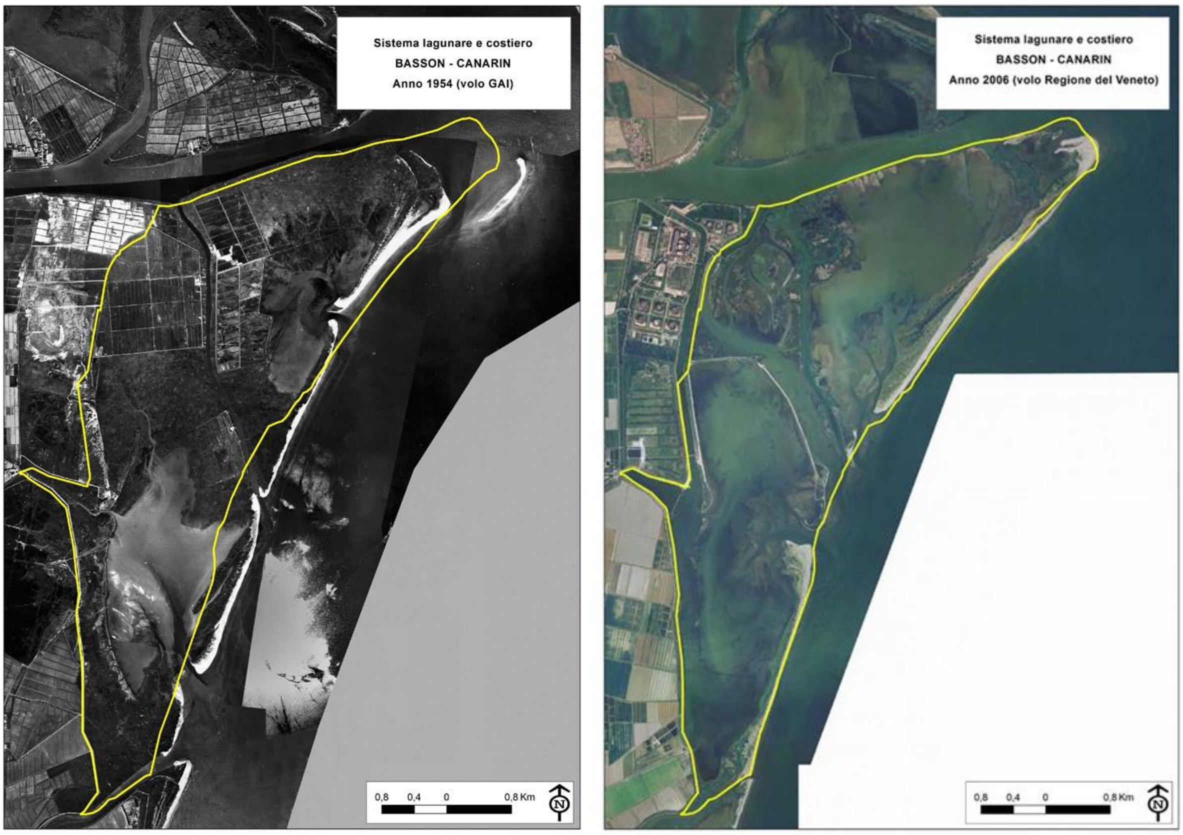


Figure 3-53: Views of the Basson-Canarin system from different years: 1954 on the left and 2006 on the right. Sacca del Canarin is located in the southern part of the system. Source: Verza, E., & Cattozzo, L. (2015). Atlante lagunare costiero del Delta del Po.

More recently, several hydraulic works have been conducted to regulate the flow of water and sediments from the sea, with the aim of guarantying the tidal circulation, the functionality of the mouth, and to preserve the oxygenation of the lagoon for shell farming.

These interventions have limited the extension of the reeds, which were widely present in Sacca del Canarin especially in its northern part, where oysters were also visible.

- **Sacca di Goro**

The Sacca di Goro is a shallow-water lagoon, with an average depth is approximately 1.5 m. It receives freshwater inputs from the Po di Goro, which is bordering the lagoon on the north-east but the lagoon is considered part of the basin of the Po di Volano, an artificial canal laying in the ancient bed of a former Po River branch, namely the Po di Volano. The Po di Volano Canal is hydraulically regulated by the Local Water Authority, the Consorzio di Bonifica della Pianura di Ferrara, and is the quantitatively most important freshwater input to the western and central part of the Sacca di Goro.

Figure 3-54: View of Sacca di Goro, source: https://www.ferraraterraeacqua.it/it/goro/scopri-il-territorio/ambiente-e-natura/luoghi-di-interesse-naturalistico/sacca-di-goro

The current physical structure of the Sacca di Goro is the result of both natural processes and anthropic interventions, such as land reclamation of the bordering managed lagoons, locally called “valli”, once used for extensive aquaculture. Also completed in the '60s is the realization of impressive embankments for coastal defence. Other works date back to the '90s, as canals' excavation and sectioning, for improving internal navigability, water circulation within the lagoon and strengthening the littoral structures, as the Scannone di Goro, the outer sand bank, which closes the lagoon on the south.

The morphological, hydrological and ecological complexity of the lagoon is associated with the intrinsic natural variability, typical of shallow lagoons with limited interchange with the open sea, which naturally promotes the extreme variation of water circulation and therefore different sedimentary depositional patterns.

In the recent, the evolution of the Sacca di Goro is characterized by excessive accretion of the outer sand bank, the Scannone (Figure 3-55), which has led to the progressive narrowing of the main lagoon mouth. To maintain tidal circulation, several interventions have been made by public authorities and anglers cooperatives, comprising both the recurrent excavation and reshaping of internal submerged canals and sediment removal for widening the lagoon mouth, particularly in the last years. Although necessary and extensive, these interventions were not sufficient to prevent summer dystrophic crises, which occurred in some of the years from 1987 to 2016.

General climatic features characterize the lagoon as cold-temperate, with temperature annual minimum in January and a maximum in July. The average precipitation is less than 600 mm per year. Near the coast rainfall shows a tendency to concentrate in the winter, with little precipitation in spring.

In the last 25 years, a significant increase of short-term intense meteoric events has been registered, together with an increase of summer peak temperatures. This trend has not helped the mitigation of eutrophication, dystrophy and mortality of farmed clams, which has been affecting the Sacca of Goro, since the late ‘80s. The blooming of the seaweed Ulva rigida and other species of the genera Enteromorpha and Chaetomorpha and the consequent decomposition and long lasting anoxia have threatened clam farming in the lagoon. Several actions for mitigating eutrophication related phenomena have been promoted and set in practice in the last 40 years, with results the most variable, from almost irrelevant to very promising.

Figure 3-55: Satellite picture of the outer sand bank of the Sacca di Goro, with indicated the Bassunsin inlet, in clear green.

3.5.1.3. Administration, main economic activities, recent development, land use

The Po Delta of Veneto Region extends for about 470 square kilometers, including several valleys and lagoons. There are over 73 thousand inhabitants in the entire delta area. The territory is primarily agricultural and the population density is quite low with urban centers consisting in small towns, hamlets, and isolated houses (Figure 3-56).

Figure 3-56: Satellite image of the Po Delta. The Fish Valleys are highlighted together with the lagoons and Sacche. The merged part of the territory is completely cultivates, while the urbanization is low. (Quaderni Cà Vendramin n.0)

In the first half of the 20th century, extensive land reclamation works involved the lowlands with the drainage of marsh areas and fish valleys. Today most of the arable lands in Polesine is occupied by monocoltures, consisting in relatively large farms, with a low incidence of tree crops. Maize, wheat and soya prevail throughout the territory, and they are mainly cultivated in large areas alternated with forage crops. Vegetables are widespread close to the coastal areas, thanks to the sandy soil, and they consist in high-quality products, such as asparagus, garlic, pumpkins, watermelons, and melons. Important is the presence of rice fields, fundamental also for the conservation of some bird's species, although they are under the growing pressure of the salt intrusion. In the past, beet plantations were common, and they were connected to the sugar refineries, which only recently have been dismantled.

In the Po River Delta, as in whole the Po plain, the number of small-medium livestock farms has reduced in the last decades, leaving the pace to larger farms. Poultry and cattle farms are present, but the latter ones are not connected to the milk production.

Additional activities typically related to fishing, aquaculture, and tourism have occupied a prominent role in the development of the area. A significant production sector includes the fish supply chain, consisting of professional fishing activities and companies operating in the processing and marketing of fish products. The fish sector production, which encompasses traditional and typical products, is quite large and well diversified. In particular aquaculture is well developed in the fishery ponds with precious and common fish species, whereas mussel-farming is widespread in the lagoons (i.e. mullet from Polesine, clams from Polesine, blue fish, mussels from Scardovari, marinated eels from Delta del Po, sardines and marinated anchovies from the Po Delta). The production is based on fishing cooperatives. The most important fish market is located in Porte Tolle.

Tourism in the area is another important economic source, and it is connected mainly to the valorization of the Park from a historical and naturalistic point of view.

A secondary sector based on small and very-small enterprises has developed in various fields such as the chemical, metalworking and textile one, and it is mainly founded by local entrepreneurs.

Concerning the focus areas, which are shallow lagoons, the main activities rely on mussel and clam farming.

- In Sacca del Canarin additional touristic activities have recently developed, consisting in sailing, sport fishing, and bathing along the scanni. The traces of the anthropic interventions connected to the realization and management of the ENEL power plant are well visible, together with all the actions to improve and protect the crops and the settlement behind it.
- In Sacca di Gorro, by far the most important economic activity is the Manila clam farming (Ruditapes philippinarum) while the traditional fisheries have greatly reduced and currently represent only an integration of the main income, given by clam farming.

3.5.1.4. Main problems and management objectives (focus on the lagoon environment)

The morphological and environmental features of the lagoons represent a peculiar aspect in the management objectives of these areas. In this respect, some crucial features can be highlighted:

1. Low depth (1-2 m)
2. Connection to the sea through one or more mouths, which regulate the exchange of marine water.
3. Important annual temperature variation.
4. Large salinity variation.

The main problems of the lagoons are connected to the intrinsic and highly variability of their environmental and morphological conditions (as explained more deeply further in the chapter), which tend to change quickly in response to the external factors. In particular:

- the salinity levels are extremely mutable and depend on the water exchanges with the sea and Po river (through floods);
- the oxygen content in the shallowest areas has a large impact on the production activities;
- the water quality is threatened by algae blooming and nutrients (phosphates and nitrates) coming from the fluvial waters;
- the infilling of the lagoons, due to sediment deposition, influence the internal circulation and consequently the fishing and shell-farming production;
- the continuous erosion of the external spits that usually protect the lagoons from the open sea threaten the same existence of the lagoon areas.

One of the main challenges is the stabilization of the lagoon environment for the economic and development purposes, without deteriorating their value, especially considering the mutable conditions that the Climate Change will bring.

The phenomenon of the salt intrusion mainly affects the internal area of the Po River Delta, and in recent decades, it has assumed increasingly worrying proportions with a progressive intrusion almost in all the water bodies of the area. The main impacts are on agriculture influencing the withdrawals for irrigation in the Po Delta.

On the other hand, the intrusion of the saline water along the river mouths of the Po River, by modifying the environmental and trophic conditions of the delta branches, often leads to favourable situations for the settlement of juveniles of marine / brackish species, some of which of considerable interest for the local economy. Recently, the final part of Po della Pila has started to host large settlements of clam juveniles Tapes philippinarum, becoming an area of economic interest, as it represents an exploitable natural fishing area.

- **Sacca del Canarin**

The Sacca del Canarin is shallow lagoon, communicating with the sea only through a north mouth. In the past the Canarin lagoon has encountered eutrophic phenomena linked to the development of macroalgae of the genera Ulva and Gracilaria (Sanavio et al., 2005), which have led to oxygen scarcity (hypoxia) and in some cases anoxia, especially in layers of water close to the bottom.

The dynamics responsible for the eutrophication are connected to the exchange of fresh and salt water within the lagoon,

For this reason, works of vivification of the lagoon are necessary as well as the monitoring of the sedimentological and chemical characteristics of the water, with the aim at preserving the delicate environmental balance and conditions of high biodiversity.

- **Sacca di Goro**

Sacca di Goro is a constantly evolving system, and various areas change rapidly, with visible modifications even in just one year, thus varying the production potential for the Manila clam rearing.

Presently, the most crucial element of the whole sector is the availability of Manila clam seed, the so called spat, which settles down preferentially in areas located on and out of the mouths of the lagoon or in a recently formed inlet, locally called "Basunsin". In recent years, this area has undergone to reduction of hydraulic circulation and consequently, macroalgal accumulation and bottom anoxia, especially in its eastern, more confined, portion. This is likely due to increased sediment deposition and has brought serious consequences, with not only the risk of hampering the productivity of clam farming in the whole lagoon, but also causing the worsening of environmental quality of this extremely important area with consequent loss of biodiversity. For these reasons, the most important interventions in the near future, other that maintaining the opening of the main mouth of the lagoon, must address actions aimed at restoring and maintaining high quality standards for the Basunsin area.

3.5.2. Available sedimentological data, studies, maps

The sedimentology and stratigraphy of the study area are closely correlated with the geomorphological evolution, therefore, many sedimentological aspects have been dealt with in a wider context, which contemplates the general sedimentary dynamics of this depositional system. For this reason, in the following lists that collect the data, maps and most significant previous studies, most of information used for the geomorphological study of the pilot area are reiterated. Some specific data concerning nourishment and geognostic, geophysical and sample analysis data have been added; moreover.

3.5.2.1. <u>Topo-bathymetric surveys, aerial and satellite images</u>

Regarding Veneto Region:

Topography (national, regional and/or local cartography, GPS surveys)	Regional topographic maps at different scale
High resolution DTM (from lidar, etc.)	2006 (1m); 2008 (2m-MATTM); **2009** (1m); 2012(0.5m); **2018**, Lidar for Rovigo coast, including logoons of Caleri, Vallona, Barbamarco, Canarin, Bonelli and the southermost part of the Scardovari lagoon. The 2018 lidar flight was executed in April, covering an area of almost 100 km^2, with a resolution of 1 x 1 m, and accompanied by orthophotos having a resolution of 20 x 20 cm, perfectly aligned to the laser survey as they were acquired simultaneously.The flight was realized during a period of low water spring tide, as the previous lidar flights along the Rovigo coast. Therefore, the altimetry of semi-emerged areas of the lagoons and of the foreshore was obtained. During the flight duration, some changes of the water level occurred due to the tide, but the water level always remained 20 cm below the mean sea level.

	Regarding Sacca del Canarin, the water level tide during the flight period over the area resulted in the range 0f -0.25 and -0.30 m a.s.l, and the water surface in the lagoon was almost around -017 m a.s.l., due to the offset between the sea and lagoon tides.
Bathymetry	2018 July, Lagoons: Sacca del Canarin, Sacca di Scardovari, Laguna di Caleri Laguna di Barbamarco. The bathymetric surveys aimed at verifying the altimetry of the channels and of the mouth of Sacca del Canarin after the dredging works carried out in the area, for the “works for the vivification of Sacca del Canarin, aimed at the valorization of the habitat and protected species through dredging of lagoonal channels, realization of velme and barene and protection of the sand spit” project. The project was a collaboration of the “Ente Parco Regionale Veneto del Delta del Po” and Veneto Region- Civil Engineering Unit. 1. 2014, from Po di Levante to Po di Goro, every 1 km 2. 2012, Rosolina shoreline, every 200 m from Adige to Po di Levante 3. 2008, Rovigo district, 57 crossing, more near the coast 4. 2005, Rovigo district, 57 crossing, more near the coast Bathymetric surveys and topographic campaign between Eraclea and Isola Verde in the period 2002-2010 (Magistrato alle acque).
Aerial and satellite images	Aerial photos: 1933 (1:20.000), 1944 (RAF Flight, 1:25.000), 1955 (GAI Flight, 1:35.000), 1977 (1:30.000), 1999 (1:34.000), 2008 (1:16.000), 2014, 2018. 2003, Digital orthophoto (with colors) TerraItaly it2000 NR 2003 “Compagnia Generale Riprese aeree S.p.S. Parma 2007, Digital orthophoto (with colors) TerraItaly it2000 NR 2006-2007 “Compagnia Generale Riprese aeree S.p.S. Parma 2012, Digital orthophoto (with colors) AGEA 2012 Interpreted by Ruol et al., 2016 “Analysis of the coastal erosion in the Po delta from 1933 to 2008 through aero-multi-temporal photogrammetry”, Fabris, Achilli e De Gennaro 2012
Rivers bathymetry	Topo-bathymetric surveys of about 163 cross sections along the Po Delta branches in the years 1990, 2005 (only Po di Venezia and Po di Goro), 2018.

Regarding Emilia Romagna Regions

Topography (national, regional and/or local cartography, GPS surveys)	Regional topographic maps at different scale (1:250000; 1:5000); regional topographic data base.

High resolution DTM (from LIDAR, etc.)	Lidar surveys of the coast: RER (2004, 2010) and PNT (2008), RER mosaics (DTMSGSS2012). DTM of the Po river: ADBPo (2005), AIPO (2015).
Lagoons bathymetry	Topo-bathymetric survey were completed in the years 2013, 2012, 2008, 2007. Data are available from regional RER-SGSS database.
Rivers bathymetry	Topo-bathymetric surveys of about 163 cross sections along the Po Delta branches in the years 1990, 2005 (only Po di Venezia and Po di Goro), 2018. available on web service http://geoportale.agenziapo.it/cms/
Coastal areas bathymetry	Topo-bathymetric surveys were conducted by ARPA on behalf of RER in the years 2000, 2006, 2012 and 2018. Data are available from regional RER-SGSS database. Sea-bottom maps (RER): 1901, 1950, 2000, 2006, 2012.
Aerial and satellite images	Aerial photos: 1996, 1994, 1998, 2002, 2005,2006,2008,2011,2014 (RER, regional coverage); RAF flight (1943-45), GAI flight (1954), 1976-78, 1982, 1991, 1992, 2005, 2010 (RER, local coverage, coast); satellite images (RER): quickbird (2003), Landsat (1992-93)

3.5.2.2. Cartography

Regarding Veneto Region

Shorelines (e.g. photogrammetric, remote sensing, or site surveys)	Shoreline variation 2006-2009, 2009-2012 and 2012-2018 (from Lidar). Different contour levels (0,25 – 0,5 m), n. 57 crossing land-sea (Veneto Region); Shorelines from photo-interpretation: 1933 (1:20.000), 1944 (RAF Flight, 1:25.000), 1955(GAI Flight, 1:35.000), 1977 (1:30.000), 1999 (1:34.000), 2008 (1:16.000), 2014,2018 (surveys from 1955 to 2008 with stereoscopic coverage)
Geomorphological maps	1987, Geomorphological map of Veneto Region, paper; 1954-2003, Geomorphological map of Po River Delta derived from aerial photo surveys (Flights GAI 1954-55 and TerraItaly NR 2003) Monitor Project; 2009, Geomorphological map of Rovigo Province (from PTCP: Provincial Territorial Coordination Plan)
Geological maps	1988, Geological map of Veneto region, paper, Veneto Region, Geomorphological Map of the Po River Plain, (1:250.000) Geological map of Italy (1:50.000), sheet 187 “Codigoro”

Regarding Emilia Romagna Region

Land Use maps	Coastal zone: 1943, 1982, 1998, 2005; entire region (RER): 1954, 1976, 2003, 2008, 2014
Shorelines (e.g. photogrammetry, remote sensing, or site surveys)	Shorelines from photo-interpretation: 1943, 1982, 1996, 1998, 2005, 2011, 2014, 2006, 2012, 2014; shoreline from GPS surveys: 2006, 2012, 2018.

Maps of lithology, maps of sediment	Sedimentological map CNR (1982); granulometric analysis ARPA: 2006, 2012; study of sediments in the Sacca di Goro 1998
Geomorphological maps	Coastal geomorphological maps (RER): 1943, 1982, 1998, 2005; national geological cartography at 1:50000 scale (CARG project); Geological Po Plain Map (RER) at1:250000 scale.
Geological maps	National geological cartography at 1:50000 scale (CARG project); Geological Po Plain Map (RER) at 1:250000 scale.

3.5.2.3. Coastal and hydraulic works

Regarding Veneto Region

Hydraulic works	Information of defence works and pumping stations in the Rovigo province up to 2018
Hydraulic hazard maps, hydraulic risk maps	Flood Directive Maps

Regarding Emilia Romagna Region

Hydraulic coastal Defense Works	Mapping from photo-interpretation and attributes from regional territorial agency experts: 1943, 1982, 1996, 2000, 2005, 2011
Hydraulic works (sump pumps, pumping stations, navigation basins, etc.)	Available on web-gis of Remediation Consortium of Ferrara plain. Topographic surveys of the levees elevation 2014-2018, both along the river Po and the coast (AIPO).
Nourishment and dredging (data, volumes, etc)	Regional nourishment database from the 80s to present

3.5.2.4. Trends and dynamics

Regarding Veneto Region

Information on evolutionary trends (eg. Coastal erosion maps, subsidence trends, etc.)	Shoreline variation 2006-2009, 2009-2012 and 2012-2018 (from Lidar). Different contour levels (0,25 – 0,5 m), n. 57 crossing land-sea (Veneto Region);

	Shorelines from photo-interpretation: 1933 (1:20.000), 1944 (RAF Flight, 1:25.000), 1955(GAI Flight, 1:35.000), 1977 (1:30.000), 1999 (1:34.000), 2008 (1:16.000), 2014,2018 (surveys from 1955 to 2008 with stereoscopic coverage)

Regarding Emilia Romagna Region

Information on evolutionary trends (eg. Coastal erosion maps, subsidence trends, etc.)	Interferometric analysis to monitor subsidence (RER), periods: 1992-2000; 2006-2011; 2011-2016. Assestimeter in Gorino (Fe), working since 2013, to measure lowering of the soil due to the compaction of recent deposits ; Historical shoreline analysis (since XIX sec), period: 1943-2014, 2000-2014. Carta delle Criticità Costiere scala 1:10000 (RER)

3.5.2.5. Geognostic, geophysic and sample analysis data

Regarding Veneto Region

Sampling (granulometric, mineralogical analysis, etc.)	2005, Grain size characterization of costal area. year 2005, (particulary Adige mouth; Caleri mouth; busa Tramontana; Scardovari lagoon) 2018, Characterization of the sediments coming from the excavations and aimed at the nourishment of the beaches under erosion (Sacca del Canarin) 2018, Environmental characterization of the sediments along the lagoon channels in Sacca del Canarin – Porto Tolle (RO)

Regarding Emilia Romagna Region

Geognostic tests (corings, CPT, etc.)	Regional geognostic database (RER-SGSS) with over 200 corings and 2500 CPTU; CNR-ISMAR database of corings of seabed; new specific surveys from 2018 with the realization of corings and CPTU on the beach and in the nearshore in the Ferrara coast.
Geophysic investigation (seismic, geolectrical surveys, etc.)	Dense seismic chirp profiles network of the regional nearshore (from 2010 by CNR-ISMAR and RER-SGSS); CNR-ISMAR seismic profile database.
Sampling (granulometric, mineralogical analysis, etc.)	Geotechnical analysis of samples (RER-SGSS). Multiannual particle size analysis of the shallow sea bottom (ARPAE). Coring analysis (XRF, magnetic susceptibility), sample analysis (granulometry, C14) by CNR-ISMAR.

3.5.3. Acquisition of new in-situ data to complete knowledge

The bathymetric survey of the Po delta branches, which was an objective of the present project, was planned to provide new information regarding the conformation of the riverbed near the mouth and therefore to identify bottom structures due to sediment transport and any accumulations.

The results of this activity, assigned to AIPO (Agenzia Interregionale per il fiume Po) by the partner Emilia Romagna Region, were not delivered due to several reasons including the covid-19 emergency.

3.5.4. Current status (qualitative, quantitative) of the site sediment stocks

The Po delta system is characterized by an extensive delta plain, a broad asymmetric prodelta deposit and a land-sea transition zone. In this latter part, two sedimentary systems can be distinguished, one external represented by the sand spits, and one internal defined by the sacche and the lagoons.

All the elements are influenced in different way by the sea currents, the fluvial inflows and the meteorological variables.

3.5.4.1 The historical evolution of the Po Delta

The Po plain can be considered the Foredeep of the Alps and Apennines, whose fronts emerge in the northern and southern sides of this region, folded by multiple thrust faults. Since the Cenozoic (65 million years ago) it has collected thick sediment deposits coming from these mountain chains. The natural subsidence characterizing the Po basin remained strong during the Pliocene and Quaternary, affecting the thickness of the deposits formed during this period. Afterwards, the sea retreat following the Würm Glaciation left the basin uncovered until the Holocene, when it was submerged again. The last 6000 years have been characterized by the progradation of the Delta lobes towards East.

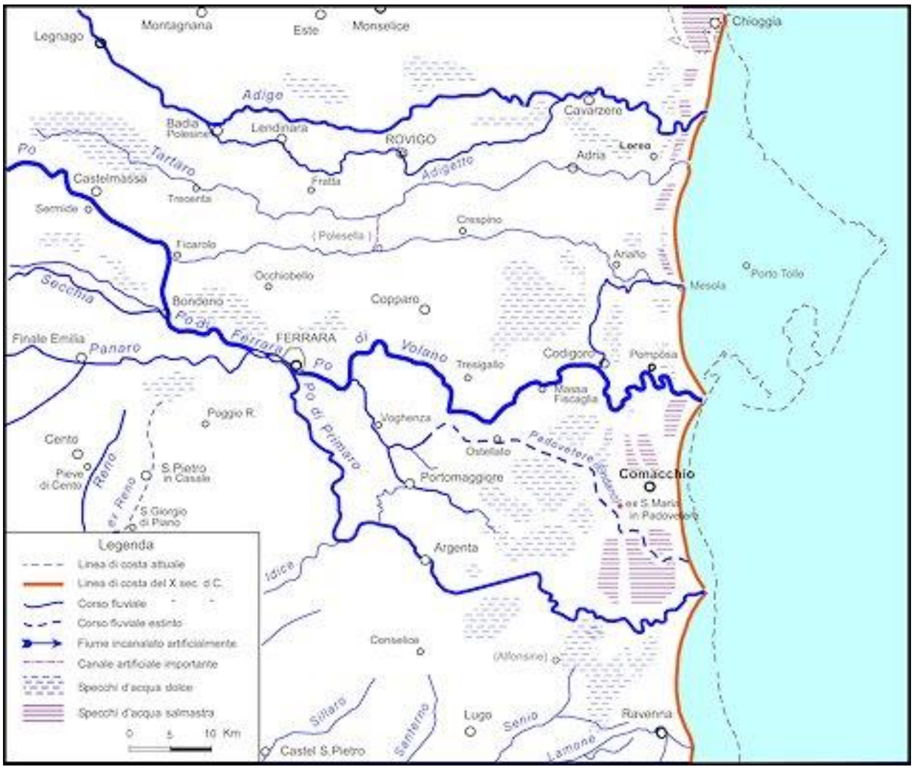
The Po River Delta is composed by soils of Quaternary age (since 2 million years ago), comprising alluvial sediments and loose deposits of sand and silts. They develop on the top of Pliocene deposits reaching a depth of almost 2000 m.

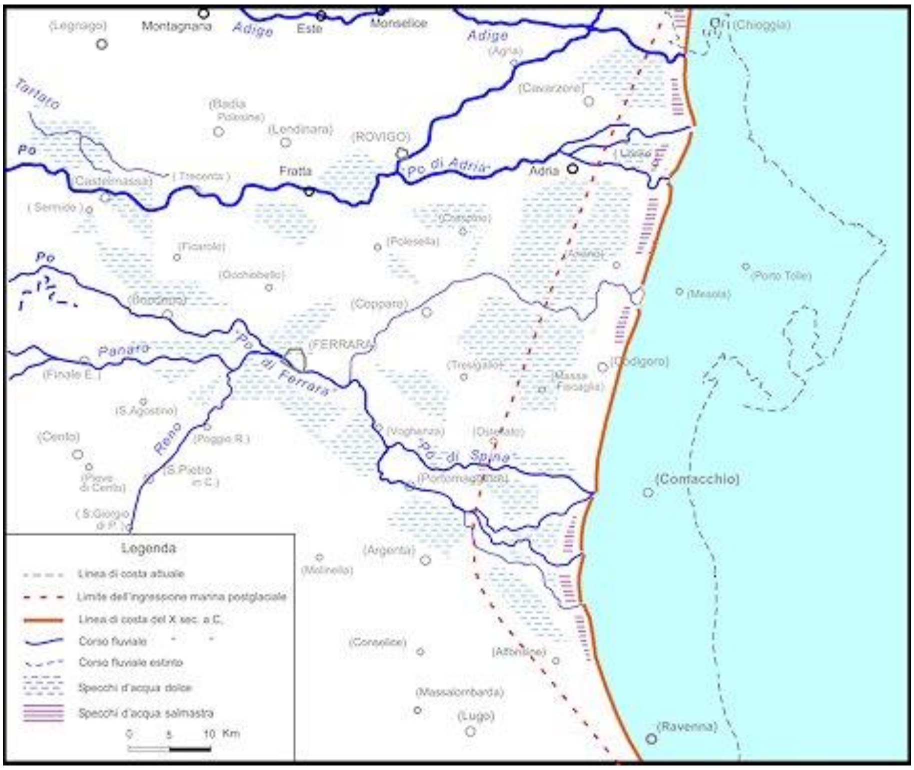
The evolution of the delta is strictly correlated to the sediments transported by the Po River, which have been always responsible for the aggradation and avulsion of the river and the progradation of its mouth towards the Adriatic Sea, causing in the same time frequent flooding events (*rotte*) and changes in the watercourse direction.

During the Etruscan period, the easternmost lands were under the sea and the coastline was located along the ancient dunes of the Ariano Island. This dune belt divided the open sea from the lagoon and it was used by the Romans to build the littoral road joining Altino to Ravenna (Romea road). Starting from the Roman period, anthropic and natural changes affecting the utmost parts of the Adige and Po River and the coastal lands between them have profoundly modified the Po River Delta, resulting in the current configuration of the region.

From the Roman period until the Middle Age the main delta developed in the plain of Ferrara, while the coast was rectilinear and placed backward from the current position. The main branch of the Po River was Po di Volano, which now is disconnected from the main watercourse.

The modern Delta originates from two main historical events: the Ficarolo breach in 1150 and the Porto Viro cut in 1604.The first change led to the accretion of the Delta seawards, with the formation of Sacca di Goro due to the progradation of the Po delle Fornaci towards North (with its three branches of Tramontana, Levante and Scirocco) and Po di Goro towards South. In this period, the territory of Taglio di Po and Porto Tolle was still occupied by the sea.




Legenda
Linea di costa attuale
Limite dell'ingressione marina postglaciale
Linea di costa del X sec. a C.
Corso fluviale
Corso fluviale estinto
Specchi d'acqua dolce
Specchi d'acqua salmastra
0 5 10 Km
Montagnana
Este
Monselice
Adige
(Chioggia)
(Rovigo)
Fratta
Po di Adria
Adria
Po
Panaro
Po di Ferrara
(FERRARA)
Reno
Po di Spina
(Comacchio)
(Ravenna)

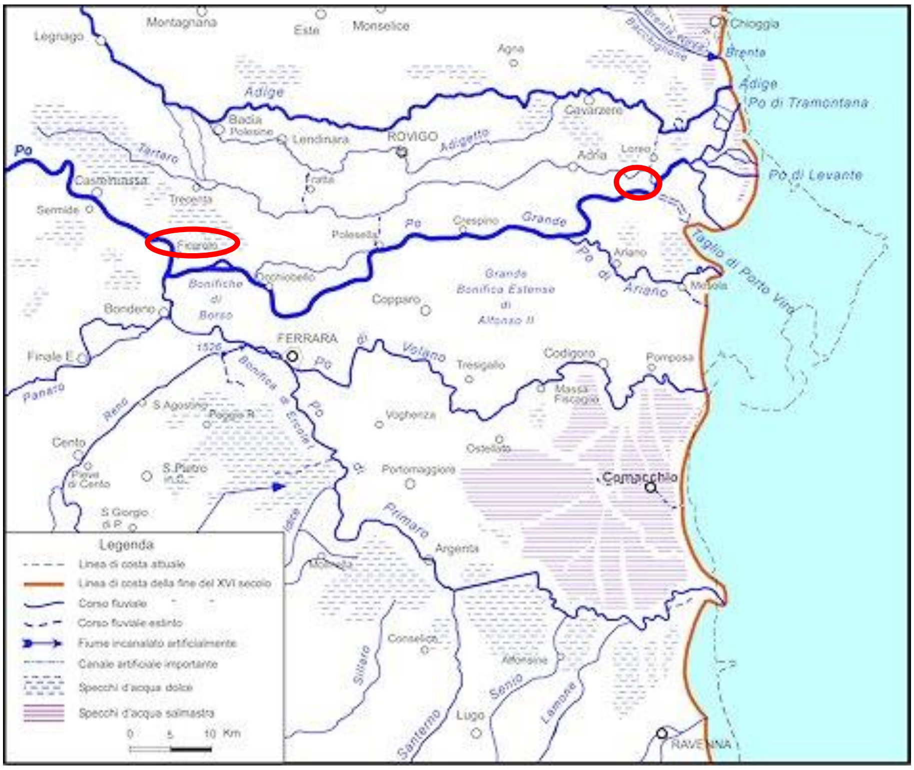

Legenda
Linea di costa attuale
Linea di costa della fine del XVI secolo
Corso fluviale
Corso fluviale estinto
Fiume incanalato artificialmente
Canale artificiale importante
Specchi d'acqua dolce
Specchi d'acqua salmastra
0 5 10 Km
Montagnana
Legnago
Este
Monselice
Chioggia
Brenta
Adige
Po di Tramontana
ROVIGO
Adria
Po di Levante
Po Grande
Po di Ariano
Taglio di Porto Viro
FERRARA
Po di Volano
Comacchio
Reno
Panaro
RAVENNA

Figure 3-57: Evolution of the Po Delta. 1) X century b.c., 2) Roman period, 3) 1300 after the rotta di Ficarolo, 4) 1599 after the Porto Viro cut (images from the remediation Consortium for the Ferrara Plain)

The quick accretion of the Po towards North convinced the Republic of Venice to deviate the river course towards south, by building an artificial canal flowing into Sacca di Goro, with the aim of preventing the infilling of the Venice lagoon. The intervention is crucial in the evolution of the modern Delta, and the new branch of Po di Venezia contributed to the formation of the territory of Porto Tolle during the XVIII century.

The accretion of the Po River Delta accelerated during the XIX century, with the increased sediment supply delivered by Po di Goro and Po di Gnocca due to the artificial closure of some branches detaching from Po di Maistra. Sacca di Scardovari emerges in this century together with the southeastern part of Polesine Camerini. Po di Goro moved forward of 20 km in 240 years, Po di Maistra of 24 km and Po di Tolle of 23 km, with an average accretion of 83 m/year (Giandotti).

A first deceleration of this process occurred in the XX century, with a turnaround between 1950 and 1960, when the coastline retreated due the ground lowering, leaving large portions of the territory under the sea level. The high subsidence rates were registered in connection with the extraction of methane from the groundwater, decreasing only once the gas exploitation was interrupted. Afterwards, the mine activities along the Po River course caused the main problems in the delta. Several studies reported that between 1968 and 1973, in the coastal area between 0 and 6m of depth, there was a lack of -1.1 million of m^3/year of material, corresponding to the same amount extracted from the river basins.

As pointed out in report 3.2.1, currently sediment starvation threatens some coastal regions that are subject to erosion, while other sectors show a low tendency of progradation. A general redistribution of the material characterizes the Po River Delta, with the predisposition of the lagoons to be infilled by the transported sediments.

3.5.4.2 The Prodelta stratigraphy and bathymetry

Today the Po delta protrudes in the sea for almost 25 km, bordered by a wide region occupied by a submerged prodelta (Figure 3-58), which extends for 6 km in the north and 10 km in the south (Biondani, 2008).

Two different types of depositional patterns are detectable from Very High Resolution (VHR) seismic lines recorded offshore: a) the delta lobes fed by individual distributary mouths, onlap onto each other and reflect autocyclic processes, driven by discharge and sediment load variations, and human interference; and b) erosional features locally detactable close to individual distributary channels.

For an evaluation of the evolution of the Po delta, DTM (250 m) of the bathymetry from the 1886 Ing. Stella map with data of 1877 survey and DTM of current bathymetry obtained by the integration of various singlebeam and multibeam data were compared. The differences vary between - 12m and about + 19m with areas of strong erosion off the mouths of the Po di Tolle and the Po di Maistra and a deposition area in front of the Po della Pila distribution channel.

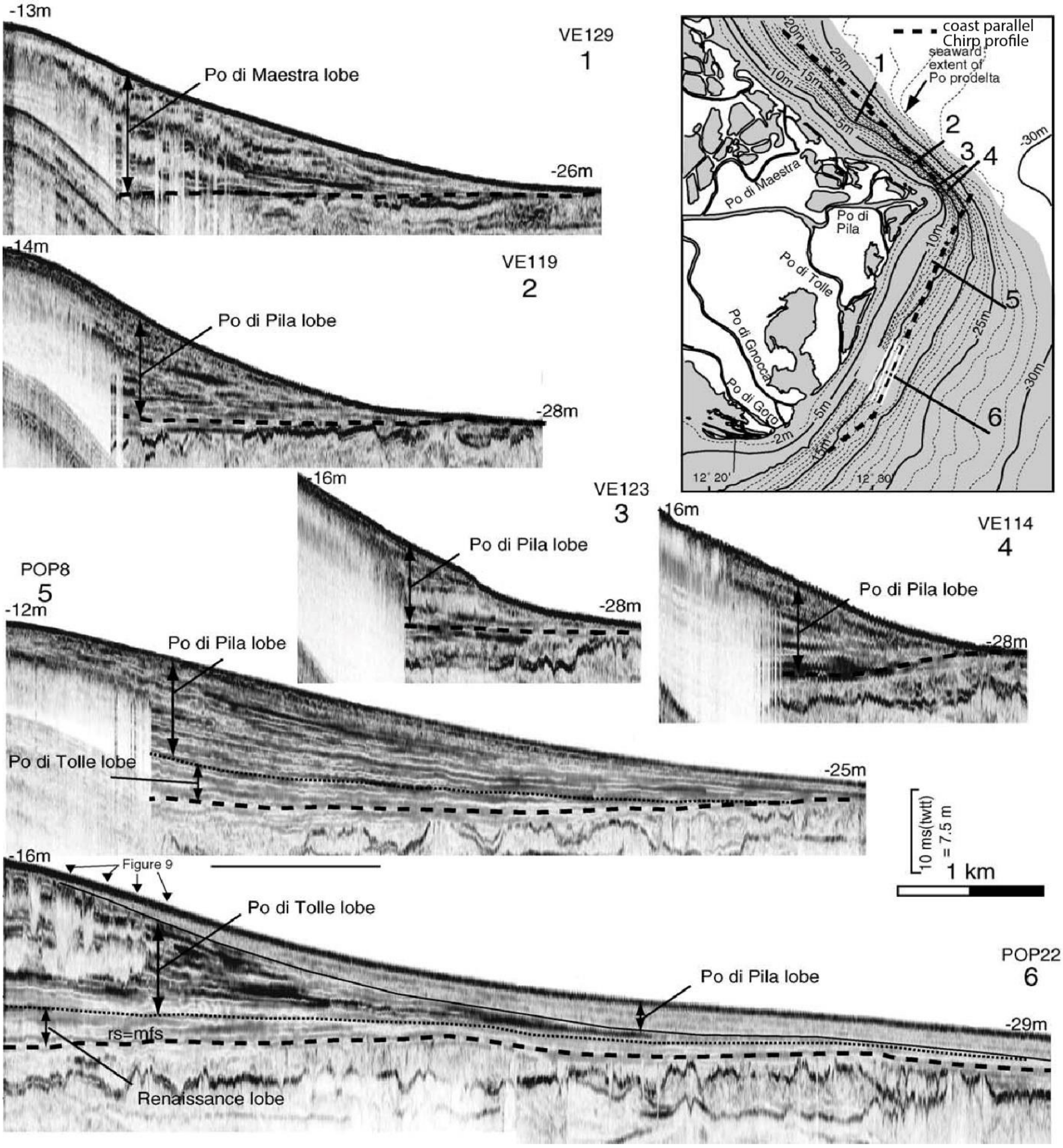


*Figure 3-58: Chirp-sonar profiles perpendicular to the coastline illustrating the internal geometry of the Po prodelta lobes above the basal ravinement surface (**rs**), that corresponds also to the maximum flooding surface, **mfs**, see Correggiari et al. (2005). Each prodelta lobe is named after the river mouth of origin. The surfaces separating prodelta lobes are distinctive seismic reflectors that can be correlated laterally. The dashed line on the map shows the location of the composite profile parallel to the coast.*

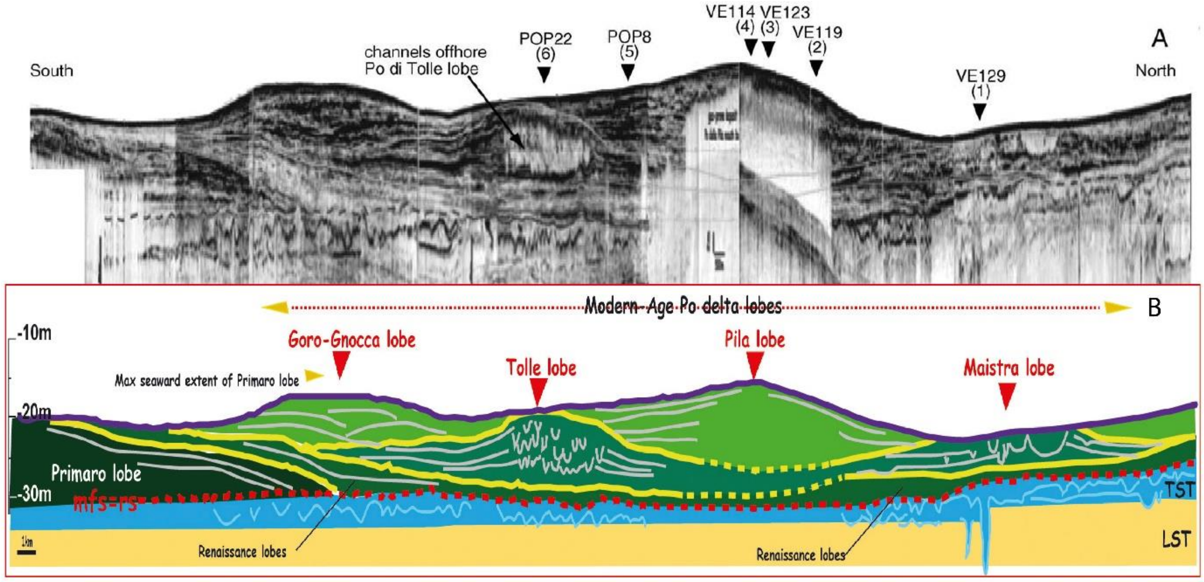


Figure 3-59: A composite Chirp-sonar profile sub-parallel to the present-day coastline of the Po Delta summarizes the stratigraphic relationship among individual prodelta lobes (profile location is on the inset on the left). The pre-Modern Age Po di Primaro lobe lays in the South (left in this figure) and is partially draped by a weakly reflective stratigraphic unit that corresponds to the growth of the late Middle Ages and Renaissance cuspate deltas located north of Primaro. The Modern Age lobes of Maistra, Pila, Tolle and Goro-Gnocca record the last few centuries of delta growth. Vertical exaggeration is extreme (about 500 times) to enhance the stratigraphic relations among delta lobes

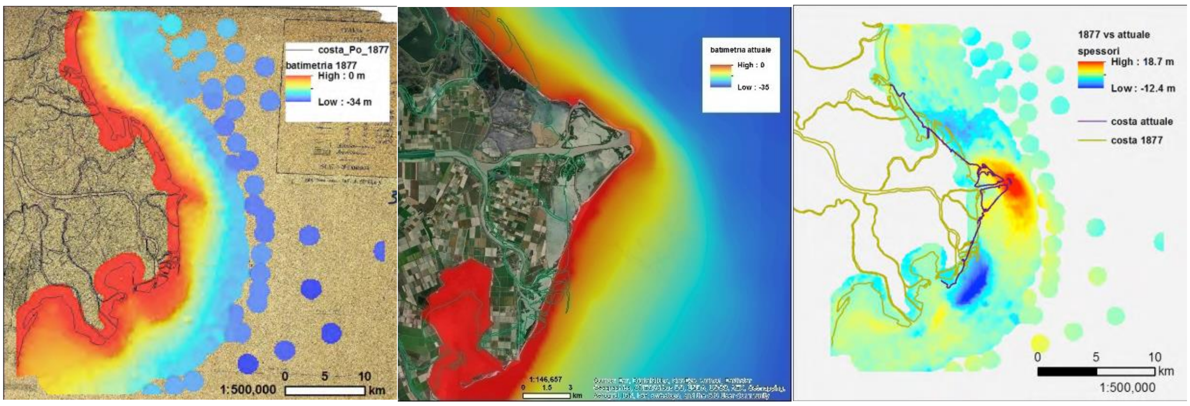


*Figure 3-60: **left** DTM created on georeferenced Ing. Stella Map of 1886. **Center**: current bathymetry from singlebeam and multibeam data. right: result from difference between modern and historical bathymetry.*

To better appreciate the variations in the three most significant sections, the morphobatimetric profiles obtained from the two DTM were compared. Only the section out of the mouth of the Po della Pila shows a progradation that has moved the mouth towards the sea by 4 km in 130 years with a consistent increase in the volumes of sediment deposited. The other two sector of the delta are in constant erosion.

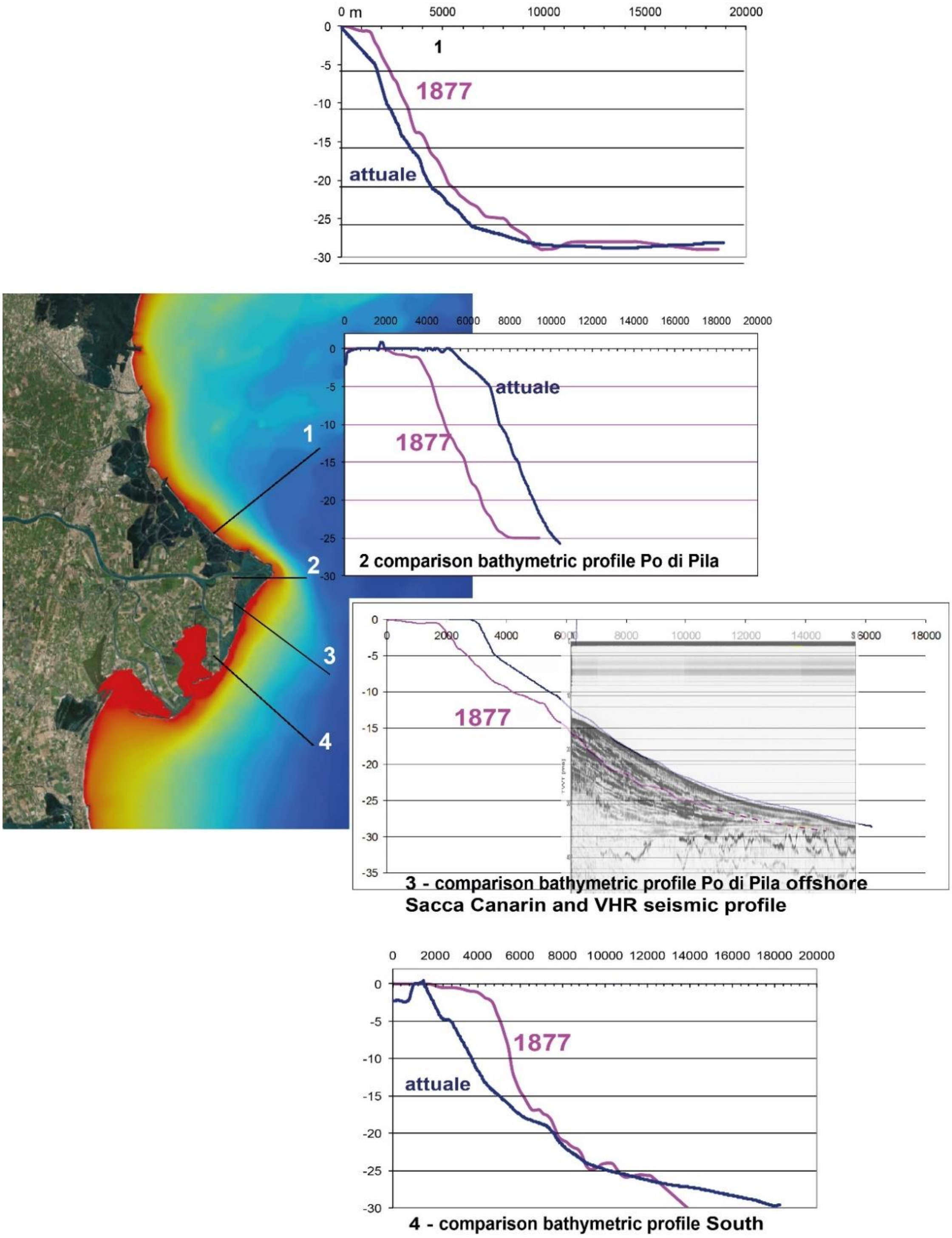


Figure 3-61: Comparison between 4 morpho-bathymetric sections obtained from the two DTM 1877 and current one

3.5.4.3 Current status on the sediment stocks in the coast and transition region

A sedimentological campaign carried out in 2006 by the Veneto Region led to the sedimentological characterization of the area around the Po Delta coast. The samples were collected along lines orthogonal to the shoreline or, in some cases, according to squared grids (in proximity of two mouths of the Po River).

As expected, material having a mean diameter > 0.5 mm (Figure 3-62, top left) is missing, while most of the seabed along the Po River Delta is characterized by fine sediments. The sedimentological distribution in the surface littoral area is strongly influenced by the sediment outflows coming from the Po River branches, which successively is mobilized and redistributed along the Delta by the sea currents.

Medium sand (Figure 3-62, top right) is concentrated in the proximity of the main Po River mouth (Po di Pila), where sediment transport is stronger, while fine sand sediments (Figure 3-62, bottom left) predominate close to the other mouths that deliver lower water and solid discharges. Far from the coast, silt deposits (Figure 3-62, bottom right) are prevalent, especially close to Sacca of Scardovari.

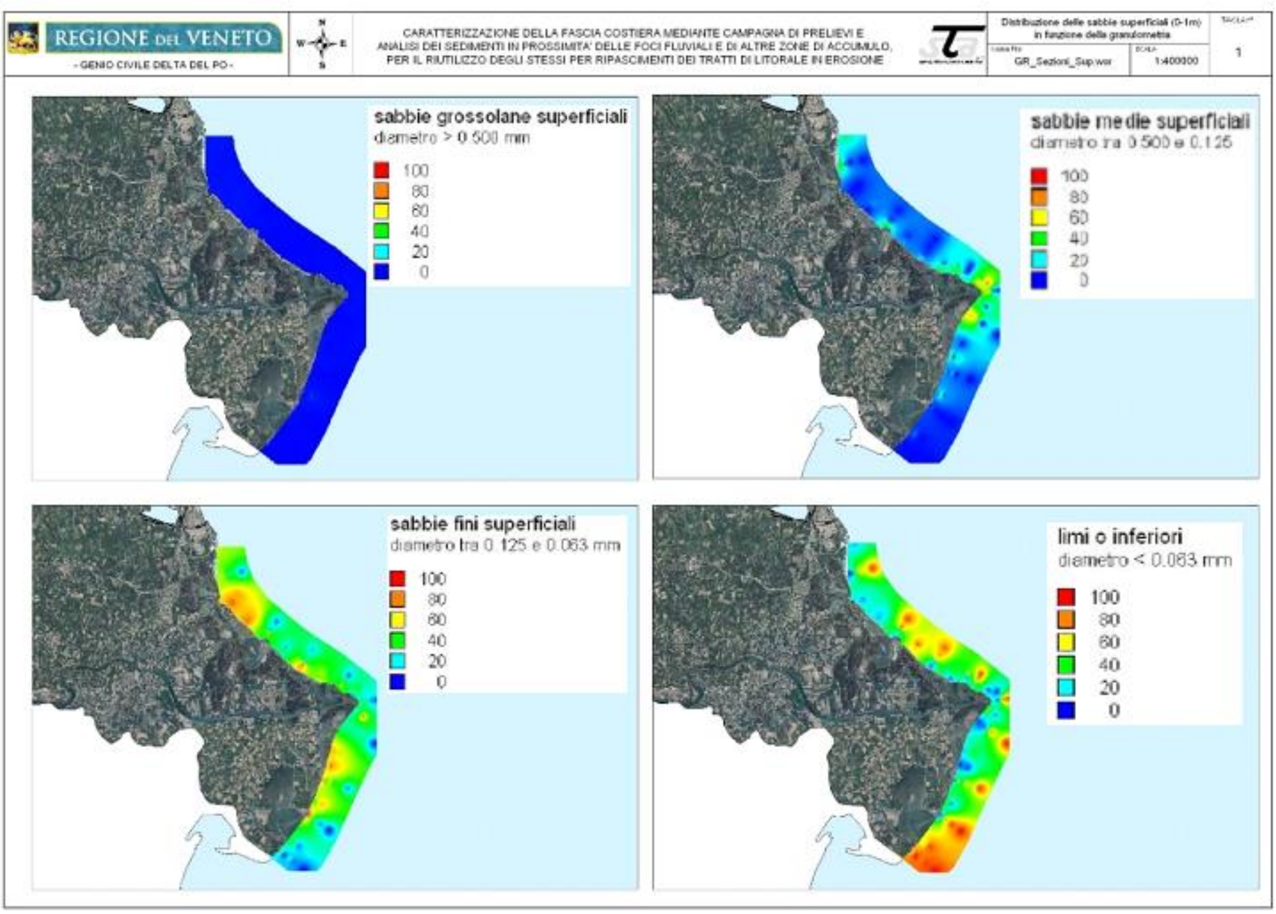


Figure 3-62: Spatial distribution of four different grain-size classes in the coast of the Po River Delta. Top-left: coarse sand having d_{50} between 0.125 and 0.500 mm; top-right: medium sand having d_{50} between 0.125 and 0.500 mm; bottom-left: fine sand having d_{50} between 0.063 and 0.125 mm; bottom-right: silt. Soruce: Arpa Veneto Region (2005)

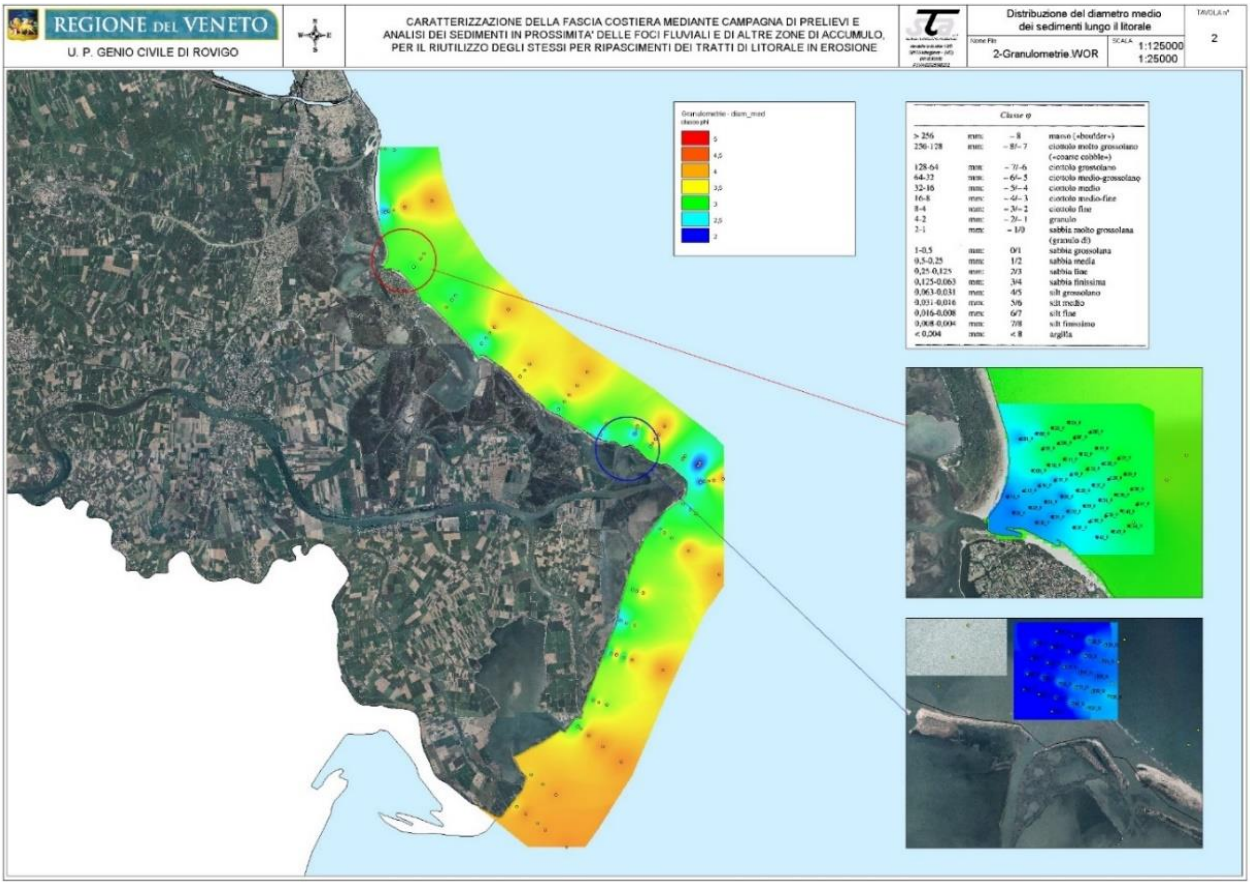


Figure 3-63: Sedimentological distribution in the coast of the River Po Delta: φ classification= -log2 (mean diameter)

Figure 3-63 reports the ϕ classification, which transforms the grain size values according to a logarithmic scale (inverted). Consequently, higher values of ϕ correspond to finer sediments.

- **Sacca del Canarin**

Sedimentological maps and stratigraphic studies are still missing for Sacca del Canarin, but a general characterization of the lagoon can be drawn on the basis of samples and cores collected in the course of recent maintenance works. The samples, taken between May and June 2020 (Veneto Region, Patti, S., Selvi, G. Chiarion P., 2020 and Chiarion P., 2020), are located around the dredged canals indicated in Figure 3-64 and Figure 3-65, along the nourished beaches and on the external sand spit, providing valuable information on the area that is closer to the sea.

According to the analysis carried out on the sampled material, there is a progressive coarsening of the sediments seawards, with sandy deposits towards the lagoonal outlet, and silty sand in the channels closer to the sea. Moving inside the lagoon, the silty-clayey sediments prevail over the sandy accumulation, with few variations locally. The discrepancies between the surface layers (from the ground level to -0.5 m) and deeper deposits (to -1m) are negligible.

The emerged morphological features reflect the same sedimentological distribution of the lagoon bottom and the channels, with silty sand forming the external spit (Scanno del Canarin) and silt with clay in the innermost part of the lagoon (Figure 3-65).

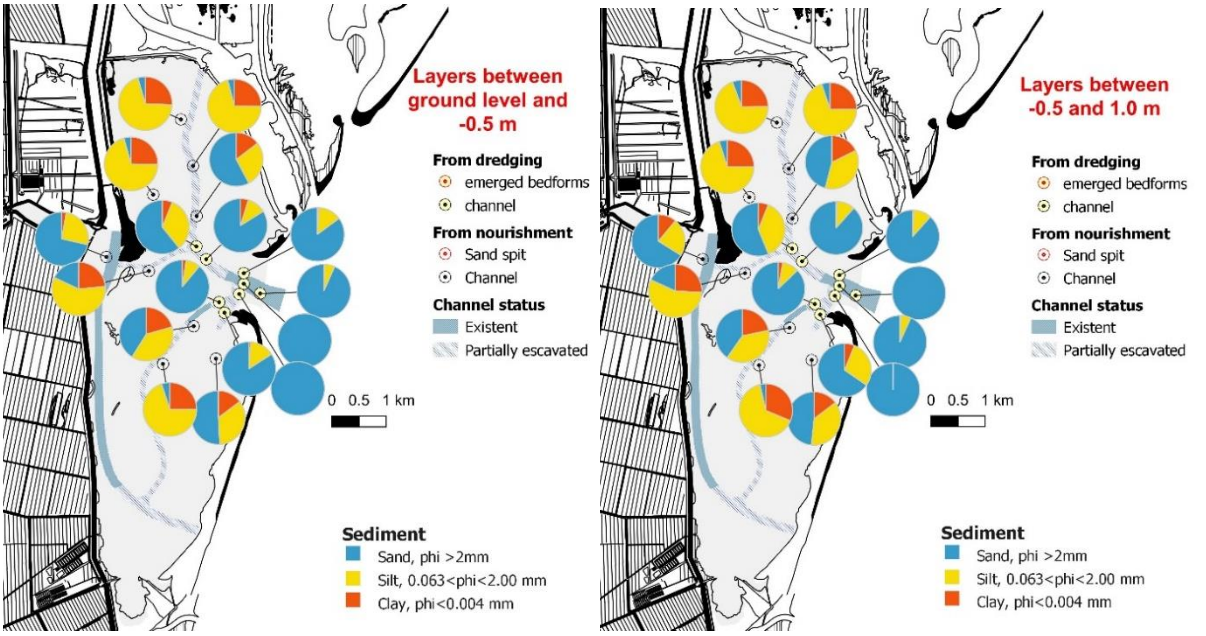


Figure 3-64: Grain size distribution of the samples and cores collected in Sacca del Canarin during the works of maintenance: surface and medium layers.

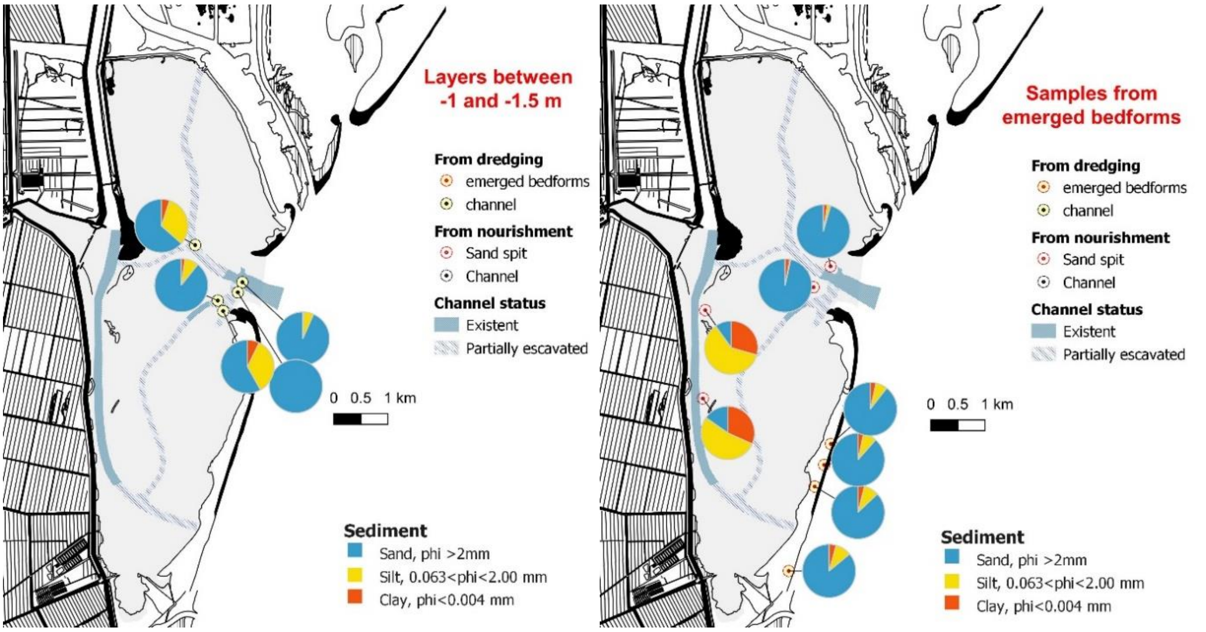


Figure 3-65: Grain size distribution of the samples and cores collected in Sacca del Canarin during the works of maintenance: deep layers and emerged morphological features

The sedimentological distribution results from the hydrodynamic circulation characterizing Sacca del Canarin (IPROS Ingegneria Ambientale S.r.l, 2018), which exchanges fresh and salt water mostly through the outlet enclosed by the sand spit.

The main process affecting the ordinary circulation inside the lagoon is the tide range that usually is of ca. 50 cm, while the wind contribution often remains marginal and strongly aleatory. The tidal wave (for both the incoming and out-coming flux) reaches a maximum velocity of 0.5 m/s in the vicinity of the sea outlet, where it is capable of mobilizing and depositing sand sediments. In contrast to the external part of the lagoon, the velocity inside the lagoon drops to 0.10 m/s due to the high resistance exerted by the low bottom, and the conditions become unfavorable for the transport of coarse materials. Therefore, clay and silty deposits prevail in these regions. In the southern area of the lagoon the velocity is practically zero (Figure 3-66).

The channels represent the preferential direction for the flow, but they are exposed to infilling and sediment deposition processes (flood/ebb tidal delta) that progressively limit the exchanges between the sea and the lagoon. Winds exacerbate the sea currents mostly in front of the lagoon with direct consequences on the sand spit, while their effect tend to diminish within the lagoon waters. Consequently, they do not alter consistently the sediment distribution inside Sacca del Canarin.

The outlet at the sea is not only the main access to salt water but also to fresh water that comes from the River Po mouths located at south (Busa di Bastimento) and north (Busa di Scirocco) of Sacca del Canarin (Figure 3-67). In fact, during floods, most (.ca 66%) of the fresh water penetrates the lagoon through the Bocca del Canarin after having saturated the surface layers in the frontal sea sector, while smaller quantities enter through a southern access near Busa del Bastimento (.ca 21%) and through a northern connection to the lagoon of Basson (.ca 11%).

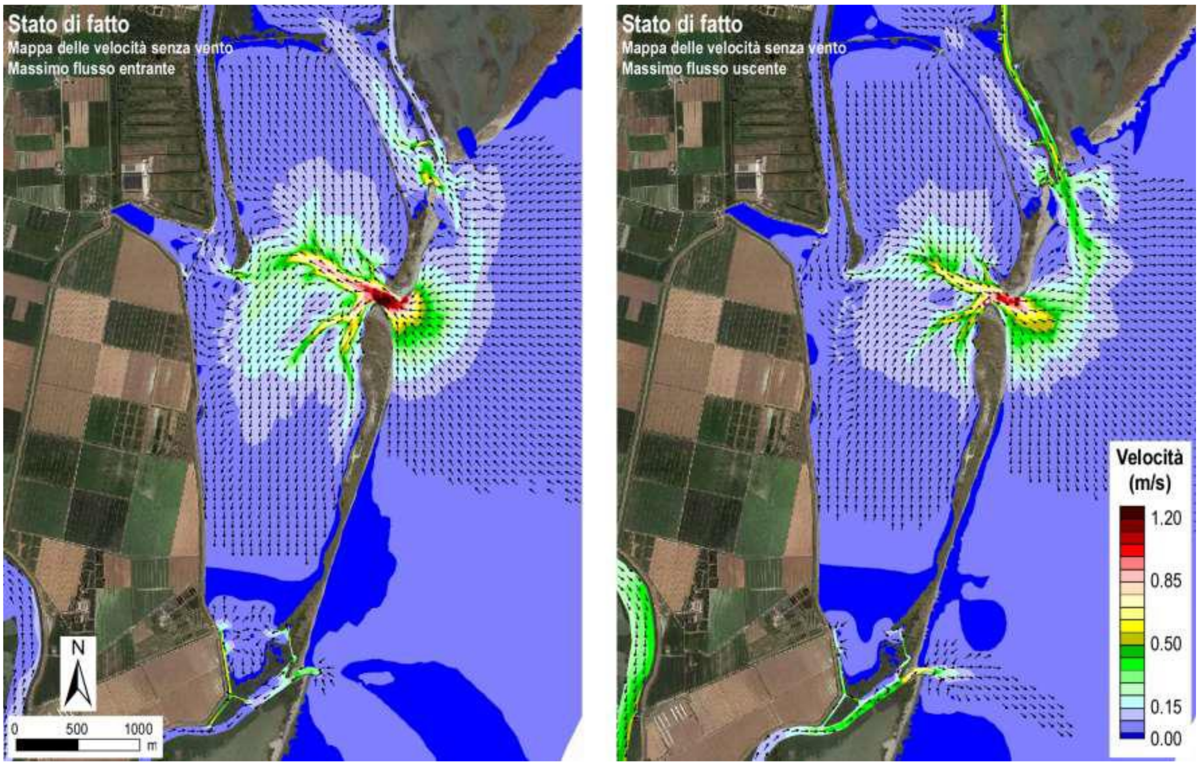


Figure 3-66: maximum velocity field in the Sacca del Canarin for the incoming (left) and out-coming flow(right) during the tide range. Simulation without considering the wind contribution Soruce: IPROS Ingegneria Ambientale S.r.l. 2018

Figure 3-67: Location of the main access of the fresh water input in Sacca del Canarin with corresponding percentages.

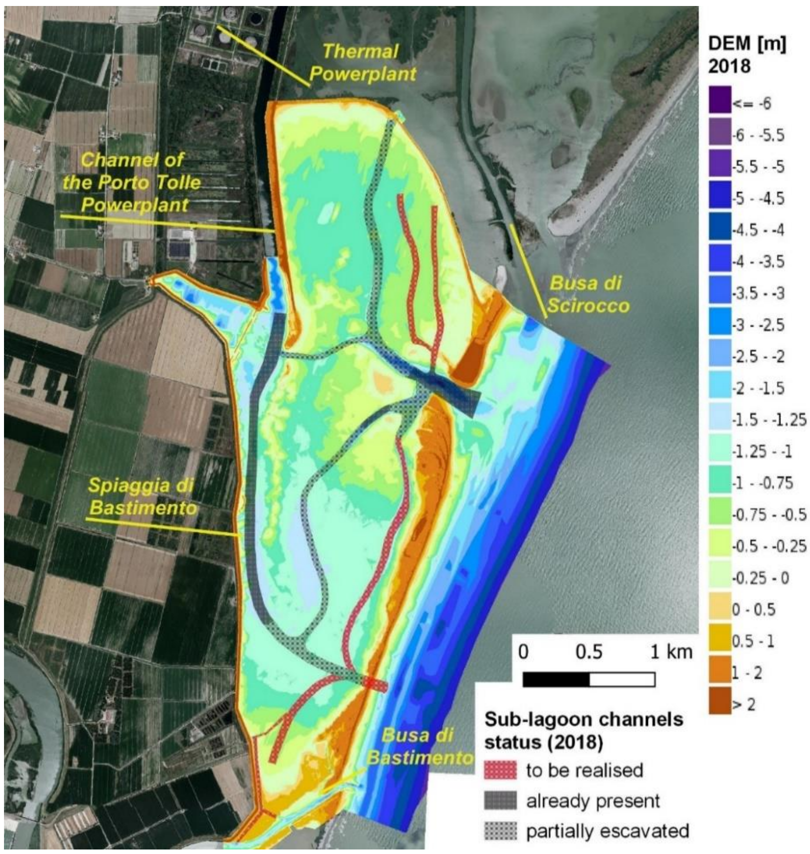


Figure 3-68: Digital Elevation Model of Sacca del Canarin (2018).

The recent topo-bathymetric surveys (Figure 3-68) confirm that the deepest regions are situated close to the sea outlet where the erosion/depositional processes are stronger, and in the proximity of the lagoon channels, characterized by a maximum depth of -3 m. The average depth of the lagoon is ca 80 cm below the sea level.

The sand spit has a maximum height of 2 m, and it shows a thinning trend caused by recurring storm-surges. Few emerged morphological features are clearly detected by the digital terrain model, such as the two sediment accumulations in front of the sea-outlet.

- **Sacca di Goro**

The characteristics of the deposits have been described in the past by sedimentological maps, on the basis of samples and cores of the lagoon and seabed.

A stratigraphic study, started in 2009, based on a dense network of chirp seismic profiles acquired by CNR-ISMAR and RER-SGSS, highlights the relationships between the different geological bodies distinguished on the basis of the lithological and depositional characteristics.

Valuable information is also provided by the analysis of the changes in the morphology of the seabed obtained from the digital models available.

Sedimentological map and sampling

The samplings carried out by different authorities (CNR-ISMAR, ARPA-RER, ENI, University of Trieste) in various monitoring surveys in the years 1982, 1984, 1994, 1997, 1998, 2012 provided the basic information necessary for the preparation of the sedimentological maps available.

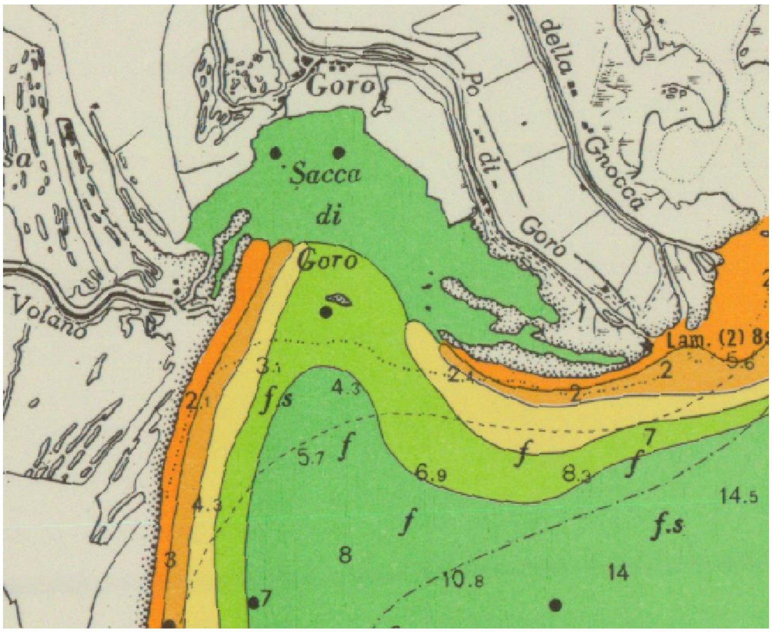


Figure 3-69: Detail of Sedimentological Map of the Northern Adriatic Sea at 1:250000 scale (CNR, 1982); legend sand = orange, pelitic sand = light orange, very sandy pelite = yellow, sandy pelite= light green, pelite= green

The maps, starting from 1982 (CNR), describe a rather stable general condition: a progressive fining of the sediments towards the open sea, passing from the sands of the beach and bars to the silts and clays of the prodelta of the Po di Goro while in the lagoon are spead silty-clayey sediments over mainly sandy deposits.

Some variations have occurred over time as the increase of sand deposits in the nearshore of the Volano spit and the decrease in the sandy fraction in the Scannone di Goro.

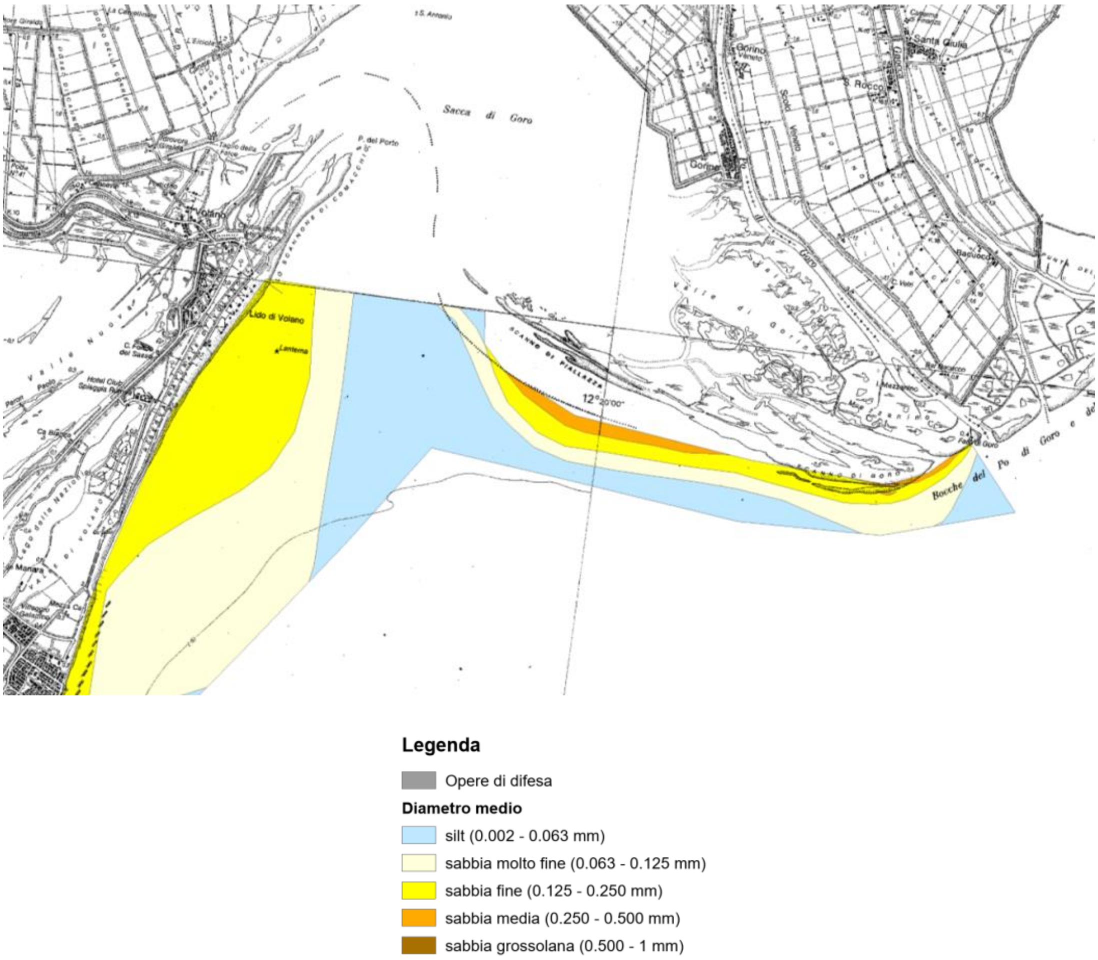


Figure 3-70: Average diameter map at 1:50000 scale (ARPA, 2013)

The sedimentological maps of the lagoon show a typical coarsening distribution seaward with clayey and silty deposits in the innermost portions, towards the shore that fade gradually to sandy sediments towards the Scannone, the Volano spit and lagoonal inlet. Some channels are characterized by finer deposits despite their seaward position.

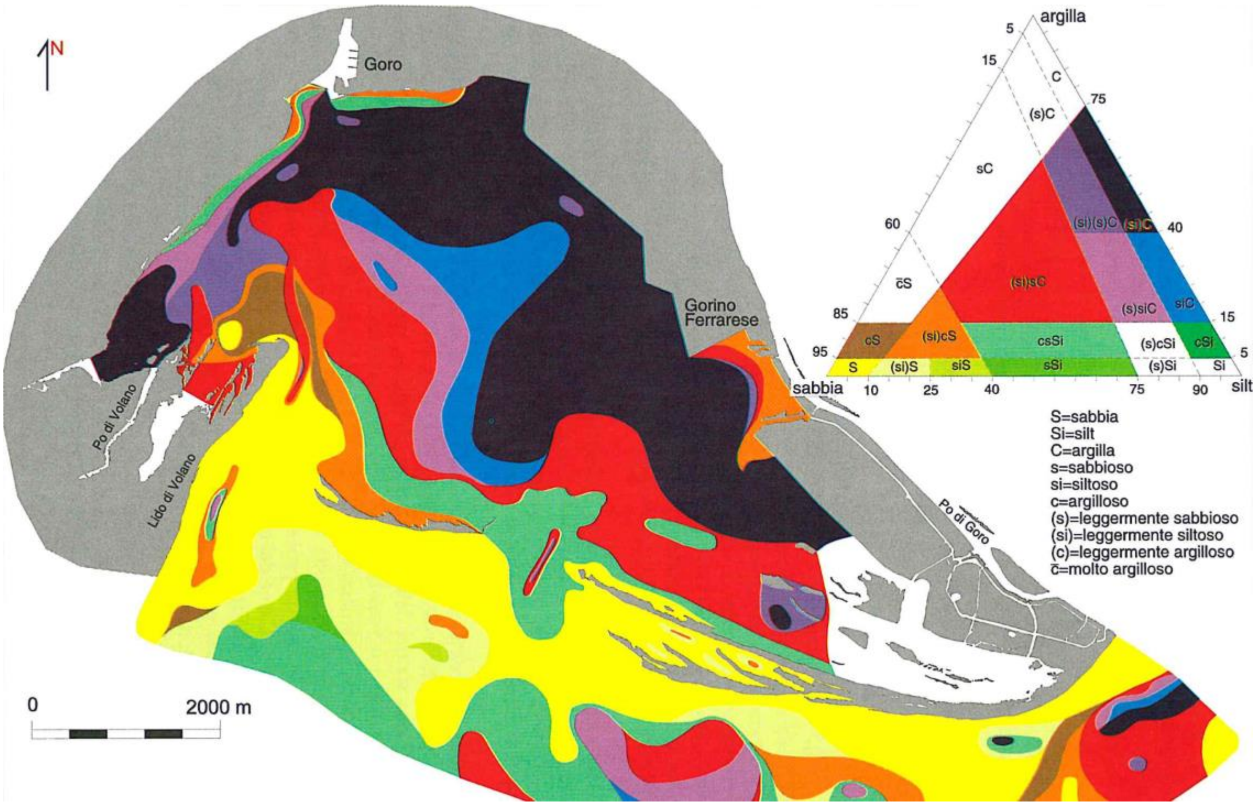


Figure 3-71: distribution of sediments in the Sacca di Goro, using classification of Stevens 1984 (from Simeoni et al, 2000).

Stratigraphy

The study of the stratigraphy of the Sacca di Goro was based on corings of the lagoon deposits and recently on geophysical investigations, especially in the nearshore portion.

The prograding nature of the mouth of the Po di Goro emerged from the geomorphological study is well documented also by the organization of the deposits in the sub-bottom: the sandy deposits of delta front and spit overlay the fine prodelta deposits while the bed of the lagoon is formed by relict sands abandoned during the advance of the mouth and covered by silty-clay sediments with varying thickness from 0 to 1.5 meters, deposited in the lagoon when it was well protected by the Scannone.

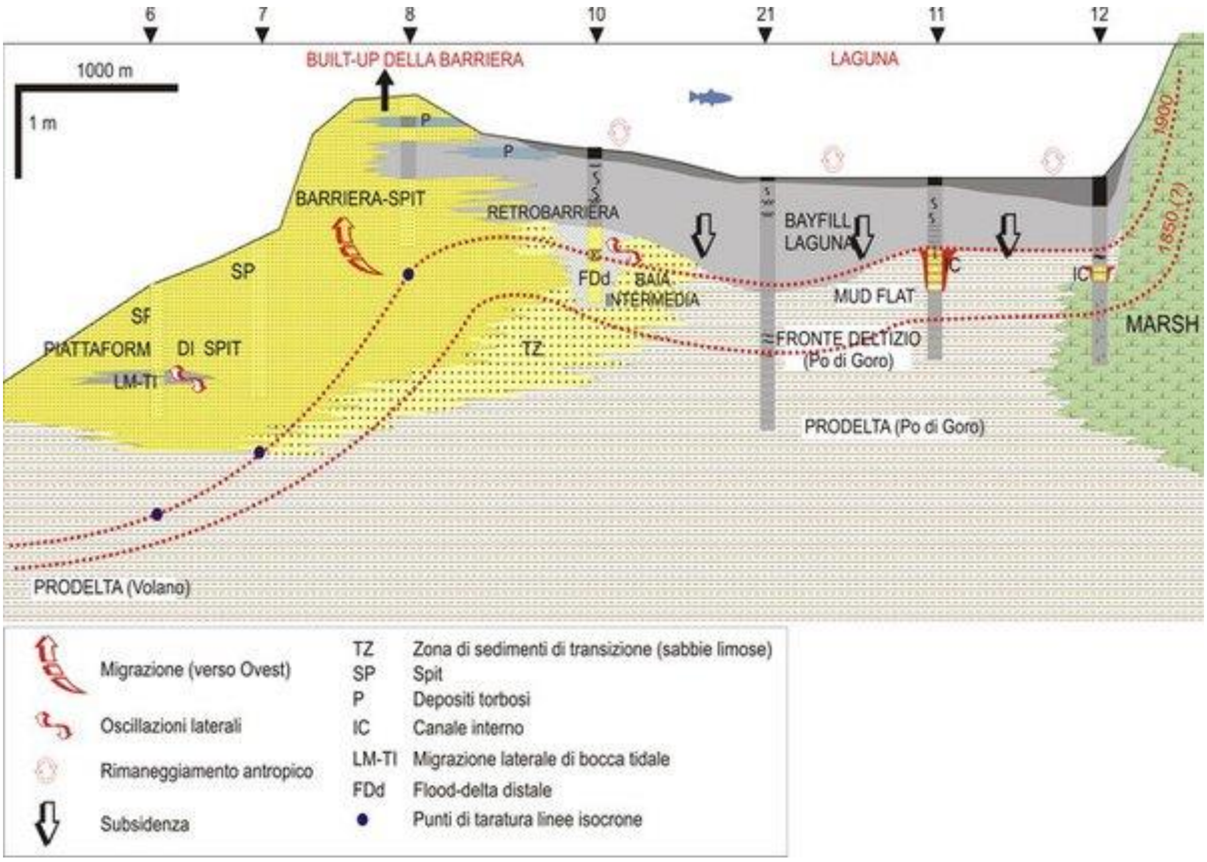


Figure 3-72: schematic cross-section of Sacca di Goro (Fontolan et al., 2000).

Integration of seismic chirp profiles and geognostic investigations (corings and CPTU) have allowed the construction of a three-dimensional geological model of the study area in which the different depositional lobes as volumes and therefore their dominant lithologies are distinguished.

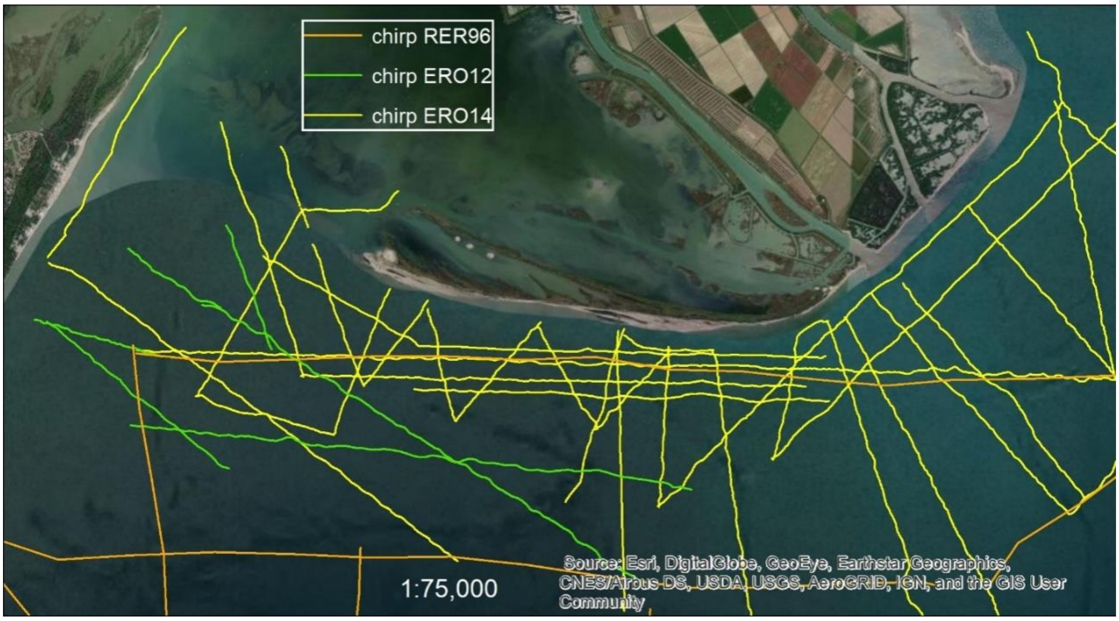


Figure 3-73: Network of seismic profiles in the open sea sector of Sacca di Goro

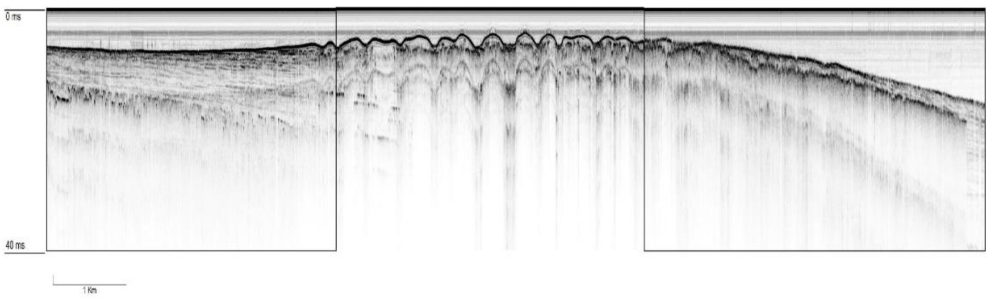


Figure 3-74: Chirp profile parallel to the Scannone (vertical exaggeration 50x): the undulations created by the oblique bars and the presence of strong reflectors can be observed; these denote the stratigraphic complexity of the substrate with lithological contacts, erosive or discontinuous surfaces.

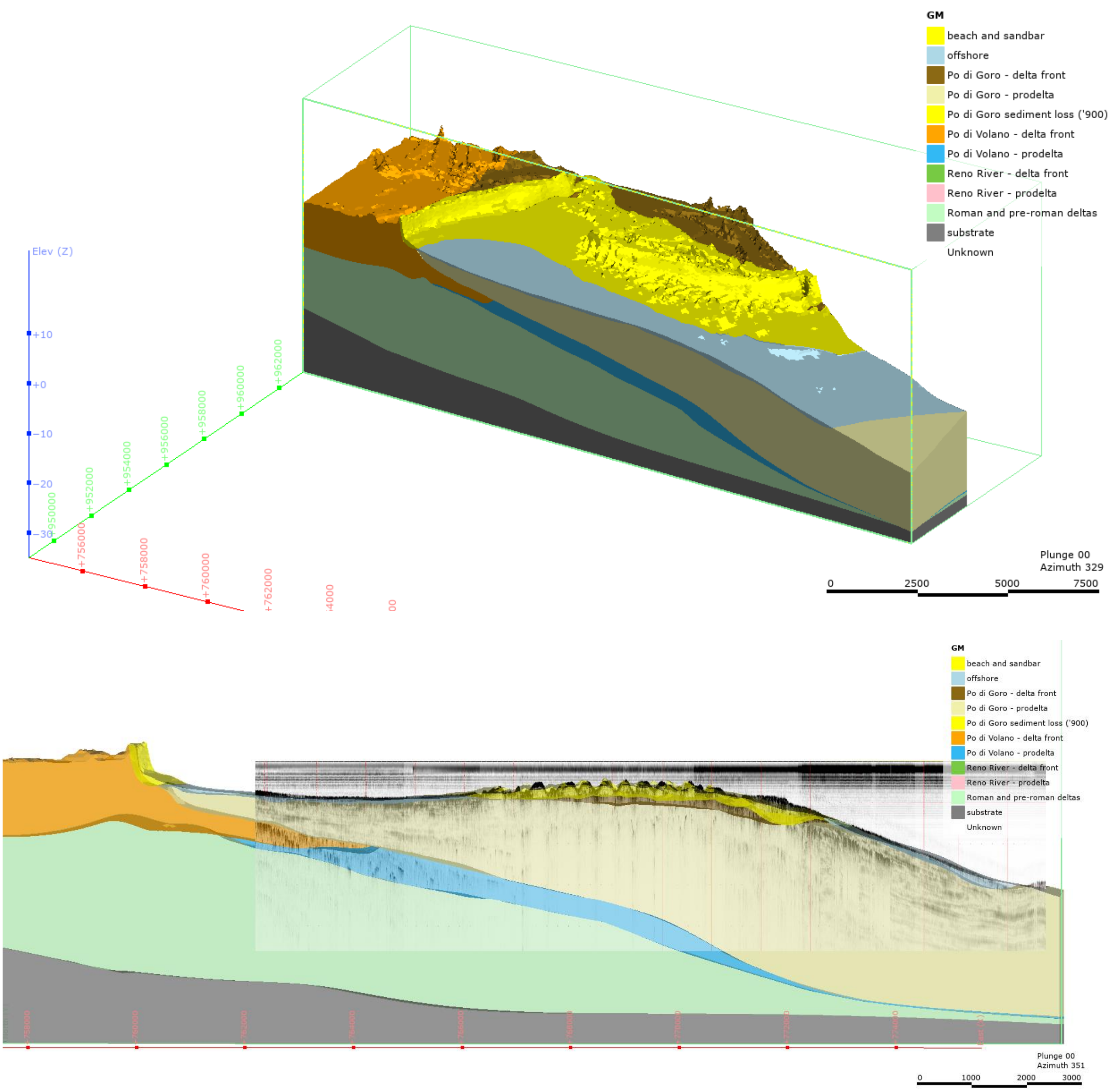


Figure 3-75: 3D geological model of the Sacca di Goro, in which different depositional lobes are distinguished on the base of environment, age and feeding deltaic branches,detail of the Scannone area. In the same seismic profile of Figure 3-74 the different units are distinguished.

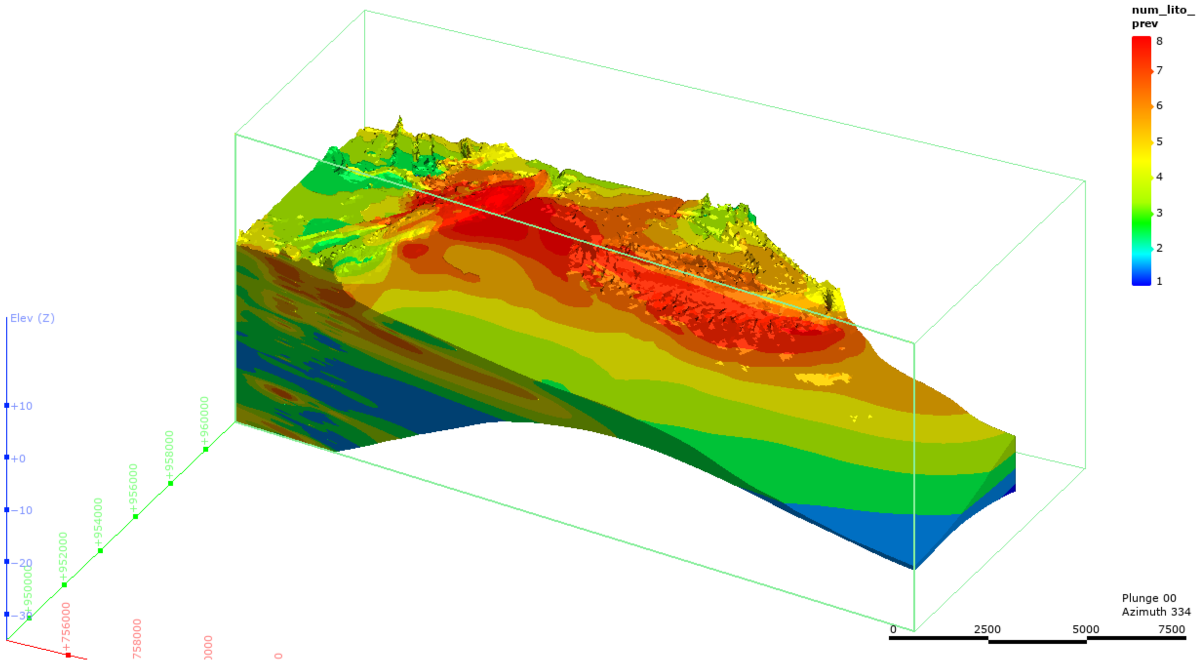


Figure 3-76: 3D lithological model of the Sacca di Goro, detail of Scannone area;lateral and vertical changes of clayey (blue to green), silty (green to yellow) and sandy (yellow to red) mixtures are represented.

Morphological changes of sea bottom

The comparison between different digital models of the seabed has highlighted the morphological changes that have occurred over time, highlighting erosion and accumulation areas; the impossibility of making the older models homogeneous with the more recent ones for resolution, reference datum, georeferencing and distribution of the raw data, limits the use of this information to qualitative rather than quantitative aspects. In the most recent models, the quantitative aspect is more reliable.

Comparison between 1901 and 1953 digital bathymetric models shows a deepening in front of the Po di Goro mouth and in the lagoonal inlet next to the Volano spit, probably due to erosion processes in the delta front and excavation of the channel to favor navigation. The shallowing in the prodelta is probably associated with an accumulation of sediments.

In the period 1953-2000 a further deepening in the delta front is appreciable whereas a shallowing in the western margin of the Scannone is present.

Comparison between the most recent digital bathymetric models (2000 and 2012) highlights that the deepening trend in front of the mouth is still active as well as the shallowing in the west side of Scannone; sea-bottom near to Volano spit is shallowed too.

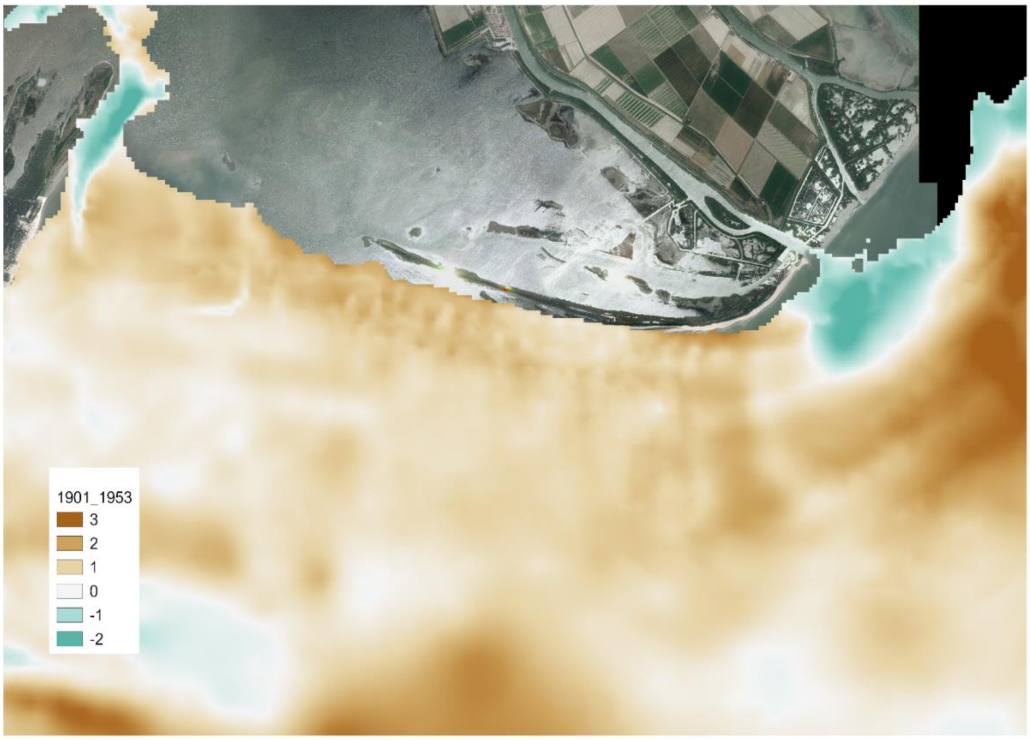


Figure 3-77: bathymetry difference between the digital model of the seabed of 1901-1904 and 1953: negative values indicate deepening (blue colors),positive values indicate shallowing (brown colors)

Figure 3-78: bathymetry difference between the digital model of the seabed of 1953 and 2000: negative values indicate deepening (blue colors),positive values indicate shallowing (brown colors)

Figure 3-79: bathymetry difference between the digital model of the seabed of 2000 and 2012: negative values indicate deepening (blue colors),positive values indicate shallowing (brown colors)

Arpa used the topo-bathymetric surveys to estimate quantitative information, based on the variation of the seabed in terms of accumulation and erosion.
With reference to the most recent surveys (2006 and 2012) it's recognized a sedimentary trend of the open sea part of the Sacca di Goro, considering the beach up to a depth of about 5 meters.

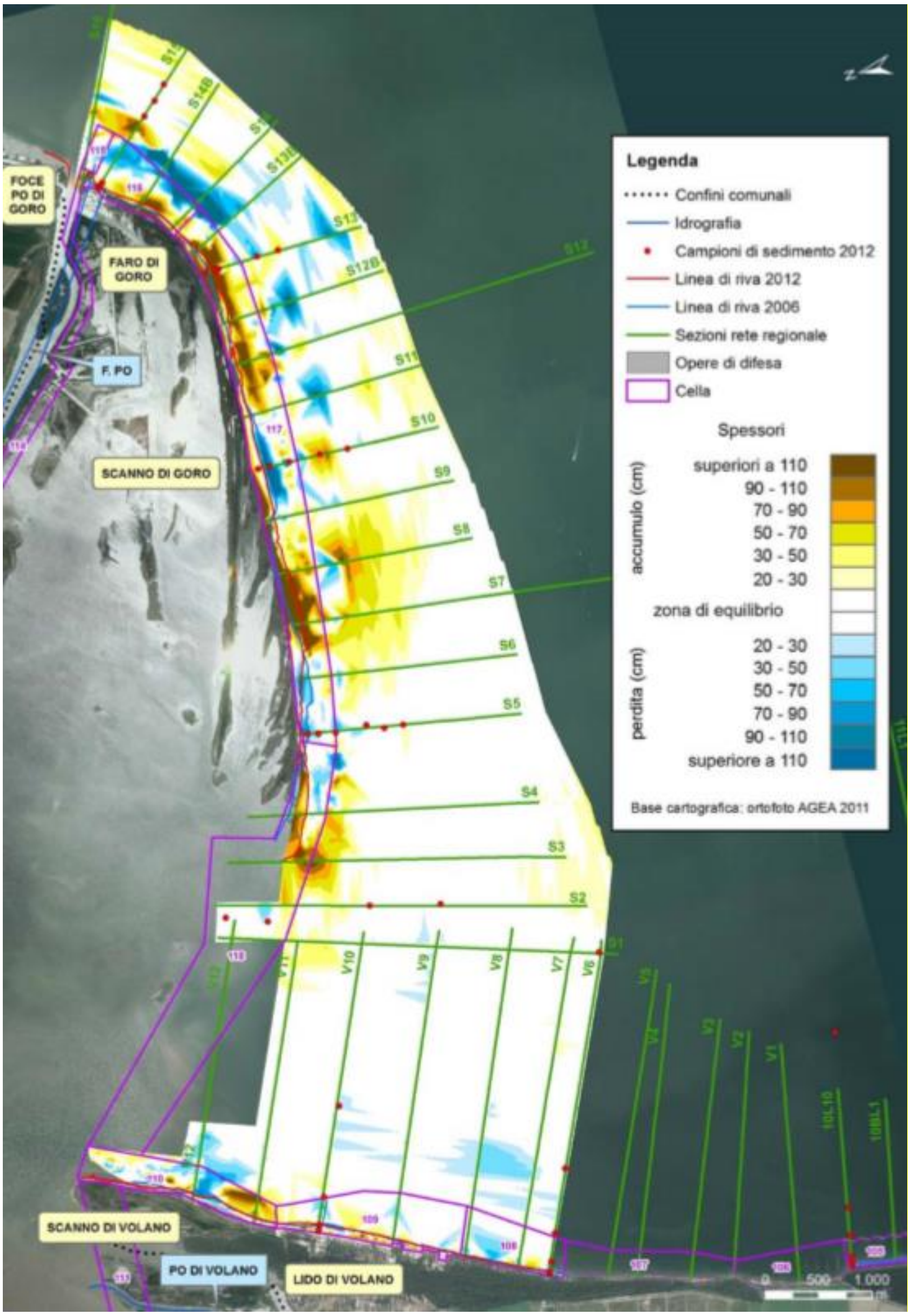


Figure 3-80: loss and accumulation map in the 2006-2012 period (Arpa, 2013)

The results of the quantitative analysis were used to subdivide the coast of the Emilia-Romagna region into sedimentary cells (Sicell Regione Emilia-Romagna, 2010) and to evaluate its status in terms of the nearest nearshore balance, if it is in erosion stability or in accumulation.

Based on this classification (ASPE) the portion of the beach within the depth of 3 meters in the Volano spit (cell no.110), the Scannone and the lagoonal inlet (cells no. 115-118) are mainly in stability or accumulation both in the 2000-2006 period and in the 2006-2012 period.

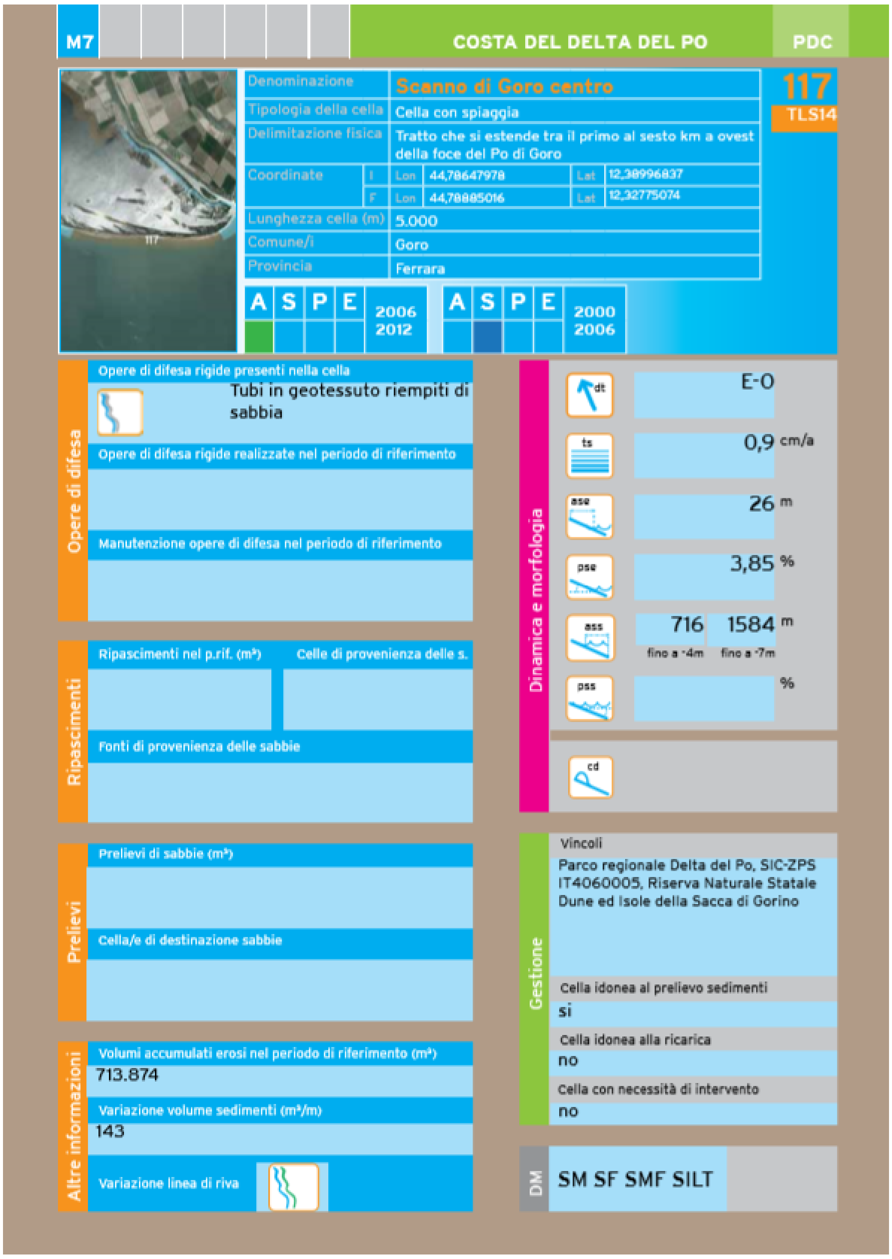


Figure 3-81: Table of cell n. 117 (central part of the Scannone): among other information, the volume accumulated in the period 2006-2012 is reported.

3.5.5. Analysis of recent trends of the sediment stocks

3.5.5.1. Po Delta and very recent bathymetric surveys

The modern Po Delta, a multiple-lobe, supply-dominated system, is the result of increased sediment flux in the last few centuries, derived from past climate changes (glacial and interglacial periods) and human impact both on the catchment area and on the river delta.

Historically a growth rate of 47 m/year was reported for the Po della Pila lobe after 1886 when the main branch of the Po River was artificially straightened to protect the delta plain from flooding (Visentini and Borghi, 1938). In historical and recent times the entire Po delta system underwent extensive human alteration for land use and freshwater management; the lobes and the morphologies have been continuously repositioned by river diversion and changes in sediment supply (Trincardi et al., 2004; Maselli and Trincardi, 2013). Since 1950, the Po delta has been subjected to a strong degradation and a partial retreat, primarily due to the lack of sediment supply caused by exploitation of inert material from the riverbed and by the channelization of watercourses (Stefani and Vincenzi, 2005).

Realized in the framework of the Italian Ritmare flagship Project, to study the variation of the morphology of the recent-most delta lobe of the Po river in correspondence to Po della Pila area, repeated high-resolution multi-beam surveys were organized in 2013, 2014 and 2016 (red, blue and green area in Figure 3-82). In 2014, a survey was also carried out to acquire seismic Chirp profiles, white track-lines in Figure 3-82.

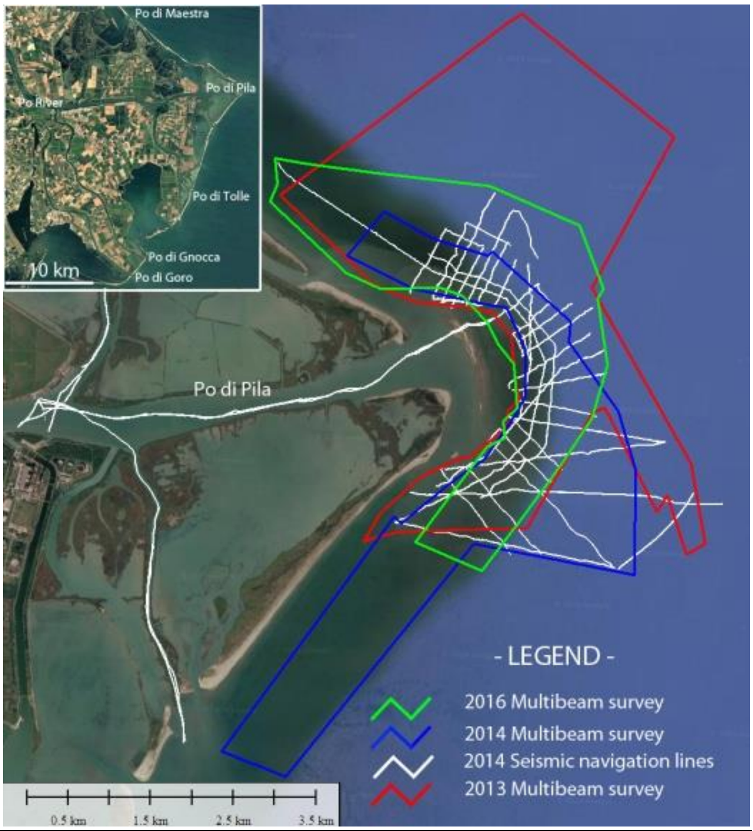


Figure 3-82: Track-lines of the surveys (2013-2016) on Po della Pila area. From Bosman et al 2020

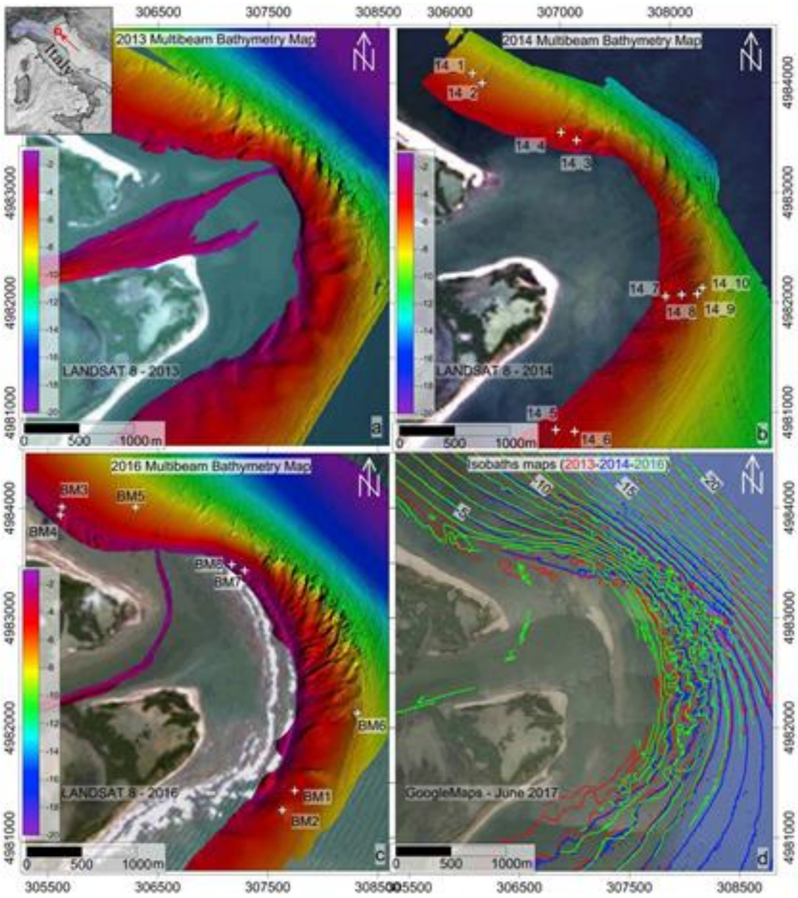


Figure 3-83: Example of map of bathymetric data. From Bosman et al 2020

A high variety of geomorphological features and depositional bodies were observed from the mouth bar to the prodelta slope such as, for example, the alongshore and transverse bars, formed under the effect of marine currents, gravitational-instability phenomena and collapse depressions, driven by fluid expulsion.

The comparison of bathymetric data collected in 2013, 2014 and 2016 (Figure 3-85) points out important morphological changes in the seabed (positive and negative bathymetric residuals), attesting to the dynamic evolution of the delta lobe (Bosman et al 2019). The residual map and related comparative sections among the three datasets (2013, 2014 and 2016) show areas with different behaviour. In the northern area of the Po della Pila lobe, the bathymetric residuals close to the northern channel highlight the presence of a 4 m-thick depositional body elongated in the East-West direction (Figure 3-85). The sediment accumulation in this sector of the delta front and slope can be related to the river flood event occurred in November 2014. In front of the delta mouth, elongated negative residuals on the delta slope (in blue in Figure 3-85) primarily reflect the gradual southward migration of transverse bars in the 3-years time frame.

The high-resolution DEM and related bathymetric sections extracted from the 2013 and 2016 data show a southward migration of the transverse bars of hundreds of meters at 5–10 m water depth.

Negative values up to - 2 m in the residuals 2013–2016 are also locally observed in the delta slope and at the foot of the prodelta slope, where many, often coalescent, collapse depressions occur on the seabed.

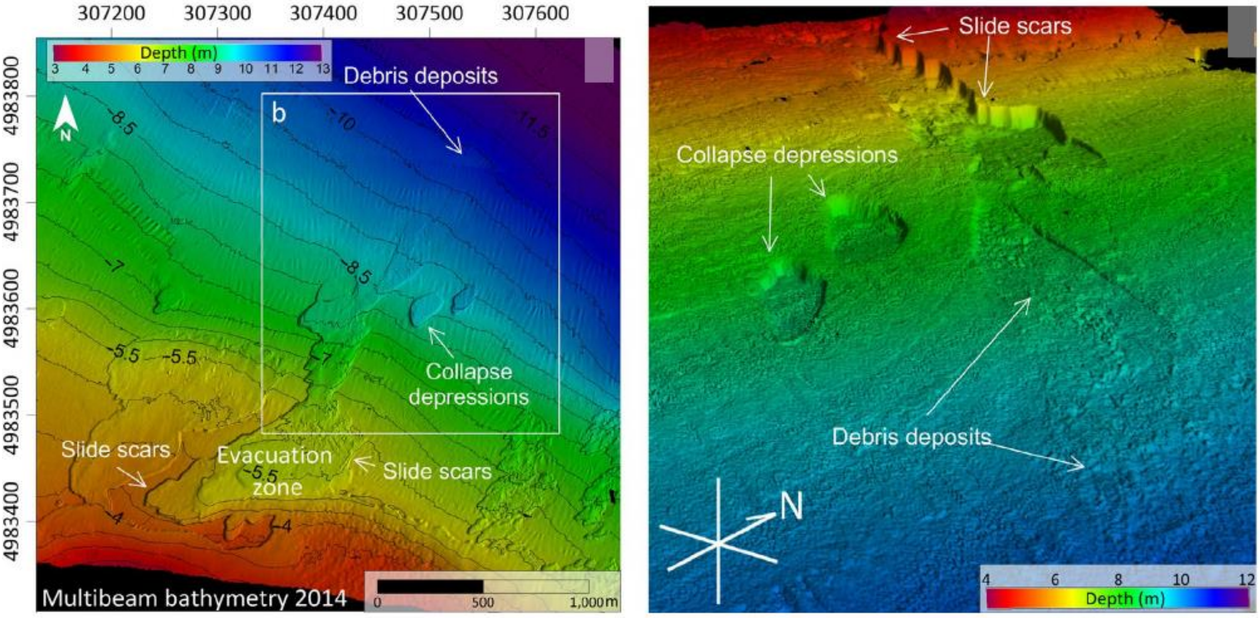


Figure 3-84: Submarine landslides scars and associated deposits located on the upper part of the prodelta slope and small collapse depressions from the 2014 survey. Trincardi et al (2020)

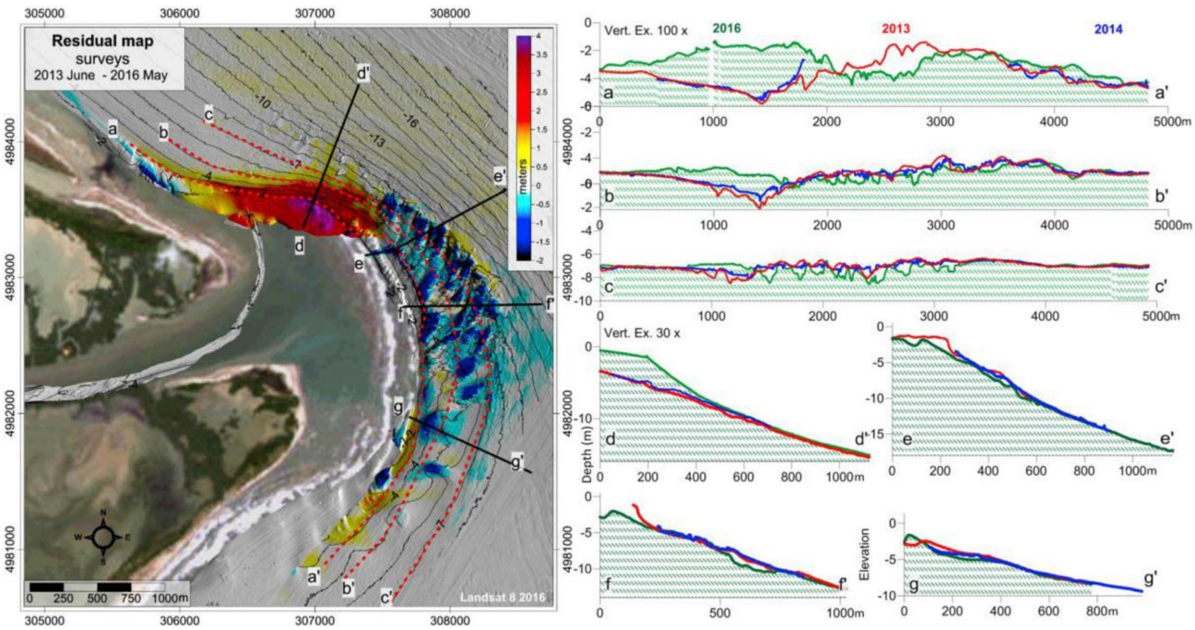


Figure 3-85:Cumulative bathymetric residual map of Po della Pila DEM between 2016 and the 2013 datasets highlighting the bathymetric changes occurred in the time frame. On the right, the bathymetric sections extracted from the 2013, 2014 and

2016 datasets are compared. Sections a-a', b-b', c-c', running at different depth parallel to contours in the front and prodelta lobe, show local depth differences in the seabed up to some metres over a 3-year time interval. A general deepening of the seafloor is evident on the eastern side of the prodelta slope (blue tones in residual map and section f-f'). From Bosman et al 2020

Here local positive residuals are related to the obliteration of collapse depressions and other morphological lows (Figure 3-84). In the southern area of the Po della Pila, the bathymetric residuals highlight the presence of slight positive residuals in the form of depositional bodies 1 m-thick, with elongated or sinuous shape (Figure 3-85, section a-a').

High-resolution Chirp profiles were collected on the Po della Pila mouth and distributary channel after the first multibeam bathymetric survey of 2013 and before the one of 2014 (Figure 3-82.for the track-line in white). The bathymetric profiles from multibeam data of 2013 (red), 2014 (blue) and 2016 (green) are plotted on the Chirp lines inFigure 3-86: they indicate that between 2013 and 2014 there were no substantial differences in the seabed, while the 2016 bathymetry highlights the deposition of new sediment carried by the flood of the end of 2014 also evidenced by the residual map.

The composite Chirp profile (from CP01 to CP07) parallel to the mouth bar of Po della Pila (Figure 3-86) shows clear evidence of the subsurface deposits architecture before the sedimentation shed by the 2014 flood. In the prodelta environment, the deposits present mostly transparent seismic facies, related to sandy sediment in the proximal delta front or homogeneous very fine-grained silty sand in channel-fill deposits (Correggiari et al., 2005). Another common acoustic facies consists in high-amplitude reflections related to a change in acoustic impedance, normally caused by silty/clay sediment or alternating thin layers of fine sand, silty clay or clay (due to flooding events) but also possibly caused by shallow gas trapped under low-permeability layers. In particular, in the central part of the CP 03 profile, a concave paleo-surface is shown close to the previous main channel mouth (mcm2013 in Figure 3-86a).

Seismic profiles in Figure 3-86b-f have been acquired in cross-shore direction in the northern portion of the Po della Pila's mouth bar before the deposition of the November 2014 flood event. Seismic profile CP12 (Figure 3-86 b) is characterized by a shingled reflector pattern formed by several erosive remnants (transparent acoustic facies) of sand transverse bar system draped by thin muddy layers (high-amplitude reflectors). The location of the subsequent deposit is highlighted by the green morphological profile of the 2016 multibeam bathymetry (more than 3 m of thickness over the 2013 and 2014 seabed).

In Figure 3-86 c (profile CP24) some older transverse bars related to a previous depositional phase are also preserved under the seafloor with crests and troughs.

In Figure 3-86 d (profile CP14) buried transverse bars are less evident, possibly due to the concurrent delivery of sediment in the alongshore transport. Two subdued morphological steps are evident in the CP 67 Chirp profile (Figure 3-86 e) and the most recent deposit (corresponding to green morphological profile) follows a similar shape.

An example of sedimentation of a new forming bar in a trough is shown Figure 3-86 f (profile CP 25) where the easternmost portion of the 2014 deposit (green morphological profile at minimum depth of 2–3 m below sea level) lies on the muddy veneer between two pre-existing crests. (Bosman et al 2019)

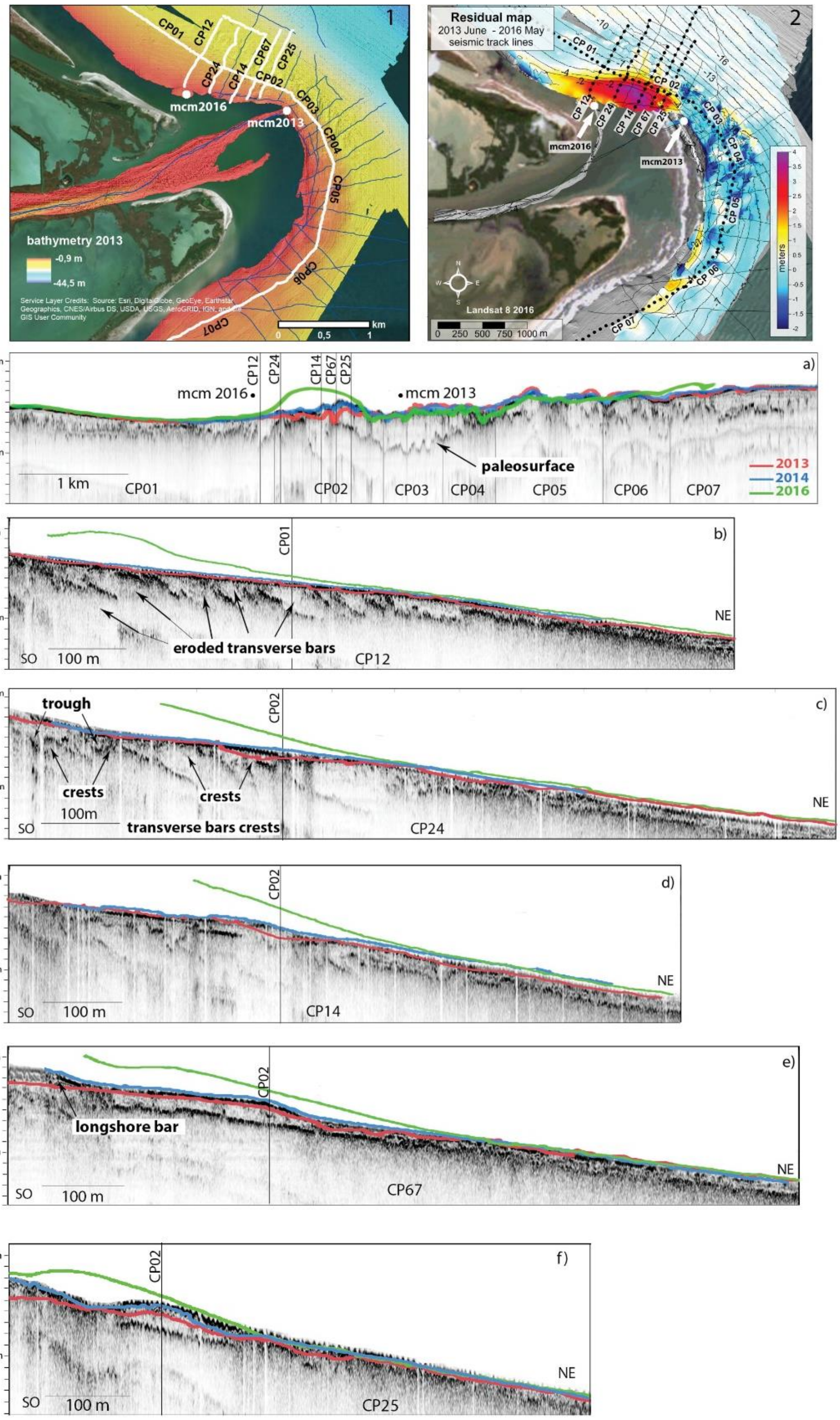


Figure 3-86: Navigation map of seismic profiles a to f, acquired in June 2014 after the bathymetric survey of 2013 and before the 2014 one. In the map 1 the Chirp profiles are located on the 2013 bathymetry, while in map 2 they appear on the cumulative

bathymetric residuals 2016–2013. In the first composite longitudinal Chirp profile (a), not at the same horizontal scale as the other (shore-normal) profiles, the two positions of the main channels of Po della Pila mouth are identified with "mcm2013" and "mcm2016" (mcm means main channel mouth)

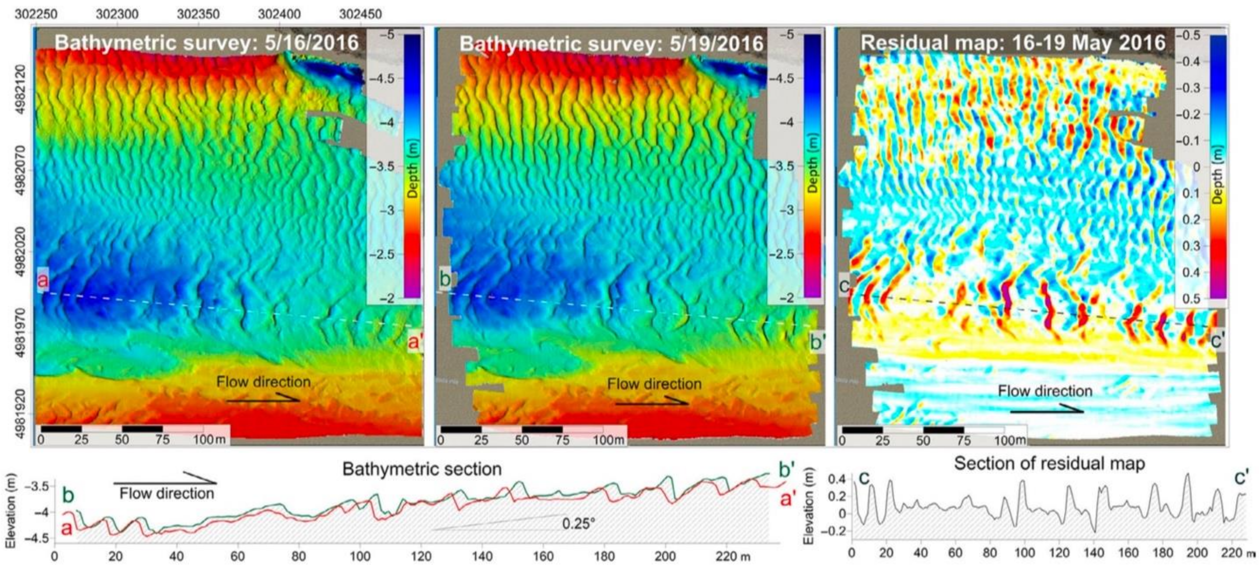


Figure 3-87: Po di Pila distributary channel - Multibeam images on the left and center were gathered 3 days apart during the 2016 survey. The image on the right represents the residual map between the two bathymetric maps, allowing quantification of the migration rate of the bedforms. Bottom, comparison of bathymetric sections a-a' and b-b'. Section c-c' is reported for the residual map. River flow from left to right; see Figure 3-86 for the location (Trincardi et al 2020).

Example of a surveys, (reported on Trincardi et al 2020) in Figure 3-87, repeated with just a 3-day lapse in the Po di Pila channel, about 4–5 km upstream of river mouth, highlighted the migration, toward the river mouth, of dunes up to 0.5 m high and 10–20 m inwavelength with slightly sinuous crests. The migration rate is upto5min3days. Bedforms in the topset migrate daily in the river thalweg; their orientation is a good indicator of the channel orientation, where the river channel is straight to the mouth bar, the orientation of the dunes on its floor can be a reliable paleo environmental indicator of the direction of delta growth. (Trincardi et al. 2020).

The Po Delta, therefore, turned into a fragile and vulnerable regime until the 21th century, for which a new progradational phase of the Po di Pila has been proposed based on satellite data (Ninfo et al., 2018). Satellite data, however, cannot capture the full depositional history of a delta, especially of its submerged or buried segments. The analysis of high-resolution bathymetries coupled with seismic profiles suggests that deposition and erosion after 2013 are operating simultaneously in different parts of the system. In such a highly dynamic environment to fully understand the evolution is important to collect continuous data.

3.5.5.2. Sediment stock evolution

Systematic bathymetric surveys along the entire coast are necessary to assess the sediment stock evolution along the Po delta. However, the available data do not cover the whole delta and they are often inhomogeneous and incomplete.

As reported in Ruol et al. 2016, a recent work of Fontolan et al. (2013, 2014) tried to evaluate the volumetric variations occurred along the coast by comparing the existing bathymetric surveys taken in 2008 and 2013/2014. The measured sections are generally 1000 m apart, and they have been classified based on the occurred changes as areas (Figure 3-88 and Table 2):

- (A) in accumulation;
- (S) stable;
- (P) in precarious equilibrium;
- (E) subject to erosion;
- (N) with not available information

Table 2: Table of the eroded/accumulated volumes in the Po Delta Region according to Ruol et al. (2016)

Cell	Position	Sub-cells	Period	Tot (m3/year)	Class
RO1	Adige Caleri mouth	LRC1 LRC LCR3	2008-2013	-11.27 -18.35 21.95	E E A
RO2	Caleri -Porto di Levante mouth	IAC1	2008-2013	-20.89	E
RO3	Porto di Levante -Po Maistra mouth	SCC1	2008-2014	10.88	A
RO4	Po Maistra mouth-Busa di Tramontana	SPC1 SPC2 SPC3	2008-2014	0.88 14.65 138.40	S A A
RO5	Busa di Tramontana-Busa Dritta	BPC1 BC2	2008-2014	4.03 13.68	S A
RO6	Busa Dritta- Busa di Scirocco	BPC3	2008-2014	67.22	A
RO7	Busa di Scirocco- Busa Storiona	BPC4 BAC1 SBC1	2008-2014	47.33 2.45 -20.64	A S E
RO8	Busa Storiona- Po di Tolle mouth	SBC2	2008-2014	33.14	A
RO9	Po di Tolle - Po di Gnocca mouth	SSC1 SSC2 BBC1	2008-2014	0.14 41.68 102.29	P A A
RO10	Po di Gnocca-Po di Goro mouth-	BBC2 BBC3	2008-2014	-45.33 23.67	E A

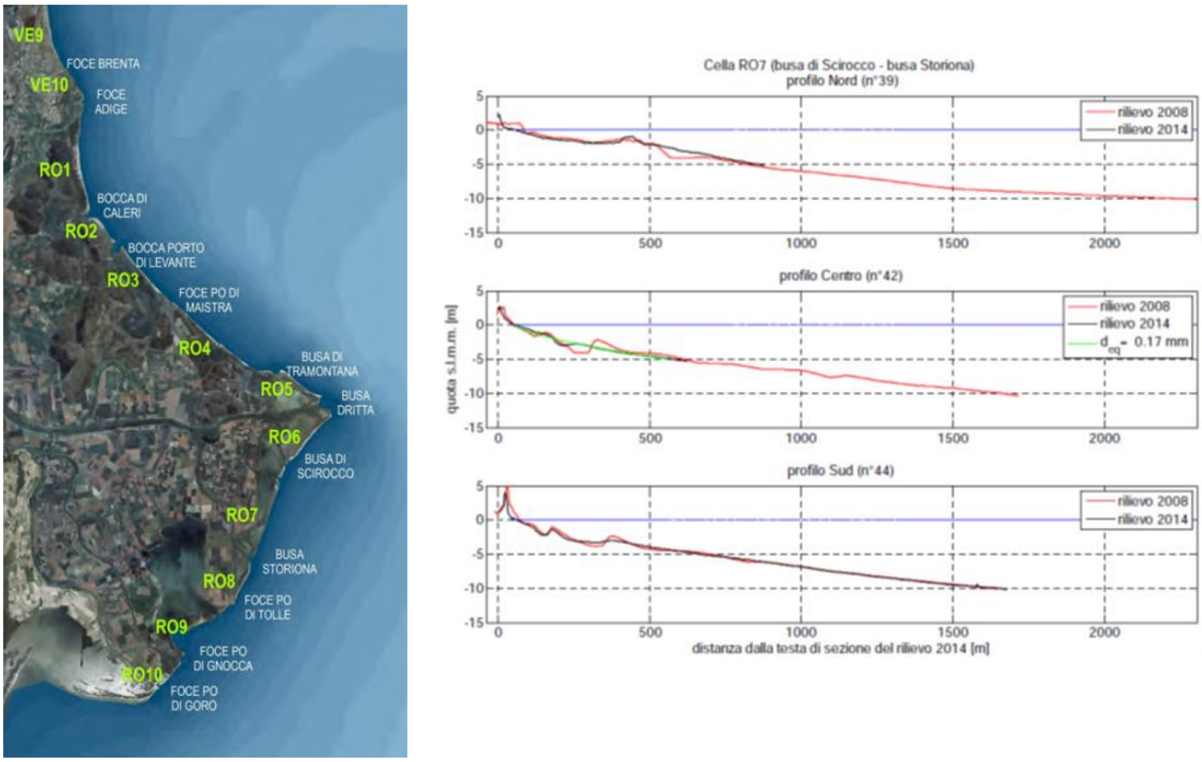


Figure 3-88: Sections analyzed in Ruol et al. 2016 and comparison between the surveys conducted in 2008 and 2014 between Busa di Scirocco and Busa Storiona

The volumes result from the multiplication of the average volumetric variation for each section for its length. In some cases, the values are affected by errors due to the presence of hydraulic works, or due to the maintenance works occurred between the two surveys.

- **Sacca del Canarin**

Lately, storm surges have repeatedly affected the sand spit delimiting the Sacca del Canarin, especially the tip at the southern side of the sea outlet, where the protection against the wave action is not guaranteed by any type of barrier.

Orthophotos taken in different years reveal the changes occurred in this region, with the sand spit retreating southwards and losing large portions of material in the area that is more exposed to the sea.

The comparison between the two digital models regarding the Scanno del Canarin in 2009 and 2018 clearly shows this trend, representing the amount of material that has been eroded in 10 years under the action of the sea waves. On the other hand, the green regions correspond to the nourishment interventions carried out during the time to maintain and protect the lagoon from the storm surges.

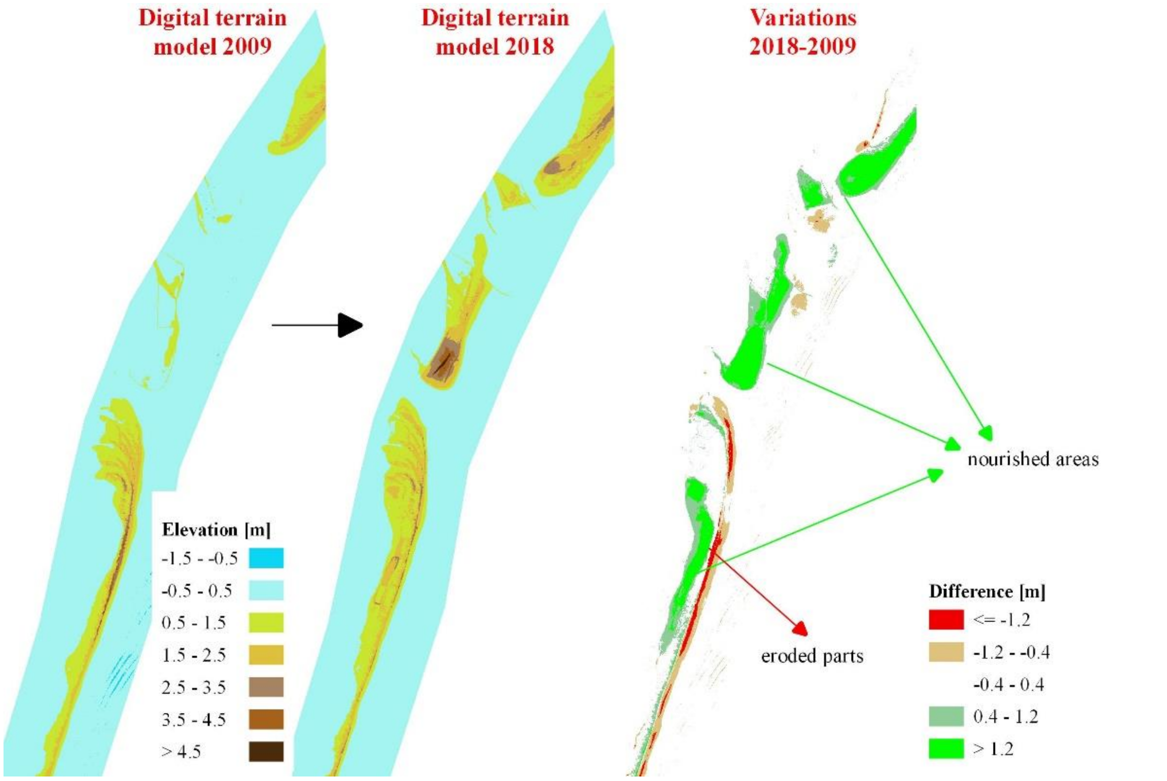


Figure 3-89: Comparison between the digital terrain model of the scanno del Canarin between 2018 and 2009. The green areas correspond to the regions affected by nourishment and the red ones to the eroded parts.

On the 28th October 2018, extreme weather conditions, characterized by abundant rainfalls and persistent winds from SE, have caused violent storm-surges. In the northern part of the Adriatic coast the waves reached 3 m in Veneto, while 6 m along the coastline of Emilia Romagna and Marche regions.

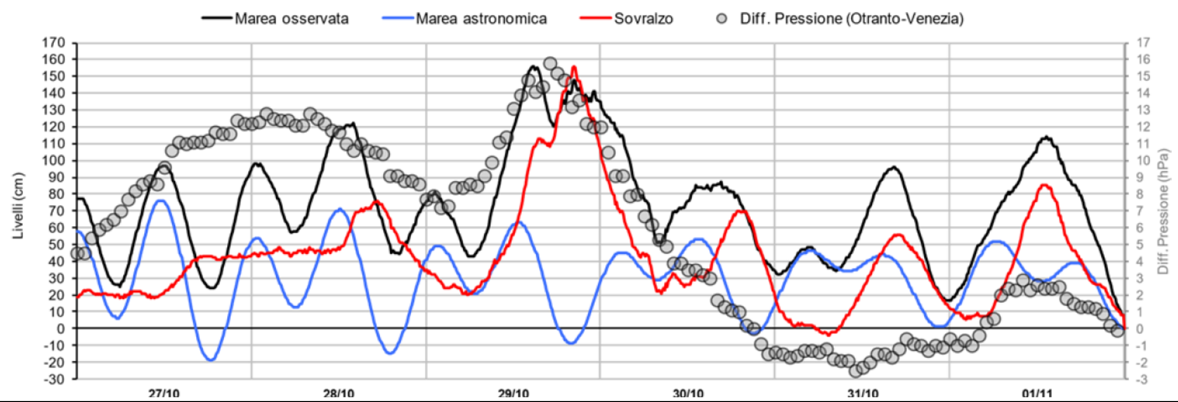


Figure 3-90: sea level during the high tide event at the end of October 2018

Despite the reduction of the wind strength, starting from the 2nd of November, other tides peaks of +100 and 110 cm were observed, within an interval of 24 hours (seiche phenomenon).

Because of these wave heights, extensive flooding occurred along the entire coast and inside the lagoons.

Figure 3-91: flooding of Sacca del Canarin on the 5th of November 2018, Satellite 2

- **Sacca di Goro**

The available data show a rather complex recent sedimentary dynamics, whose correct interpretation must be based on the definition of the relationships between accumulation and erosion areas and a reliable sedimentary balance. It is evident that the delta front, close to the mouth of the Po di Goro, has experienced a deepening as the expression of erosive processes since the beginning of the second half of the twentieth century. At the same time, deposition was observed in the prodelta and in thespit. The accumulation in the spit, nourished by long-shore transport to the west, first appeared widespread and subsequently concentrated particularly in its western margin, testifying a possible variation in the sedimentary flow.

The quantitative studies carried out by Arpa (2008, 2013) highlight the most proximal nearshore trend with the aim of giving answers to management needs. It emerged that this portion of beach of the lagoonal inlet and the Scannone, as well as the Volano spit shows an accumulation trend which has generated surplus deposits already used for the nourishment of other suffering beaches in the regional coast.

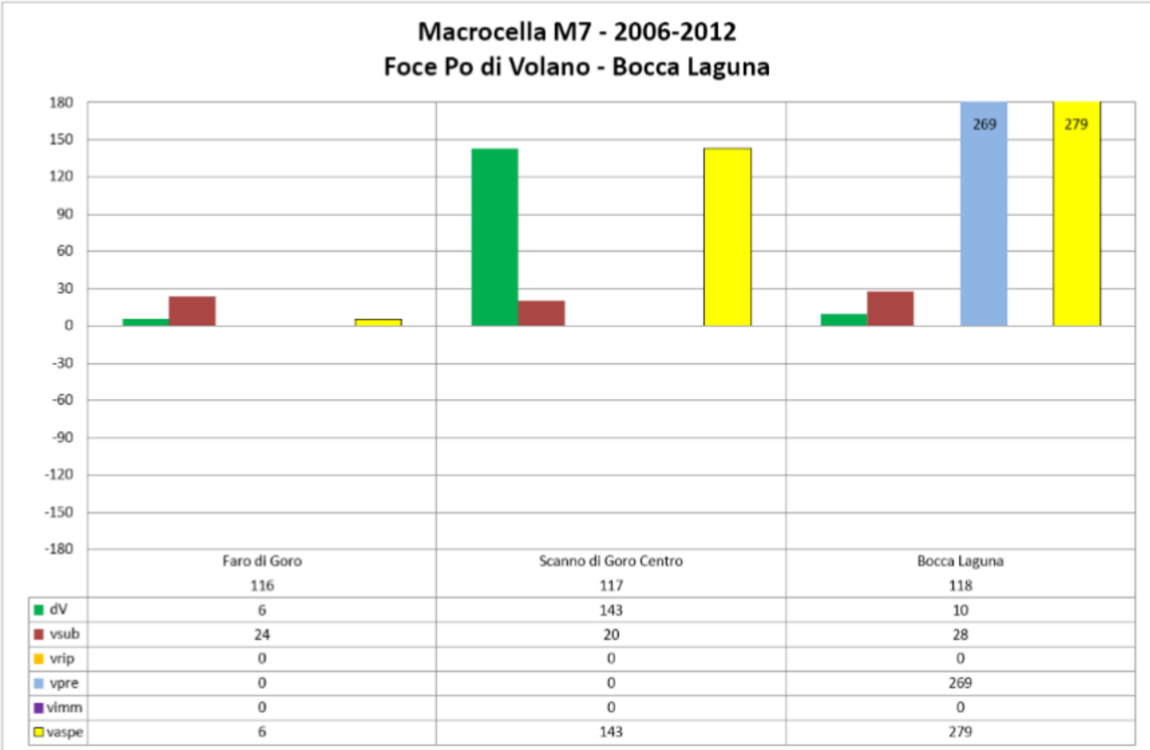


Figure 3-92: sedimentary budget in the nearshore of cells "Faro di Goro", "Scanno di Goro Centro", "Bocca Laguna" in the 2006-2012 period. ***dV (green)****: volume changes;* ***vsub (red)****: losses due to subsidence;* ***vrip (orange)****: nourishment;* ***vpre (light blue):*** *withdrawal,* ***vimm (purple)****: inserted volumes,* ***vaspe (yellow)****: complex variations of volumes: dV-vrip+vpre. (ARPA, 2013)*

If the target is to evaluate the evolution of the entire depositional system, this information must be integrated in a broader knowledge framework, which takes into account what happens up to the depth of closure of the depositional profile and external contributions to the system. For these reasons, the reconstruction of the recent evolution of the Sacca di Goro can be trusted if the wider delta context is considered, because it becomes crucial to identify the source area of the sands that feed this sector. Therefore, the contribution of the mouth of the Po di Goro, as well as the origin of sediments from more oriental portions of the delta are to be carefully investigated.

Other system variables such as subsidence and sea level rise must also be taken in consideration. The acquisition of new information and, above all, a wider vision of the system and processes can help us understand how the system will evolve.

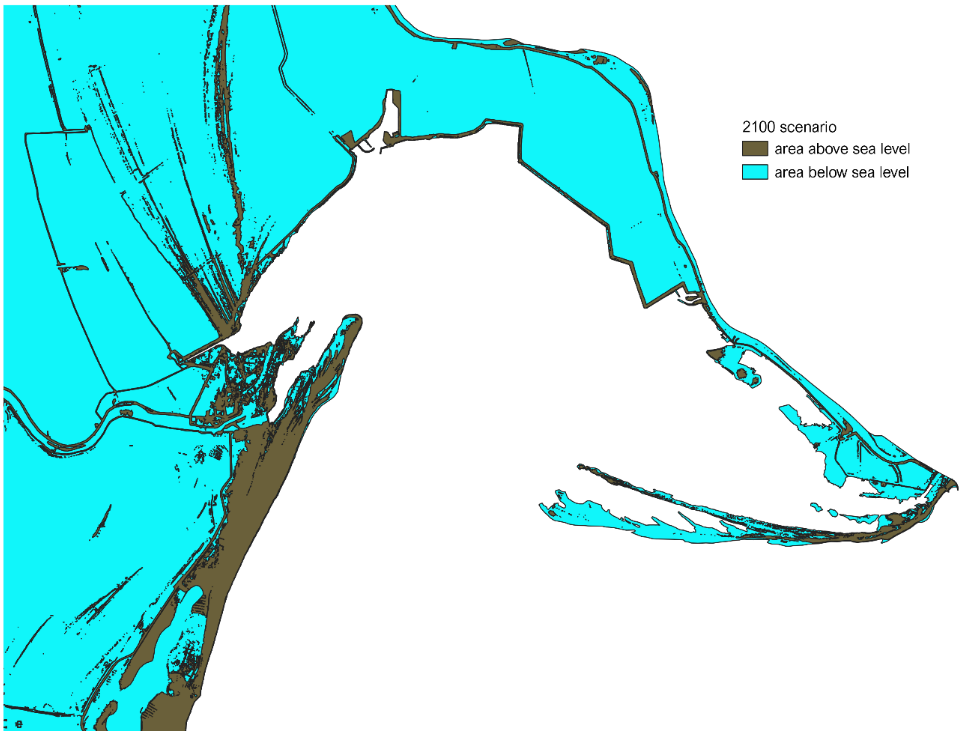


Figure 3-93: a recent study (Perini et al, 2017) shows the land above the sea level (brown) and land below sea level (blue) at 2100, due to the combined action of current subsidence and expected sea level rise.

3.5.6. Conclusion

3.5.6.1. Results of the activities and discussion

According to the original proposition of the project, the update of the current morphological framework in the Po Delta area should have pursued by specific campaigns, and precisely by performing bathymetric surveys on coastal and transitional zones. However, the results of these surveys, commissioned by the Emila Romagna Region and assigned to the Interregional Agency for the Po River (AIPO), were not delivered. For this reason, the present report could not take advantage of the new investigations on the sediment stocks along the Po River branches.

Nevertheless, the available data have been sufficient to draw a general picture of the sedimentation processes in the Po Delta area. The overall analysis (including the results of WP 3.2.1) confirms that the Po Delta is still changing, especially as it concerns the coastal area, with some lobes of the Po Delta still prograding, some portions retreating, and other parts stabilized by human interventions. There is a general tendency of the lagoons to flatten, either by erosion of the tidal flats or through siltation of the channels, which in some cases have been filled completely (Antonioli et. al, 2017). Flattening of the submerged landforms are leading to a morphological simplification, which could result in lagoons that lose their typical shallow estuarine characteristics and change into marine embayments. External sand barriers are prone to erosion and quick changes as they are exposed to the shattering waves during storm surges.

Considering these elements, the expected sea level rise consequent to the climate change is likely to worsen the problematics that have been observed in the coastal areas.

- Sacca Del Canarin

The sedimentological data retrieved for Canarin regard mostly the areas of the lagoon canals and the sand spit, and they refer to the most superficial layers. A homogeneous grid for a proper granulometric characterization is not available in the lagoon. On the other hand, LIDAR surveys and historical and recent aerial photos have proven to be useful to reconstruct the geomorphological evolution of the Sacca. They have confirmed the erosion of the external sand barrier delimiting the lagoon and the formation of lens-shaped body at the mouth, which has been interpreted as an ebb-tidal delta.

- Sacca di Goro

The available data, mainly the digital models of the seabed and the results of the geomorphological analysis (treated in Deliverable 3.2.1), allow to outline the past sedimentary evolution, the current state of the stocks and possible future scenarios. Other crucial data regard the sedimentary succession of the marine substrate such as corings and seismic profiles that depict the stratigraphic architecture of the deposits involved in the recent dynamics.

The stratigraphic analysis, in particular, allow to define the geometry and thickness of the sandy bodies belonging to the spit and partly also present in the lagoon, buried under a bed of silt and clay; sand bodies form thin lenses, a few meters thick and floating above the fine deposits of prodelta that outcrop in the immediate nearshore, between the oblique littoral bars.

The comparison between the different bathymetric surveys and the reconstructed geomorphological dynamics shows that erosion of the delta front takes place at the same time as the accumulation in the western portions of the spit, where the feeding is provided by the sandy masses moved by the long-shore transport to the west. How much the sedimentary contribution of the Po di Goro can contribute is not yet clear; the survey of the morphologies of riverbed has among its objectives the identification of any evidence of bedload transport.

3.5.6.2. Problems and solutions

From a sedimentological point of view, it is challenging to perform a correct sediment budgeting in the entire Po Delta area, due to complexity of the system influenced by multiple and interacting factors.

Working on a local scale allows for a better identification of the morphological trends, and to the assessment of the sediment stock evolution.

- Sacca del Canarin

The main problems highlighted by the analysis of the available data are:

1. Infilling of the lagoon inlet. Since there are neither groynes nor breakwaters, the inlet is subject to infilling due to the sediment transport induced both by normal currents and storm surges.
2. Flattening of the lagoon bottom. Due to the lack of emerged areas, the wave motion induces a resuspension of sediments in the lagoon and a subsequent homogenization of the shoal bottoms. Furthermore, in the innermost parts of the lagoon, this condition causes water stagnation. Therefore, the recent evolution of the central part of the basin has been accompanied by a reduction of the bottom depth of the lagoon, probably due to the ingression of sediments from the Bocca, with the formation of a typical flood tidal delta. The infilling of the lagoon also represents a further barrier for the ingression of the sea water.
3. Erosion of the scanni. The surrounding area of the Scanno is characterized by a fragile equilibrium between sediment depletion and accumulation, where the latter one occurs primarily in correspondence of Busa Scirocco, close to the buried reef at the outlet of the old Enel power plant. There is also a system of dunes, whose integrity is often under the threat of breaching.

Several anthropic interventions have been carried out during the time to assure the continuity of the dunes and the functionality of the scanno, as well as for the activation of the hydrodynamic circulation in the lagoon.

The reduced hydraulic circulation within the lagoon has a large influence on the water quality and consequently on the fishing activities, which can be damaged by fluxes of fresh water and fine sediments during floods (with a reduced salinity that affect the clam production) and by the eutrophication processes that can develop where the exchanges with the sea waters are very low.

- **Sacca di Goro**

The main problem is to quantify the accumulations and losses in order to have a real sedimentary balance. The most significant trends that influence the distribution of stocks have been identified and with the acquisition of new bathymetric and stratigraphic data it will be possible to define the volumes involved. A broad approach that considers the entire southern delta remains essential in order to identify feeding areas and to create reliable future scenarios. Another fundamental problem will also be assessing how much current sources can guarantee the maintenance of stocks, also considering the impacts of climate change.

In the short term, a problem of extreme interest concerns shellfish farming since the present-day movement of sand can block the communication channels between the lagoon and the sea, reducing the oxygenation of the cultivation areas. In this case, engineering intervention solutions can be considered to remedy the onset of critical issues. This problem, connected with the sedimentary flow and the morpho-dynamics of the spit, could solve in the medium and long period as modifications of the general conditions will occur; in this regard, a reduction of the sediment supply and a progressive flooding of the spit itself are expected as effects of climate change.

3.5.6.3. Analysis of data quality

Overall, the sedimentological and bathymetric data regarding the whole Po Delta area are not spatially and temporally homogeneous. Some areas have received much more attention when compared to others due to their economic and environmental value. Above all, the available bathymetric surveys have not always regarded the same sections along the delta coastline, precluding an appropriate comparison among the profiles taken during the time.

Concerning the Veneto coastline, a proper monitoring network to assess the sedimentological evolution of the Po delta is still missing. However, the ensemble of transects explored in 2007, 2008 and 2014 and analyzed by Fontolan et al. (2013, 2014) represents an adequate base for this purpose. Repeating the surveys along the same sections at least every five years could be adequate to: i) obtain an estimate of the eroded and accumulated volumes at regional scale; ii) evaluate the erosion trend of the seabed, also in connection to the storm-surges; and iii) anticipate the evolution trends of the shoreline.

Some crucial aspects should be highlighted regarding this monitoring network. Some sections are representative only of the local dynamics that occur where the survey has been carried out. For example, the data coming from sections taken in correspondence of a river mouth cannot be extended to a larger region, since they reproduce just the evolutionary trends at the river outlet. Therefore, for this region a refinement of the surveys is needed to have more reliable and interpretable information on the sedimentological budget.

4. SUMMARY AND CONCLUSION

The Adriatic Sea is a mostly shallow and semi-enclosed and elongated basin, connected to the Mediterranean Sea (which in turn is a relatively closed basin) through a narrow and deep channel. The hydrodynamics, the chemical, physical and biological features are strongly influenced by the Climate (with a high seasonality) and by the inflows from the mainland (the ratio coastline length/marine area is relatively high).

The project sites have been designed in different types of the coastal area: fluvial delta, lagoon, coastal lake and embayment.

Therefore, the sediment dynamics are very different among the sites, also due to the different geological nature of the mainland and to the local coastal currents.

Several factors influence the evolutionary trends of these areas, comprising geomorphological processes connected to the river flows, subsidence, tidal regimes, wave motion, and, furthermore, structural interventions that were realized during the years by the administrations and by the managing authorities that are responsible for the maintaining works of the sites.

The complexity of the Pilot Sites analyzed during the Change We Care project results from the interaction among environmental aspects and usage of the territory.

Considering the coastal alterations (erosion/deposition), some sites are more dynamic in comparison to others (banco Mula di Muggia and lagoons of the Po Delta), and consequently more fragile and prone to substantial modifications following the future climate changes

The goal of the WP 3.2.2 activity is to “provide information on sediment characteristics and a base for the identification of the extent and fate of sediment delivered from the mainland”. The study recalls some aspects that were developed in the 3.2.1 Deliverable (geomorphology) and in the 3.3.1 Deliverable (sediment fluxes), but it is mostly based on surveys, bathymetric studies and analysis of the coastal transport.

A central question that has been highlighted during the compilation of the present report is the availability of experimental and numerical data, which is fundamental to build a strong knowledge base of the Pilot Sites. This point assumes an important role when considering high dynamic systems, characterized by variables and parameters that evolve continuously and act at different scales.

Furthermore, the quantity of the available data is variable among the different Pilot Sites, going from high (Banco Mula di Muggia) to low (Jadro River). The number of surveys to reconstruct the temporal variations of the transported and deposited sediments along the river branches and the coasts are poor, except for some cases where specific studies have been carried out (like Banco Mula di Muggia and between the Grado and Isonzo mouths, where in any case, the topo-bathymetric surveys have a inhomogeneous coverage). Therefore, the analysis has clearly shown that further studies and researches are needed to estimate the sedimentation and erosion rates in the different Pilot Sites.

Specific campaigns were planned, but not carried out before the conclusion of this report due to several reasons including the covid 19 emergency.

For the Croatian pilot Sites only a gross estimate on the sedimentation rates and the current sediment depth was possible based on bibliography.

The anthropic activities play an important role in the morphological and sedimentological evolution of the Pilot Sites. For example, the urbanization increase has contributed significantly to the surface erosion and to the mud inflow at the mouth of the Jadro river, while the construction of the hydropower plants in Bosnia-Herzegovina in the last decades have strongly modified the hydrological regime of the Neretva river. The original hydrodynamics of Sacca del Canarin has been modified by the works following the realization of the power plant of Porto Tolle.

Overall, in all the Pilot Sites the regulation and the diversion of the rivers have caused a consistent decrease of the sediments transported to the sea, accentuated by the presence mine activities and water withdrawals. These factors are added to the discharge modifications caused by climate changes. This results in a negative balance of the sediment stocks and to a consequent erosion of the coasts.

Generally speaking, the evidences have shown that the sediment stocks are subject to a strong anthropic influence. Therefore, the control of the local and regional planners is fundamental and should be carried out according to an integrated environmental management that considers the configuration of the territory, the land use, the economic and social development and the valorization of the territory and resources.

The prediction of the future scenarios is arduous due to the complexity of the system, but it is highly likely that the erosion and sedimentation rates will be strongly modified by the future climate changes.

Finally, the realization of studies and databases, the collection and updating of the data are crucial to analyze and reconstruct the sedimentological, hydraulic and morphological regimes along the coastlines.

This implies theoretical and practical problems, regarding the sampling methodologies, the creation of a monitoring network, with the final aim of homogenization of the data. A coordination at national and international level is thus important, in order to guarantee the safety of the territory and to guide future choices in the management of the territory.

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6. ANNEX

Turbidity plumes in the Po Delta area[4]

An important aspect to consider when investigating the delta evolution is the dynamics of the sediments delivered in the Adriatic Sea by the Po River.

Most of the solid discharge arriving in the Adriatic Sea consists in suspended sediments, whose velocity reduces abruptly when entering seawaters. Here they start to disperse and coarser sediments deposit (~15%) until they are reworked by marine forcing (FOX et al. 2004, NITTROUER et al. 2004).

The typical silty-clay sediment load of the Po is characterized by electrostatic charges on the surface leading to particle aggregation in ionic solutions (saltwater) (NITTROUER et al. 2004) and to flocculation. The riverine water forms a buoyant plume due to density difference with sea water. The plume is the carrier of suspended particulate matter which is slowly dispersed to the outer sea under decreasing sediment flux until external forcing, like bathymetry and seabed morphology, wind, waves and circulation, modifies its dynamics (FALCIERI et al. 2014).

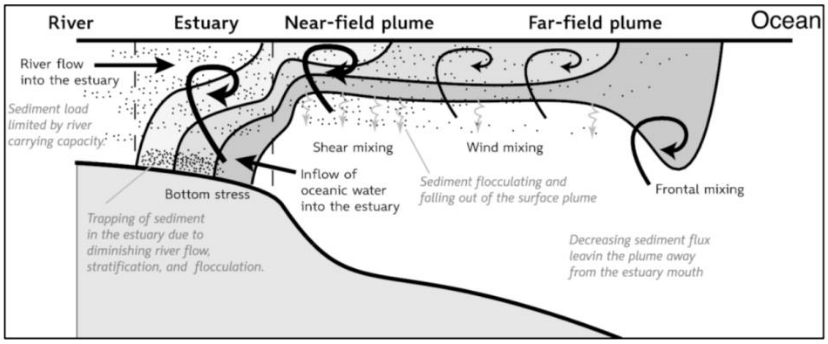

Figure 6-1: Cross-section of a river plume entering sea water (HETLAND & HSU 2014, p.58).

The transport of the sediments along the coast is strictly connected to the circulation in the north Adriatic Sea, as it is described in paragraph 2.1.1. The main currents are:

- The Western Adriatic Coastal Current (WACC), which originates at the Po river delta and is responsible for the coast-side transport of 84% of the Po river freshwater,
- The Northern Adriatic Current (NAdC), which is a cyclonic current along the Italian coast that connects with the WACC in the south,
- The Dense Water Outflow Current (DWOC) (BOLDRIN et al. 2005, BRAGA et al. 2017), which develops at the bottom flowing south along the coast,

[4] *Anne Trampe,The detection of turbidity plumes in the Po river prodelta using multispectral Landsat 8 and Sentinel-2 imagery Masterthesi, MSc. Environmental Geography & Environmental Management, DOI: 10.13140/RG.2.2.32032.69128. PROUST*

- The Eastern Adriatic Current (EAC), which pushed the fresh water from the south,
- The Cyclonic Northern Adriatic Gyre (NAdG) that is an anti-cyclonic gyre extends from the delta southward (KOTNIK et al. 2015).

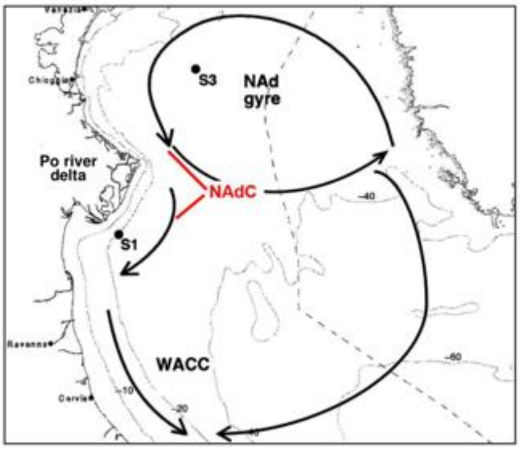

Figure 6-2: Sea currents

The coastal circulation and sediment dispersal at the Po delta coast is modified and dominated by four main wind climates: Bora, Scirocco, Mistral and Libeccio.

The high sediment supply of Po di Pila and the cuspid morphology of the delta mouth favored mass accumulation of river-borne and marine sediments to a rate of 2.1 g/cm^2 per year in the very-near vicinity of the Pila mouth (Frignani et al. 2005). Predominant northeasterly winds and the southward Adriatic circulation transport material to the southern coast. In addition, the southern delta mouths supply sediments to the coast of different magnitude. Thus, a wide depositional area with accumulation rates of 0.3-1.5 g/cm^2 per year is formed south of Po di Pila (Frignani et al. 2005) (Figure 6-3).

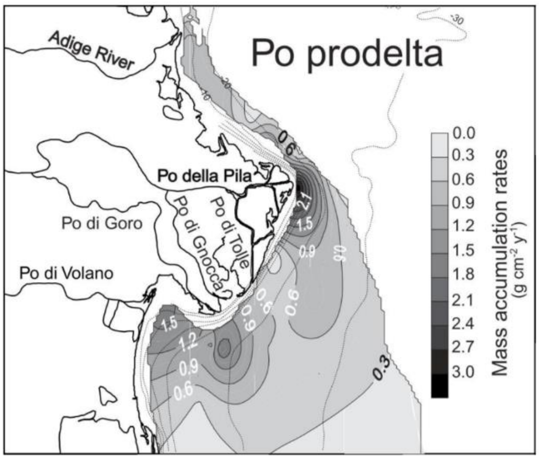

Figure 6-3: Mass accumulation rate of the Po prodelta in g/cm2 per year (from Frignani et al. 2005)

Sediments are not only provided by river discharge, but also by sediment resuspension. The motion is dominated by vertical diffusion produced by friction/shear stress by wind and wave action in the boundary layer (Wang and Pinardi 2002).

Resuspension is highest in shallower water, with conditions of prolonged winds and waves, often in conjunction with spring tides. Sediment resuspension on the coast is usually caused by wind speeds exceeding 8 m/s with sediments remaining for two to three days after the end of the wind event (Chen et al. 2010). Even minor storms can penetrate the whole water column and resuspend sediments due to the low bathymetric gradient at the Po coast (Fox et al. 2004). Wave heights in winter reach about 2-3 m on the area of the submerged delta enhancing resuspension that leads to sediment concentration of about 50 g/l at the sea bed (Bever et al. 2009).

The processes governing sediment dynamics near the coast are reported in a master thesis developed in collaboration with the Institute of Marine Sciences of the Italian National Research Council (CNR-ISMAR) of Venice (PROUST).

Between January 2016 and April 2017, 16 Landsat-8 and 9 Sentinel-2 images in the region of Po di Pila were selected from EarthExplorer of the U.S. Geological Survey (USGS). The atmospheric corrected water-leaving reflectance is converted into turbidity as Formazin Nephelometric Unit (FNU) by the algorithm of Dogliotti et al. 2015.

To validate satellite derived data, in situ data were collected during a field survey from 18^{th}until 21^{st} of April 2017, when the Sentinel-2 satellite overpassed the area of the Po river delta. Along transects hydrological, optical and biological parameters were collected. Statistical analysis indicated a fairly good correlation between satellite-derived turbidity and CTD measurements in the field (r = 0.7129).

The results indicate a strong link between hydrological and meteo-marine conditions and turbidity patterns of the selected images.

In flood discharge conditions, the plume extension is first determined by the river flow and secondly it is influenced by winds and the coastal current off the coast (Harris et al. 2008). Turbid plumes driven by flood events, as those visible on the selected images of 4th of March 2016 and $2^{nd}$of December 2016, (Figure 6-4) are characterized by a large area of turbidity exceeding 400 FNU and even higher values near the distributaries, each forming a sharp plume on the ambient ocean water.

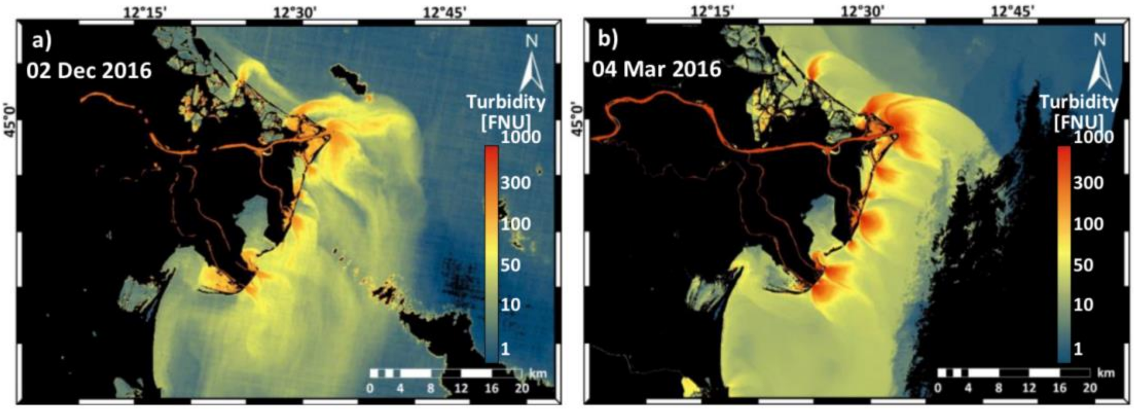

Figure 6-4: Turbidity maps (log scale) in high discharge conditions from a) the 2nd December 2016 and b) the 4th March 2016

In <u>intermediate and low discharge</u> (500-2000 m^3/s), data at the coast suggest that the observed turbidity pattern is not entirely due to river discharge. Source of suspended sediments can also be erosion of adjacent beaches and resuspension in shallow water areas of the delta (e.g. lagoons) by wind-induced waves, as well as particle transport by strong tidal currents (Filipponi et al. 2015).

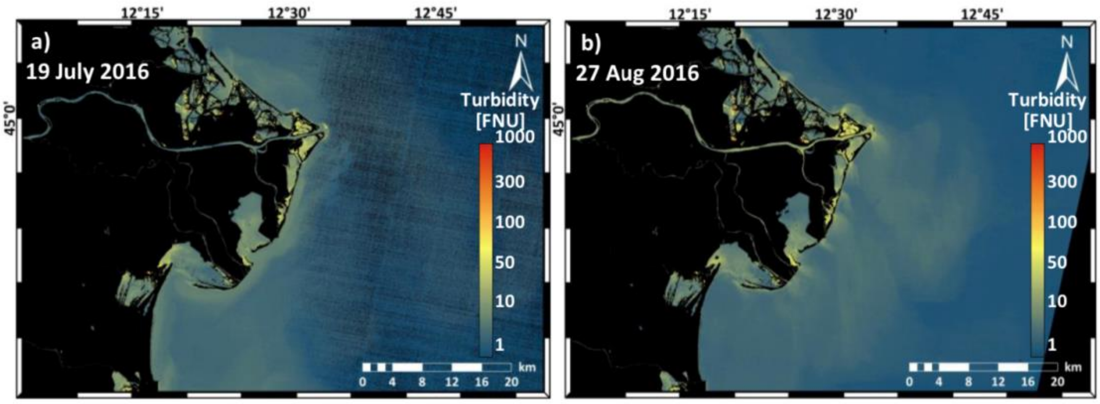

Figure 6-5: Turbidity maps (log scale) in low discharge conditions from a) the 19th December 2016 and b) the 27th August 2016

Events of <u>intermediate discharge and low wind speed</u>, such as the 26th of December 2016 (Figure 6-6), show the river distributary plumes that form a multiple jet-like structure

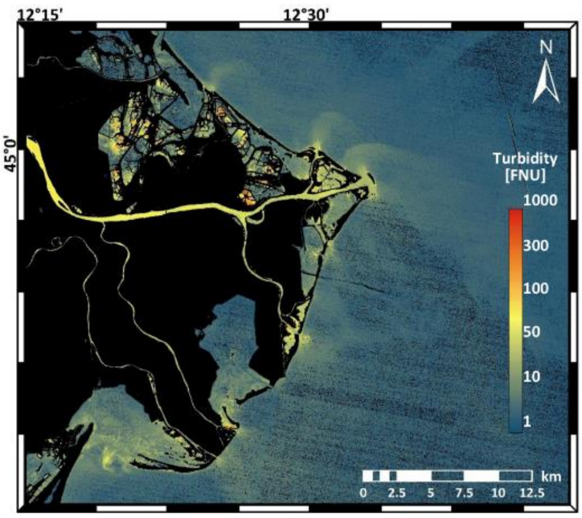

Figure 6-6: Turbidity maps (log scale) in low wind speed on 26th December 2016

Higher turbidity values are found in maps corresponding to strong and/or long-lasting wind events. In this case, sediments are mobilized from the beaches or resuspended from the sea bottom. Turbidity maps show plumes that are directed off the beaches and narrow strips of high turbidity along the coast (Figure 6-7).

Figure 6-7shows the variability of turbidity patterns with wind direction. Each wind direction forms a characteristic plume. The intense Bora wind favors sediment resuspension due to plunging waves and increased bottom shear stress in all the northern Adriatic coast and the related coastal current (Figure 6-7 a) forces the transport of sediments southward (Filipponi et al. 2015, Braga et al. 2017). The Bora wind compresses the plume against the coast and limits the offshore dilution (Braga et al. 2017). Thus, sediments are transported closer to the shore (Sclavo et al. 2013).

Wind events from Scirocco (Figure 6-7 b) and Libeccio/Mistral (Figure 6-7c) showed instead an offshore spreading of the turbidity plume.

The southeast Scirocco drives a northward transport and the sediment trails spread offshore to larger extent than what is observed for Bora and have a more diffusive character (17th of April 2017, Figure 6-7). Resuspension during Scirocco is not only present at the coast but also offshore of Po di Pila. Scirocco winds further decrease the speed of the coastal current (Harris et al. 2008).

Libeccio from southwest and Mistral from northwest favor an offshore spreading of suspended sediments forming jet-like turbidity plumes at the distributary mouths and direct them orthogonal to the shoreline on the southern delta coast (e.g. 14th of April 2016, Figure 6-7 c) or deviate on a coast-parallel direction at north. The selected image showed that when Libeccio and Mistral are particularly strong, sediments can be resuspended from the beaches and in the lagoons.

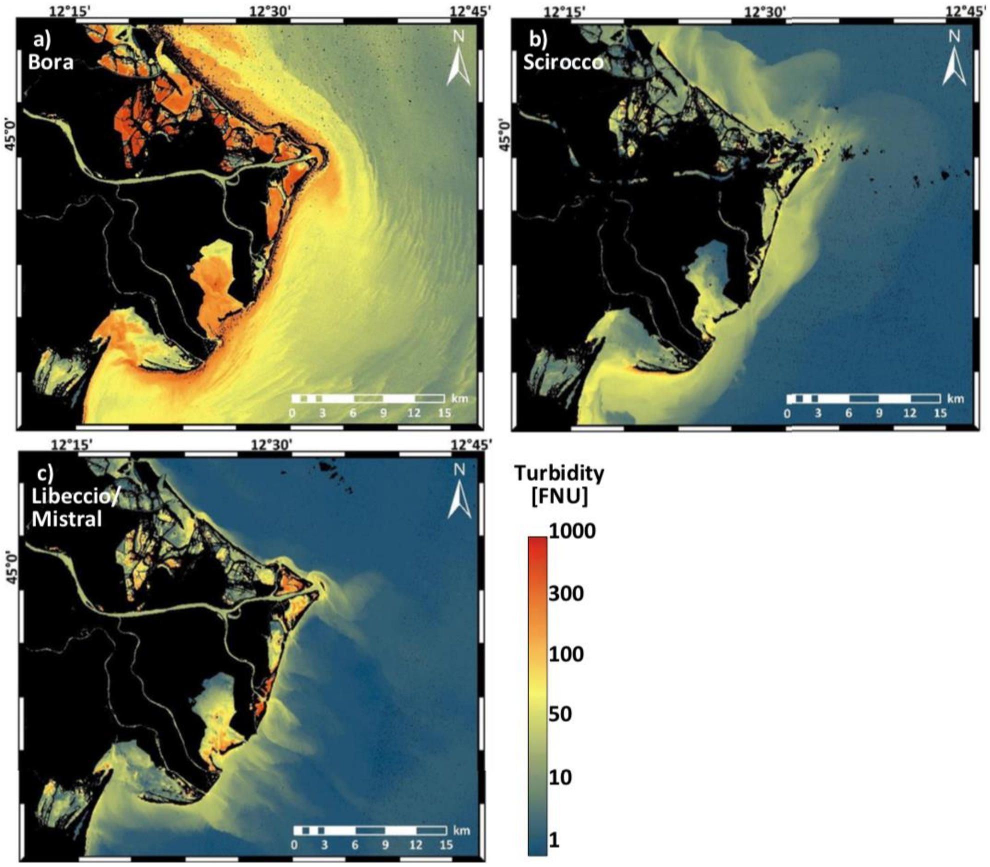

Figure 6-7: turbidity plumes (log scale) of typical Bora (18thof January 2017), b) Scirocco (17thof April 2017) and c) Libeccio/Mistral (14thof April 2016) wind event; visible is the different shape, direction and extent of the turbidity plume in correspondence of the dominant wind.

The study showed that winds and waves not only modify coastal currents, cause erosion of the shoreline and lagoons, and shape morphological features of the delta like the front bar at Po di Pila, but also affect the distribution of sediments in the area. This was also suggested by Braga et al. 2017.

As an example, Scirocco winds (up to 9.3 m/s) during the field survey induced breaking waves that resuspended sediments on the edge of the northern distributary mouths, the beaches and the front bar leading to increased turbidity in the prodelta area. This effect on the front bar of Po di Pila is visible as jet-like turbid trails originating from the erosion of the bar edges by the plunging waves in the comparison of the RGB image (a) and the turbidity map (b) (Figure 6-8).

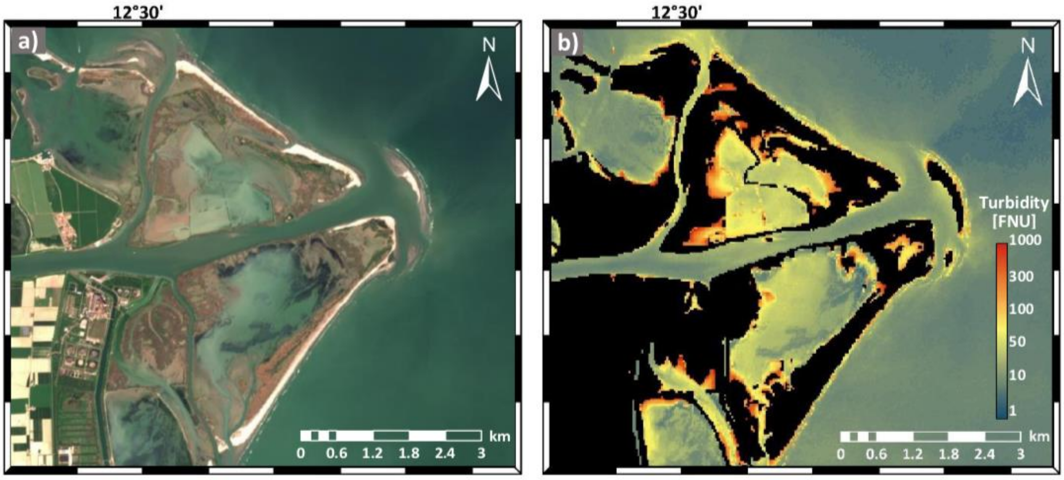

Figure 6-8: RGB image and turbidity map of the mouth of Po di Pila on the 21st of April 2017. Black pixels correspond to land area and the emerged bar under low tidal level

The turbidity around the bar can be overestimated because of bottom reflectance in optically shallow waters (Volpe et al. 2011). The lagoons show similar effects (Figure 6-8). However, the high turbidity (~300 FNU) might be due to either bottom reflectance of submerged area or wind induced resuspension of the bottom sediments.

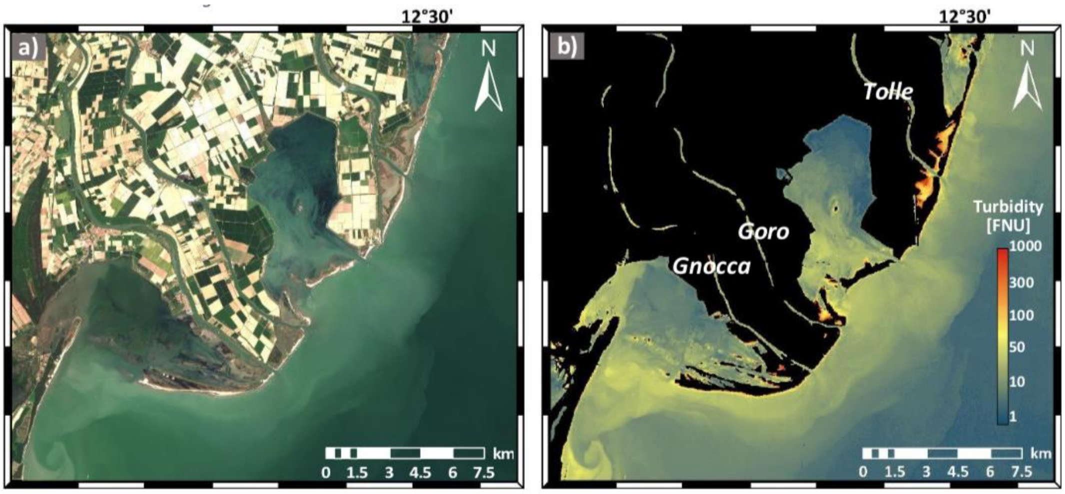

Figure 6-9: RGB image and turbidity map in the southern part of the Po River Delta, close to Goro lagoon (21st of April 2017)