

# REPORT ON PILOT AREAS GEOMORPHOLOGICAL MAPS

Activity 3.2

Task 3.2.1

Delivery date 30/06/2020

Version n. 1.0

## DELIVERABLE 3.2.1

### PROJECT CHANGE WE CARE

<https://www.italy-croatia.eu/web/changewecare>

Work Package:	WP3 Knowledge base improvement: status and recent trends of coastal and transitional system processes
Activity:	3.2 Geological and geomorphological setting and recent history
Phase Leader:	Veneto Region
Deliverable:	3.2.1 Pilot areas geomorphological maps: highlighting geomorphological setting and historical evolution of the pilot areas based on historical cartography and geomorphological, geophysical and geological data.

Version:	Final 1.0	Date:	30.06.2020
Type:	Report		
Availability:	Public		
Responsible Partner:	Veneto Region		
Editor:	Marina Aurighi & Veneto Region's staff		
Contributors:	Partnership		

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## 1. INTRODUCTION

### 1.1. Climate change in the Adriatic Region

According to the Intergovernmental Panel of 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.

Besides the increase in intensity and frequency of floods and storm surges, coastal human 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 would 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 and; 4) soil characteristics and land use (Figure 1-1 as example of the negative effects of sea-level rise and global warming in a coastal city).

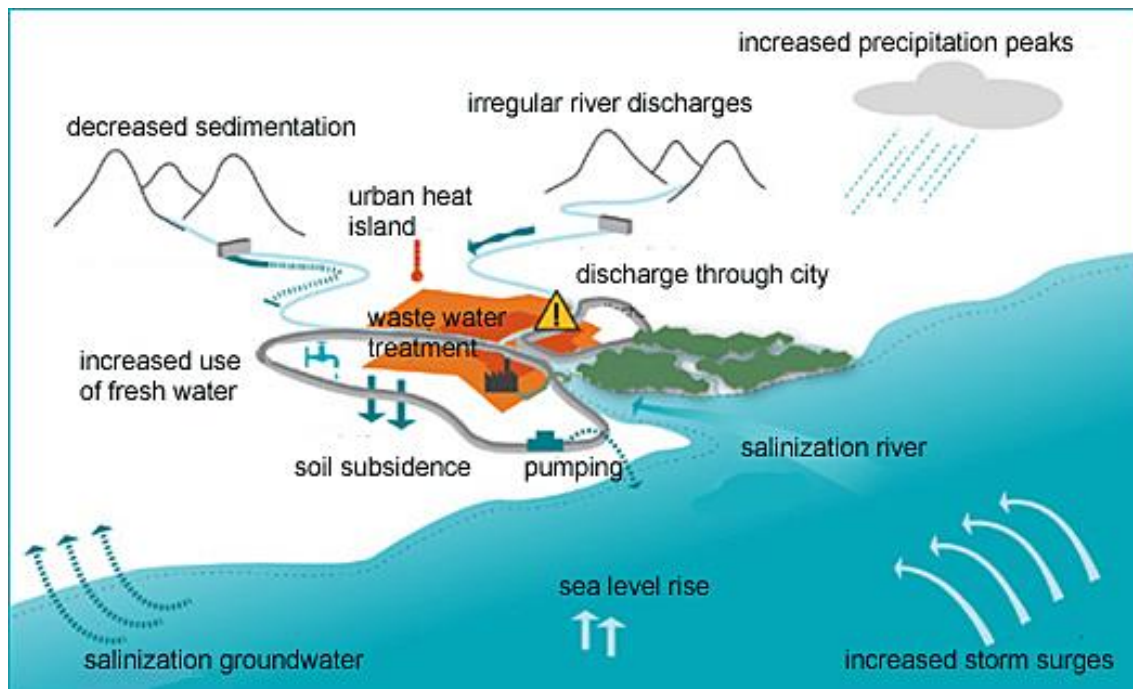


Figure 1-1: Climate change impact for a town situated in a river delta.



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, salt intrusion. 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 trend 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 made on the basis of 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 defences. 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.

Three deliverables are produced by the Activity 3.2:

**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 3.2.1 “Pilot areas geomorphological maps”, has been drawn up with the contribution of the partners. It describes, for whole north-Adriatic region and for the pilot sites:

1. geological and geomorphological data collection:
  - a. historical maps
  - b. aerial photos
  - c. satellite images
  - d. topographic surveys
2. acquisition of data in situ to complete the geological and geomorphological framework
3. general description of coastal evolution trend based on data analyse, with focus on artificial elements
4. maps of coastal evolution trend.

The pilot sites are:

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 a) Sacca del Canarin - b) Sacca di Goro



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

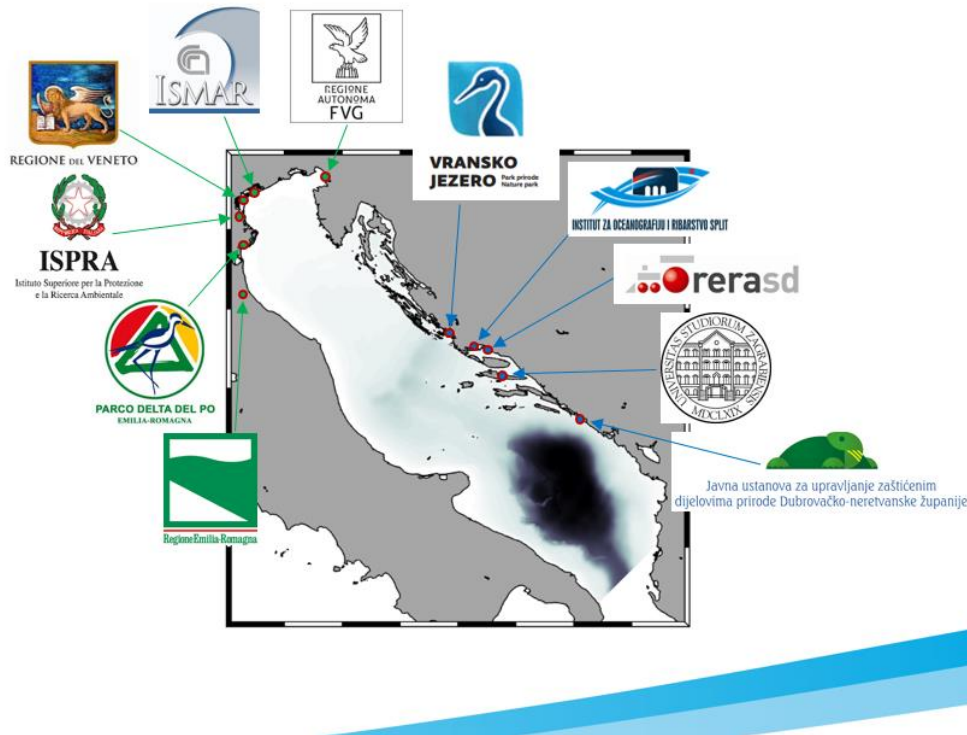


Figure 1-3: Partners involved in the Change We Care project

#### 1.2.4. Data collection methodology

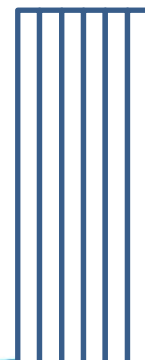
First of all, we tried to collect all the available data, useful for the preparation of the three planned reports.

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 this structure:

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

Columns:

- 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)

Rows:

- 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



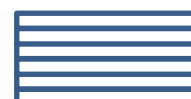
- GEOMORPHOLOGICAL PARAMETERS

- 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 (from lidar, etc.)
- Land Use maps
- Shorelines (e.g. photogrammetry, remote sensing, or site surveys)
- Information on evolutionary trends (e.g. Coastal erosion maps, subsidence trends, etc.)
- Hydraulic Defence 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
- Hydroperiod



- BIOLOGICAL PARAMETERS

- Maps of different habitats (43/92 / EEC)
- Phytoplankton
- Macroalgae
- Phanerogam
- Clams



- ADDITIONAL DATA

- Specific measures defined in SIC and ZPS areas
- Aquaculture, Clam, Mussels (Location and extension of the areas)
- Minor fishery (macrobenthic fauna in the lagoon, e.g: corbola, etc.) - Location and extension of the areas

- 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

#### 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 we proceeded to the reorganization of the data, and the selection of the most useful data and studies to prepare the **reports** relating to 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	TYOLOGY (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 s or by models	YEARS / REFERENCE PERIOD (and, if known, indicate the monitoring frequency)	AVAILABILITY of the data (institution, contact person, e-mail)
<b>PILOT SITE 4: BANCO MULA DI MUGGIA - RFGV</b>						
RFGV RFGV	Bathymetry Rivers Bathymetry Lagoons	shp -point, GeoTiff	Bathymetric data along transects collected by Consiglio Nazionale delle Ricerche, Gruppo di Studio dei Littorali, digitalization and DTM by Costal Group UNITS	originally 54 bathymetric sections between Timavo and Tagliamento; 15 section in the Pilot area Mula di Muggia	Bathymetric surveys along transects	1968 Servizio Geologico Regione FVG (Antonio Brattus) Università degli Studi di Trieste Dipartimento di Matematica e Geoscienze (Giorgio Fontolan)
		shp -point, GeoTiff	Bathymetric 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 29 bathymetric sections (until 10 m depth) between Timavo and Tagliamento; 8 section in the Pilot area Mula di Muggia.	Bathymetric surveys along transects	1978 Servizio Geologico Regione FVG (Antonio Brattus) Università degli Studi di Trieste Dipartimento di Matematica e Geoscienze (Giorgio Fontolan)
RFGV	Bathymetry Coastal areas	shp -point, GeoTiff	Bathymetric data from Regione Autonoma Friuli Venezia Giulia, 1985 Studio sedimentologico e marittimo costiero dei littorali 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	35 bathymetric sections (until -6m) between Grado and Primero, Pilot area Mula di Muggia	Bathymetric surveys along transects	1985 Servizio Geologico Regione FVG (Antonio Brattus) Università degli Studi 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	TYOLOGY (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)
<b>PILOT SITE 4: MULA DI MUGGIA - RFGV</b>						
RFGV	Maps of sediments/ granulometry rivers					
RFGV	Maps of sediments/ granulometry Lagoons	geotiff	Sedimentological map of MZ (gh) from Regione Autonoma Friuli Venezia Giulia, 1985: Studio sedimentologico e marittimo costiero dei littorali 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'Irrigazione, 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 Brattus) Università degli Studi di Trieste dipartimento di Matematica e Geoscienze (Giorgio Fontolan)
RFGV	Maps of sediments/ granulometry Coastal areas	pdf	Morpho-sedimentological map from GORDINI E CARESSA S. MAROCCO R., 2003 Nuova carta morfologico-sedimentologica del Golfo di Trieste (Da Punta Tagliamento alla foce dell'Isosno) Gortana, AN Museo Friuli, di Storia Nat., 5-29	Gulf of Trieste		
RFGV	Suspended solid transport					

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

## 2. RECENT GEOMORPHOLOGICAL PROCESSES IN THE ADRIATIC COASTAL SYSTEM

### 2.1. General description

The Adriatic Sea is the northernmost part of the Mediterranean Sea and it separates the Italian Peninsula from the Balkans, stretching from the Strait of Otranto to the gulf of Trieste. Clockwise from the northeast, it is bounded by Slovenia, Croatia, Albania, Montenegro, Bosnia and Herzegovina, and Italy, while southwards it is connected to the Mediterranean Sea through the Ionic Sea. It can be divided into three main sub-basins, the northern, central, and southern basins, whose depth increases moving towards the Otranto Sill.

The Adriatic Sea basin is 200 x 899 km wide and it elongates NW-SE between the Italian peninsula and the Dinaric-Balkan region. It is mostly characterized by a very low-gradient shelf in the northern and central part and by steeper gradients in the southern sector. Here a small basin called Meso-Adriatic Depression (MAD) develops, reaching a depth of 1200 m in the southern Adriatic.

The Adriatic region can be considered as an independent microplate within the Africa - Eurasia collision zone. This **Adriatic** or Apulian **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/Apulian Plate is thought to still move independently of the Eurasian Plate in NNE direction with a small component of counter-clockwise rotation (1).

---

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





Figure 2-1: The Adriatic/Apulian Plate

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. It is dominated by water carbonate Mesozoic successions and siliciclastic deposits belonging to the Cenozoic, which underwent profound changes during the Tertiary and Messinian, when erosion processes took place together with the deposition of Evaporites. Between the Miocene and Early Pliocene, the tectonic activities led to the uplift of the Apennines and to the complex faulted, folded and thrust structures of the Dinaric Strike.

The current configuration of the Adriatic floor is mainly due to the depositional processes and to the glacio-eustatic oscillations that occurred during the Quaternary period. The rapid succession between glacial and temperate phases caused strong fluctuations of the relative sea-level, which in turn induced a sequence of deposition and erosion phases and the formation of different systems that are now recognizable in the Adriatic Basin (see next chapters).

## 2.2. Status and trend of coastal evolution

### 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

leads to the complete filling of the foreland basin. (PIERI&GROPPI, 1981; DONDI *et alii*, 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 (favourable 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 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.

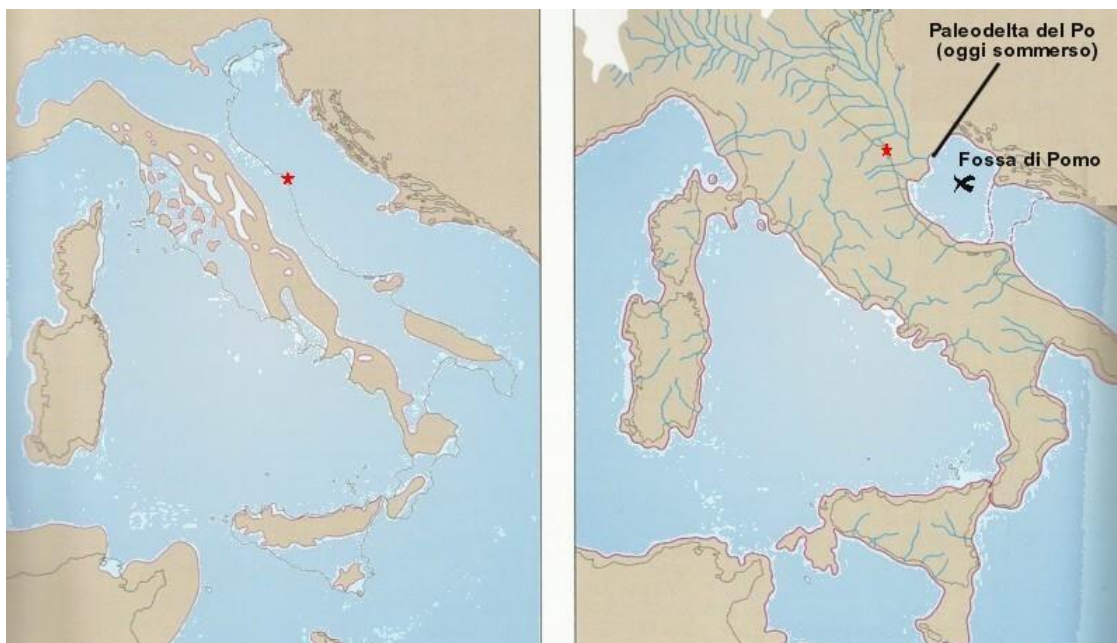


Figure 2-2: Extension of the Adriatic sea in Early Pliocene (right) and in Pleistocene (left – glacial maximum c. 18.000 y BP), the red asterisk indicates the current position of the delta

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 2-2 and Figure 2-4). 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.

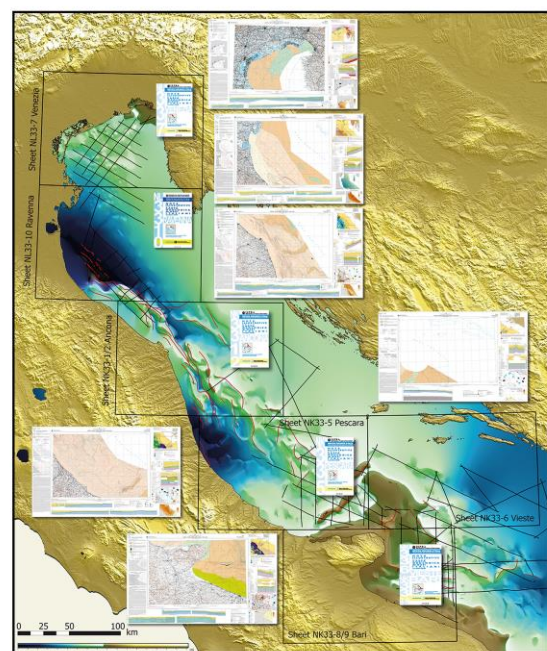
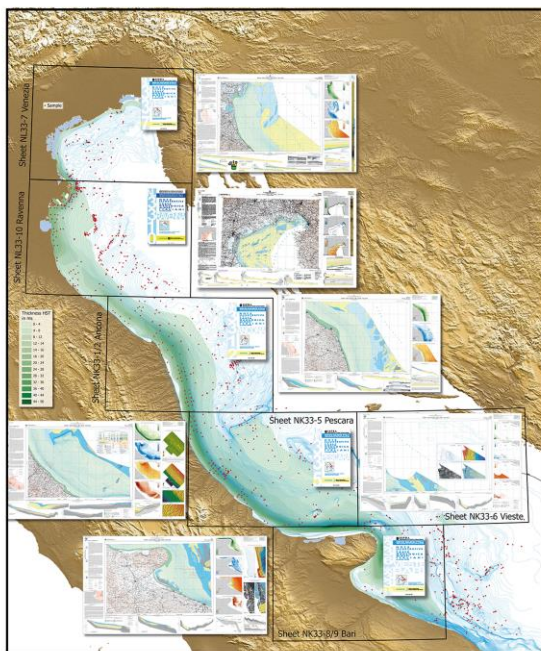


Figure 2-3: Marine Geological map of the entire Adriatic, left surficial geology and right referred to the base of the Plio-Quaternary, published in "Geological Mapping of the Italian Seas" at the scale 1:250.000\*, sponsored by the Italian Geologic Survey (SGI, now part of ISPRA) (online: [https://www.isprambiente.gov.it/Media/carg/index\\_marine.html](https://www.isprambiente.gov.it/Media/carg/index_marine.html))<sup>2</sup>

The six geological maps together with their explanatory notes contain the late Quaternary deposits representing the principal phases 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)

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).

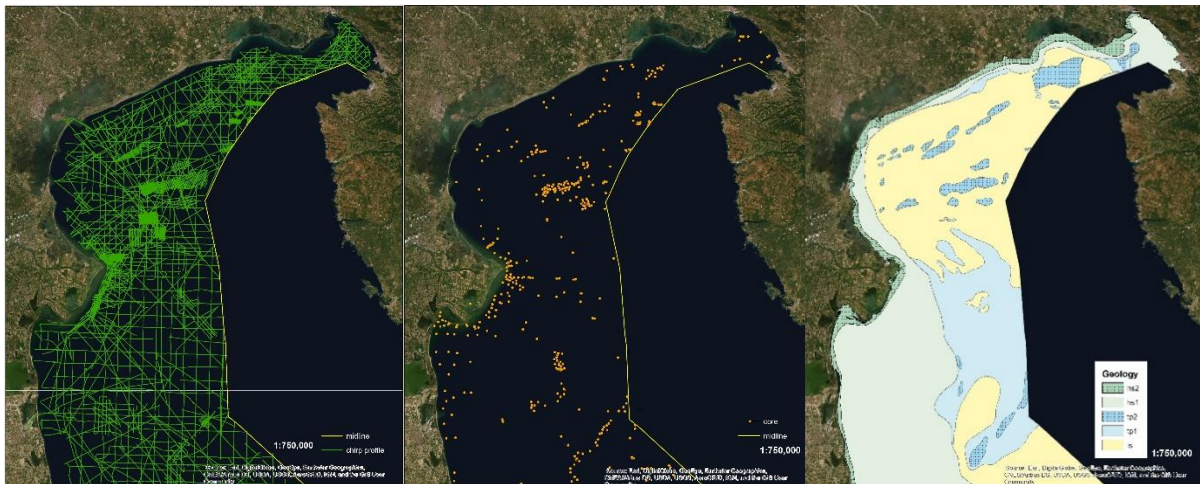


Figure 2-4 - **left**, chirp: tracklines of the seismic profile owned by ISMAR-CNR used for mapping the seafloor of the Adriatic Sea. **center**: location of the core acquired by ISMAR-CNR used to study the seafloor. **right**, Marine Geological map published in "Geological Mapping of the Italian Seas" 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.

<sup>2</sup> \*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

During the Last Glacial Maximum (LGM .ca 25.000-18.000 years Before Present, Figure 2-5) 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.

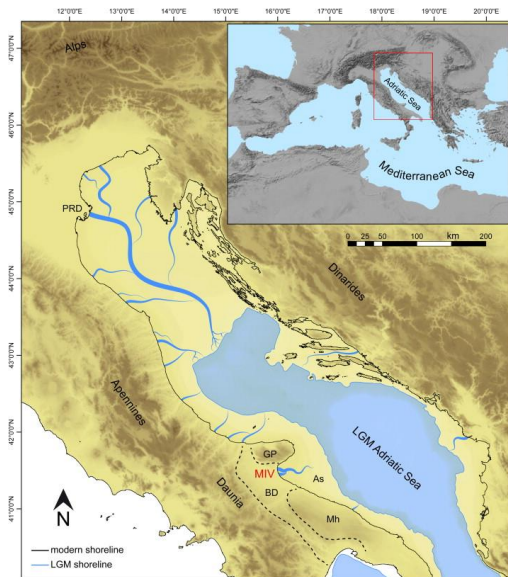


Figure 2-5: Last Glacial Maximum (LGM .ca 25.000-18.000 years Before Present)

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.

The **transgressive deposits (TST)** 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 barriers complex system.

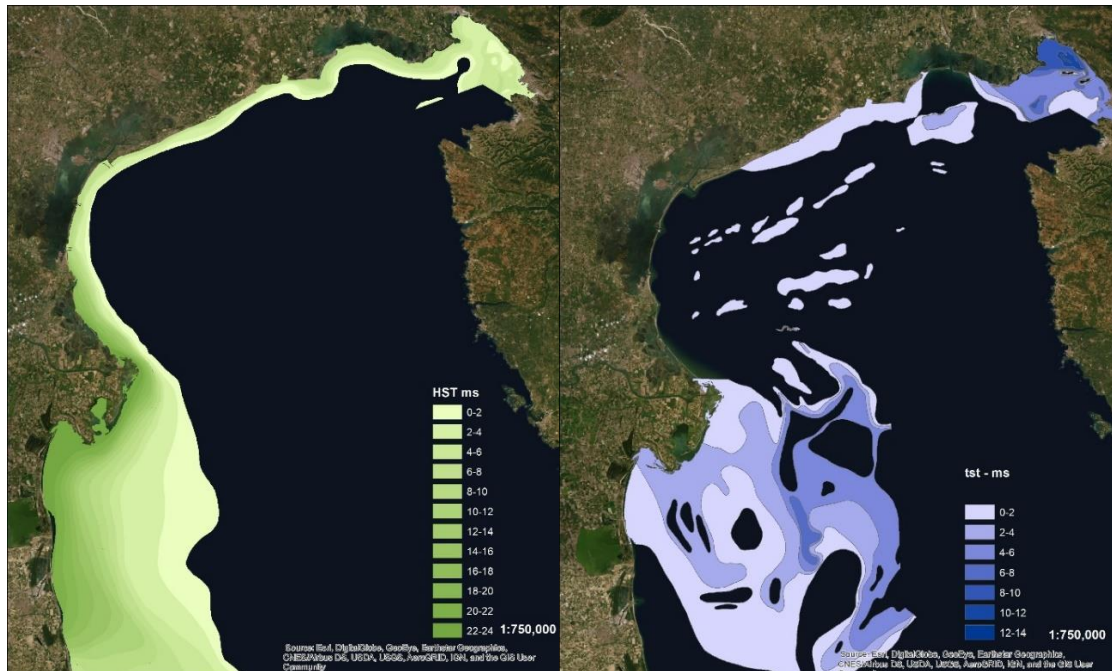


Figure 2-6: Maps of the thickness (in millisecond ,10 millisecond=7.5 m) of the high stand system tract (HST). right and of the thickness of the transgressive system tract (TST) (Thickness in millisecond ,10 millisecond=7.5 m) . Transgressive deposits in north Adriatic emerge in limited and discontinuous 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.

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.

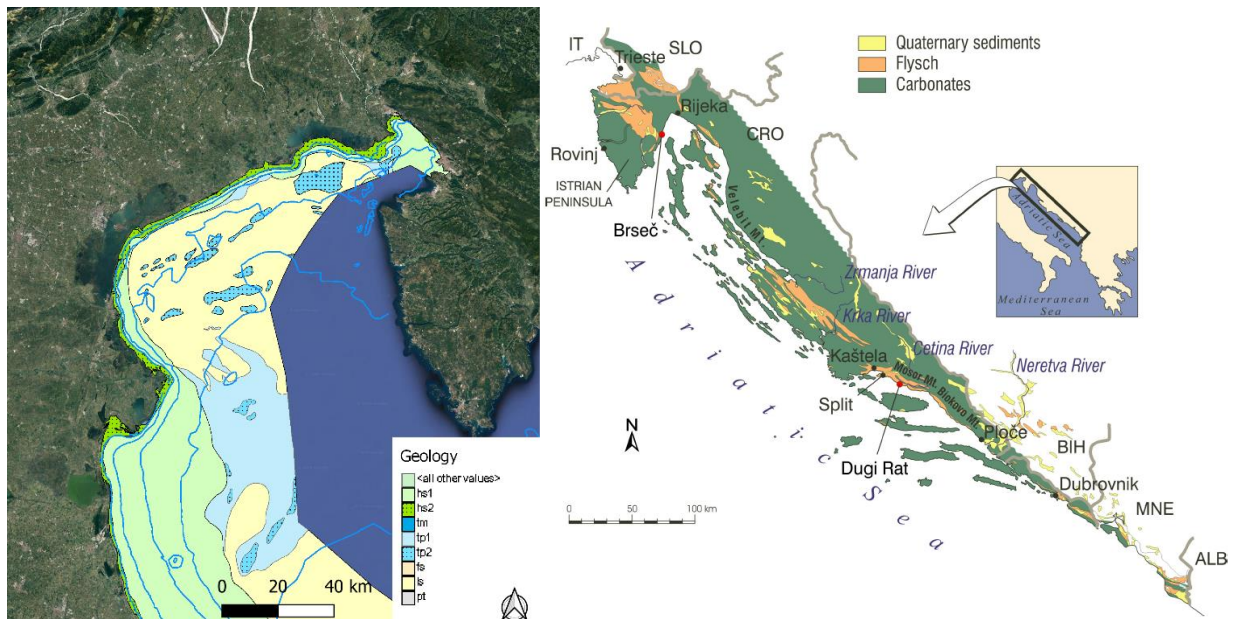


Figure 2-7: left: Quaternary formations along the Italian shelf (CARG dataset); right) geological setting along the Croatian coast (from Pikelj et al. 2016)

The late-Holocene Adriatic **Highstand Systems Tract (HST)** (5.5ka 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.

### 2.2.2. Coastline morphology

Two distinct morphological areas can be distinguished in the Adriatic basin: the western coast belonging almost entirely to Italy, and the eastern coast, which spread through different States.

The **western coast** is alluvial or terraced, dominated by the clastic sediments that are transported by the Po and other rivers from the inland drainage basin to the sea. The continuity of the coasts is interrupted by several rivers and lagoons.

The northernmost part includes the Venice and Grado lagoons and some small deltaic environments, located to the river mouths of Isonzo, Tagliamento, Piave and Adige. In this area, regressive deposits belonging to the high stand system tract emerge as prodelta facies (hs1 in the map) overlaid by sand deposits of foreshores (hs2). They comprise a prograding wedge of slight thickness since the fluvial bedload is dispersed with the currents driven by the Bora and Scirocco winds. Transgressive deposits of continental (tc), paralic (tp1) and foreshore environments (tp2) are also present, alternated with deposits of low stand tract (ls) (Trincardi et al. 2011).

The southern part shows a similar configuration, being dominated by the deltaic plain of the Po River and occupied by formations belonging to the high stand system tract. Two distinct depocenters can be

recognized in this area: the first one, towards the land and parallel to the coast, consists of marine deposits of platform, while the second one (TST) includes coastal and paralic relics (lagoon and estuarine environments) and develops seawards.

Generally speaking, the northern and western coasts of the northern Adriatic are generally sandy, and the nearby land is flat (alluvial plains). Thus, this area is mostly susceptible to multiple morphological changes like erosion, whose rates are connected to the intensity and type of the shaping processes, as it will be shown in the next chapters.

As regards the **eastern Adriatic coast** most of the islands and the mainland coast are composed of the Mesozoic carbonates (limestone, dolomite, and carbonate breccia), covered by bauxite and *terra rossa*. Eocene flysch (alternation of marl, siltstone, sandstone and carbonate breccia) covers approximately 6% of this portion, and, in some cases, it is weathered, and covered by Quaternary sediments. Igneous rocks and pyroclasts covers a small portion of the eastern Adriatic coast (Babić et al. 2012).

The coast is characterized by a very low sedimentation rate, due to the karstic hinterland and poorly developed network of rivers carrying sediments.

From a geomorphological point of view, the eastern coast is steep, rugged and highly indented, and it hosts few short and narrow beaches. It is characterized by features associated with the chemical dissolution of carbonates, like karrens, drowned dolines, marine lakes, uvals and poljes, which are semi-enclosed bays with concave forms, and drowned canyons of karstic rivers (Pikelj et al. 2013, 2016). These latter features originated by rivers that cut their canyons during the lower sea level and then were submerged by seawaters. They are often partially covered by sediments transported by the karstic catchment of the river. Moreover, speleological features are quite diffuse along the coast, hosting typical chemical sediments like speleothems, which are a proxy for the processes that took place in the Adriatic Sea.

Three types of coasts can be recognized in the carbonate formations (Pikelj et al. 2016):

1. Steep inaccessible coasts, formed in steep carbonated rocks. Their origin is tectonic, resulting from a vertical movement along fault planes of longitudinal faults in the Dinaric direction. Vertical scarps of these slopes are up to 250 m high and are partially reshaped by abrasion and weathering.
2. Exposed upper surfaces of limestone strata (northern Dalmatia islands) ubiquitous in the islands.
3. Gravel and pebble beaches. The former ones derive by the crushed and weakened carbonate rocks that have been reworked by the action of the waves, and they are often located in the southern part of the islands exposed to large waves (Jugo wind). Pebble beaches come from the combination of fluvial processes and stagnation of the sea level in the carbonate rock formation, and they are often nourished by landfalls.

The areas occupied by the soft and easily weathered Flysch are characterized by a higher percentage of beaches, alternated by high cliffs.



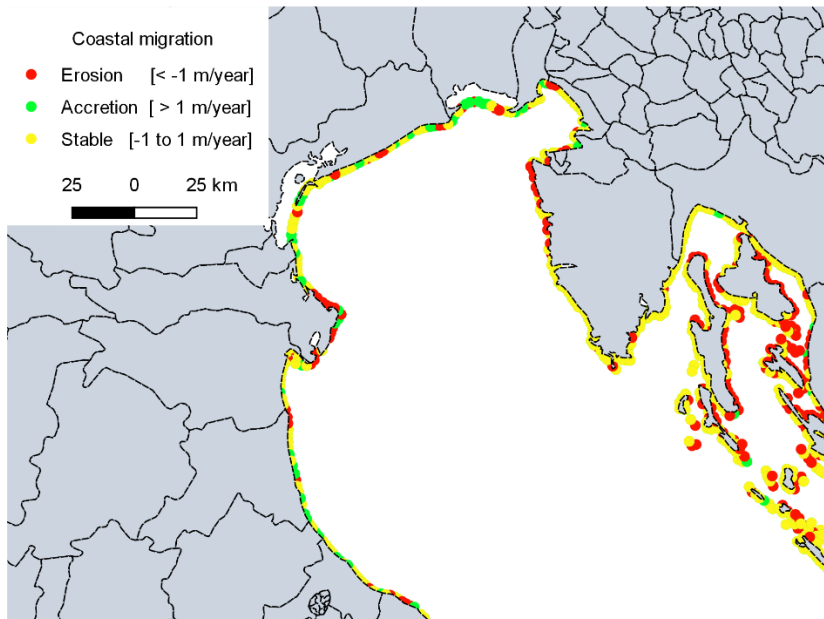


Figure 2.10. Emodnet data- coastal migration between 2007-2017, computed by Gerben et al. 2018

### 2.2.3. Subsidence

Subsidence affects mostly the western coast of the Adriatic basin.

According to Ruol et al. (2016), the principal areas exposed to the subsidence are the Venice lagoon and Po Delta, due to a combination of anthropic and natural causes that have been contributing to the general lowering of the subsoil.

The lithological nature of the deposits in the littoral areas as well as the geodynamic regime of the region are responsible for a slow-natural lowering of the area, while the deployment of the fresh-water aquifers and the gas deposits have been the main causes for the fast- recent movements of the subsoil.

The evolution of the subsidence has changed with time according to the modifications in the resource deployment of the subsoil as well documented by Carminati and Martinelli (2002).

Before the industrial development in the area, the subsidence was due exclusively to the tectonic movements of the Adriatic plate and to the compaction of sediments, which have caused the Venice lagoon to sink at a rate of 1.2 mm/year, while the Po Delta at a rate of 2.5 mm/year.

Afterwards (1950-1957), the construction of deep wells for the exploitation of the aquifers together with the extraction of the methane gas led to higher subsidence rates, which reached 30 cm/year in the inner part of the Po Delta, and 1.5 cm/year and 1 cm/year respectively in the industrial area and in the town of Venice.

The restrictions imposed after the 1970 in the land-use have interrupted this trend, bringing back the subsidence rates to 5mm/year, as measured by Teatini et al. 2011 and reported also in the Monitor project<sup>3</sup>. In particular, the current rate registered around Venice is mostly caused by the oxidation of organic soils and the compaction of deposits, which are relatively young and composed mainly by clay.

Subsidence is also reported along the Neretva River valley in the Eastern part of the Adriatic Sea, as a consequence of the decrease in the sediments transported by the Neretva River. Here, the ground's lowering is over a meter in some regions (Vranjes et al., 2013).

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<sup>3</sup> Interreg IIIB CADSES- Project Monitor "Hazard Monitoring for Risk assessment and Risk valuation". The Geological Survey of Veneto Region applied satellite borne SAR interferometry to Risk analysis in the Po river Delta

## 3. GEOMORPHOLOGICAL PROCESSES AT PILOT SITES

### 3.1. Neretva river delta

#### 3.1.1. General site description

Neretva River 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 22.3 km (Juračić, 1998). In the upper and middle part of the flow 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 (LjubenkoVranješ, 2012). The stream base forms a main stream, which 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 Kutu. 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 which 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 Modrooko.

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 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 lake. 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 Vlačka, Parila and Kutu. Modrooko 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, Fistanić, 2000). Large amounts of water come in the delta area through sources which 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 in the summer there, so it's July and sometimes with no precipitation, and the annual evaporation

is 500-900 mm. The mean annual flow of the river is 269 m<sup>3</sup> / s, the minimum is 44 m<sup>3</sup> / s (probability 0.05), and the largest 2,179 m<sup>3</sup> / 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, 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 trough fracture karst system and through alluvial valley (Ljubenko, Vranjes, 2012).

Moreover, the entire valley main inflow of salt water (sea) occurs in the deep layers of alluvium (Vranješ, Prskalo, Džeba 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 riverbed upstream up to Gabela. Under the influence of freshwater wedge is pushed downstream until it is fully ejected out of the riverbed (Ljubenko, 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 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. The consequences of those actions will be felt in the Neretva delta, Mali Ston and the Župa Bay, and water sources in the Dubrovnik coast (Vranjes et al., 2013). The consequence 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.

Trough is widened to 2-3 m near Komin and Rogotin bridge. 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 (Vranjes et al., 2013).

#### 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 (Figure 3-1 and Figure 3-2), 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. 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).

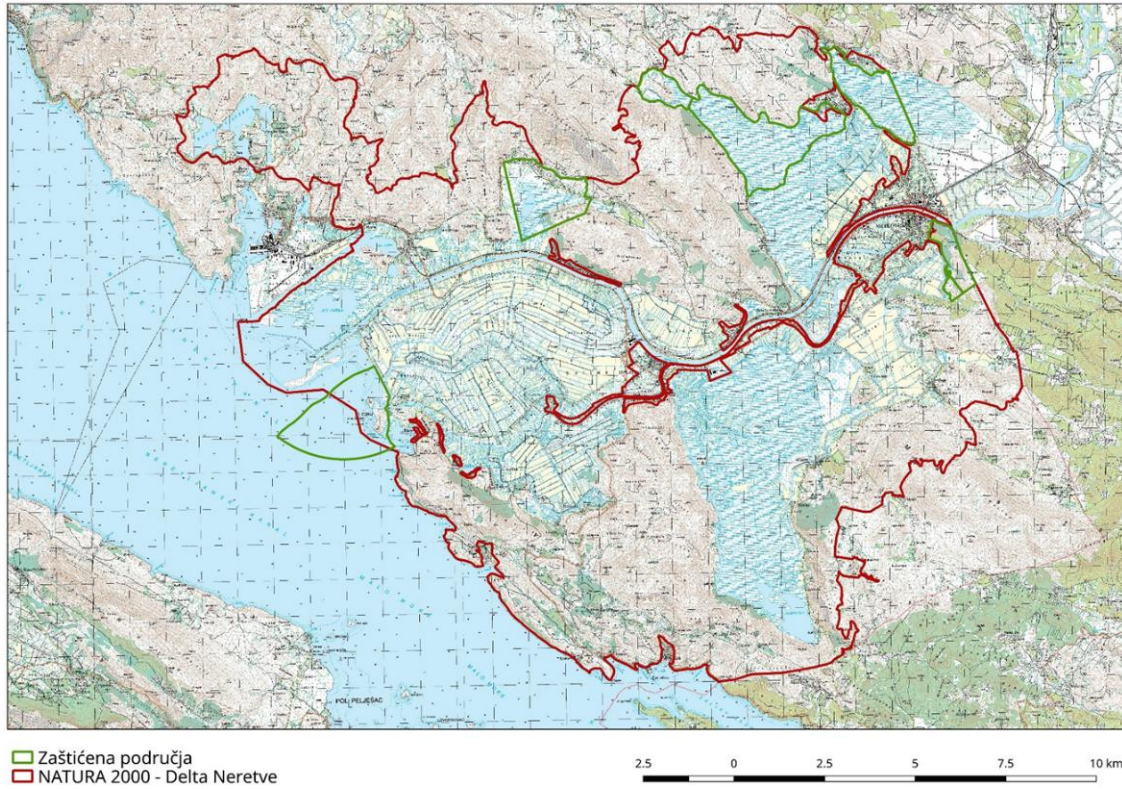


Figure 3-1: Protected areas (in green color) and NATURA 2000 site Delta Neretve (in red color)



Figure 3-2: Mouth of Neretva River Delta (source: Biportal).

#### 3.1.1.2. Physical and environmental features

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 cca 7°C, although temperatures can go down to -5°C or even below. The temperatures are highest in July (average cca 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%).

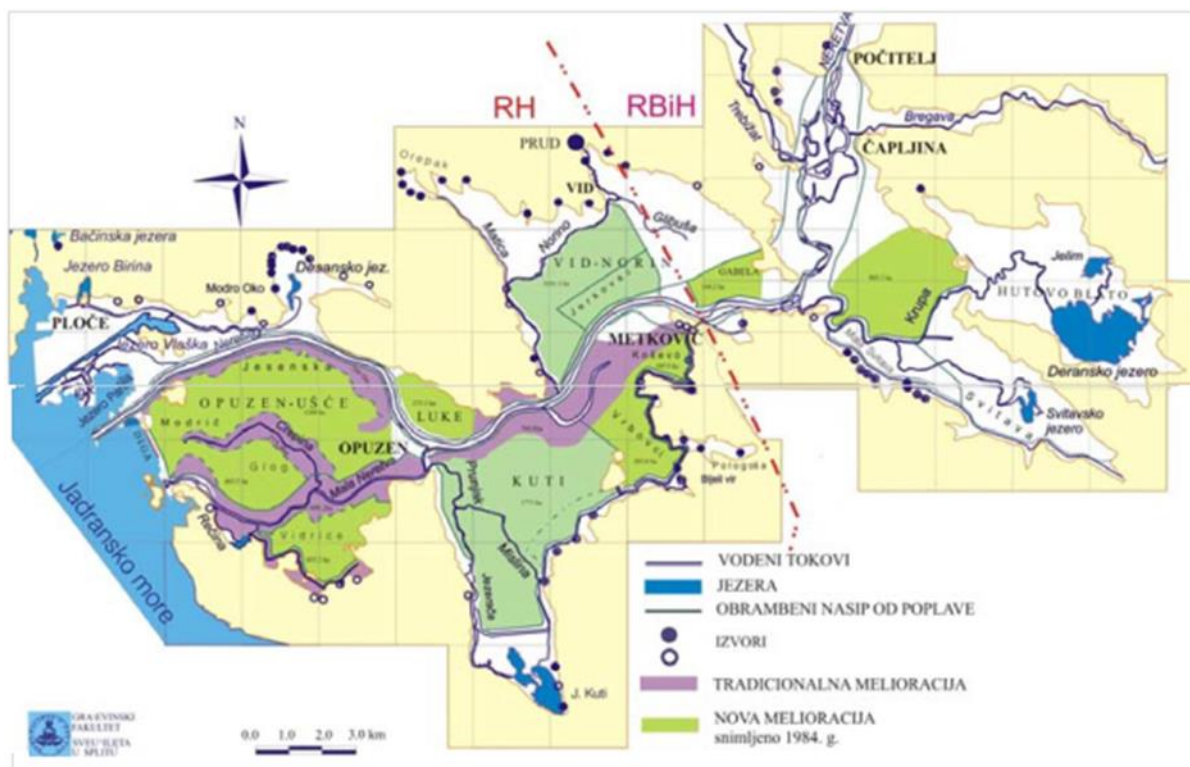


Figure 3-3: Hydrological status in Lower part of Neretva today (Source: Vranješ et al., 2013).

Neretva River is dominant watercourse of the area (Figure 3-3). Its main characteristics in this final section are: average annual water level of  $91 \pm 13$  cm (range 65-124 cm); average annual water flow of 269  $m^3/s$  (range 44– 2,179  $m^3/s$ ); 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 3-4 and Figure 3-5).

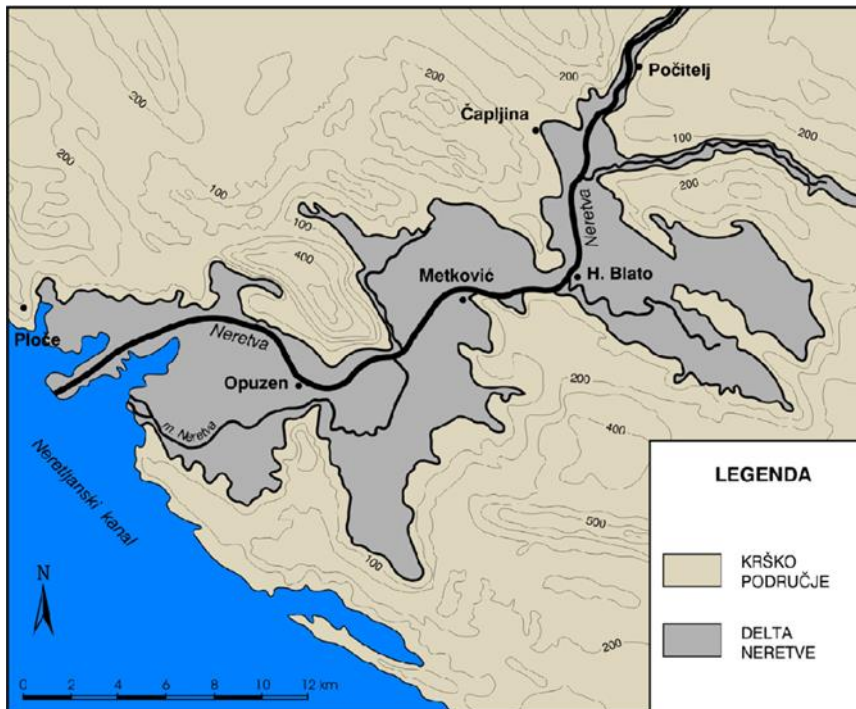


Figure 3-4: Karst frame and Neretva River Delta (Source: <http://geol.pmf.hr>).

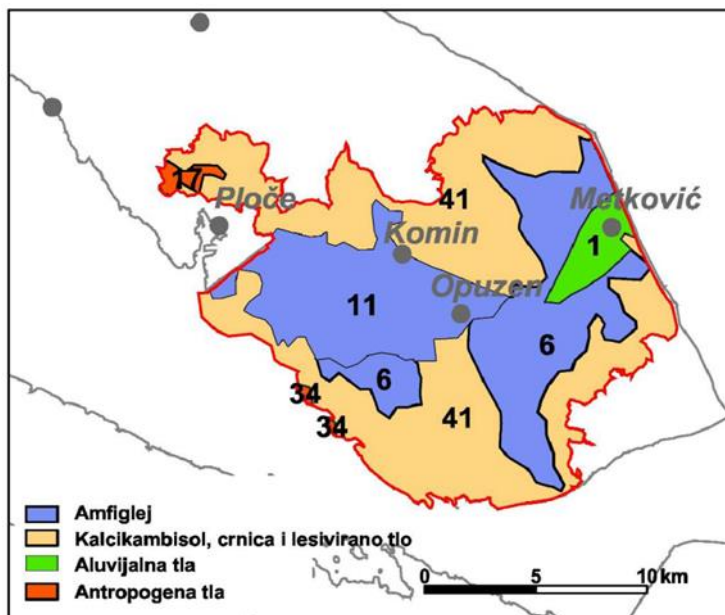


Figure 3-5: Soil map of Neretva Delta River (Source: Soil map of Republic of Croatia, Martinović, 2000)

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



The most important cities are Ploče, Opuzen and Metković. 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 and for production, but also for activities such as hunting, fishing and aquaculture. 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.

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.

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.

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.

#### 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 an obvious 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. Redirection of waters from so called Upper horizons (“Gornji horizonti”) of Trebišnjica River into the area of Lower horizons (“Donjihorizonti”) 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 even increase these activities and to take the most of available water for additional use of hydropower plants in eastern Herzegovina.

### **3.1.2. Available geomorphological data, studies, maps**

Most of the geomorphological data are available through the DGU portal: DGU portal: <https://geoportal.dgu.hr/>.

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

There are no new in-situ data available for the area of interest.

### **3.1.4. Current status of site geomorphology (methods, discussion, maps)**

Neretva River and its delta is the major and dominating geomorphological feature in the area. Delta area is composed of three triangular extensions that are tectonically predisposed and created as a result of tectonic movements during the last orogenic phases. Neretva Delta took current form after the transgression of sea 10 000 years ago. Two of those extensions are in Croatia.

Mesozoic rocks that make up the wider perimeter of the delta were created in the geological past in the area, which we call Adriatic carbonate platform (Vlahović et al., 2005). Neretva Delta in general geotectonic division is situated in the external Dinarides that are characterized predominantly by highly deformed carbonate rocks (Korbar, 2009). There are three general morphological units of the delta area: the karst hinterland, lowland area of the delta and the coastal strip (Nature Park Neretva Delta, 2007). Karst bedrock outcrops in the surrounding hinterland of Neretva delta is characterized by a dissected relief, numerous caves and sinkholes within the fractured carbonate rocks. Predominantly carbonate rocks of Mesozoic and Cenozoic age build karst hinterland of the Neretva delta (Figure 3-6).

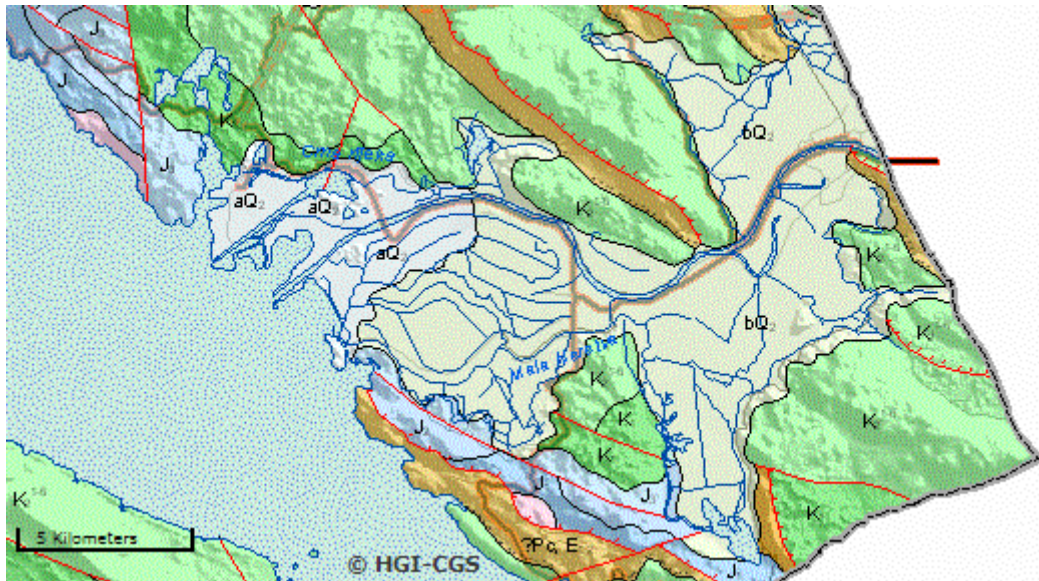


Figure 3-6: Crop of the Overview geological map of the Neretva delta area. Grey - delta sediments (aQ2 – alluvial, bQ2 – palustrine), Orange – Cenozoic carbonates and some clastics (Pc, E), Green – Cretaceous carbonates (K), Blue – Jurassic carbonates (J), Purple – Triassic carbonates (T). Source: HGI-CGS: <http://webgis.hgi-cgs.hr/gk300/default.aspx>

Cretaceous limestones and dolomites predominate in the area but there are also overlying Paleogene carbonates and clastics. A zone of Jurassic carbonates outcrop along the NW-SE striking zone at the river mouth. The oldest rocks outcropping sporadically in the coastal area are the Upper Triassic dolomites.

Within the regional geomorphological and geological framework the karst hinterland of the Neretva delta can be simply defined as a flattened bedrock area along the lower river channel covered by superficial Quaternary loose sediments (Juračić, 1998), that developed because of the river activity and advancement of the delta. Southwest of Metković is represented by organic - swamp sediments, and west of the Opuzen to the river mouth are represented by Delta sediment, sand, gravel and sand - clay material. It can be assumed that the beginning of the creation of today's delta fall in the age of sea level rise, roughly before 8000-6000 years (Juračić, 1998).

## 3.2. Jadro river

### 3.2.1. General site description

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

Jadro River is located in the central Dalmatia (Croatia), in the central part of the eastern Adriatic coast (Figure 3-7 and Figure 3-8).

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.

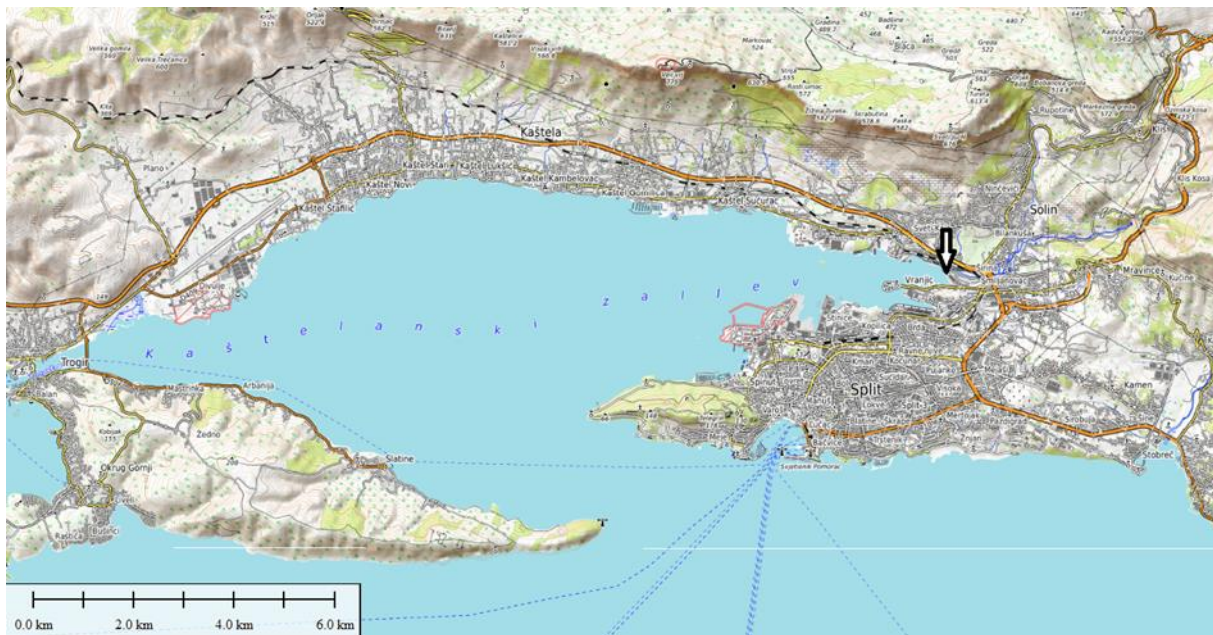


Figure 3-7: Location map of Jadro River (mouth is marked by arrow) at the easternmost tip of Kaštela Bay (Kaštelanskizaljev) in the town of Solin - ancient Roman Salona (Source: Open Topo Map).

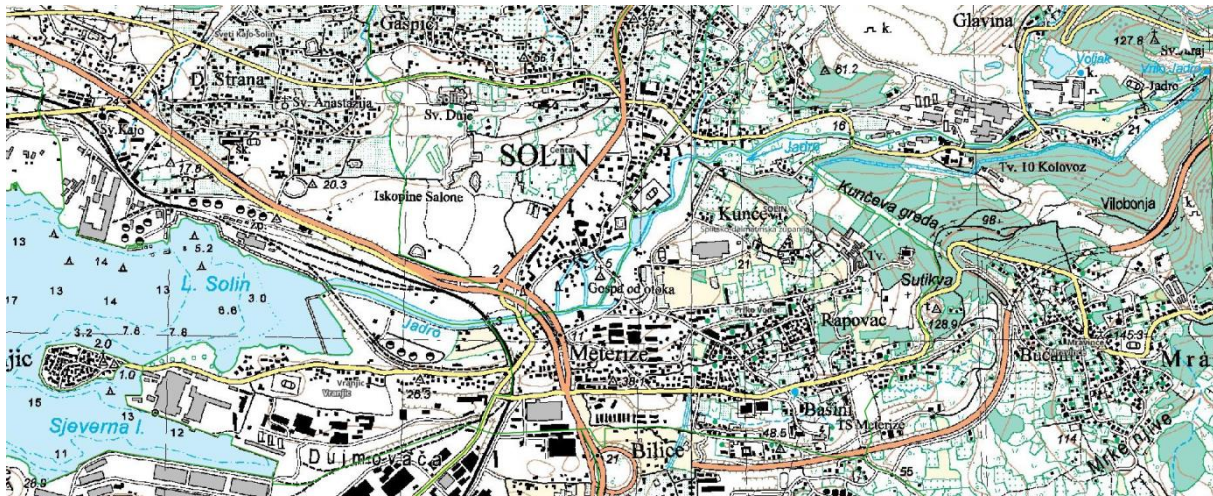


Figure 3-8: Location map of Jadro on the official topographic map (Source: DGU: <https://geoportal.dgu.hr/>). Coordinate grid is 1 km.

### 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 (Kaštelanskizaljev) 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 3-9). 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 characterized 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 (Kaštelanskizaljev, Figure 3-9). 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<sup>2</sup> 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 3-9: 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 (E<sub>2,3</sub>) 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 Solinis located in the eastern part of the Bay, in the area of the ancient Roman town of Salona. The medieval town of Trogiris 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 3-10 and Figure 3-11.



Figure 3-10: Overview of the land use in the area of Jadro river (Source: DGU: <https://geoportal.dgu.hr/>).

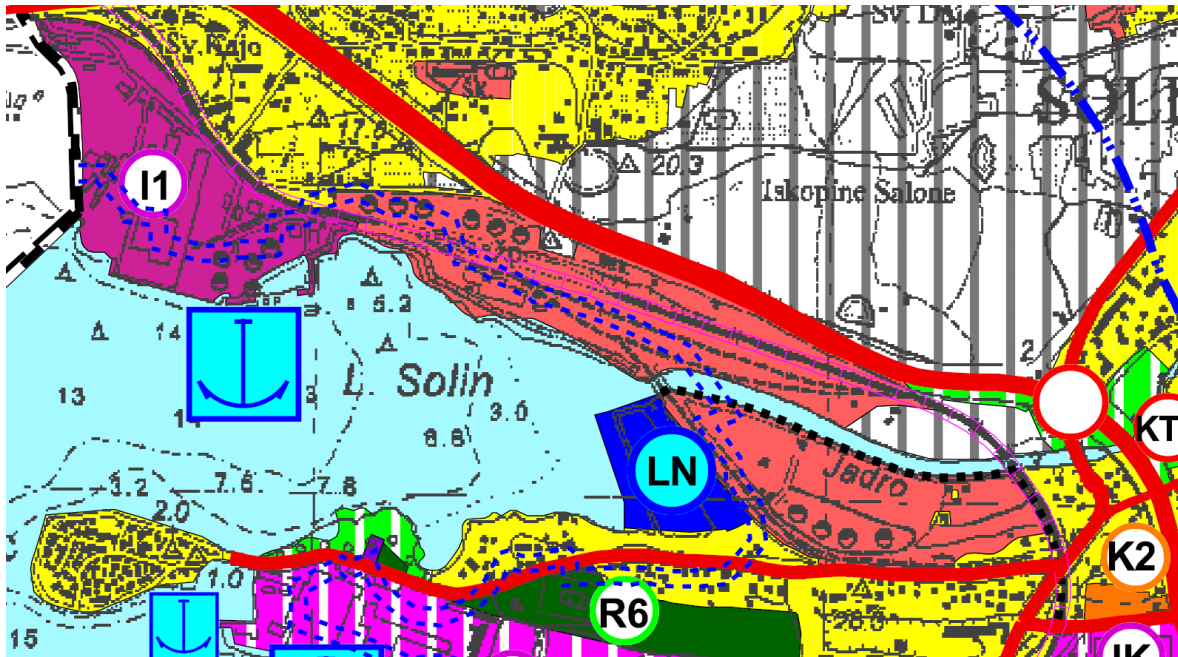


Figure 3-11: The town of Solin land use map in the area of Jadro estuary and the mouth (ZZPU-SDZ, 2017).

#### 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 industrialisation and urbanisation without development of appropriate urban infrastructure, in particular of a wastewater collection and disposal system. The main conflicts because of that are between industry and tourism, industry and housing, and wastewater 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 project's 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 & BARIĆ, 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 references 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 geomorphological data, studies, maps**

#### 3.2.2.1. Jadro River spring and the estuary



The source of Jadro River is located 34.2 m above mean sea level (LJUBENKOV, 2015). The total length of the watercourse is 4.3 km (Figure 3-12). The topographic catchment of the Jadro is relatively small and covers about 22 km<sup>2</sup>. The upper stream is under the influence of a substantial discharge (Figure 3-13) and relatively high topographical gradient, while the lower stream is characterized by estuarine circulation (Figure 3-14 and Figure 3-15). 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.

The average annual discharge of the Jadro River measured at the Majdan station (Figure 3-13), is 7.9 m<sup>3</sup> s<sup>-1</sup> (1961–2010), the highest mean annual flow being 12.8 m<sup>3</sup> s<sup>-1</sup> (1970) and the minimum 5.1 m<sup>3</sup> s<sup>-1</sup> (1983). Within a year there is a considerable variation of the flow. Thus, the largest flows occur from November to March, with averages larger than 10 m<sup>3</sup> s<sup>-1</sup>. The minimum mean monthly flows are observed in summer (July, August and September) and attain values of 3.3 m<sup>3</sup> s<sup>-1</sup>, 2.9 m<sup>3</sup> s<sup>-1</sup> and 3.7 m<sup>3</sup> s<sup>-1</sup>, respectively. It should be noted that even during the winter months relatively small flow rates can occur with monthly averages less than 4 m<sup>3</sup> s<sup>-1</sup>.

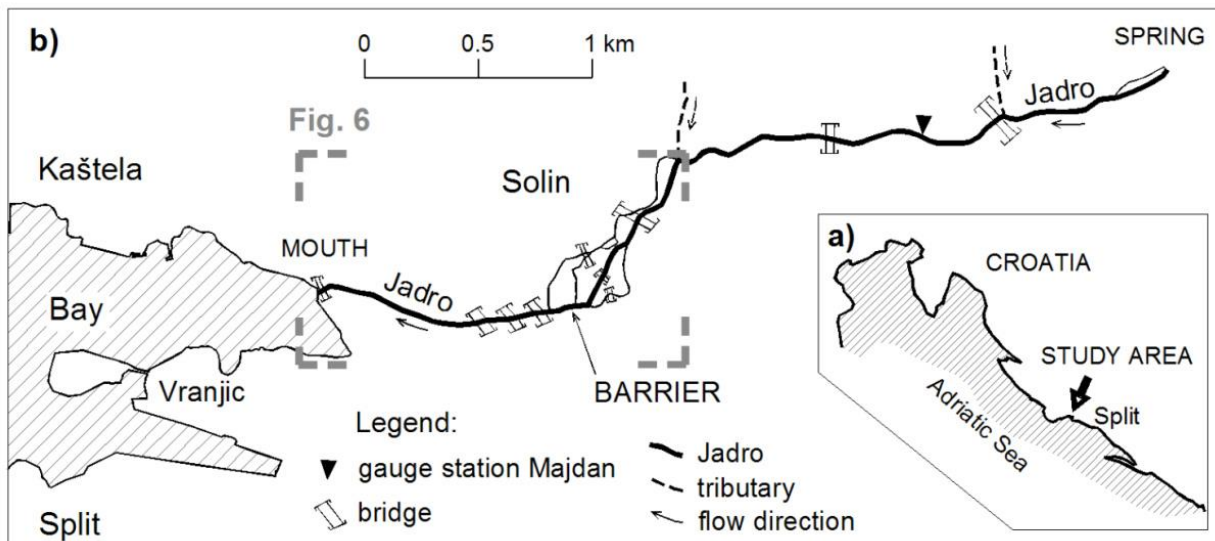


Figure 3-12: Location map of a) the study area and b) Jadro River (after LJUBENKOV, 2015).

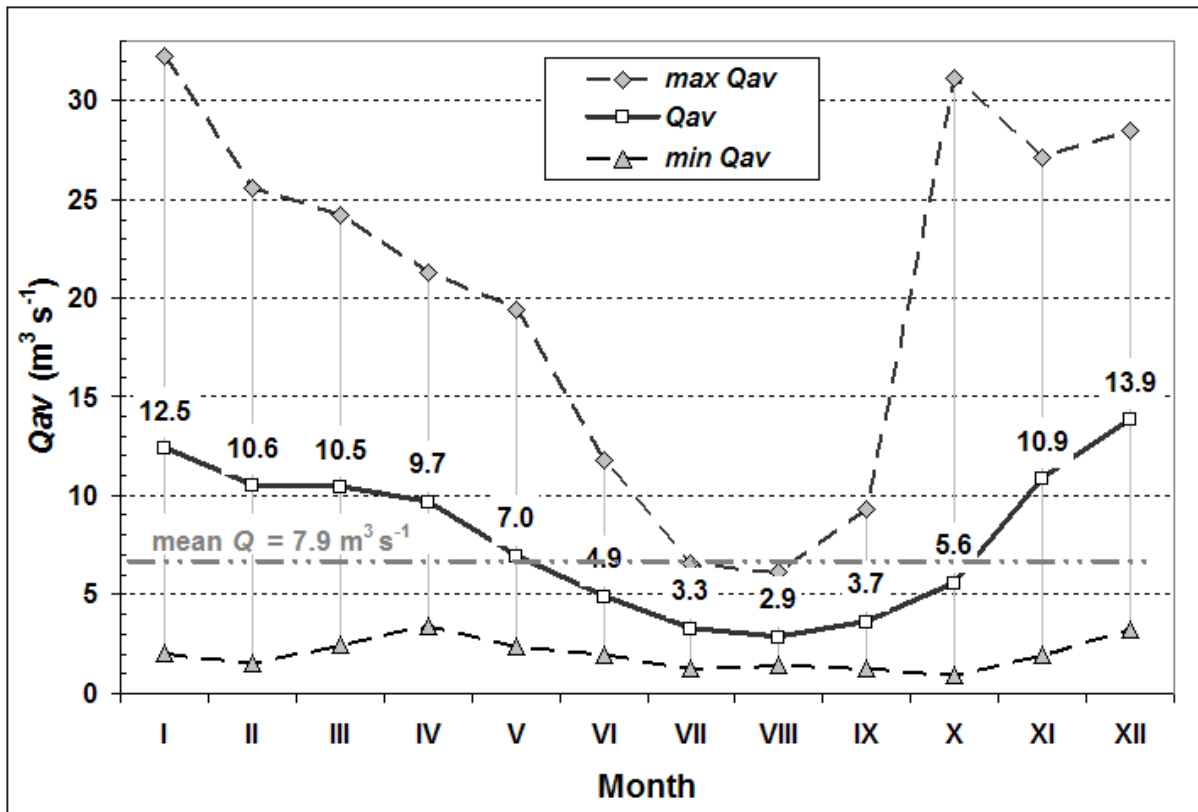


Figure 3-13: Monthly discharges of the Jadro River at gauging station Majdan (in the period 1961–2010) ( $Q_{av}$  is average discharge,  $maxQ_{av}$  is maximum mean monthly discharge and  $minQ_{av}$  is minimum mean monthly discharge) (LJUBENKOV, 2015).

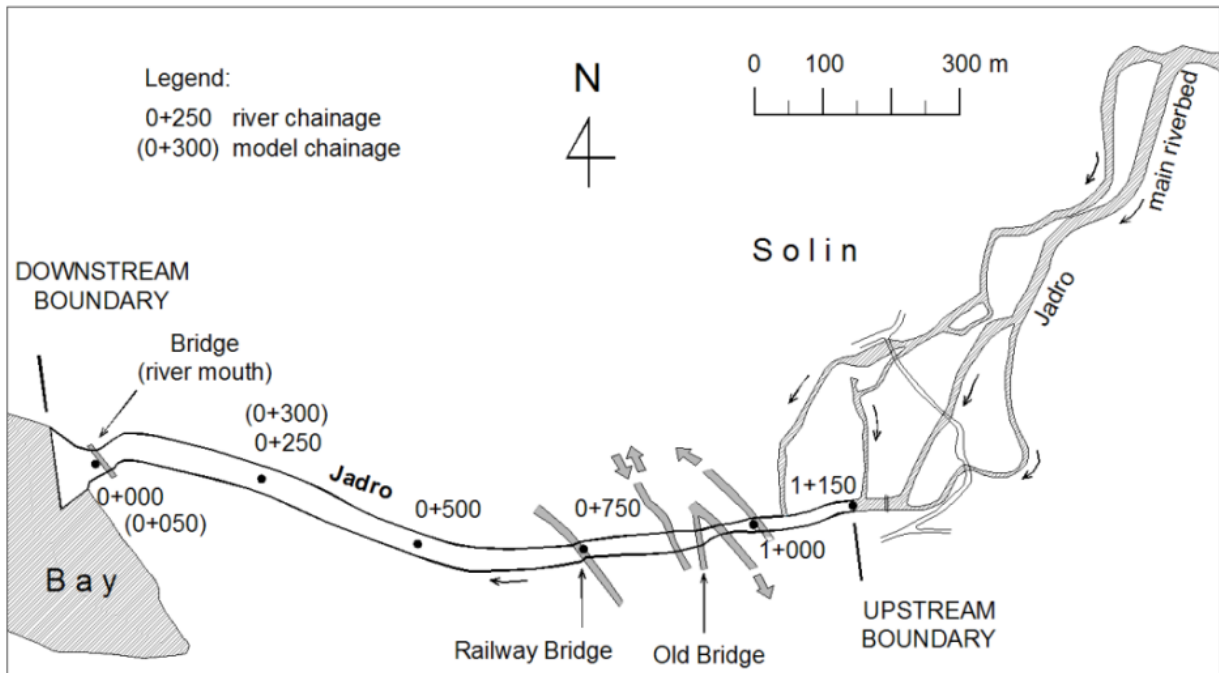


Figure 3-14: The Jadro River estuary with numerical model boundaries (LJUBENKOV, 2015).

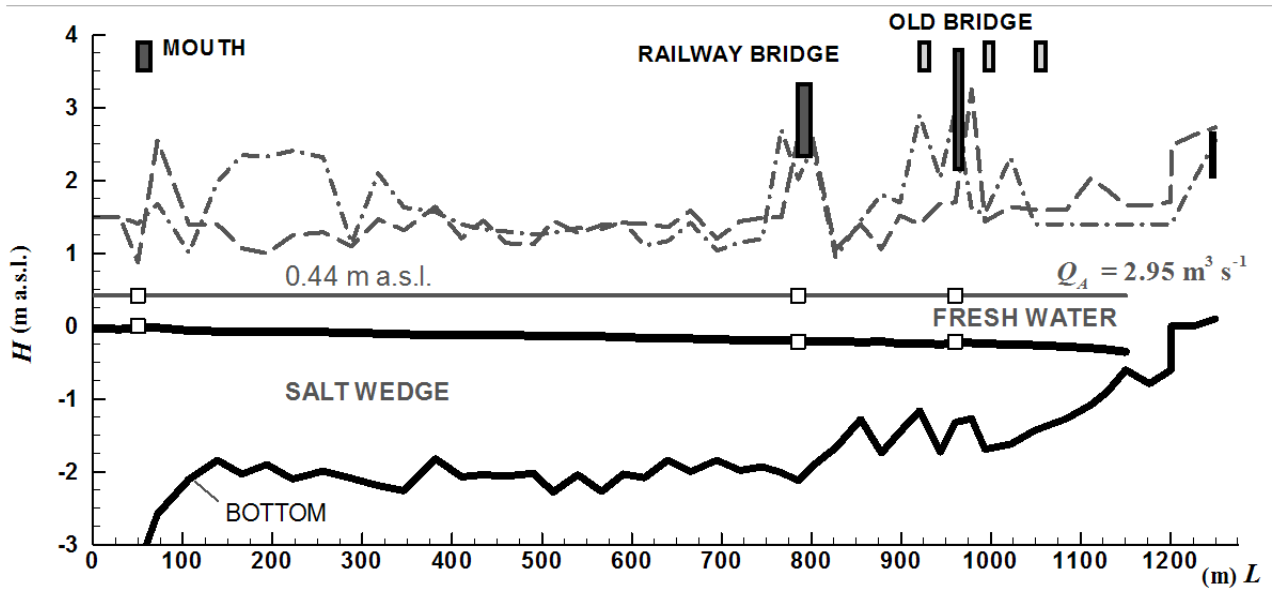


Figure 3-15: Estimated water surface and interface within Jadro estuary at 11h on July 26th, 2012 ( $Q_A$  is fresh water discharge) (LJUBENKOV, 2015).

The measurement (LJUBENKOV, 2015) confirmed the stratified character of the estuary where fresh water flows in a thin layer over denser sea water. Furthermore, a numerical model was set up for simulating unsteady stratified flow without mixing between the layers. The model is applied for the Jadro River and field measurements are used for calibration. In addition, the steady state of stratification within the estuary is analyzed by a box model which assumes mixing between layers. Results of the numerical and the box models were compared. The flushing time estimated with the box model is approximately 1.5 day for summer steady conditions. Numerical analysis however shows that the residence time is much larger owing to flow unsteadiness.

#### 3.2.2.2. Jadro River mouth and Vranjic Bay

The Jadro River mouth is situated in well-protected embayment (Vranjic Bay in the easternmost part of Kaštela Bay). The average 2 m depth of the estuarine part of Jadro River (Figure 3-15) deepens to more than 3 m at the mouth in the easternmost part of Vranjic Bay, and deepens gradually toward the western part of the Bay to 19 m (Figure 3-16 and Figure 3-17).

The Jadro River mouth and the estuary is situated in well-protected embayment (Vranjic Bay in the easternmost part of Kaštela Bay) and thus is mostly under the influence of the stream itself. The influence of the waves, sea currents, and tidal processes is insignificant, and should be evaluated in Act. 3.1. The influence of sedimentological processes will be evaluated in Act. 3.2.2.

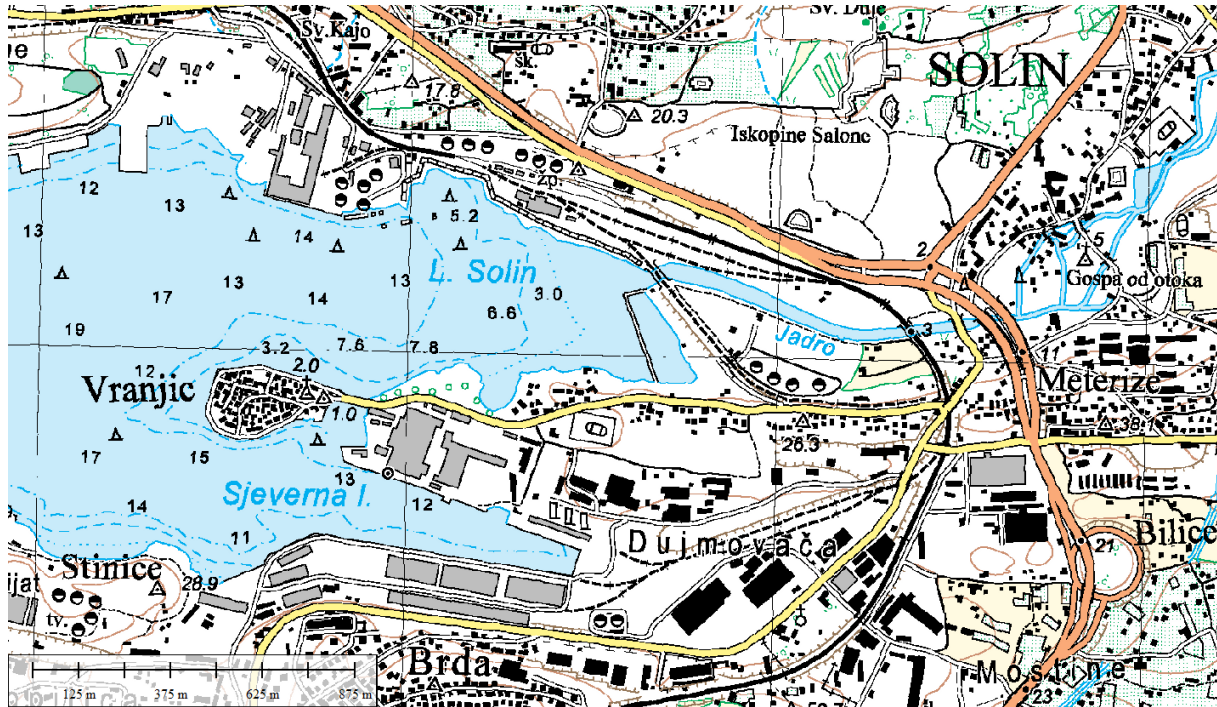


Figure 3-16: Crop of the topographic map of Jadro River mouth and Vranjic Bay (<https://geoportal.dgu.hr/>).



Figure 3-17: Crop of the orthophoto image of Jadro River mouth and Vranjic Bay (<https://geoportal.dgu.hr/>).

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

There are no available more precise bathymetric data for the Jadro River and the eastern part of Kaštela Bay (Vranjic Bay). Acquisition of modern geodetic methods is suggested (multibeam, photogrammetry, laser scanning etc.).

### **3.2.4. Current status of site geomorphology (methods, discussion, maps)**

There are no previous analyses of the geomorphological processes on the pilot-site Jadro River and Vranjic Bay. However, comparison of available historical data, i.e. orthophoto images from 1968 and 2017, reveals that during last 50 years geomorphology along the coast and at the Jadro River mouth has not been changed significantly (Figure 3-18).



Figure 3-18: Comparison of orthophoto images of Jadro River mouth taken in 1986 (upper image) and in 2017 (lower image).  
Source: <https://geoportal.dgu.hr/>.

### **3.2.5. Analysis of recent trends of the geomorphological processes**

There are no recent geomorphological studies of the pilot-site Jadro River mouth and Vranjic Bay.

### **3.2.6. Conclusion**

#### **3.2.6.1. Results of the activities and discussion**

1) The Jadro River is highly anthropogenically influenced short karstic River that is situated in highly populated area of the Split-Kaštela basin, in the administrative territory of the town of Solin (ancient Roman Salona);

2) 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;

3) The Jadro River spring is a major karstic spring in the area that is used as a major regional source for potable water supply;

4) The spring is situated 34 m above sea level and is out of influence from the sea in any climate change scenario. However, the runoff is highly under the influence of the climate changes and should be evaluated in Act. 4.1.;

5) The estuary is highly anthropogenically modified and thus protected from natural erosional processes;

6) Comparison of available historical data revealed no significant change in the Jadro River mouth (pilot-site) geomorphology during last 50 years.

7) The Jadro River mouth and the estuary is situated in well-protected embayment (Vranjic Bay in the easternmost part of Kaštela Bay) and thus is mostly under the influence of the stream itself.

8) The influence of the waves, sea currents, and tidal processes is probably insignificant, and should be evaluated in Act. 3.1.;

9) The influence of sedimentological processes will be evaluated in Act. 3.2.2 (next chapter).

#### **3.2.6.2. Problems and solutions**

Generally, the geomorphological situation on the pilot-site Jadro river mouth is under strong anthropogenic influence and thus is 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 3-19). 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.

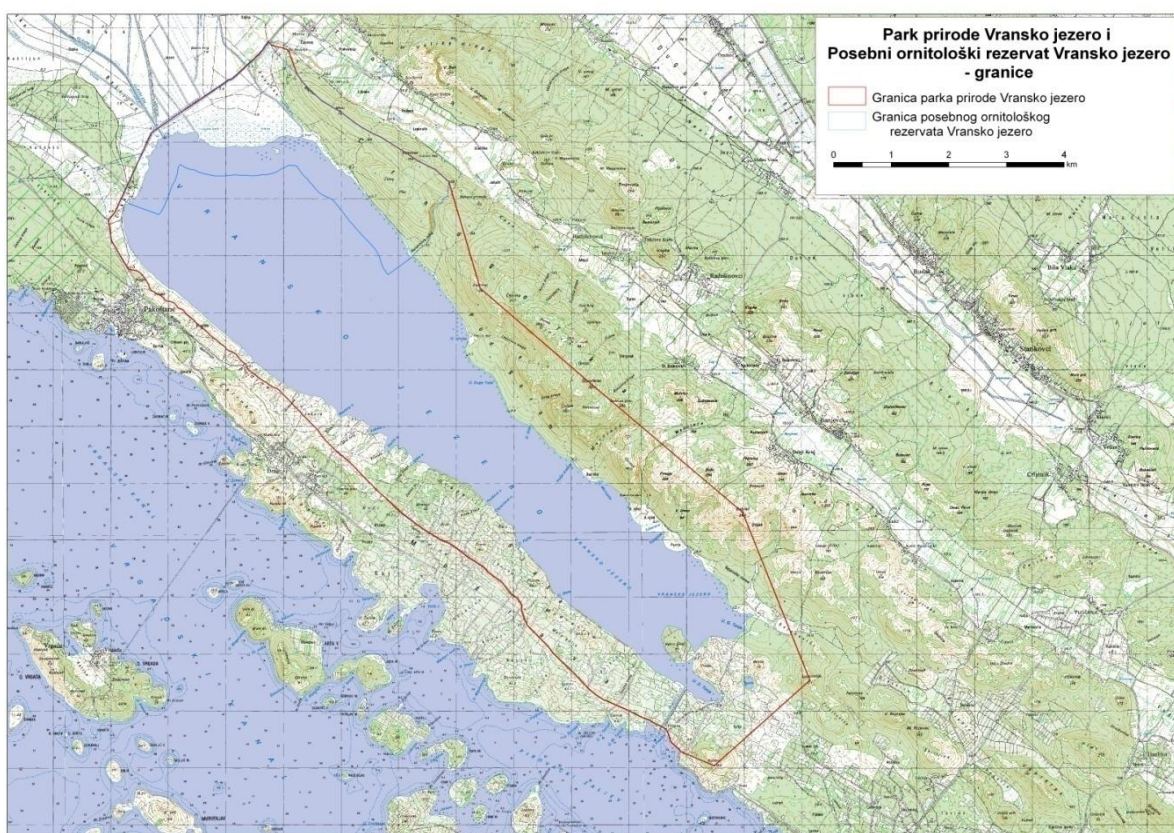
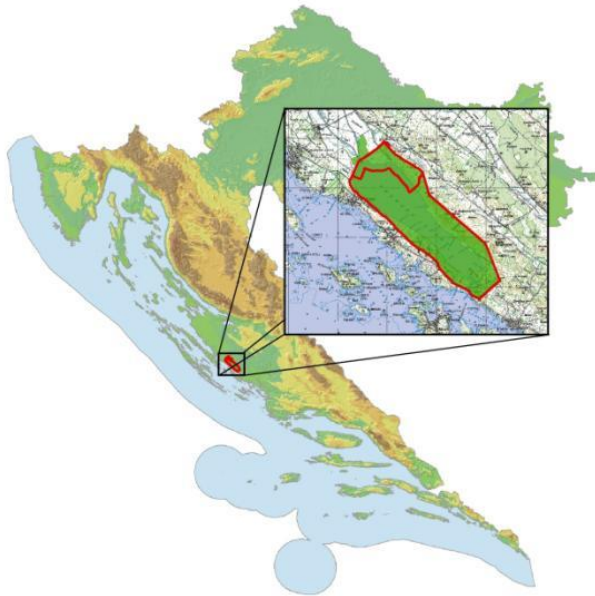


Figure 3-19: Area of Nature Park Vransko lake, Nature park borders-red line, Special ornithological reserve -blue line.

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 20) is within two Croatian counties, with 42 km<sup>2</sup> (74%) in the area of Zadar County and 15 km<sup>2</sup> (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, Radašinci, 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 21). 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 3-20: Location of Vransko lake Nature park in Croatia.*



Figure 3-21: 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 km<sup>2</sup>, was declared a Nature park on July 8, 1999. Due to wildlife biodiversity, especially birds, an 8,65 km<sup>2</sup> area in the northwestern part of Lake Vrana, was declared an Ornithological Reserve by the Municipality of Biogradna 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 Kopačkirit, 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 VranskoJezero 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 VranskoJezero Lake and its usage for water supply, but the idea was abandoned due to problem of salinization. Springs from Vranskojezero's catchment (Kakma, Biba, Škorobić, Turanjskojezero, Kutijin stan) are, however, regularly exploited for water supply, and Begovača seasonally. Springs Tinj, Mali Stabanj, VelikiStabanj, Pećina are used for irrigation of arable land. During rainy season Vranskojezero'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: Prosikaharbor 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 biodiversity. 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 1.9x10<sup>6</sup> m<sup>3</sup> for water supply and about 1.0x10<sup>6</sup> m<sup>3</sup> 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,

allochthonous 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 geomorphological data, studies, maps**

#### **3.3.2.1. General geomorphology of the subaerial part of the Park**

In general, altitudes of up to 100 m prevail in the most part of the Park (Figure 3-22). As mentioned above, the whole Park area is formed in the submerged karstic depression formed after postglacial ingression into the elongated and previously folded and faulted karstic relief. The NE karstic ridge is characterized by mountain terrain, causing a smooth lake coastline in most of its NE segment. The highest point in this area is Štandarac (303 m.a.s.l.) on the NE border of the Park, located on one of the carbonate ridges (anticline) (Figure 3-23). The ridge on its SW side is an overturned anticline, generally lower compared to the previous one (max. height 113 m a.s.l.).

The most prevailing relief slope class is 0-2° (plain areas) and it comprises most of the NW land area as well as relatively wide areas of the highest zone on the SW ridge (Figure 3-23). The second class is 2-5°, prevailing on ~25% of the Park, mostly areas inclined lakeward. The third-class 5-12° is represented by inclined terrains, mostly on the lakeward slopes. In these zones, mass various movements may be expected.

According to the geologic fabric (Eocene and Cretaceous limestones; Mamužić, 1982) main processes are rockfalls or soil erosion (to a lesser extent). The same and more pronounced processes may occur on significantly sloped areas (12-32° class), present mostly on the NE carbonate ridge (Figure 3-23). The last two classes of slopes (32-55° and >55°) comprise together up to 0.5% of the subaerial part of the Park. Relief forms that can be recognized in these areas are gullies and dry valleys on the NE ridge and tectonic cliff on the SW ridge (Figure 3-22)

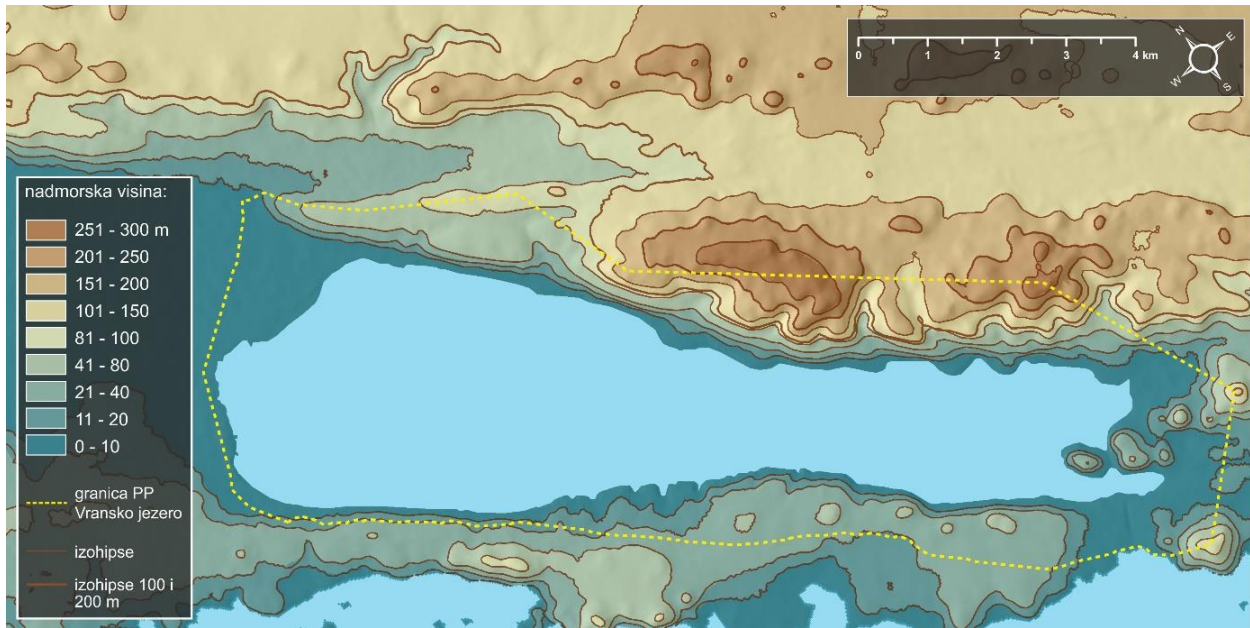


Figure 3-22: Hypsometric map of the Nature Park Vransko Jezero area. Legend: nadmorskavisina – hypsometric classes in m a.s.l.; yellow dashed line – Park border; thin brown lines – height contours; thick brown lines – 100 and 200 m contours (Perica et al., unpublished).

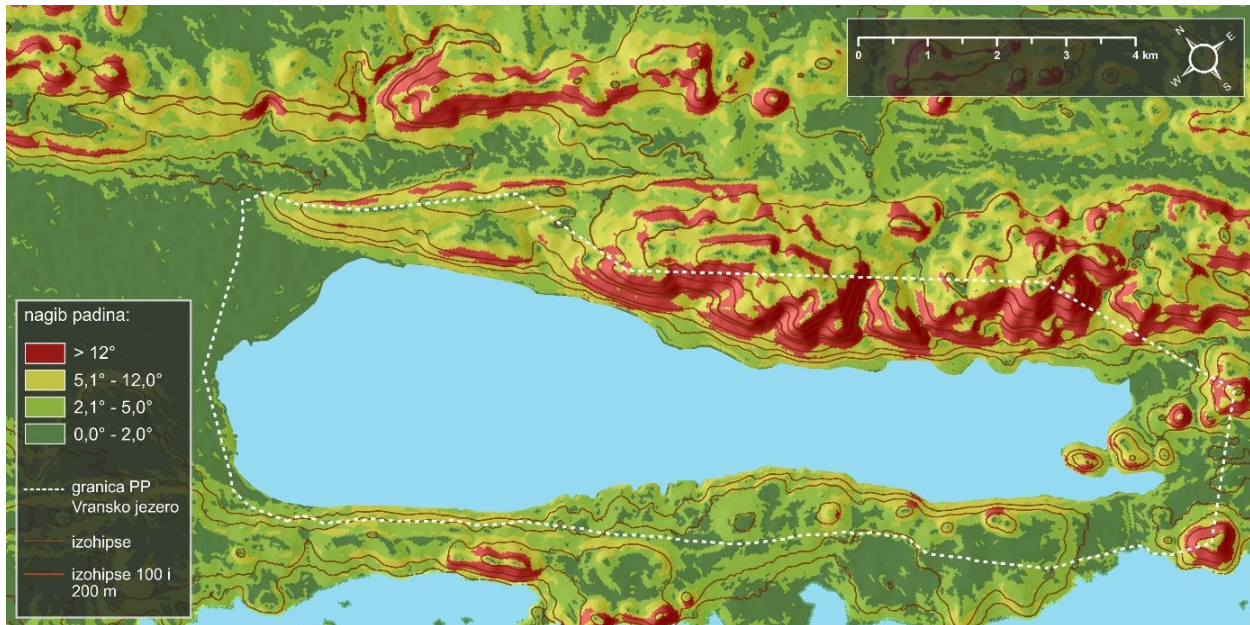


Figure 3-23: Slope relief map of the Nature Park Vransko Jezero area. Legend: nagibpadina – slope inclination; white dashed line – Park border; thin brown lines – height contours; thick brown lines – 100 and 200 m contours (Perica et al., unpublished).

### 3.3.2.2. General geomorphology of the lake

As previously stated above, the Vrana lake is a result of the submersion of the karstic depression (polje) in its deepest segment (Figure 3-24). Main rock assemblage under the lake sediments is Eocene flysch – a

rock complex composed of sandstones, breccias, siltstones, marls in alteration and with a significant compositional spatial variation along the Croatian coast (Pikelj and Juračić, 2013).

Based on the thickness and composition of the Quaternary sediments, deposition of the sediment material was continuous during the Quaternary, resulting in up to 30 m sequence in its thickest part (Fritz, 1983, 1984).

According to the present-day bathymetry (Figure 3-25 and Figure 3-26), outcrops of basement rock in the middle of the Vrana polje, it is obvious that the thickness of the lake sediment rises proportionally to the terrain slopes, i.e., runoff directions remained the same during the Quaternary– southeastward (Fritz, 1984).

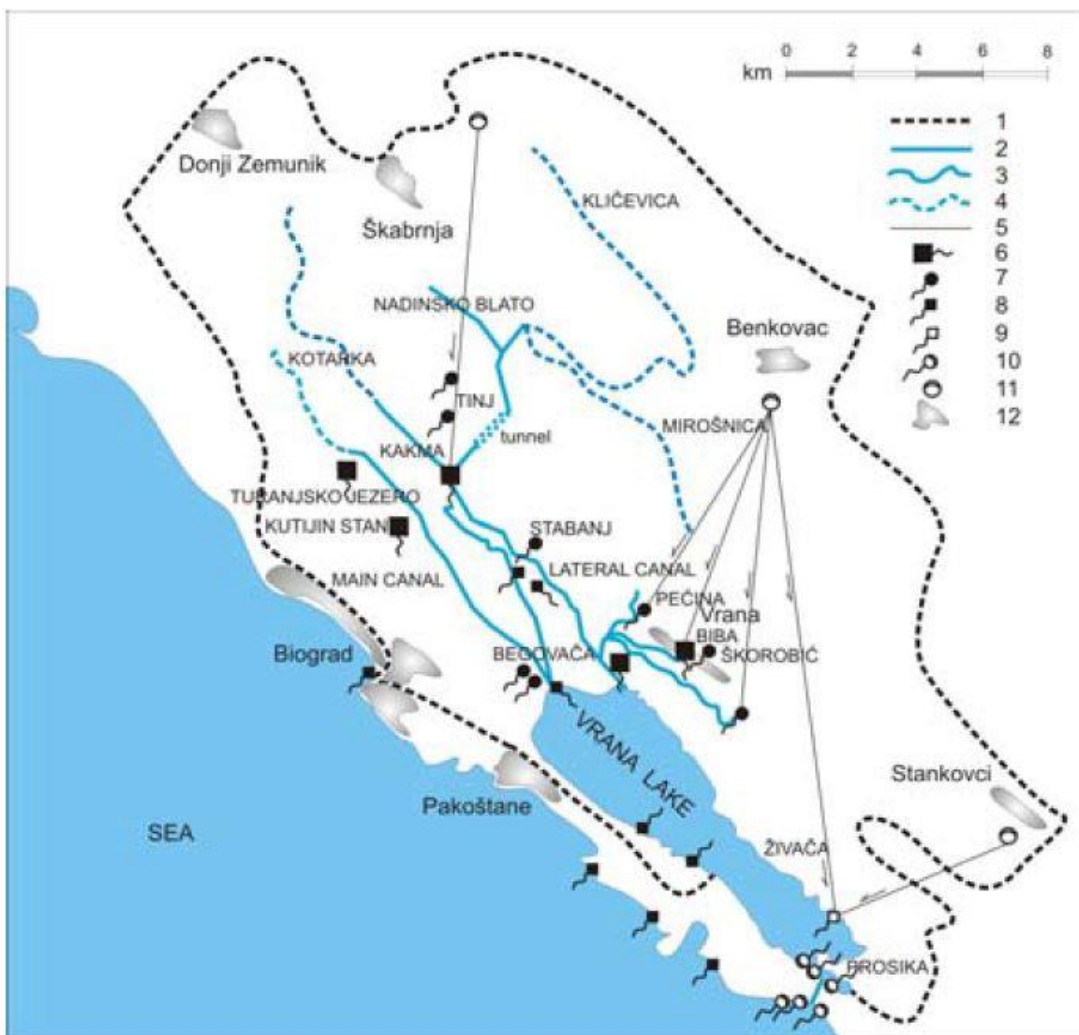


Figure 3-24: Schematic overview of Vrana lake. Legend: 1 – hydrogeological catchment boundary; 2 – regulation channel; 3 – permanent natural courses; 4 – intermittent natural courses; 5 – underground hydrological connection; 6 – water intake for water supply; 7 – affluent natural spring; 8 – brackish spring; 9 – vrulja; 10 – estavelle; 11 – ponor; 12 – settlement.



The area of depression of the Vransko Polje belongs to the type of structural karst fields. The basic feature of these fields is the steep sides, the flat bottom filled with younger sediments, and the karst hydrology. Depression of the Vransko Polje is structurally predisposed. Specifically, the bottom of the field is predisposed by a syncline, constructed of waterproof deposits of the Eocene flysch. The lateral, elevated sides of the field belong to the wings of the anticline, which are constructed of water-permeable ore limestone of the Cenomanian.

Water flows into the lake surface and underground. Superficially, water is drained from four river basins: Kotarka (131 km<sup>2</sup>), Kličevica (50 km<sup>2</sup>), Tinj-Kakma-Stabanj (122 km<sup>2</sup>), Pečina-Biba-Škorobić-Živača (167 km<sup>2</sup>) (Figure 3-27Figure 3-24). The main feature of surface tributaries is the marked annual difference in flows. During the cold part of the year, they abound in water, while during the summer they usually dry out.

At the very perimeter of the field, along its northeast and western edges, water appears from numerous permanent and occasional springs. The springs include Škorobić, Vrilo, Biba and Pečina sources. Also, there is movement of water through the SW carbonate ridge, in its southern part. This movement of water is twofold: in the humid period freshwater drains towards the sea, and in the case of droughts, the sea water flows into the lake.

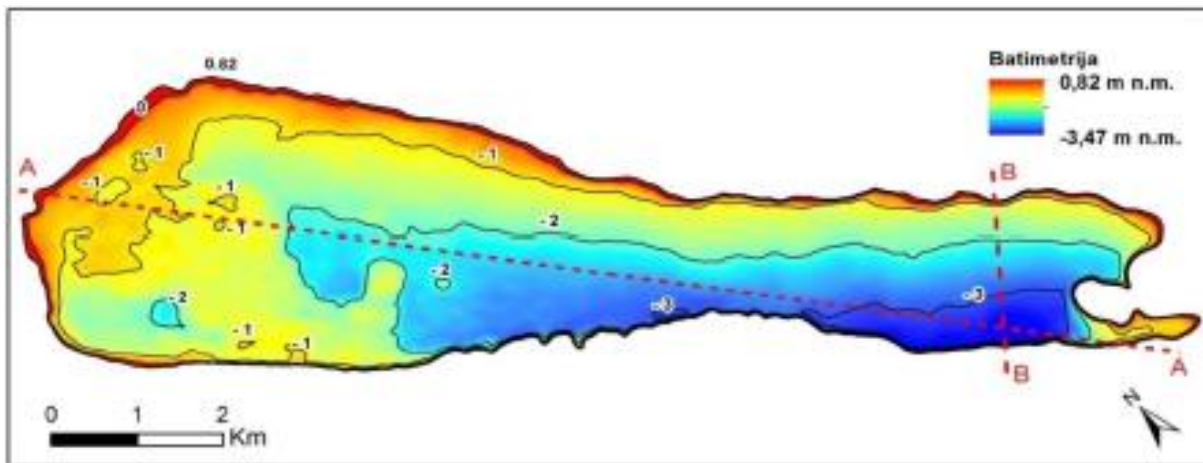


Figure 3-25: Bathymetric survey of the bottom of Vrana Lake: situational imaging (Rubinić, 2014, according to data measured by Teodolit 2012).

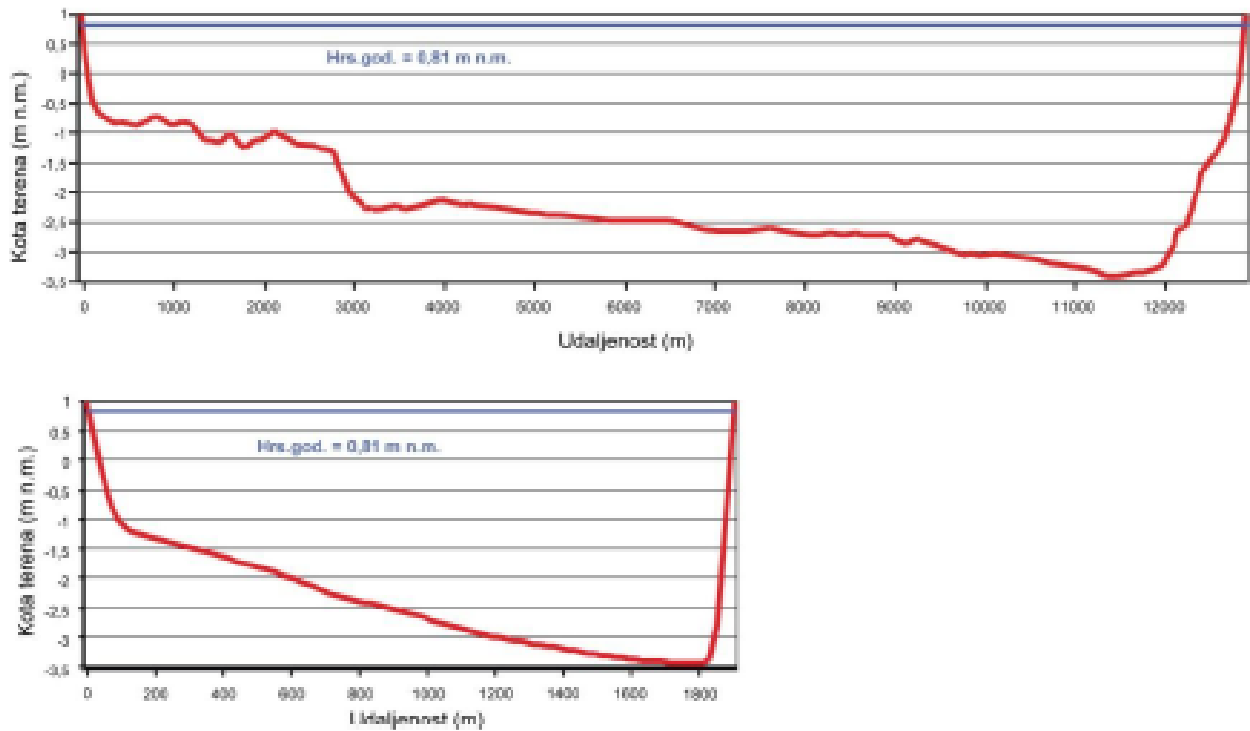


Figure 3-26: Bathymetric survey of the bottom of Vrana Lake: cross section A - A, cross section B-B (Rubinić, 2014, according to data measured by Teodolit 2012).

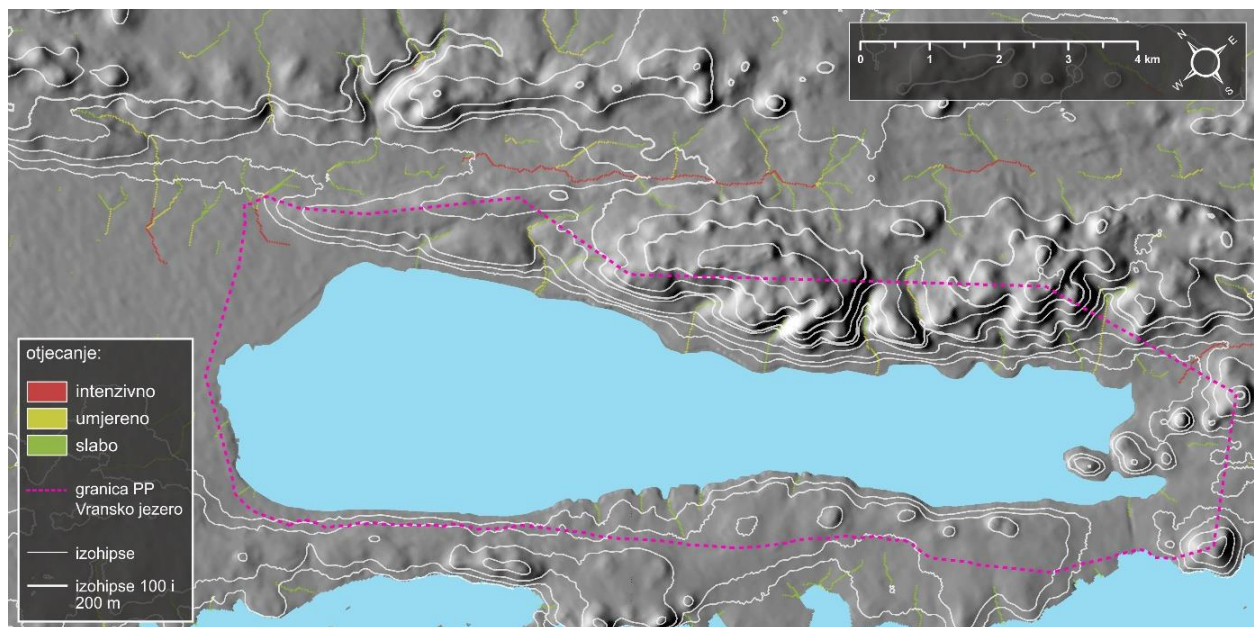


Figure 3-27: Map of the surface runoff of the Nature Park Vransko Jezero area. Legend: Otjecanje – runoff; intensive – red; moderate – yellow; weak – green. Purple dashed line - Park border; gray lines – height contours; white lines – 100 and 200 m contours (Perica et al., unpublished).

### **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 of site geomorphology (methods, discussion, maps)**

#### **3.3.4.1. General relief characteristics present in the Nature Park Vransko Jezero**

The most relevant geomorphological maps are given in section 3.3.2. and all of them can be used in the following chapters. Therefore, the current relief forms will be presented in this section.

The starting point for all geomorphological features in the Park area is the lithology in combination with climatic characteristics of the area. The main morpho-structural features of the Park are results of basic tectonic (mostly Mesozoic) structure of the wider area together with younger movements and postglacial sea-level rise. As already mentioned above, there are two prevailing morpho-structural units: ridges-anticlines and depressions-synclines. In general, anticlines correspond to positive relief features. The anticlines-synclines system is the consequence of sedimentary compressional tectonics, with the maximal stress, oriented SW-NE at the end of Mesozoic, followed by the formation of flysch basins and continued compression (Vlahović et al., 2005). As a result, complex faulted and folded structures were formed. In the wider Park area folds are especially well visible. Exposition of crushed and cracked carbonate structures to subaerial conditions served as the base for karstic relief development. It is assumed that karstification may have started during Miocene (Mocochain et al., 2009) and it is being continued until the present days. Carbonates are predominant lithology in the subaerial part of the Park. Consequently, karstic relief dominates as well.

Karstic relief forms in the Park are more diverse and significantly larger on the horizontal surfaces and slightly inclined slopes (up to 12°), due to the loss of the surface water in the underground and translation of corrosional processes in the same direction. The main climatic characteristic of the Park area is the Mediterranean pluvial regime, with higher precipitation during cold season. Park is significantly affected by the proximity of the sea, resulting in a negligible number of cold days and negligible influence of ice-related karstic processes. A considerably high number of hot days during the warm season result in a general drought, thus, the intensity of corrosion and biocorrosion is low.

The main relief feature of the Park is the lake itself – partially drowned karstic polje. The whole depression is a structural polje: structurally predisposed depression of flat bottom and relatively steep sides, filled with thick sediments and characterized by karstic hydrology. Due to the repeated flooding, the Lake was artificially connected with the seabyprosika channel. Part of the water is being used for the water supply and melioration processes.

Karrens are common surface forms in the Park area and occur in various forms (rills, roundkarren etc.) and dimensions (less than 1 cm – to >10 m). The main feature of the endokarst in the Park zone is one cave on the SE ridge.

Slope processes are common along the carbonate slopes within the Park, mostly as gully formation and related processes. Gullies occur on slopes 12-32° and are mostly structurally predisposed. Movement of material along gullies resulted in soil and vegetation removal and outcropping of the bedrock. At the foot of such slopes, proluvial fans were formed and occasionally lake beaches are formed by waves.

Rock collapses are most common on slopes inclined > 32° and in some places, cliffs were formed. The same cliffs represent high coasts of the Lake, mostly along both ridges. Low coasts were developed on the NW part of the lake, where sediment supply is enhanced.

Anthropogenic relief forms are present in the Park mostly as stone walls, especially seaward on the SW ridge.

### ***3.3.5. Analysis of recent trends of the geomorphological processes (methods, discussion and maps of evolutionary trend)***

#### ***3.3.5.1. Formation of the Vransko lake***

According to Fritz's 1984 theory, the formation of the lake is directly linked to the rise of the world's sea level. About 25,000 years ago the sea level was 96.4 m lower than the present, and since then it has been rising steadily. As long as the sea level was lower than the waters that affected the Vrana depression, the water flowed from the depression into the sea through the limestone ridge near Prosička, and the paleo relief deepened. After equalization of the sea level and the bottom of the depression, sediment deposition begins and Lake Vrana becomes an occasional accumulation during high rainfall. Comparison of the genetic structure of the Quaternary deposits and their age with the climatic conditions of the respective geologic periods support this interpretation of evolution. Then Vransko lake becomes a permanent reservoir that, according to Fritz's theory, should last another 4,600 years. Recent research on sedimentation processes in the study area changes the above mentioned Fritz assumptions. According to the results of sedimentological surveys (HGI, 2013; Ilijanić et al., 2013.) the dominant influence on the appearance of Vransko lake, with the changes in sea level, was the former Lake Pirovac, which spread in the area of today's Bay of Pirovac. Namely, according to the remains of freshwater ostracod fauna found in the sediment of Pirovac Bay, it can be concluded that there was also a freshwater phase of this very limited sea bay conditioned by the orography of the surrounding terrain.

The history of Vransko Lake was restored on the basis of the sedimentation dating of <sup>14</sup>C using the accelerator mass spectrometry (AMS) technique of the <sup>14</sup>C determination. Late Pleistocene and early Holocene (11,000 BC), with about 55 m lower sea level, drought conditions prevailed in the area of the present lake, with occasional occurrence of torrential waters and occasional barrage of sediment into the area and leakage of water through the crossed reef. to the then lake of Pirovac. By further raising the sea level to about 25 m lower than the current level (about 9,000 BC), the sea level in the Lake Pirovac also increases, which slows down / prevents the leakage of water from Vransko Lake to Lake Pirovac. Also, the

present Vransko Lake is beginning to form, which in this way is connected to the Pirovac Lake, up to about 7,500. before n.e. Then the sea begins to penetrate into Pirovac Lake and gradually affect Vrana Lake.

About 4,000 years ago n. e. the current Vransko lake water regime was established communication between the sea and the lake due to the natural predisposition (karstic aquifer) and anthropogenic actions (artificial channel construction) may affect the influence of lake ecosystem, sedimentation rate and sediment composition. The karstification processes that took place during the development of the relief, while developing underground karst forms and spaces at much greater depths than existing active hydrological links between the lake and the sea (Ford and Williams, 2007), conditioned the openness of aquifers and the presence of deep enclosed areas in the hinterland filled with salty seawater (Kapelj S. et al. 2003, 2008). Deep below the terrain level of the Vransko field extends a layer of saline water. The intensity of the connections of this layer with fresh groundwater depends on the position of the waterproof flysch layers. (Rubinić 2014).

### **3.3.6. Conclusion**

#### 3.3.6.1. Problems and solutions

Combination of limnic and karst relief in areas of highly productive agricultural area in combination of ornithological reserve and nature park - many conflicts present in all directions. Particular attention should be paid to monitoring the communication of Vransko Lake and sea water at the locations of coastal springs and hot springs in the lake and the sea. In order to find their location, classical methods of hydrological measurements and sampling, it is necessary to supplement the methods of remote sensing, using infrared satellite or aerial images. AN

#### 3.3.6.2. Analysis of data quality

New data is needed – some maps may be improved; new maps of saline intrusion or so may be produced.

### 3.4. Banco Mula di Muggia

#### 3.4.1. General site description

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

The Banco Mula di Muggia is located in Friuli Venezia Giulia Autonomous region (Figure 3-28). 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 3-29). 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 3-28 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 3-29 Location of Grado ([www.viamichelin.com](http://www.viamichelin.com)).

#### 3.4.1.2. Physical and environmental features (synthesis)

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 3-30).

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 3-32).

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 3-30-Figure 3-31). 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.

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 3-33). 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.



*Figure 3-30 Aerial view of the Banco Mula di Muggia.*





Figure 3-31: The western part of the Banco Mula di Muggia: the sandy bars and the muddy intertidal zone are visible.

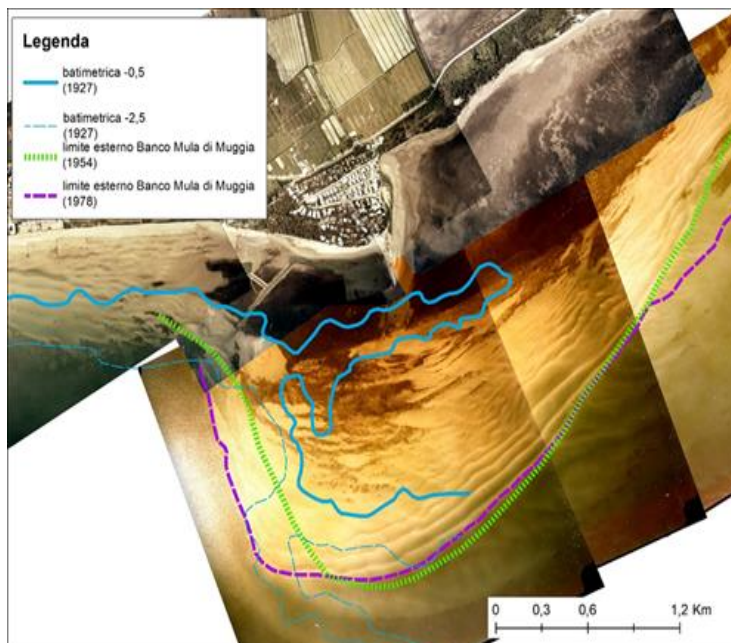


Figure 3-32 Bathymetric contours v/s years in the western part of the Banco Mula di Muggia.

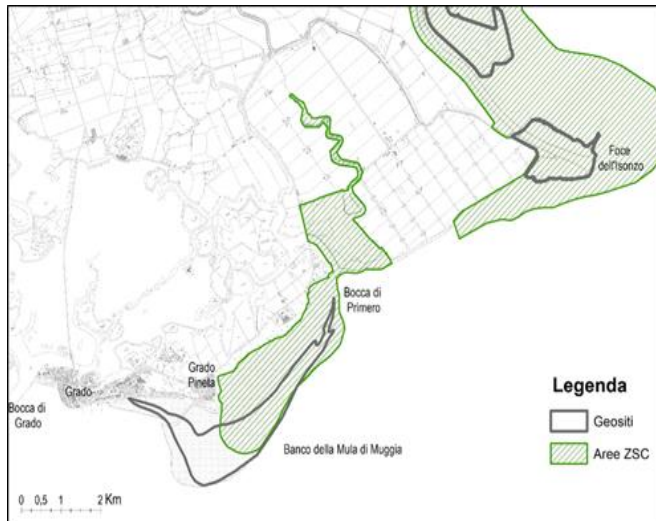


Figure 3-33: Site of Community Importance (ZSC, in Italian) and geosite perimeter.

#### 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 Law 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 3-34): 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 3-35) 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.

The Municipal Master Plan of Grado defines the whole inland as area for marine tourism development, but the wooded area between Camping and Grado Pineta has a lower anthropic pressure and this part of beach is identified as an ecological corridor (Figure 3-36)

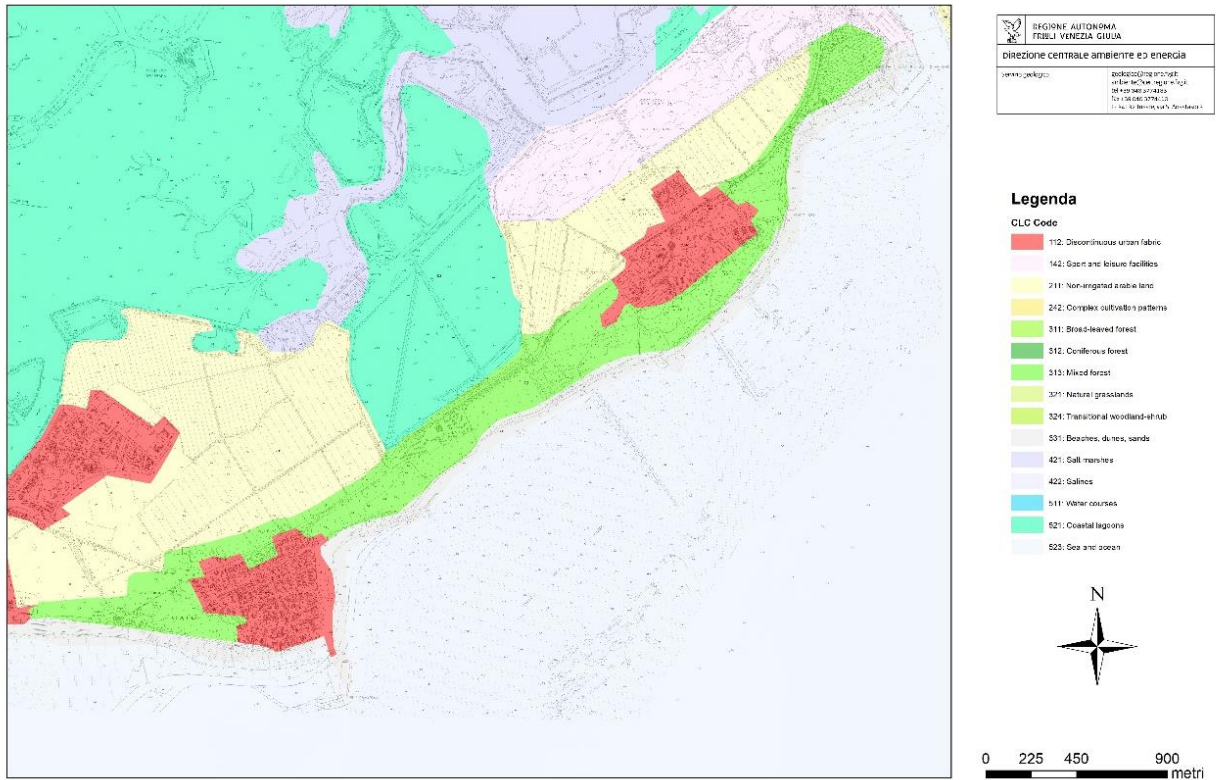


Figure 3-34: Map of land use from CORINE Land Cover (CLC) inventory (land.copernicus.eu).

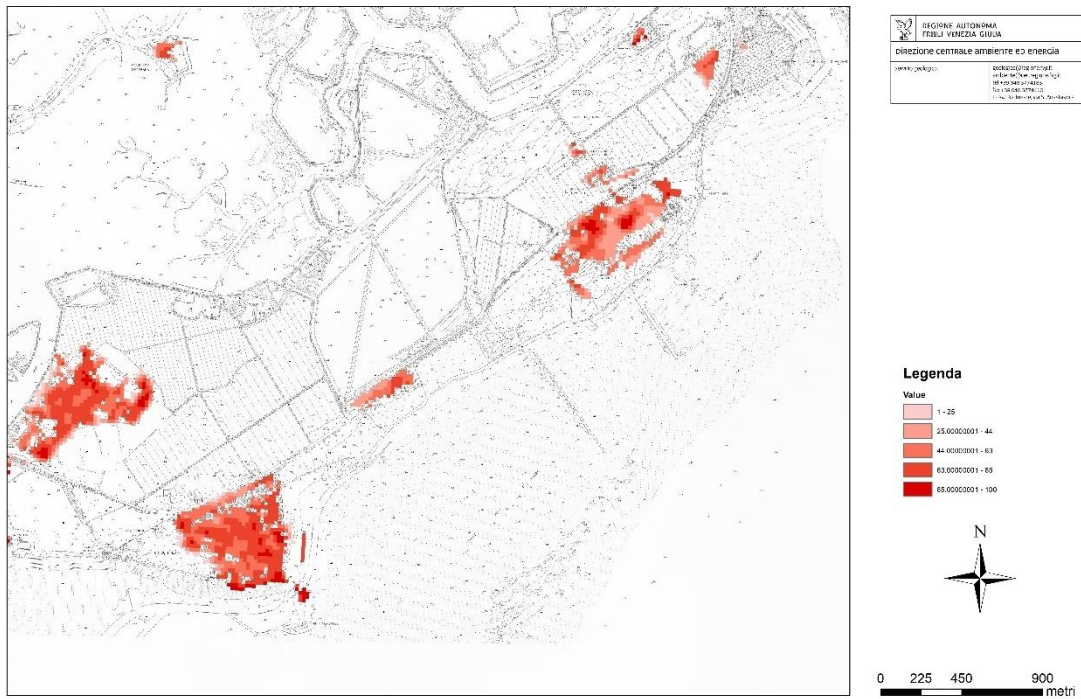


Figure 3-35: Imperviousness map (land.copernicus.eu)

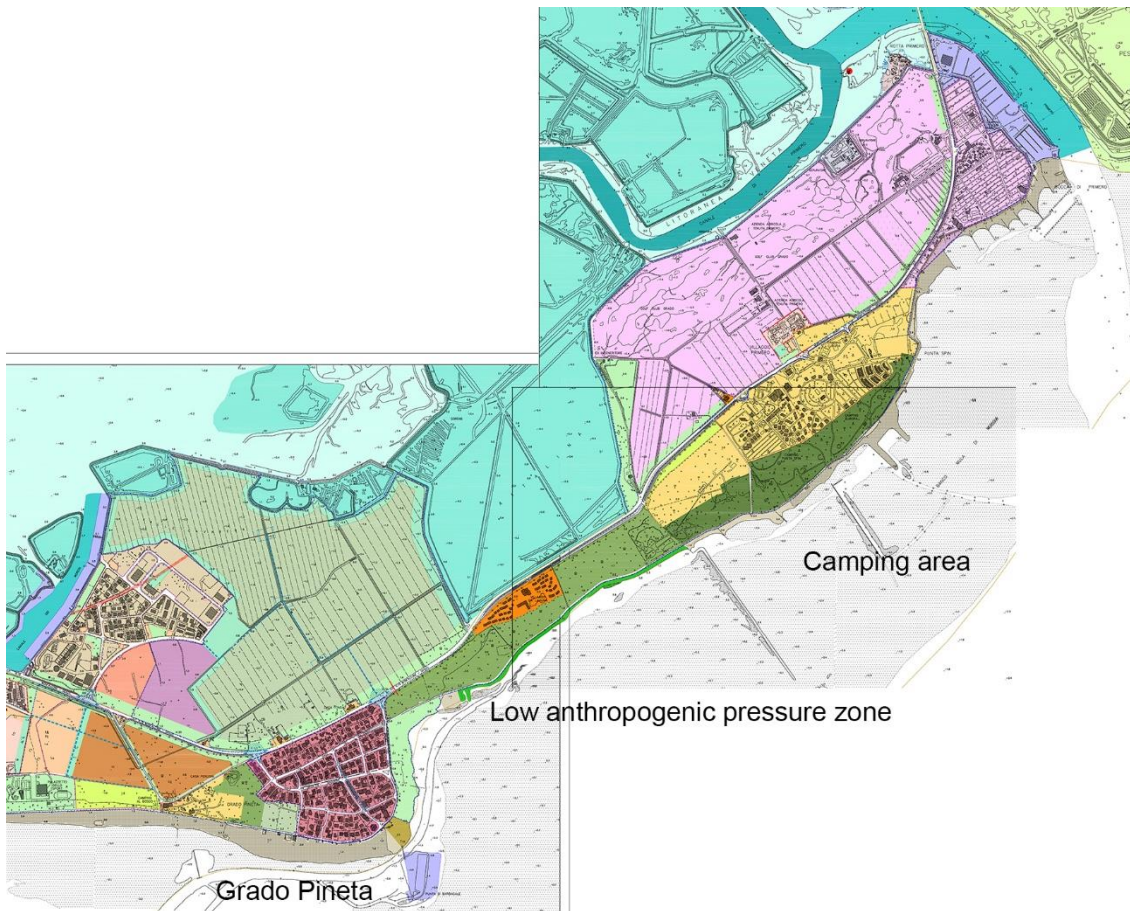


Figure 3-36 Extract from the Municipal Master Plan of Grado, the three different pressure zone are visible; from left, can be distinguished the Grado Pineta district, the low pressure wooded area and the camping area. (Municipality of Grado)

#### 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 wilderness 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.

These are great problem 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 Muggiais 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 geomorphological data, studies, maps**

#### **3.4.2.1. Cartography**

For this study, an investigation of the available historical cartography, of the cartography of the Military Geographical Institutes and Hydrographic Institutes of the Navy was carried out, also taking up the analysis of several previous studies: Varani&Zunica, 1974, Volta Study (1979), Brambati Study (1985), Favretto et. al. (2004), Timar et al. (2006).

The most interesting cartography is reported below:

- *Kriegskarte von Zach 1798 – 1805* - Carta del Ducato di Venezia, available at the San Giovanni library of the University of Trieste in the 2005 edition of the Benetton foundation, 1:28.800 scale.
- *Carta di cabotaggio del mare Adriatico*, I.R. Istituto Geografico Militare di Milano 1822 -1824, 1:175000 scale, depths reported in french feet; 1 french foot =32.48 cm).
- *Carta corografica del Catasto Franceschino (Franzische Landesaufnahme)*, 1830 1:28800 scale, available at the Archivio di Stato of Trieste and online at *MAPIRE The Historical Map Portal* (<http://mapire.eu>).
- *Carta topografica della Venezia*, 1849 scale 1:86400, reported in *Studio Volta* (Regione Autonoma del Friuli Venezia Giulia, 1979). *Carta Golf von Trieste*, 1867 1: 80000 scale, displayed in the *Studio Volta* (1979);
- *Franzisco – Josephinische Landesaufnahme* (1869-1887) available at <http://mapire.eu> as *The Third Military Survey* (Molnar &Timar, 2009).

- Topographische Karte, *Militargeographisches Institut* 1894/1896, 1:25000 scale, contained in the *Studio Volta* (Regione Autonoma del Friuli Venezia Giulia, 1979);
- Topographic maps of IGM (Istituto Geografico Militare) in 1:25000 scale, available at Università IUAV di Venezia, and Tavole IIM (Istituto Idrografico della Marina) in 1:12000 scale (Table 3.1 and table 3.2).

Table 3-1: Topographic maps of IGM (Istituto Geografico Militare) in 1:25000 scale, available at the IUAV of Venezia

Code ID	Name	Survey year	Update
40IISO1915	Punta Sdobba	1915	
40IISE1917	Grado	1915	1917
40IISE1927	Grado	1896-1897	1927
40IISO1938	Focedell'Isonzo	1936	
40IISE1938	Grado	1896-97	1938
40IISE1949	Grado	1896-97	1949
40IISO1949	Focedell'Isonzo	1938	1949
40IISO1959	Focedell'Isonzo	1959	

Table 3.2 – I.M.M. maps.

Code ID	Name	Survey year	Update
Grado 1928	Marina di Grado	1927	
Grado 1939	Marina di Grado	1927	1939
Grado 1949	Marina di Grado	1927	1949
Grado 1959	Marina di Grado	1927	1959

#### 3.4.2.2. Aerial photos

Aerial photos and orthophotos regarding the study area are:

- **1945:** black and white IGM aerial photos (Istituto Geografico Militare).
- **1954:** black and white GAI (Gruppo Aereo Italiano) aerial photos, available at Dipartimento di Matematica e Geoscienze, Università degli Studi di Trieste.

- **1978:** color CGR aerial photos (*Compagnia Generale Riprese-aeree*) on behalf of CNR (*Consiglio Nazionale delle Ricerche*), available at the Dipartimento di Matematica e Geoscienze, Università degli Studi di Trieste.
- **1984:** black and white Regione Friuli Venezia Giulia aerial photos available at the IGM archive, on <http://intelspeedcontest2006.tiscali.it/voli/> and reported in Marocco (2000).
- **1990:** color CGR aerial photos, lot 10 Trieste.
- **1997:** black and white ortho-photos available on Geoportale.
- **2003:** aerial photos taken at low tide provided by ARPA FVG (*Agenzia Regionale per la Protezione dell'Ambiente del Friuli Venezia Giulia*) in geo-referenced digital format. **2003:** digital CGR ortho-photos provided by Regione Autonoma Friuli Venezia Giulia. These photos do not interest the offshore sector.
- **2007 – 2008:** digital ortho-foto available on Geoportale Nazionale.
- **2008 - 2010:** digital ortho-photos provided by Protezione Civile of Friuli Venezia Giulia made in conjunction with Lidar survey, partly in 2008 and partly in 2010.
- **2012:** digital ortho-photos by HelicaSrl on behalf of Protezione Civile FVG, available on Protezione Civile webGIS. These photos do not interest the offshore sector.
- **2014:** digital AgEA ortho-photos (Agenzia per le Erogazioni in Agricoltura) provided by Regione Autonoma Friuli Venezia Giulia. These photos do not interest the offshore sector.
- **2017:** Sentinel 2 images (01/01/2017 10m resolution), available on ESA server ([https://sentinel.esa.int/web/sentinel/sentinel\\_data\\_access](https://sentinel.esa.int/web/sentinel/sentinel_data_access)).
- **2018:** Sentinel 2 images (10/02/2018 10m), available on ESA server ([https://sentinel.esa.int/web/sentinel/sentinel\\_data\\_access](https://sentinel.esa.int/web/sentinel/sentinel_data_access)).

The photos were used to recognize the landforms, identify anthropogenic changes and to interpret the phenomena in progress. A part of them were used to map the landforms over time, to identify some geomorphological indicators and to support the quantitative and budgetary analysis.

#### 3.4.2.3. Topo-bathymetric surveys

For the study area four campaigns are available (Figure 3-37):

- 1968 survey by CNR - Gruppo di Studio dei Litorali
- 1979 survey by Studio Volta on behalf of Regione Autonoma Friuli Venezia Giulia
- 1985 survey by Brambati on behalf of Regione Autonoma Friuli Venezia Giulia, Direzione Regionale dei lavori Pubblici, Servizio dell'Idraulica.



- 2007 survey by *Università degli Studi di Trieste and Istituto Nazionale di Oceanografia e Geofisica Sperimentale* within the Progetto Nazionale V.E.C.T.O.R. (*Vulnerabilità delle coste e degli ecosistemi marini italiani ai cambiamenti climatici e loro ruolo nei cicli del carbonio mediterraneo*).



Figure 3-37: Available topo-bathymetric surveys for the study area.-

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

#### 3.4.3.1. The “Change we care” survey

In order to evaluate the morphological variations of the Banco della Mula di Muggia, a topo-bathymetric survey was carried out during 2019.

The surveys were carried out between March and July 2019, except for the multi beam survey that was carried out in 2018. The adopted coordinate system is ETRS89-UTM33N. All the elevations are referred to the IGM Datum as recorded in the regional benchmark

About the sampling mesh, a double approach was chosen:

- parts of the reliefs are linear, perpendicular to the shoreline and geometrically distributed for a total of 30 profiles (Figure 3-38).
- the remaining surveys were carried out in order to detect considerable morphological characteristics. Furthermore, the acquisition was performed in more detail in corresponding of evidence morphological variations such as bars, troughs, channels.

The positioning of 15 of the 30 profiles follows the need for comparison with the topo-bathymetric data recorded in 2007 and 1968. 13 profiles were added between profiles 1 and 9 of 1968 with the aim of increasing detail and improving the topographical reconstruction of the Banco della Mula di Muggia, while two further profiles were placed east of the easternmost profile of the 1968 (profile 15) in order to enlarge the surveyed area at the mouth of the Isonzo River.



*Figure 3-38: Sampling plan for the 2019 survey, subsequently integrated.*

To obtain an accurate and detailed survey of the morphology different survey techniques were used:

- Topography with GNSS system

The topographic surveys were carried out on the beach and on the intertidal zones where the water depth was not enough for the echo-sounder to measure. 28 of the 30 profiles perpendicular to the shoreline were surveyed (Figure 3-39) and 11 profiles on the Bocca di Primo (Figure 3-40) were integrated, acquiring the morphologically significant points.



Figure 3-39: Topographic surveys during 2019, shoreline surveys



Figure 3-40: - Topographic surveys during 2019, Bocca di Primero.

The ellipsoidal elevation (WGS84) was subsequently corrected based on the ellipsoid / geoid delta calculated for the reference benchmark, converted into geoidic using the IGM Convergo software. More than 4800 points were acquired along approximately 17 km between the Bocca di Porto di Grado and the mouth of the Isonzo River. The topographic surveys were carried out on foot and by pedal boat according to the logistic needs (Figure 3-41).

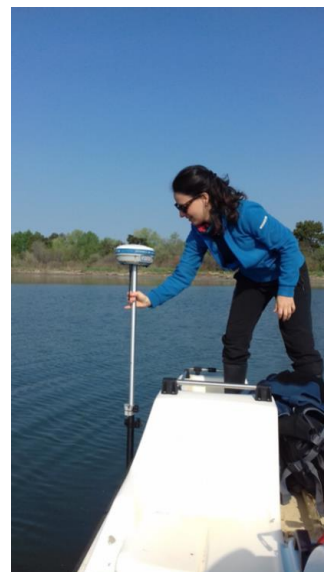


Figure 3-41: Topographic surveys during 2019.

- Photogrammetry with APR:

Aerial photogrammetric survey was performed with APR (Remote Piloted Aircraft) DJI Phantom RTK (Figure 3-42) connected to the Italpos NRTK correction network on the sandy emerged and intertidal bank. The photogrammetric surveys were carried out on 25/05/2019 with 3 flights at 72m SFC altitude, for 380

shots and a coverage of about 185 ha. The frames were processed in AgisoftPhotoscan Professional in order to obtain geo-referenced orthophotos and DSM. The resulting images were used only as orthophotos (Figure 3-43) because their accuracy of the elevation of the DSM was lower than the desired value, as it was not possible to detect ground control points.



Figure 3-42: The APR (Remote Piloted Aircraft) DJI Phantom RTK used for the survey.



Figure 3-43: Orthophoto obtained from the APR survey.

- Single Beam bathymetry

6 campaigns were carried out in the months of March, May and July 2019. The acquisition system was as follows: OhmexSonarmite 3.0 digital echo sounder, GNSS Stonex S9III in NRTK mode, CommTec Navigator Professional 6.42 acquisition software (Figure 3-44). The software saves the data collected by the GNSS and the transducer with the rate of 1Hz. The digital sounder operates at a frequency of 235 KHz, with a 10 ° cone and accuracy of  $\pm 0.025$  m RMS.

The acquired profiles overlap the topographic profiles landward for further calibration and control of the bathymetric survey.



*Figure 3-44: Equipment for bathymetric surveys during 2019*

In the processing phase, the spatial distribution of the profiles, did not appear adequate to represent correctly the western limit of the Banco della Mula di Muggia since this limit has a sub-parallel orientation

with respect to the profiles. Supplementary surveys were therefore carried out in order to have adequate coverage of the western limit of the bank (Figure 3-45).

Supplementary surveys were carried out with the aim of identifying and representing specific morphological elements such as artificial canals (Figure 3-46), the Primero ebb delta and the mouth of the Isonzo River.

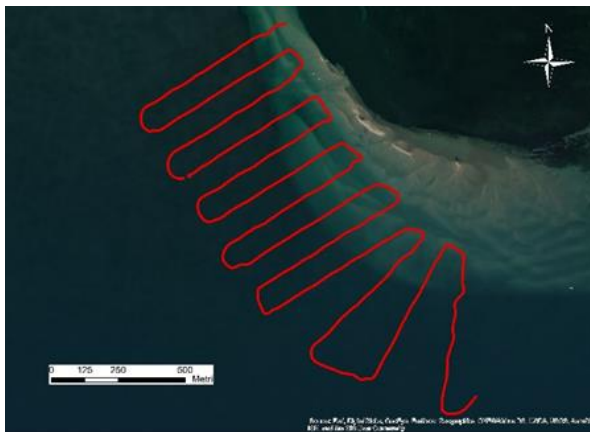


Figure 3-45: Supplementary bathymetric surveys during 2019 at the limit of the bank.



Figure 3-46: Supplementary bathymetric surveys during 2019



Figure 3-47: The whole bathymetric surveys during 2019.

The Single Beam bathymetric data (Figure 3-47) were checked for the presence of spikes and were corrected to obtain the ellipsoidal elevation of the bottom. Subsequently, the geodetic elevation was calculated by applying the delta taken from the reference benchmark using the IGM Convergno software.

Finally, they were corrected for the sound speed delta by checking the points that fell overlapping with the Multi Beam data and checking the congruence with the topographic points measured with GPS. Subsequently, a moving average of order 5 was applied to some measurements to correct the oscillations present not due to the morphologies but to the wave motion.

#### 3.4.3.2. Other recent data - Multi beam bathymetry

A Multi Beam survey was carried out on the Primero channel (Figure 3-48) by © Elmar s.r.l. on behalf of the Autonomous Region of Friuli-Venezia Giulia.



Figure 3-48: The area covered by the multi beam bathymetric surveys during 2019.

### 3.4.4. Current status of site geomorphology (methods, discussion, maps)

#### 3.4.4.1 Methods

In order to evaluate the morphological

After being filtered, all the topo-bathymetric data acquired in 2019, were uploaded into GIS with the aim of creating a digital terrain model (DTM) of the study area. In particular, topographic points, single beam bathymetric points and the regular grid of multi beam bathymetric points were used, adding linear features as constraints.

The goal was to have an updated and detailed morphological conformation of the area, to be able to perform a comparison to the previous DTMs and to interpret the sedimentary budgets and the evolutionary dynamics in progress.

#### 3.4.4.2 Geomorphological description

Once the model was created, the DTM was divided into four areas (Figure 3-49):

1. Coast in front of the city of Grado
2. Banco dellaMula di Muggia- in strict sense (back-barrier area, bar and trough area and surfaced bank)
3. The mouth of Primero
4. External area of the Banco dellaMula di Muggia



5. Coast between the mouth of Primero channel and the mouth of the Isonzo River.

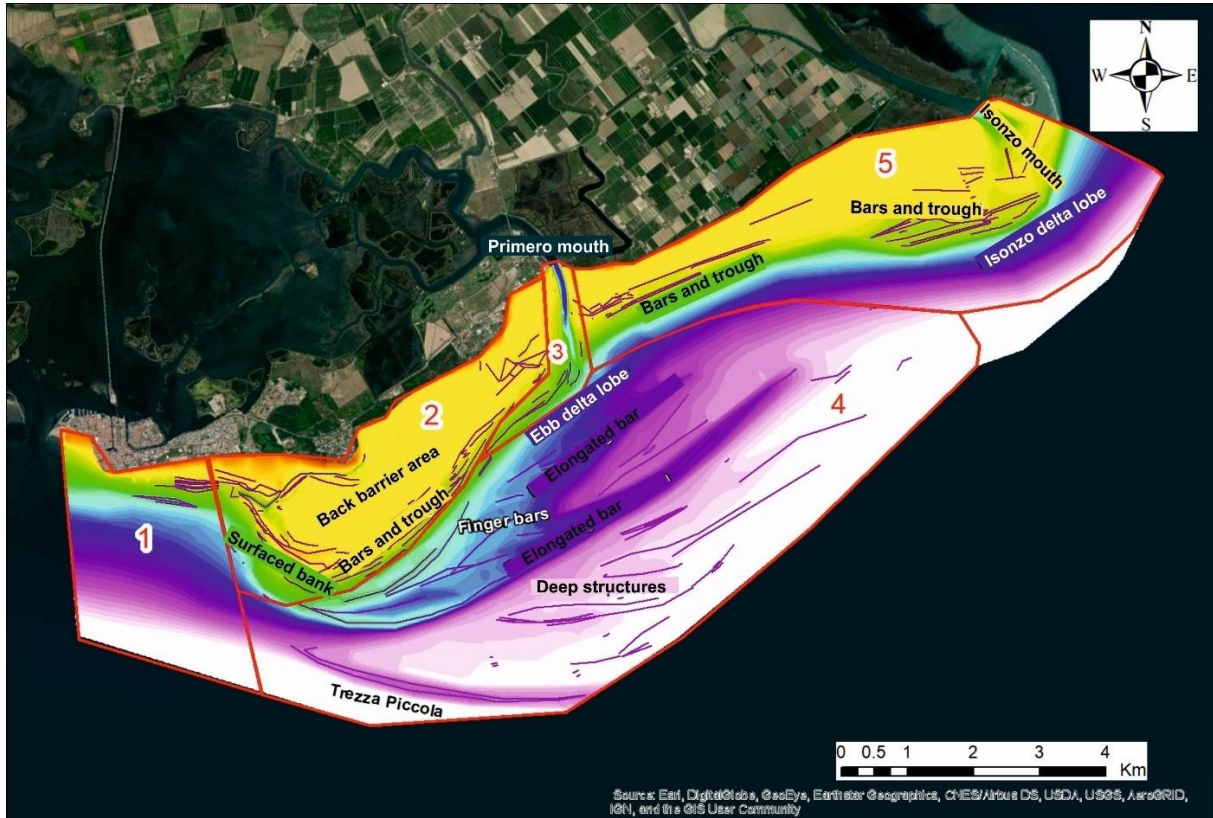


Figure 3-49: Digital model of the study area with indication of morphologies

The coast in front of the city of Grado (1) has no structures (Figure 3-50). Between 0m and -5m, the isobaths follow the trend of the shoreline. Within -3m of depth, there are some bars, parallel to the shore line

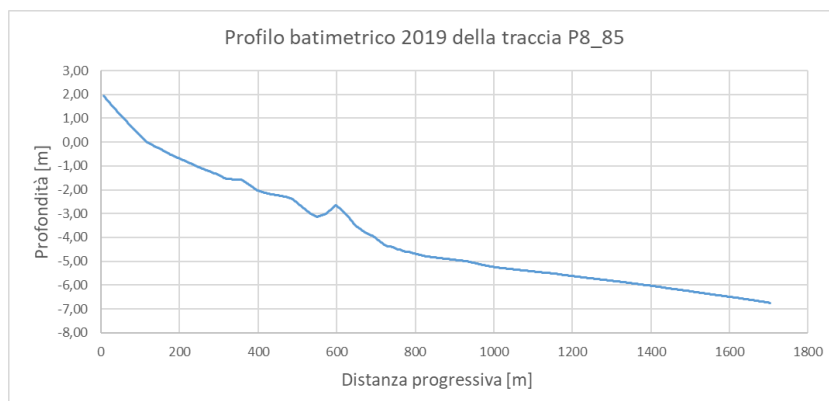


Figure 3-50: Example of bathymetric section in area (1)

The Banco della Mula di Muggia (2) is made up of a back-barrier plane between 0m and -1m. At the south-western edge, there is an emerged bank (maximum height of + 0.51m) in the shape of a concave crescent towards the shore, which continues towards the NW with gradually lower elevations, while towards the NE it develops in a system of parallel bars that go up to the mouth of Primero Lagoon. This bar system extends from approximately -0.5m to -2m ÷ -2.5m of depth.

In addition to the Brambati channel, there is a further canal, which, from the camping area, flows into the Primero Channel. All of these are clearly visible in the DTM (Figure 3-51).

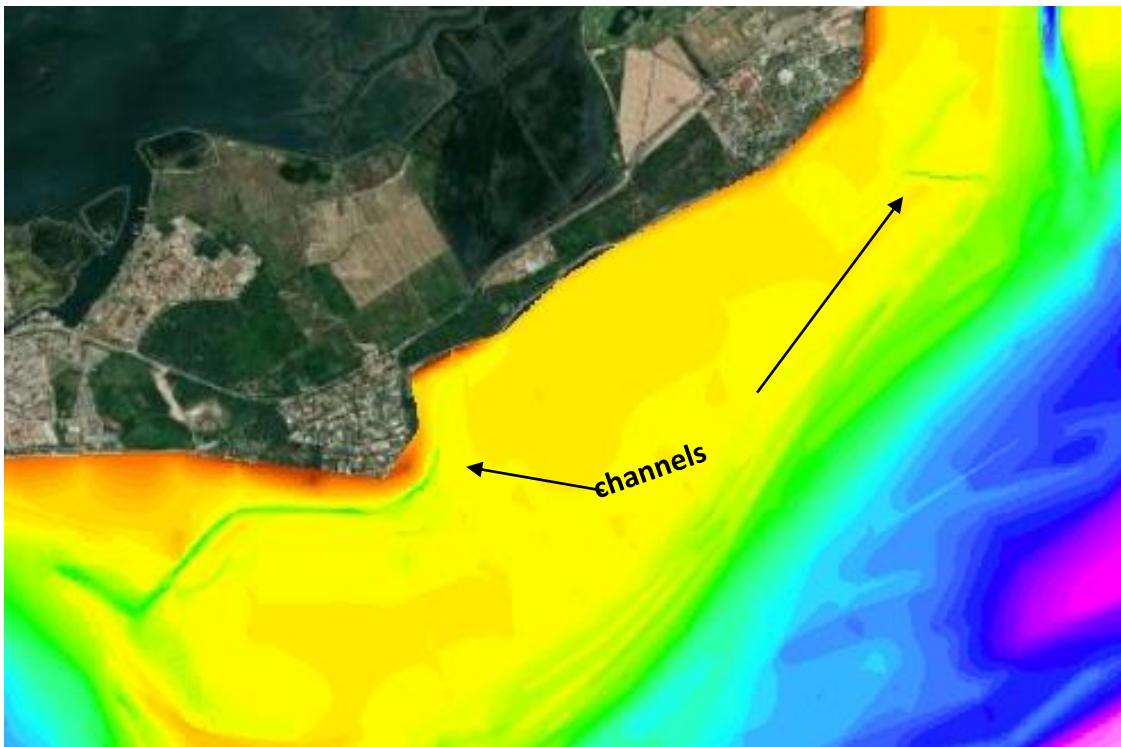


Figure 3-51: Channels in the back-barrier area, highlighted by DTM

At depths greater than -2m ÷ -2.5m, is the external part of the Banco della Mula di Muggia (4). In this area there are two types of structures: (a) finger bars and (b) elongated relict bars.

- (a) Finger bars are bars that develop in series, are generally located at depths between -3.5m and -5m and the crests have a direction of about 70° -80° in respect to the North. The seaward limit of these morphologies can be considered the limit of the closure depth or the base of the upper-shoreface. Two different types of finger bars have been distinguished: one grouping is the one identified on the bypass corridor of the Primero, characterized by very close series of bars and difficult to recognize on the DTM, while the other in the external and deeper layer of the bank

characterized by having more spaced and large bars. The origin of this differentiation is still to be verified.

- (b) The elongated relicted bars are extend from the southern vertex of the bank, curve, and continue straight in the SW-NE direction. In the outermost area of the Banco dellaMula di Muggia there are two of these bars. The external bar, the largest, is about 9-10km long and ends off the mouth of Primero, while its maximum measured elevation is about 2m with respect to the adjacent seabed. The crest of these external bars deepens towards N-E as it distances itself from the southern summit of the Banco dellaMula di Muggia.

For progressive distances greater than 3300m, the morphology of the seabed is rather flat with a very low slope. These morphologies are exemplified by the ideal profile that follows. (Figure 3-52)

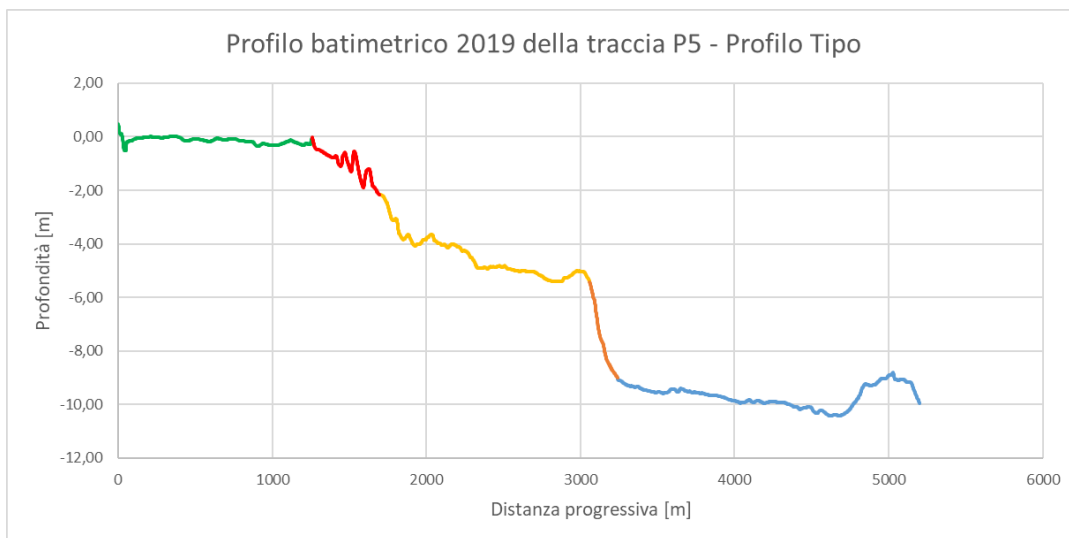


Figure 3-52: Bathymetric profile P5 of 2019 used as a standard profile to describe the different areas of the topographic profile. The colors used identify the identified bathymetric bands. The back counter area is shown in green; in red the band with bars and troughs; in yellow the offshore part of Banco dellaMula di Muggia (shoreface limit); the escarpment in orange; in blue the deep area (Gulf of Trieste) and the TrezzaPiccola.

To the NE, the boundary of the Banco dellaMula di Muggia consists of the mouth of Primero (3). The mouth has a width on the minimum section of 110m with maximum depths of about -6m. The main channel has a length of 1300 m within the study area, and an N-S trend with a curvature towards the west. On the upstream side there is the channel margin linear bar which extends for a length of about 1km and has a bulge in the terminal part towards the sea. At the terminal part of the Primero channel there is the ebb delta deposit, which extends towards the SW identifiable by two rather elongated bars. This sedimentary deposit is set in contact with the Banco of the Mula di Muggia (Figure 3-53).

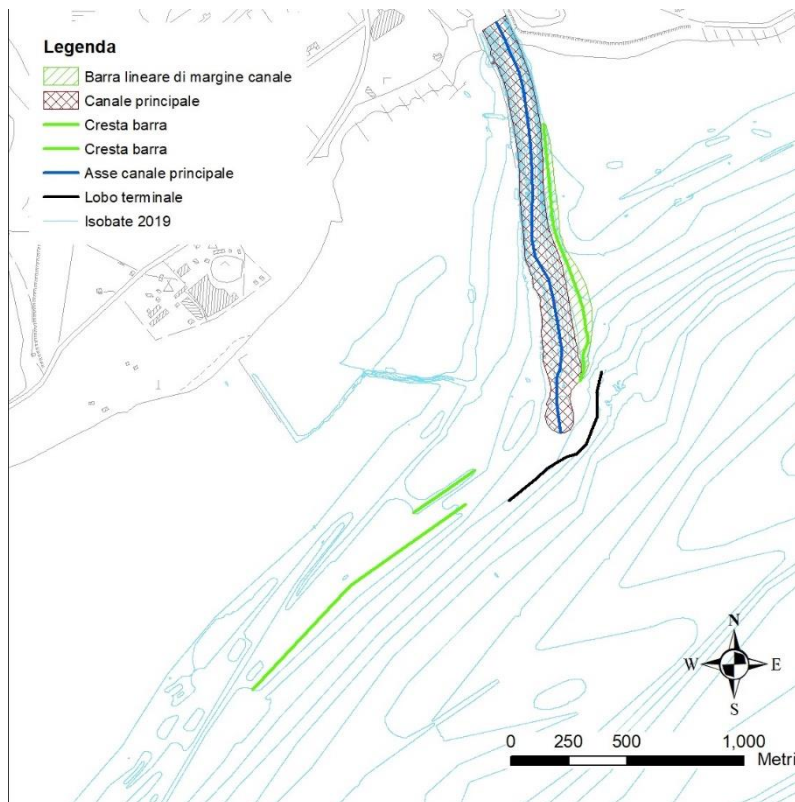


Figure 3-53: Morphologies of Primero mouth

Between the Primero mouth and the Isonzo mouth (5) the coast has a fairly regular trend parallel to the shoreline, for about 4km towards the mouth of the Isonzo. From the progressive of about 420m up to 700m, which corresponds to a depth of -2m, there are bars and troughs, morphologies in line with what was found in the area (2) at the same depths.

The eastern limit of the study area consists of the eastern delta body of the Isonzo river mouth (Sdobb river mouth). The sedimentary body of the Isonzo delta is visible in the section of Figure 3-54. It presents itself with a long plain at low depth, around -0.5m, which extends for about 1km. Subsequently, there are more irregular undulations in the profile, up to 1m deep (1600m from the beginning of the profile). From the depth of -1m to about -2m a system of bars and troughs is clearly visible. The limit of the delta lobe and the beginning of submarine production is highlighted by the presence of a sharp increase in depth, down to -3.5m, followed by a less steep slope.

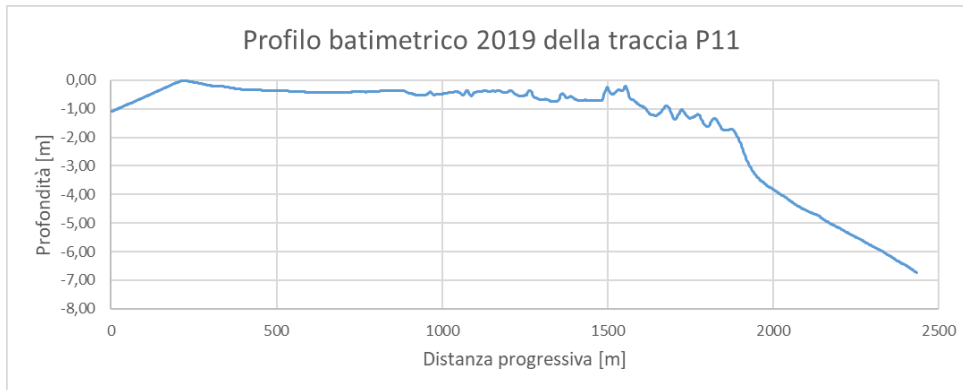


Figure 3-54: Bathymetric profile, representative of the Isonzo delta.

#### 3.4.4.3 Geomorphological map

The DTM obtained from the 2019 surveys and the morphological evidences in the aerial photo of the 2014 and of the more recent available online were used in order to create a detailed, updated geomorphological map of the area, presented in Figure 3-55.

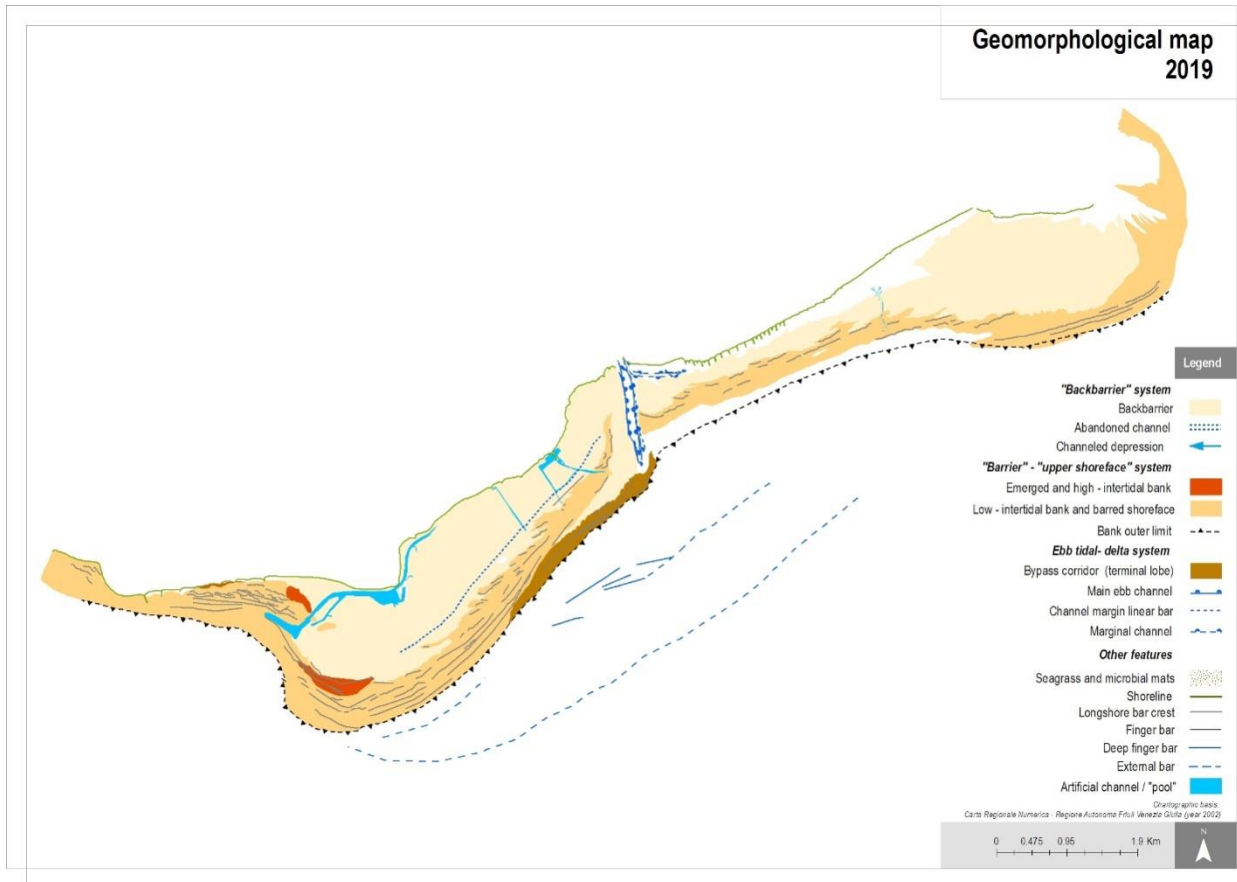


Figure 3-55: Geomorphological map of the study area

### 3.4.5. Analysis of recent trends of the geomorphological processes (methods, discussion and maps of evolutionary trend)

#### 3.4.5.1. Multidecadal analysis

The critical survey of the available data (historical cartography, aerial photos and bathymetric surveys) and the geomorphological analyses carried out in the GIS environment have allowed to define the changes that have involved the coasts between Grado and the mouth of the Isonzo since 1800.

The cartography available from 1822 to 1936 allowed, even with some limitations, to identify and describe the main elements of importance, both in terms of geomorphological aspects and those of land use modification. This led to the reconstruction of the shape, position and characteristics of the Banco della Mula di Muggia, the Primero inlet and the Isonzo delta.

Since 1954 the availability of aerial photos has allowed to give a greater precision and a better morphodynamic connotation to the elements identified, also thanks to the support of some topo-

bathimetric surveys. This led to the construction of four geomorphologic maps covering the same period: 1954, 1978, 2007. Recognition of similar forms in different years has made it possible to understand the evolution of the Banco della Mula di Muggia and the adjacent coasts.

The whole period was divided in 5 time intervals:

1. 1822-189
2. 1894 – 1954
3. 1954 – 1978
4. 1978- 2007
5. 2007 - 2019

A summary of the most important changes in the six-time intervals is presented **Annex 1: Mula di Muggia – additional maps.**

#### 3.4.5.2. Geomorphological trend

The collected data allow highlighting the progressive migration of the western limit of the Bank for the period 1830-2019, with an important modification of the morphological arrangement of the area (Figure 3-56 and Figure 3-57). The migration show a constant trend over time (Figure 3-58 and Figure 3-59).

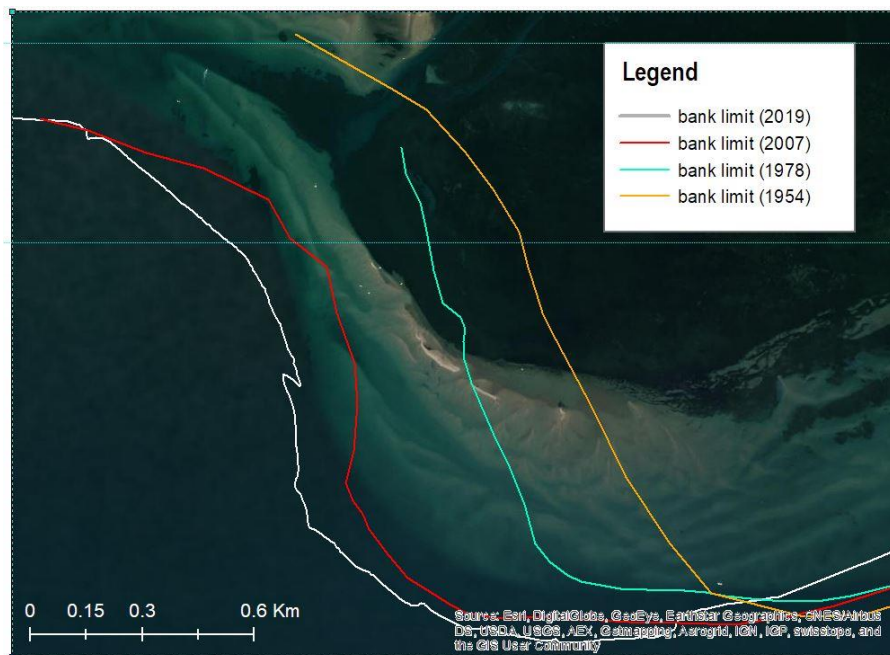


Figure 3-56: Evolution of the western limit of the bank from 1954 to 2019.

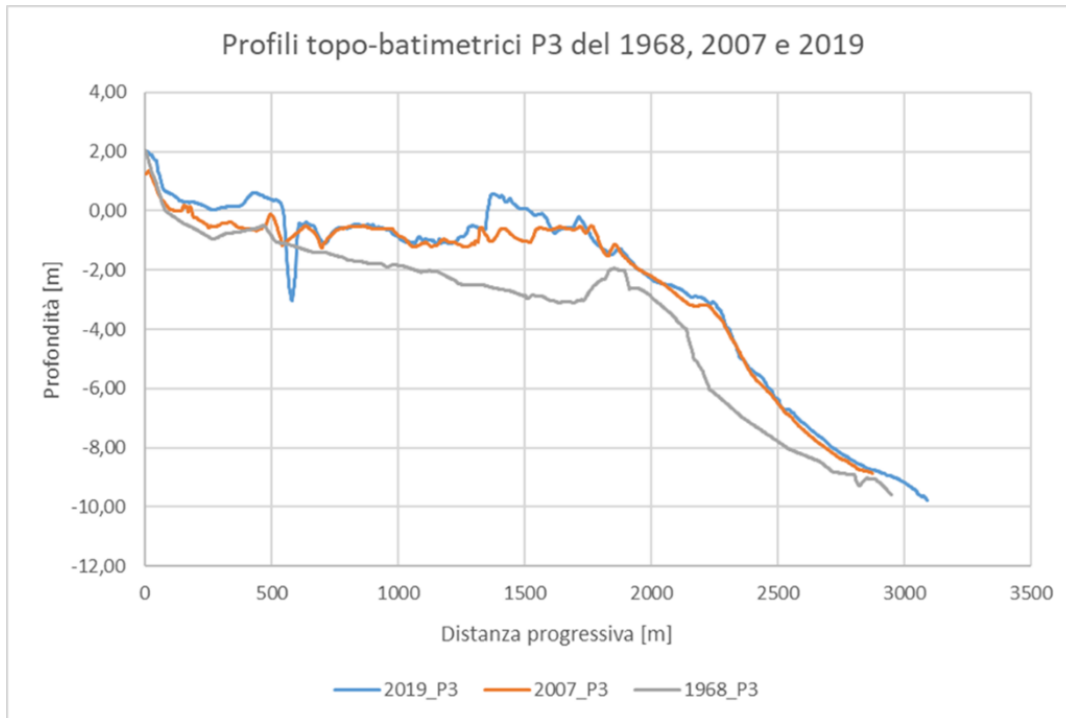


Figure 3-57: Profile evolution in the rea of maximum migration.

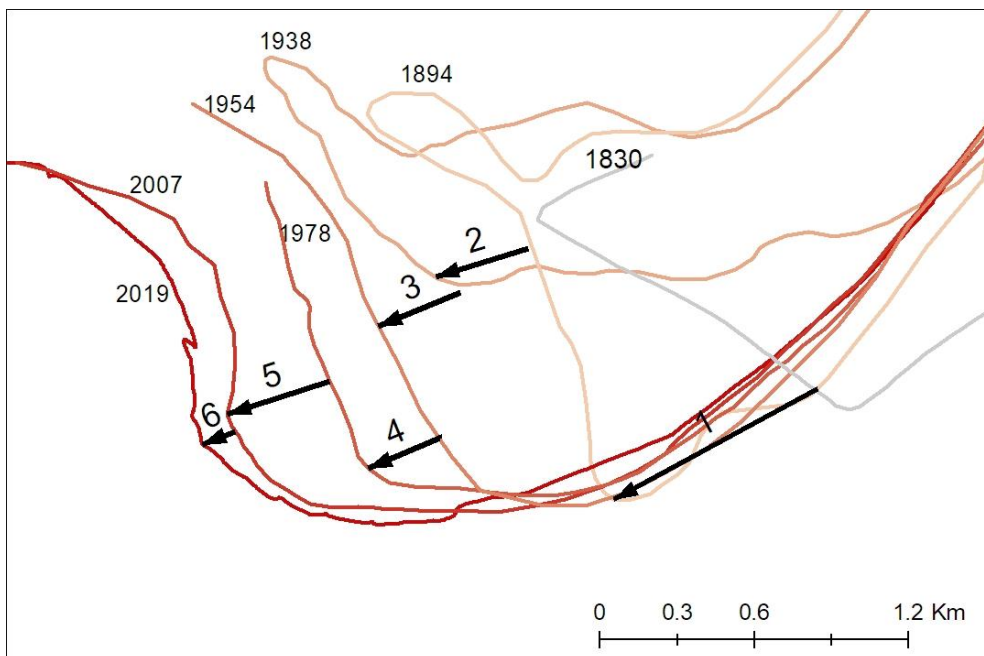


Figure 3-58: Progressive migration of the Banco from 1830 to 2014.



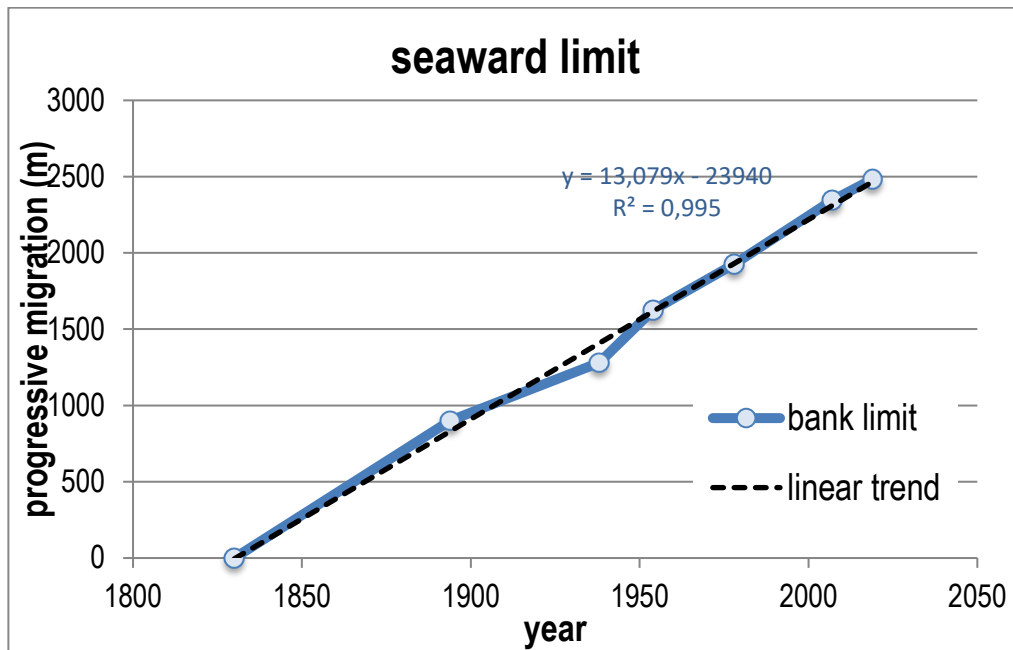


Figure 3-59: Migration trend of the Banco limit from 1830 to 2014.

### 3.4.5.3. Recent quantitative evolution

After identifying the morphological evolution of the area covered by this study, the altimetry evolution was investigated, in order to understand the erosional / accumulation process in act. Starting from the

DTM of 1968, 1985 and 2019 we obtained 2 maps of the differences for the couple 1968-2019 (Figure 3-60) and 1985-2019 (Figure 3-61).



Figure 3-60: Map of altimetry differences from 1968 to 2019 with, superimposed, a geometric partition in littoral cells.

The map in Figure 3-61, regarding the longest time interval allows identifying different zones (Figure 3-62 and Figure 3-63):

1. Back-barrier cell
2. Delta apex
3. Eastern longshore cell
4. Western longshore cell
5. Bank migration cell
6. Offshore cell

1. Back-barrier cell: this area is characterized by accumulation, in prevalence of fine sediments due to the shelter conditions against wave action.

2. Delta apex: represents an area of strong sedimentary accumulation. This characteristic can be seen both from the topo-bathimetric, and the morphological evidences. The profiles show a typical progradation process and the delta lobe shows a marked protrusion.
3. Eastern longshore cell: includes the bar and trough zone from the delta area to the Primero channel. This area is substantially balanced, from the point of view of the sedimentary budget. Morphological evidence testifies a strong longshore transport from east to west.

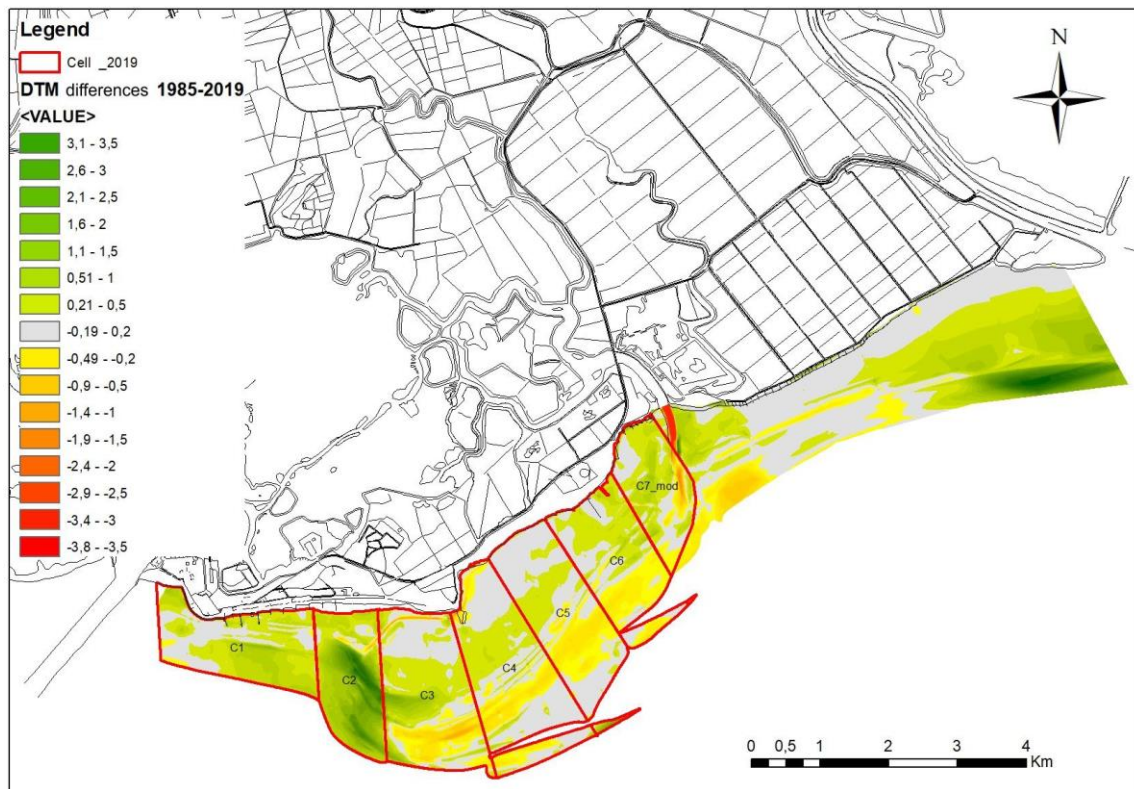


Figure 3-61: Map of altimetry differences from 1968 to 2019 with, superimposed, a geometric partition in littoral cells.

4. Western longshore cell: includes the bar and trough zone 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 testifies a strong longshore transport from east to west and includes this the sediment bypass proves involving the tidal inlet of Primero.
5. Bank migration cell: this area shows strong sedimentary accumulation, 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 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 port mouth of Grado are gradually lower.

6. Offshore cell: from the bank outer limit to the closure depth within the range -2 -2.5m and -5.4 m, and appears interested by erosion processes. From the morphological point of view 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

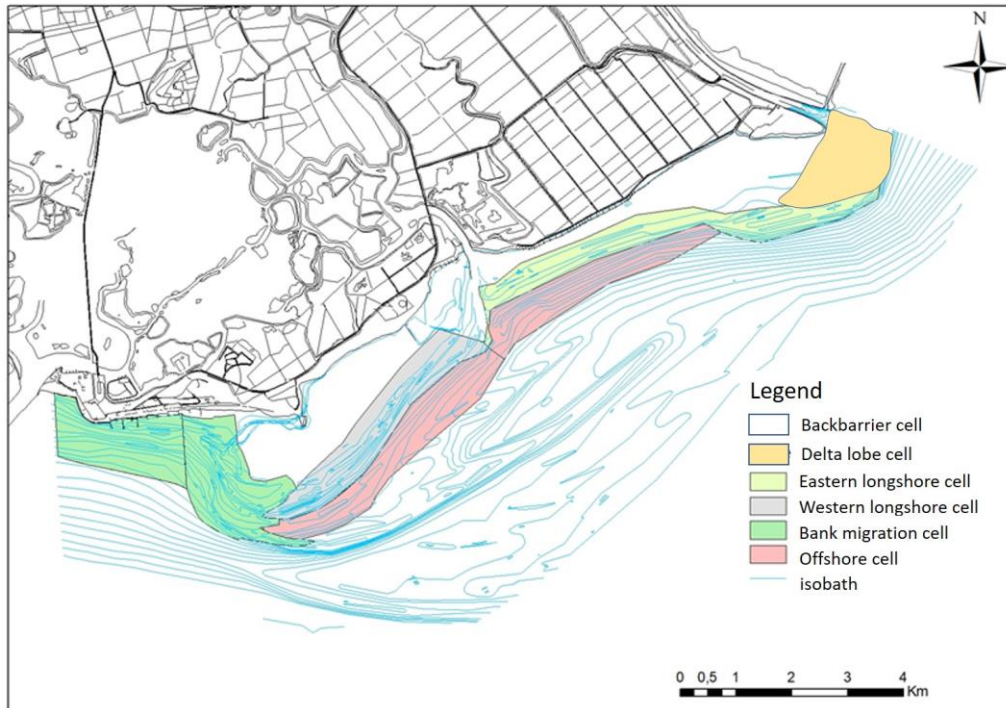


Figure 3-62: Sub division of the coastal area in cells with different sediment budget and dynamic processes

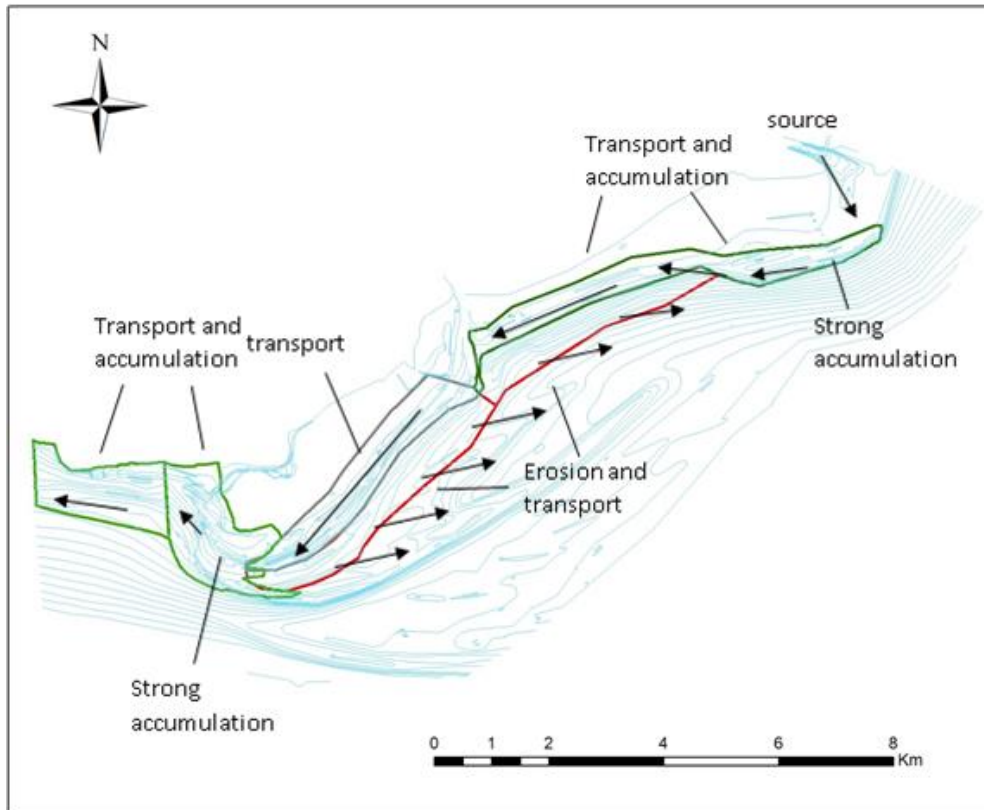


Figure 3-63: Representation of the sandy sediment dynamics in the study area.

### 3.4.6. Conclusion

#### 3.4.6.1. Results of the activities and discussion

The examined area includes a unique environment in the Upper Adriatic: it is a semi-submerged sandy bank of triangular shape extending from the Bocca di primero to the east to the GIT beach (Grado ImpiantiTuristici) of Grado to the west.

The objective of this activity was to analyze and understand the dynamics of the coast between the inlet of Grado and the mouth of the River Isonzo, on the basis of a multidecadal morphological analysis. To update the analysis within this loan in 2019 was carried out a new topographic and bathymetric campaign, useful for the detailed reconstruction of the bank's morphological structure. The resulting DTM was compared to the older DTM available for the area: 1968, 1985 and 2007.

The historical analysis documents the presence of the bank morphologies since 1822, long before the urban development of the area. With reference to the sedimentary balance and to the morphological evidences, the coasts of Grado, which includes the Banco dellaMula di Muggia, has can be subdivided into sectors with different characteristics of sedimentary dynamics.

The sectors of the delta apex and the western part of the Banco show 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.

The analysis confirms that the direction of longshore transport is directed towards SSO. The sediments conveyed to the mouth by the river Isonzo 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.

#### 3.4.6.2. Problems and solutions

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

The morpho dynamics of the area includes complex aspects that need to be further explored. These aspects concern 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 della Mula di Muggia survives and evolves migrating, occupying spaces now dedicated to seaside tourism. But this morphology constitutes an important sandy reservoir that should be understood as a strategic reserve for the conservation of our coasts, in consideration of the diffused erosive crisis of the coasts and the increment of the frequency 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

With the aim to developing an appropriate scientific knowledge base which could serve as a basis for coastal planning, we developed an activity of collecting the previous existing data and analysis on these coasts.

For the study area there is a fair amount of previous data in terms of historical cartography, topographic surveys and aerial photos, but the available material is often fragmented, difficult to find and in formats not usable for analysis in digital environment.

The first step of this work was the collection, reordering and critical reading of the available material and the digitization of what was deemed useful and/or appropriate for the purposes. The created

database represents a coherent basis, directly usable and upgradable. The analysis has considered the extent and quality of past data, highlighting limits and deficiencies.

For the new surveys the combined use of different survey techniques (topographies with RTK system, Single and Multi Beambathymetrics and drone aerophotogrammetrics) is the only possibility to obtain a wide coverage of the area and to overcome the difficulties imposed by its morphological characteristics.

The construction of the DTM requires particular care and represent a problematic phase in the elaboration process:

- an accurate manual integration of the standard data interpolation procedures offered by GIS geostatistical analysis software is necessary;
- data quality is an essential factor for the model to have a high degree of reliability;
- the density and mesh of the measurements influences the quality of the reconstruction

### 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 catchment, and it develops as a flat region with a surface of 472.55 km<sup>2</sup> (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).

In this region the Po River is divided into different branches: Po di Levante, Po di Maistra, Po di Pila (with the mouths of Scirocco and Tramontana), Po di Tolle, Po di Gnocca, Po di Goro (Figure 3-64).

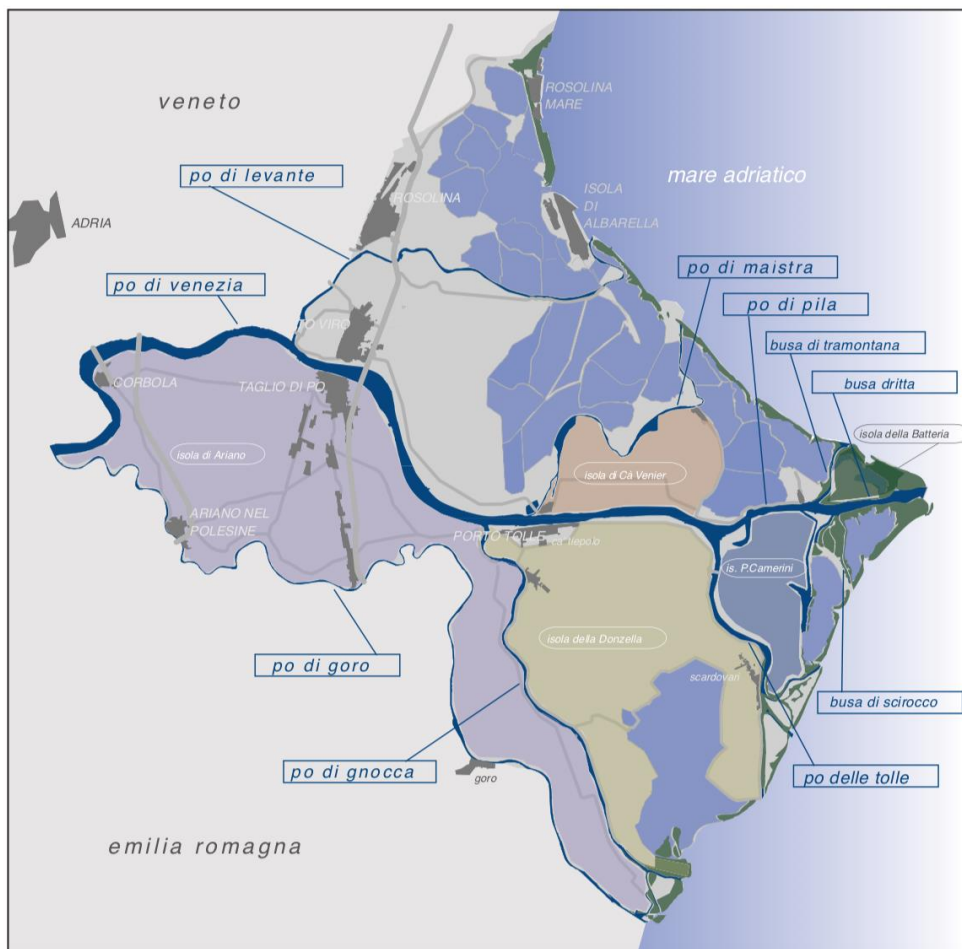


Figure 3-64: Po Delta region with its branches and lagoons (Atlante Delta del Parco)

More specifically, the branches composing the Po Delta begin at Papozze (Rovigo), where the main course deviates northward and then towards west-east. Here, the main course divides into three branches: on the right, Po di Goro which flows toward south-east and Po della Gnocca that flows parallel to Po di Goro and on the left Po di Maistra. The branch of Po di Venezia divides into two branches, the main branch of



Po della Pila towards east, and Po delle Tolle that flows southward. The branches of Po della Gnocca, Po di Venezia and Po di Tolle delimit the Donzella Island respectively to the west, north and east. Further branches of the Po della Pila are called “buse” (the “Busa dritta” is considered the main mouth of the river).

This is an area of recent formation, created by a slow sedimentation of the soil and extraordinary interventions of human reclamation; it is still in continuous evolution and in continuous expansion (60 ha / year) due to the great contribution of sediments. In particular, the present Po Delta is the results of a long history of reclamation and hydraulic interventions, which started at the beginning of the last century and were completed in the '60s. Most of the territory is below the sea level and is kept emerged by the continuous work of several pumping plants. The levees along the Po branches together with the lagoon banks, constitute the important defence line of this fragile territory, both against the Po floods and the marine water.

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 considered a heritage of inestimable naturalistic, cultural and social value, so much that a good part is counted among the wetlands of international importance under the Ramsar Convention (1971) and it is a UNESCO World Heritage Site.

Due to its great environmental value, it is an "ecosystem" to protect and preserve, also in accordance with the "Habitat" Directive (92/43 / EC) and the "Birds" Directive (79/409 / EC). In this area, in fact, there are Sites of Community Importance (SCI) and Special Protection Areas (SPAs) which are part of the Natura 2000 Network.

The project Change We Care has a focus on two smaller areas located in the Po Delta pilot site: Sacca del Canarin, belonging to Veneto Region and Sacca di Goro, belonging to Emilia Romagna Region.

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

The Po delta is made up of all its river branches and it also includes the territory between them. Consequently, its surface is approximately 18,000 hectares. According to this definition, the Po Delta falls entirely in the province of Rovigo, or Polesine, and occupies a vast portion in the eastern part of the Po River (from the branch of Po di Goro to the sea) representing an example of "active delta".

In a broader sense, it encompasses the largest area of the historical delta, the one included among the ancient delta branches of the Po River and this allows us to consider the part of the province of Ferrara forming a cusp shape between the vertices of Stellata, Sacca di Goro and Comacchio Valleys.

Therefore, the whole territory includes the province of Rovigo (Veneto Region) and Ferrara (Emilia Romagna Region), comprising different municipalities: Adria, Ariano nel Polesine, Carbola, Loreo,

Popozze, Porto Tolle, Porto Viro, Rosalina and Taglio di Po in the Veneto Region, and Comacchio, Argenta, Ostellato, Goro, Mesola, Codigoro, Ravenna, Alfonsine and Cervia in the Emilia Romagna Region.

The territory is primarily agricultural and, consequently the population density is quite low with urban centres consisting in small towns, hamlets, and isolated houses.

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.

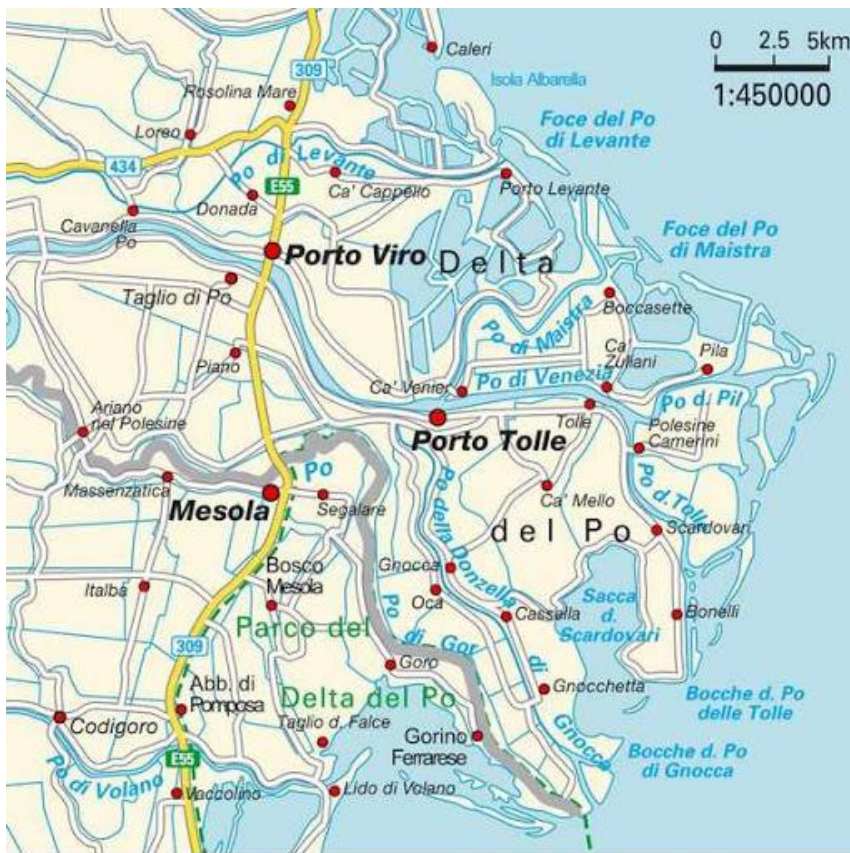


Figure 3-65: Location and access routes of the Po Delta region

The Po delta includes protected natural areas established in the geographical area of reference:

- Veneto Regional Park of the Po Delta - operating since 1997, it includes practically the entire geographical delta of the Po, as defined above.
- Po Delta Regional Park of Emilia-Romagna - established in 1988, operating since 1996, it also includes territories that are part of the reservoir of other rivers (including the Reno). It includes the southern part of the historic Po delta, and a small part of the current delta (the “active delta”).

The **Sacca del Canarin** is located in the municipality of Porto Tolle, in the southernmost part of the Po Delta Park of the Veneto Region. It has a surface of almost 6.5 km<sup>2</sup> and it extends between two of the Po mouths, Busa di Scirocco in the north and Busa Bastimento in the south (Figure 3-66).

The **Sacca di Goro** is located in the northernmost part of territory of the Po Delta Park of the Emilia-Romagna Region. The lagoon has a total area of 26 km<sup>2</sup> and falls within the administrative borders of the Municipality of Goro and of the Province of Ferrara (Figure 3-66).

Both sites fall in the network of the protected areas of Natura 200. Sacca del Canarin belongs to the Sites of Community Importance (SCI/SIC) SIC-ZPS IT3270023, code SIC IT3270017, while Sacca di Goro is also the core area of the SIC-ZPS IT4060005 site "Sacca di Goro, Po di Goro, Valle Dindona, Foce del Po di Volano", established in 2009 (DGR 512/09).



Figure 3-66: Po Delta Park of the Veneto Region (light green) and SIC-ZCS (dashed light green), Po Delta Park of Emilia Romagna (light red) and SIC-ZCS (dashed blue). Location of the two focus sites of Canarin and Goro (Regional webgis).

### 3.5.1.2. Physical and environmental features

The modern Po Delta develops in the NS direction ranging between the Adige mouth and the Reno River and it encompasses five active branches that spread toward the Adriatic Sea for several kilometres. From

north to South, there are Po di Maestra; Po della Pila or di Venezia, which develops in three different mouths (Busa di Tramontana, Busa Dritta and Busa di Scirocco); Po di Tolle (with the branches of Bastimento, Bocca del Po and Tolle); Po di Gnocca; and Po di Goro. Other abandoned or regulated branches are located south of the present delta.

With exception of embankments and dunes, most of the delta plain is completely below the mean sea level, with maximum depths of -4 m in some points. The territories between the river branches and the sea are defined “island” while the marsh areas close to the coast are lagoons, such as Caleri, Marinetta-Vallona, Barbamarco, Burcio, Basson, and the two focus areas of Canarin and Scardovari.

Here fresh and brackish waters coexist, generating an ephemeral landscape that changes with the variation of the inflows from the watercourses or from the sea. Salinity usually reflects this dynamic environment, showing a high spatial and temporal variability.

Particular hydrodynamic conditions characterize the entire area, in which 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 distinctive morphological features (Figure 3-67), like *velme*, *barene* and *scanni*, and it hosts an extensive range of habitats ideal for the life of numerous species of migratory species and plants, representing an area with high level of biodiversity.

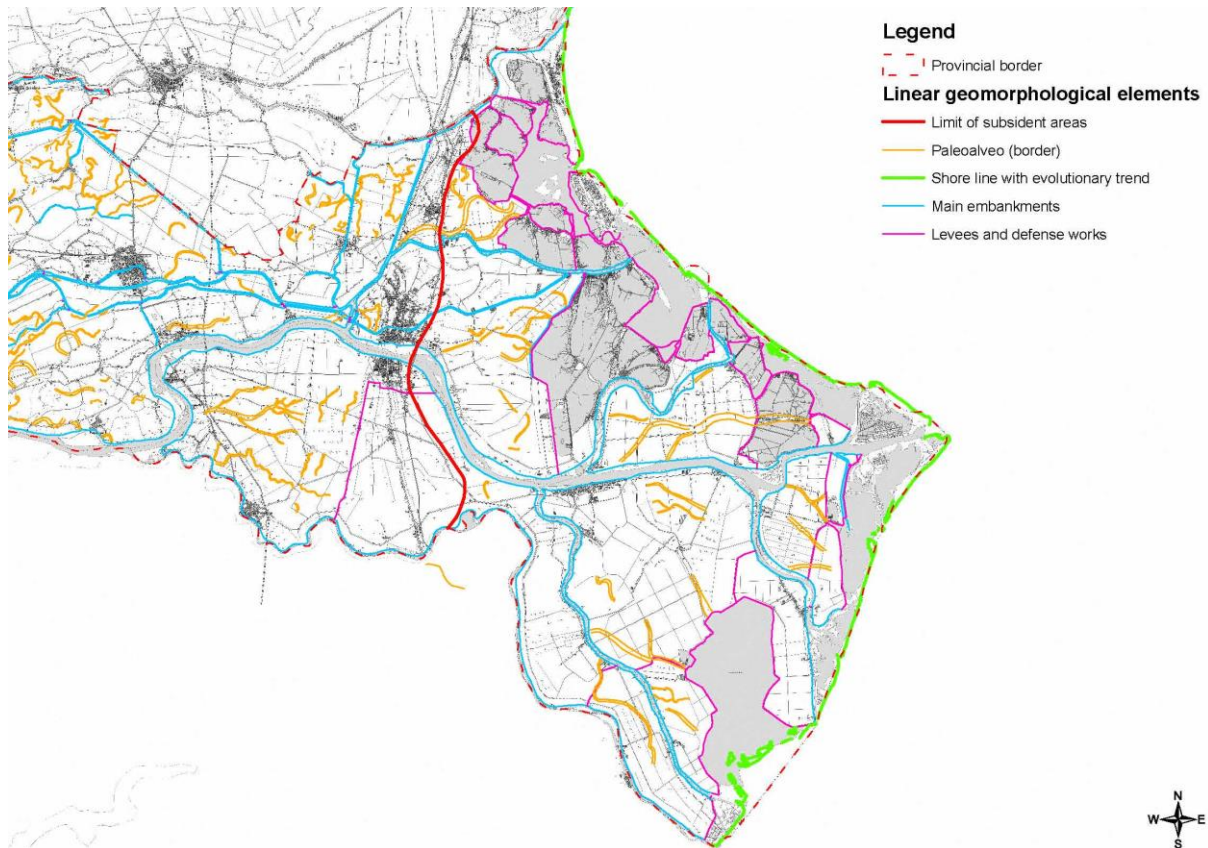


Figure 3-67: Geomorphological map of Rovigo Province, emphasizing the main embankments in the river network and along the coastline. Source PTCP: (Provincial territorial Coordination Plan), year: 2009, available at: [http://www.pianificazione.provincia.rovigo.it/nqcontent.cfm?a\\_id=2438](http://www.pianificazione.provincia.rovigo.it/nqcontent.cfm?a_id=2438)

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. Some reaches of the coast (e.g. Scanno del Palo and Bonello Bacucco) are defended through a series of wood groynes, others through a system of levees.

- **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 coast.

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.



Figure 3-68: 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). <https://emiliaromagna.cia.it/agrinsieme-ferrara-parco-nazionale-del-delta-del-po-idea-da-rivedere/>

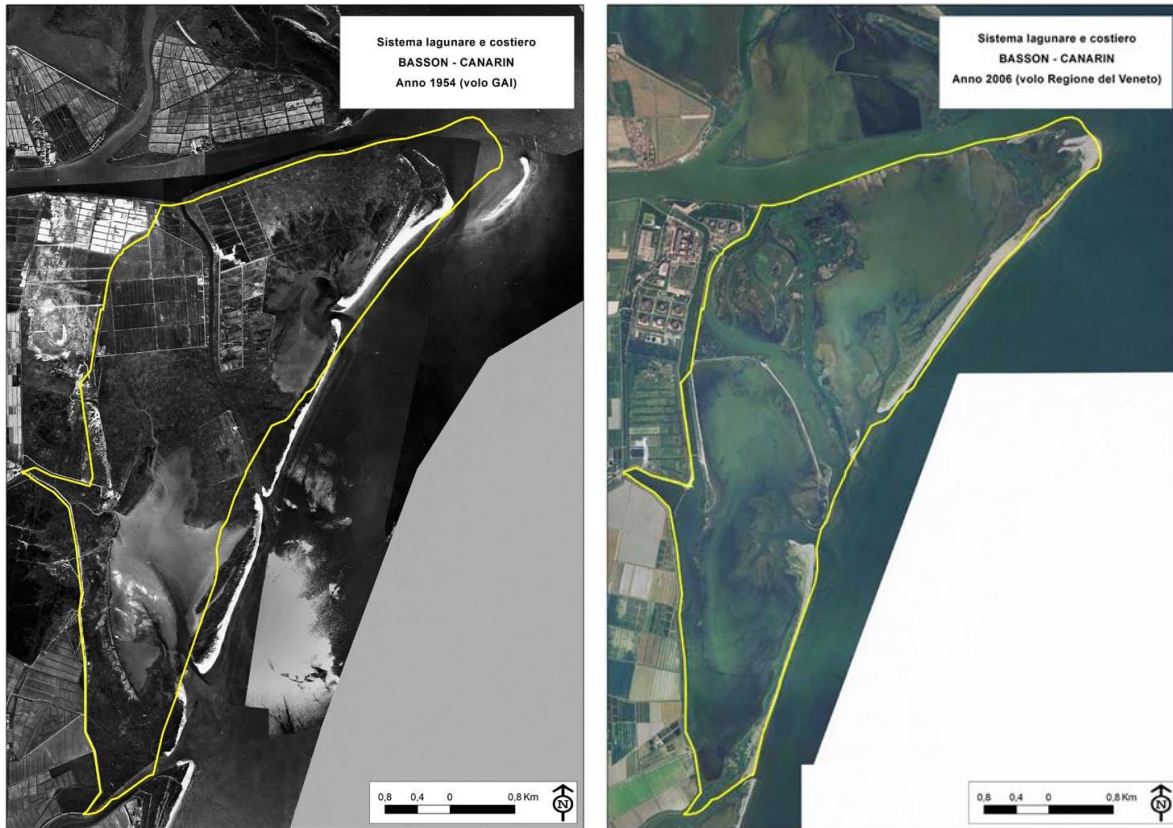
From an environmental point of view, but also considering its history, Sacca del Canarin belongs to the system of “Basson-Canarin”. An artificial embankment built during the ‘70s and that connects the riverbanks to the sand spits seawards disjoints the internal circulations of the two lagoons.

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 pretty high level of salinity, and it is characterized by the absence of islands and reeds, possessing only few submerged bedforms.

It is devoted mainly to shell-farming and fishing activities, even though recently hunting and touristic activities started to develop in the area, together with internal navigation, sport fishing and bathing along the sand spits.

Several hydraulic works have been conducted during the years to control the ingression of salt water from the sea and to preserve the oxygenation of the lagoon for the shell-farming (see paragraph 3.5.5.5).



*Figure 3-69: Views of the Basson-Canarin system of 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.*

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.

Regarding the chemical-physical characteristics of the lagoon, the agency for the protection of the territory of the Veneto Region (ARPAV) monitors the environmental conditions of the lagoon, in some cases in cooperation with the Rovigo Province, the Consortium for the Remediation of the Po Delta-Adige and together with the ULSS 19 of Adria.

The monitoring activities are continuous (every 30 minutes) and regard: i) temperature and pH, both important for the shell-farming activities and to control eutrophication connected to high temperature and algae blooming; ii) conductivity and salinity levels, whose variability depends on the water fluxes coming from the rivers, sea and rainfalls; iii) and dissolved oxygen, which changes according to the hydrodynamic circulation in the lagoon and to the algae presence.

Table 3-2: Values of the environmental monitoring activities in Sacca del Canarin.

		CANARIN				
		Temperatura	pH	Conducibilità	Salinità	Ossigeno Disciolto
I° TRIM	MEDIA	8,4	8,4	37,7	23,8	10,5
	MIN	<b>1,1</b>	8,1	<b>0,5</b>	<b>0,2</b>	7,1
	MAX	14,1	8,8	57,0	37,2	<b>18,4</b>
II° TRIM	MEDIA	20,5	8,5	25,7	16,1	9,0
	MIN	9,0	7,9	1,1	0,4	<b>1,4</b>
	MAX	28,4	<b>9,2</b>	<b>60,9</b>	<b>41,2</b>	15,7
III° TRIM	MEDIA	26,8	8,5	41,8	26,8	7,6
	MIN	17,3	7,7	12,6	7,4	2,5
	MAX	<b>32,3</b>	9,0	59,7	39,8	14,1
IV° TRIM	MEDIA	14,3	8,3	43,7	28,2	8,7
	MIN	4,8	<b>7,1</b>	9,6	5,4	2,8
	MAX	22,5	8,8	58,2	38,9	16,1

Recently several episodes of hypoxia/anoxia occurred with values of the dissolved oxygen below 2 mg/L in the lagoon, without important consequences on the shell-farming activities.

#### - 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.

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.





Figure 3-70: View of Sacca di Goro, source: <https://www.ferraterraacqua.it/it/goro/scopri-il-territorio/ambiente-e-natura/luoghi-di-interesse-naturalistico/sacca-di-goro>

In the recent, the evolution of the Sacca di Goro is characterized by excessive accretion of the outer sand bank, the Scannone (Figure 3-71), 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. This part will be addressed in detail in paragraph 3.5.1.3.



Figure 3-71: 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

As mentioned before, the “current” Po Delta falls entirely in the province of Rovigo, or Polesine, but in a broader sense, it encompasses the largest area of the historical delta. So the territory includes the province of Rovigo (Veneto Region) and Ferrara (Emilia Romagna Region), comprising different municipalities: Adria, Ariano nel Polesine, Carbola, Loreo, Popozze, Porto Tolle, Porto Viro, Rosolina and Taglio di Po in the Veneto Region, and Comacchio, Argenta, Ostellato, Goro, Mesola, Codigoro, Ravenna, Alfonsine and Cervia in the Emilia Romagna Region.

The Po Delta of Veneto extends for 786 square kilometers, of which over 160 are valleys and lagoons. There are over 73 thousand inhabitants in the entire delta area.

The Po Delta is a complex area composed of dry and wetlands, with distinct morphological and a hydrological features, which have led to different economic activities. Large part of the territory near the coast has been subtracted from the sea thanks to important reclamation works at the end of the XIX century, but it still includes several fishery ponds and lagoons.

The Po Delta is SCI/SIC area (IT3270017) and SPA (IT3270023). The Po Delta Park Authority was established with Regional Law 8 September 1997 n. 36 on the territory of the Municipalities of Rosolina, Porto Viro, Ariano nel Polesine, Taglio di Po, Porto Tolle, Adria, Loreo, Corbola and Papozze. The Po Delta SIC-SPA is an area of particular naturalistic value, and is one of the most important wetlands in the

Mediterranean. In SIC-ZPS, fishing and especially shellfish farming play considerable economic and social importance.

The economy of the Po Delta has historically developed in the traditional sectors of agriculture and craftsmanship, and activities typically related to fishing, aquaculture, and tourism have occupied a prominent role in the development of the area. Sugar production and sugar refinement represented an important source of income for local populations, with the sugar refineries developed thanks to the agricultural production and cultivation of sugar beet.

Most of the agricultural territory is occupied by herbaceous crops and arable land, which mainly is cultivated with wheat (soft and hard), sugar beet, corn, soy, alfalfa and rice, while in the least fertile areas of each farm wide portions of land are fallow. Concerning rice, its cultivation in Polesine was already documented in the mid-fifteenth century. Despite the problems of salinization due to the salt intrusion, rice production represents not only an important source of income but also a valid solution in the cultivation of these areas characterized by difficulties in the drainage and by a complex texture of the land.

The existing farms are almost entirely represented by the cattle and poultry sector, which provides an additional resource with the production of manures and slurries that are used in agriculture to improve the chemical-physical characteristics of the land and consequently to increase its fertility.

Therefore, the economy of the Polesine territory is a predominantly agricultural. Nevertheless, a secondary sector based on small and very-small enterprises has developed in various sectors such as the chemical, metalworking and textile one, and it is mainly founded by local entrepreneurs.

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. It is a peculiarity of the Polesine economy, also recognized as the Fish Industry District of the province of Rovigo.

The fish sector production, which encompasses traditional and typical products, is quite large and well-diversified (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.

In the mid-1980s, the introduction of the *Tapes philippinarum* undoubtedly represented a key factor in the economic and employment growth throughout the Polesana area. The number of operators involved in the clam farming in the Po Delta is approximately of 1800 units.

There are three local fish markets, as well as a network of processing, storage and marketing structures for fish products, which still has a high development potential.

So, the main economic activities in the area are:

- Intensive agriculture, with Rosolina as major trade centre for vegetables.

- Fishing, where the most important fish market is located in Porte Tolle.

Currently, fishery and shellfish farming employ large part of the population, especially regarding the commercialization of the product. In particular aquaculture is well developed in the fishery ponds with precious and common fish species, whereas mussel-farming is widespread in the lagoons.

Tourism in the area is another important economic source, as the Delta environment is particularly suitable for birdwatching, bathing and the practice of sports. The agritourisms that have begun to invest in multifunctionality are increasing in the area, offering activities such as horse riding, mountain biking, nature observation, etc.

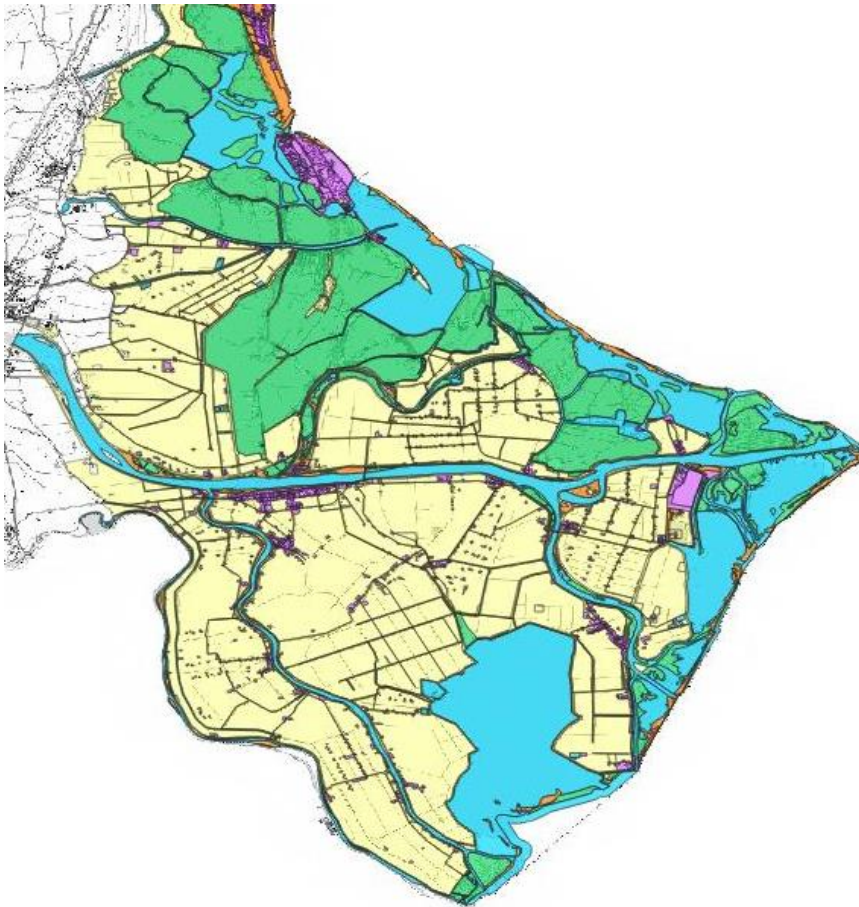


Figure 3-72: Land-use map of the Po Delta region. Yellow regions: agriculture areas; purple: artificial surface; light blue: water bodies; orange: water bodies; green regions: forest and seminatural areas; .Source from MATTM, year 2012, available from: <http://www.pcn.minambiente.it/mattm/servizio-di-scaricamento-wfs/>

- **Sacca del Canarin**

The Sacca del Canarin is affected by a significant presence of tourist activities, consisting in particular of inland navigation, sport fishing and bathing on the sandbars. Further activities developed in the area are

nursery areas for natural clams, although the location of the nurseries is not always fixed, in addition to shellfish farming.

The Sacca del Canarin is an important breeding site for protected birdlife. There are also various animal species that can be influenced by anthropic activities.

In recent years, the Sacca del Canarin has undergone anthropic interventions related to the construction and management of the ENEL plant, as well as those undertaken to improve the hydraulic safety of the agricultural and settlement area behind it.

#### - **Sacca di Goro**

For what concerns habitats' and biodiversity protection, the Sacca di Goro is managed by the Station Plan of the Po Delta Park of the Emilia-Romagna, by the Directives 79/409/ EEC "Birds" and Directive 92/43/EEC "Habitats" and by the Ramsar Convention, for the Ramsar area "Valle di Gorino" (Ministerial Decree 13/07/1981). Moreover, additional regulation within the SIC-ZPS IT4060005, concerns the State Natural Reserve "Dunes and islands of the Sacca di Gorino" (Ministerial Decree 18/11/1982) and the State Natural Reserve "Po di Volano" (Ministerial Decree 13/07/1977).

In the Sacca di Goro, 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. With respect to the ecosystem management of the Sacca di Goro, recently, through the Life Project AGREE, on the basis of monitoring results, a substantial change has been adopted. Two water gates between the Po di Goro and the Valle di Gorino have been opened almost permanently with the aim of increasing the freshwater inflow and favoring restoration of reed stands in the eastern part of the lagoon. At the same time, negotiations have started with clam farmers, to move some of the rearing areas from internal zones of the lagoon to offshore areas, located right in front of the Scannone di Goro. This action was undertaken mainly to avoiding further the risks related to seaweed blooming but at the same time, it has brought a further decrease of human presence and relative impacts within the lagoon.

Presently, the most important disturbance to these habitats is due to agricultural activities, both at the scale of the whole Po basin and locally, in the Province of Ferrara. In particular, small coastal basins that discharge drainage water directly into the lagoon (Castaldelli et al. 2013; Viaroli et al. 2018) are areas particularly prone to nutrient leaching (Aschonitis et al. 2013). For this reason, the restoration of vegetated buffer areas represent the most effective measure to reduce eutrophication and related effects.

The analysis of ESs made by Gaglio and co-authors (2019) puts in evidence that a rational use of natural resources and the promotion of multifunctional systems are needed to obtain sustainable goals. The results demonstrate the importance of aquatic vegetated habitats as a provider of regulating, supporting, and cultural ESs. In deltaic areas subjected to widespread reclamations, the loss of vegetated coastal wetlands has led to the concurrent loss of habitat for birds, resulting in a decrease in

conservation values and of potential use for birdwatching-related tourism. More on the topic is available in **Annex 5: Po Delta – Sacca di Goro, Manila Clam.**

#### 3.5.1.4. Recent settlement trends in the Po Delta and lagoon system

The recent evolution of settlement in the Po Delta lagoon system is linked to its history.

The Po Delta plain has been always an attractive place for human settlements thanks to the availability of fish, animals, vegetables and salt and due its favourable conditions for the navigation. However, numerous difficulties loom the area, since it is a high dynamic environment susceptible to quick changes.

The first period of the colonization of the Po Delta started with the remediation of the area, prompted and funded by the State in the second half of the nineteenth century. Several workers moved in the lagoon, founded small villages among the reeds and over the sandy dunes and started to live on seasonal jobs linked to agriculture and fishery. Regarding *Sacca del Canarin*, as well as Bassona, the first inhabitants came here to cultivate rise, and some of the names of the places still today refer to the old rise field owners. In the first phase, rise fields played an important role for the remediation of the area, because they used to have small embankments and served as sediment tanks, being filled with muddy sediments during floods. This process helped the area gaining elevation for the sedimentation of material coming from the river. In this first stage, the lagoons were characterized by shallow beds, a flourish vegetation, reeds, and higher *scanni* with arboreal species.

The second part of the Po Delta history starts with the extraction of the methane in the area, which take away the hydrostatic pressure that supported the sediments. The entire Po Delta underwent a fast lowering of the ground, which was worsened by the remediation activities carried out for the rise cultivation. Between 1951 and 1966 the area was flooded 20 times, and the water came from the sea. The territory changed quickly due to the ingression of salty water, with the disappearance of habitats that had previously developed thanks to the presence of fresh water. Most of the population migrated inland, and embankments were built towards the land to push away the seawater.

Until that period, the fishery was a secondary activity for the economy of the area.

However, the changes in the territory and in the biotic parameters brought some economic opportunities. Fishes populated the region, especially concerning shells.

Nevertheless, this activity needs a sandy substrate and a continuous exchange of water and it suffers during period of heavy rain or for a prolonged presence of fresh water. For this reason, recently several interventions have been planned to meet the needs of fishers.

#### 3.5.1.5. 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: i) the salinity levels are extremely mutable and depend on the water exchanges with the sea and Po river (through floods); ii) the oxygen content in the shallowest areas has a large impact on the production activities; iii) the water quality is threatened by algae blooming and nutrients (phosphates and nitrates) coming from the fluvial waters; iv) the infilling of the lagoons, due to sediment deposition, influence the internal circulation and consequently the fishing and shell-farming production; finally v) 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** consists in the movement of saline water into aquifers. The salt wedge often develops at the river mouth, propagating at the bottom of the riverbed, since it has a higher salt concentration and is consequently denser than the fluvial fresh water. In the case of the Po river, whose riverbed near the mouth is below the sea level, this process is almost always present and is pronounced in throughout the year.

In recent decades, salt intrusion has assumed increasingly worrying proportions with a progressive intrusion almost in all the water bodies of the Po Delta, which has showed a tendency to increasing salinity. The phenomenon, which in the 1930s was observed only for two or three kilometers from the river mouth, increased later extending to about twenty kilometers.

During the summer of 2003, the Po River (the water flow in Pontelagoscuro was less than 300 m<sup>3</sup> / sec) went through a serious water crisis due to the extremely low rainfall. The consequences of the drought led to a difficult situation, which affected all the economic activities, from agriculture to tourism, from river navigation to the production of electricity. Considerable damages affected agricultural activities, caused both by insufficient water supply and by salt intrusion. Moreover, between 2005 and 2006 the Po River experienced moments of serious water crisis. More recently, however, due to the more abundant rainfall, these exceptional events have not occurred again.

The effects of the salt intrusion can be summarized as follows: 1. modification of the biological characteristics with changes in the trophic chain and consequent effects on the fish population with impacts on fishing activities; 2. interruption of withdrawals for irrigation, with serious damages on agricultural activities 3. interruption of the water supply in the easternmost part of Polesine. The drinking water plants are not, in fact, able to desalinate the water; 4. salinisation of the aquifers. 5. drying up of coastal areas and micro desertification processes.

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 favorable 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 has a low average depth and reaches a maximum of 1.8 meters in the central area in front of the northern mouth, while it is much shallower in the northern and southern areas.

This lagoon underwent a first profound transformation with the closure of the Bonifazi Busa and the delimitation works in the north of the basin together with the closure of the southern mouth of the lagoon, at the Busa di Bastimento. Currently the Sacca del Canarin communicates with the sea only through the north mouth.

For this reason, important works of vivification of the lagoon are planned, with the aim at preserving the delicate environmental balance and conditions of high biodiversity. In fact, 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.

#### - **Sacca di Goro**

The areas of Sacca di Goro suitable for Manila clam rearing are not evenly distributed, as hydrodynamism, sediment, salinity, oxygen, depth and phytoplankton abundance vary from area to area and all are determinant for clams' settlement, growth and survival. Therefore, the variability of cited ecological parameters, establish the production potential of an area and determine its environmental suitability for the Manila clam rearing. It has also to be pointed out that the 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". This secondary lagoon formation is located right in



front of the Scannone di Goro and is closed from the open sea by another narrow sand bar, still under formation. These nursery areas are licensed by the Region only for the collection of the Manila clam seed, to a Consortium that groups all the cooperatives.

At present, the most important action for the whole sector of Manila clam rearing in the lagoon of Goro is the protection and management of nursery areas. Among them, the historically most important and more exposed to the risk of negative environmental changes is the so called “Bassunsin” which, in recent years, 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 than maintaining the opening of the main mouth of the lagoon, must address actions aimed at restoring and maintaining high quality standards for the Bassunsin area.

### **3.5.2. Available geomorphological data, studies, maps**

#### **3.5.2.1. Hydraulic works and subsidence**

Regarding Veneto Region:

Hydraulic works (sump pumps, pumping stations, navigation basins, etc.)	Information of defence works and pumping stations in the Rovigo province up to 2018
Hydraulic hazard maps, hydraulic risk maps	Flood Directive Maps
Information on evolutionary trends (eg. Coastal erosion maps, subsidence trends, etc.)	PS ERS descending (1992-2000), CL003_Venezia; CL002_Porto_Tolle; CL001_Comacchio, CL001_Trieste, CL001_Ponte_di_Piave. ENVISAT descending (2002-2010), CL001_Ravenna, CL001_Trieste, CL002_Rovigo, CL002_Chioggia, CL001_Jesolo. subsidence analysis (AchilliMeninFabbris) measures 2016 e <b>2018 PODELTANET</b>

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 Consorzio di Bonifica Pianura di Ferrara. Topographic surveys of the levees elevation 2014-2018, both along the river Po and the coast (AIPO).
Hydraulic hazard maps, hydraulic risk maps	Flood Directive Maps (2015).
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): <a href="https://applicazioni.regione.emilia-romagna.it/cartografia_sgss/user/viewer.jsp?service=inRisk">https://applicazioni.regione.emilia-romagna.it/cartografia_sgss/user/viewer.jsp?service=inRisk</a>

### 3.5.2.2. Cartography including topographic and geomorphological maps

Regarding Veneto Region:

Topography (national, regional and/or local cartography, GPS surveys)	regional topographic maps at different scale
Shorelines (e.g. photogrammetrist, 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, Soil Defence Directorate.

	Geomorphological Map of the Po River Plain, (1:250.000) Geological map of Italy (1:50.000), sheet 187 "Codigoro"
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Regarding Sacca di Goro, from Emilia Romagna Region:

Topography (national, regional and/or local cartography, GPS surveys)	regional topographic maps at different scale (1:250000; 1:5000); regional topographic data base.
Land Use maps	coastal zone: 1943, 1982, 1998, 2005; entire region (RER): 1954, 1976, 2003, 2008, 2014
Shorelines (e.g. photogrammetrist, 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) at 1:250000 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. Aerial and satellite images (for coastal evolution)

Regarding Veneto Region:

Aerial and satellite images	<p>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.</p> <p>2003, Digital orthophoto (with colors) Terraltaly it2000 NR 2003 “Compagnia Generale Riprese aeree S.p.S. Parma (*)</p> <p>2007, Digital orthophoto (with colors) Terraltaly it2000 NR 2006-2007 “Compagnia Generale Riprese aeree S.p.S. Parma (*)</p> <p>2012, Digital orthophoto (with colors) AGEA 2012 (*) Interpreted by Ruol et al. 2016</p> <p>Analisi dell’erosione costiera nel delta del Po dal 1933 al 2008 mediante aerofotogrammetria multi-temporale”, Fabris, Achilli e De Gennaro 2012)</p>
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Regarding Sacca di Goro, from Emilia Romagna Region:

Aerial and satellite images	<p>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)</p>
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#### 3.5.2.4. Lidar-DTM, Bathymetry

Regarding the Rovigo Province, from Veneto Region

High resolution DTM (from lidar, etc.)	<p>2006(1m); 2008 (2m-MATTM); 2009 (1m); 2012(0.5m); 2018, Lidar for Rovigo coast, including lagoons of Calerin, Vallona, Barbamarco, Canarin, Bonelli and the southernmost part of the Scardovari lagoon.</p> <p>The 2018 lidar flight (Figure 3-73) was executed in April, covering an area of almost 100 km<sup>2</sup>, 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.</p> <p>Regarding Sacca del Canarin, the water level tide during the flight period over the area resulted in the range of -0.25 and -0.30 m a.s.l, and the water surface in the</p>
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	lagoon was almost around -017 m a.s.l., due to the offset between the sea and lagoon tides
Bathymetry	<p>2018 July, Lagoons: Sacca del Canarin, Sacca di Scardovari, Laguna di Calerim 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 “<i>lavori di vivificazione della Sacca del Canarin per la valorizzazione di habitat e specie protette tramite lo scavo di canali sub-lagunari, la realizzazione di velme e barene e la protezione dello scanno a mare</i>” project. The project was a collaboration of the “Ente Parco Regionale Veneto del Delta del Po” and Veneto Region- Genio Civile of Rovigo.</p> <ul style="list-style-type: none"> <li>- 2014, from Po di Levante to Po di Goro, every 1 km</li> <li>- 2012, Rosolina shoreline, every 200 m from Adige to Po di Levante</li> <li>- 2008, Rovigo district, 57 crossing, more near the coast</li> <li>- 2005, Rovigo district, 57 crossing, more near the coast</li> </ul> <p>Bathymetric surveys and topographic campaign between Eraclea and Isola Verse in the period 2002-2010 (Magistrato delle acque- Consorzio Venezia Nuova).</p>



Figure 3-73: 2018 Lidar flight over the Po Delta area - from Veneto Region

Regarding Emilia Romagna Region:

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. Data are stored in AIPO database, available on web service <a href="http://geoportale.agenziapo.it/cms/">http://geoportale.agenziapo.it/cms/</a>
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.

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

A measurement campaign is planned to acquire the current bathymetry of the area, with the double aim of having a comparison with the previous morphological status of the lagoon together with updated information to use with the existing mathematical model to predict future scenarios.

This activity, carried out by AIPO (*Agenzia Interregionale per il fiume Po*), is currently still in progress and the expected results will define the morphological structure of the riverbed in the delta area, possibly also highlighting the connection area between land and sea at the mouth.

Moreover, an experimental campaign is currently carried out for the sedimentological and chemical characterization of the sub-lagoon channels.

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

### **3.5.4. Current status of site geomorphology (methods, discussion, maps)**

The current structure of the Po delta derives from the interactions among different overlapping processes: spatial displacements of the coastline, eustatic phenomena, discontinuity in sediment supply from both Alpine and Apennine slopes and rivers and tectonic displacements. Lastly, anthropic morphogenesis overlapped everything, creating changes in trend but also, in certain cases, rigidity in evolutionary development of coastal and river landforms

#### **3.5.4.1. Recent geological and morphological settings**

The Po Delta region belongs to the foreland between the Alpine front in the north and the Apennines chains in the south. In this region, the Po-Adriatic trench develops with a homoclinal structure, reaching the buried structures of Dorsali Ferraresi in the south.

The geological configuration of the area is connected with its evolution. Sandy and calcareous marls covering the Mesozoic substrate date back to the Paleogene, and they fill the main depressions developed during the Alpine orogeny. Sedimentation processes occurred in the Miocene, when the Po delta was a platform area with shallow sea-level and it was subject to a strong subsidence. At the beginning of Pliocene, the region was flooded by the sea, which retreated partially at the end of this era. Several transformations involved the region during the Quaternary, as stated before (par. 2.2.1), when the Po plain was completely submerged, and the sediments coming by the inland basins poured into the Adriatic basin. Most of the sediments started to fill the most depressed areas, leading to compaction processes and to a differential subsidence of the region. The glacio-eustatic oscillations shaped the depositional processes, leading also to the reduction of the marine ingression.

Regarding the geological formations that are recognizable in the delta plain, recent works (Correggiari 2005) have shown that in the most landward positions the base of the late Holocene delta deposits consists of clays and peats (ca. 5300 cal. yr BP) overlying lagoonal deposits (dated ca. 6000 cal. yr BP). Onland, the maximum flooding surface at the base of the delta system is defined by a facies change at the base of prodelta mud, where closely spaced shell lags overlay the ravinement surface and the transgressive sand sheet. Offshore, the maximum flooding surface corresponds to the ravinement surface capping the barrier-lagoon deposits of the Trasgressive System Tract (Correggiari 2005).

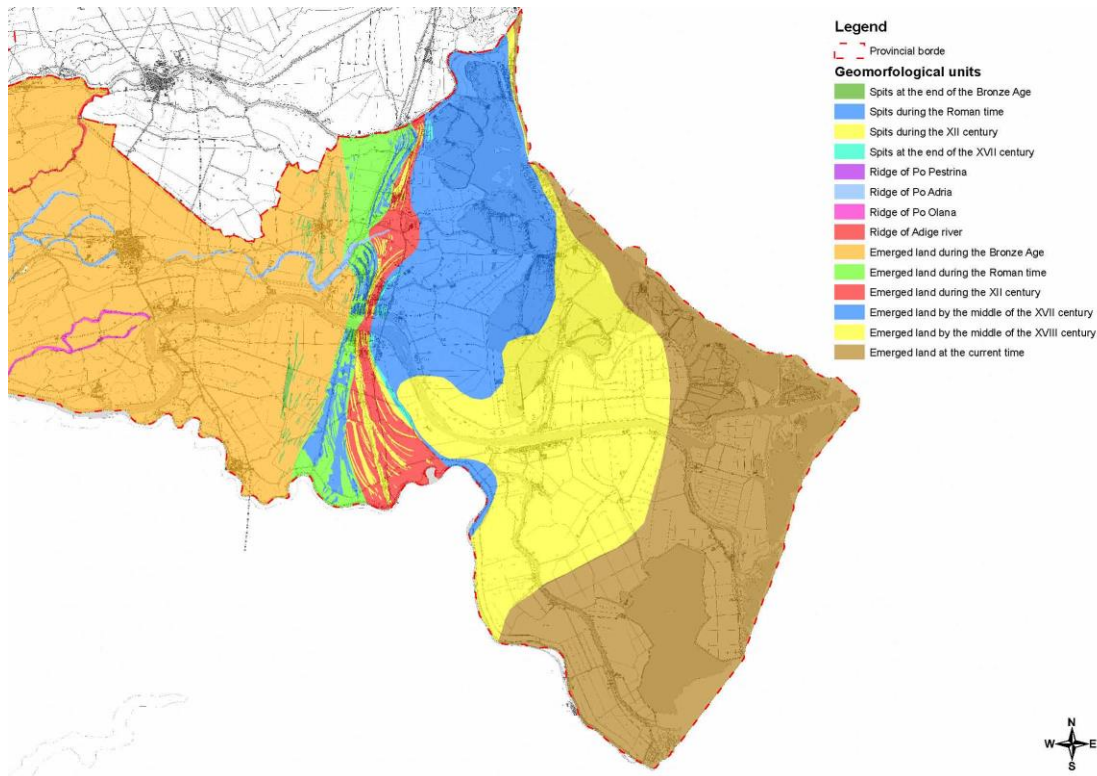


Figure 3-74: Geological units recognizable in the Po Delta region, distinguished according to the period in which they originated.  
 Source: PTCP: (Provincial territorial Coordination Plan), year: 2009, available at: [http://www.pianificazione.provincia.rovigo.it/nacontent.cfm?a\\_id=2438](http://www.pianificazione.provincia.rovigo.it/nacontent.cfm?a_id=2438):

Delta-mouth bars and barrier spits are located seaward of the main outlets of the Po River, deriving from the wave activity concentrating and reworking sediments in specific locations. Examples are the large bars in front of the Pila channel, and the barrier spits at the southernmost Goro and Gnocca outlets, where sand from the delta-mouth bars has been reworked and transported southeast, forming stranded coastal deposits of low relief (*Scanni di Goro*). These barrier spits show a shore-parallel distribution in plan-view, and a subaqueous ridge-and-swale sandy deposit.

Prodelta lobes are located at the active outlets, where the Pila channel feeds the most active one. Coastal inlets and lagoons (*sacche*) form between individual advancing delta lobes as areas of stagnant and brackish waters, and their evolution is highly dependent on the lobe construction. They can be separated by the sea by migrating coastal spits, connecting adjacent lobe headlands (Sacca di Scardovari) or be partially opened and connected to the sea (Sacca di Goro).

From a geological point of view, the Po Delta originates from the accumulation of the sediments transported by the Po River, whose discharge distributes through its branches, with Po di Pila delivering 61% of the total freshwater discharge and 74% of the total sediment load (Syvitzky, Correggiari 2005).



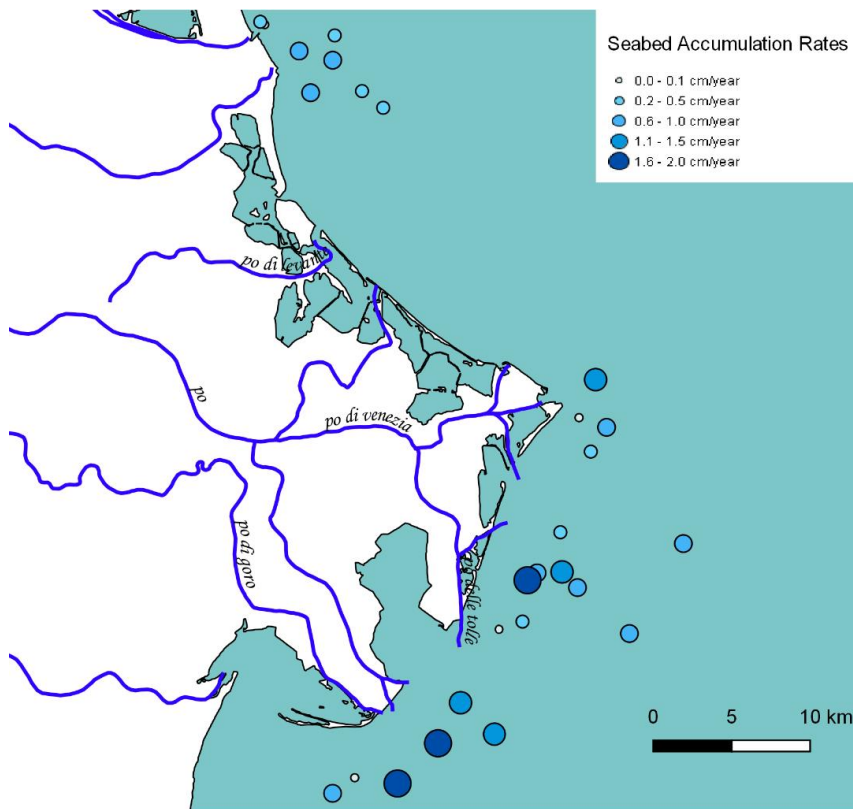


Figure 3-75: Seabed Accumulation Rates, Emodnet data from different resources: Palinkas et al. 2007, Frignani et al. 2005. Hydrographic network from [www.pcn.minambiente.it](http://www.pcn.minambiente.it).

Overall, the modern Po delta shows sediment deposition rates of 2cm/year (over 100 year 0.5 cm/year) according to Palinkas et al. 2004, 2010. Nonetheless, it has undergone a steady regression phase in the last decades due to the reduction of sediment load. According to Nelson (1970), the composition of suspended sediments transported by the Po River comprises 7% clay, 70% silt and 23 % sand, as recorded at the section of Pontelagoscuro. The sand remains confined in the top set at the mouth bars of the Po delta, while fine-grained deposits characterize the prodelta (Palinkas, Nottrover, Wheatcroft Langone 2005).

Concerning the Po Delta evolution, we can go deeper in details:

The Po delta system is characterized by an extensive delta plain, a wave-influenced delta front, and a broad asymmetric prodelta deposit. Progradation of the Po delta wedge was characterised by alternating phases of rapid advance, switch and abandonment of coastal and deltaic apparatuses, resulting in a composite deposit formed by minor units (Correggiari et al 2005). During the last ca. 3 ka the Po delta evolved from multiple phases of rapid advance and abandonment of individual deltaic lobes distributed over a coastal stretch of more than 90 km between Ravenna and Chioggia (Ciabatti, 1967; B.W. Nelson, 1970; Bondesan and Simeoni, 1983) (Fig 2.6).

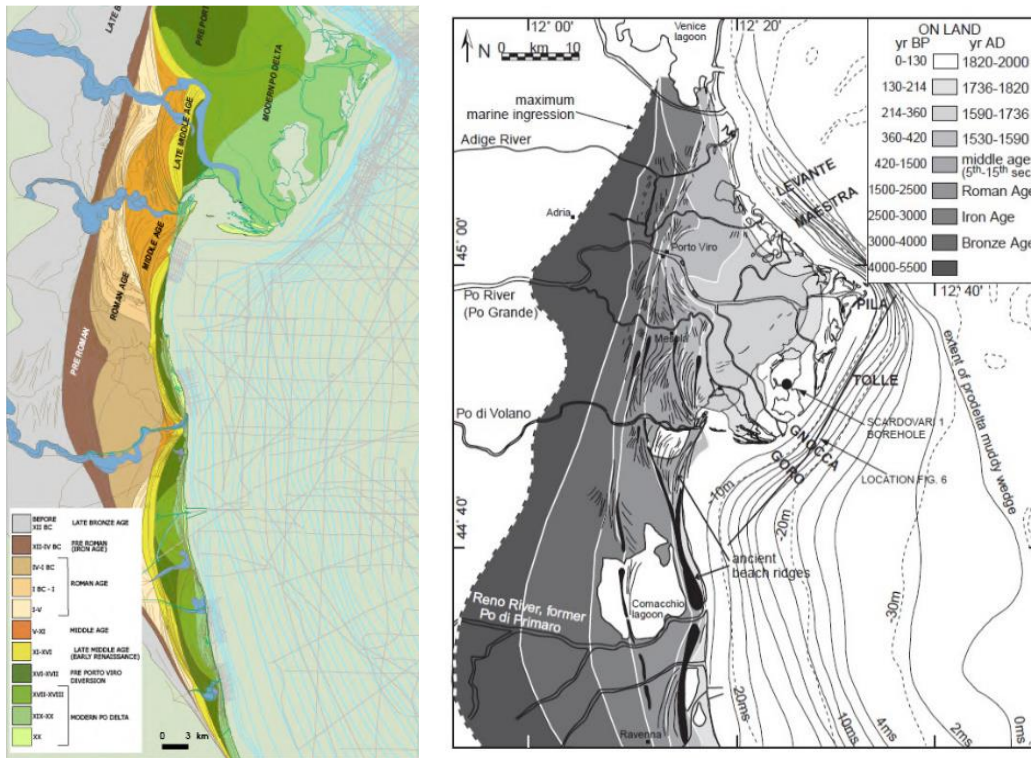


Figure 3-76: left Historical evolution map of Po Delta Calabrese L., Cibin U. et al., *Evoluzione del sistema marino costiero nel contesto geologico-climatico*, in "Il sistema mare-costa", a cura di L. Perini e L. Calabrese, Bologna, Edizioni Pendragon, 2009, pp.240. right Synthetic map of the Po Delta area showing the extent of the prodelta offshore (from Correggiari et al., 2001) and the phases of delta progradation on land (based on Stella, 1887; Ciabatti, 1967; Bondesan, 2000; Stefani and Vincenzi, 2005). The main steps of delta progradation are reported in shades of grey, and marked by white lines corresponding to historical coastlines.

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 detectable close to individual distributary channels.

Historical reconstruction and cartography show that avulsion was an important process in Po delta building, during highstand progradation. After a major natural avulsion in the 12th century, the main axis of Po river transport shifted northwards and its southern branches lost their importance. The Porto Viro cut by the Venice Republic (1600–1604 AD, more than 400 yr BP) redirected the northern branch of the Po to a southern outlet (Po Grande), initiating the rapid formation of the "modern Po delta" with a protruding morphology on the western Adriatic coast. Strong anthropogenic forcing on the river regime coupled with climate switch to colder conditions caused the huge outbuilding of the modern delta since the Little Ice Age (ca. 1450 - 1850 AD), resulting in a complete re-shaping of the northern Adriatic shoreline.

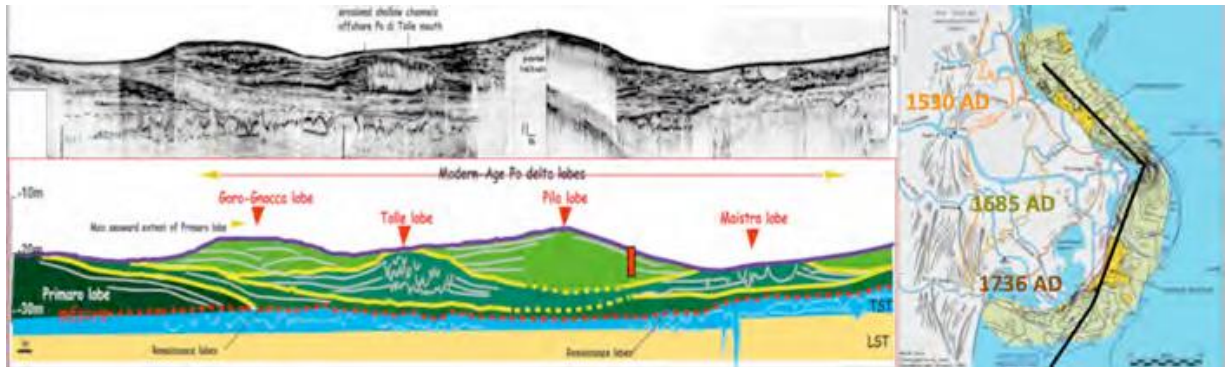


Figure 3-77: Architecture of the recent delta lobes in a composite section parallel to the coast (Correggiari et al 2005)

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 actual 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.

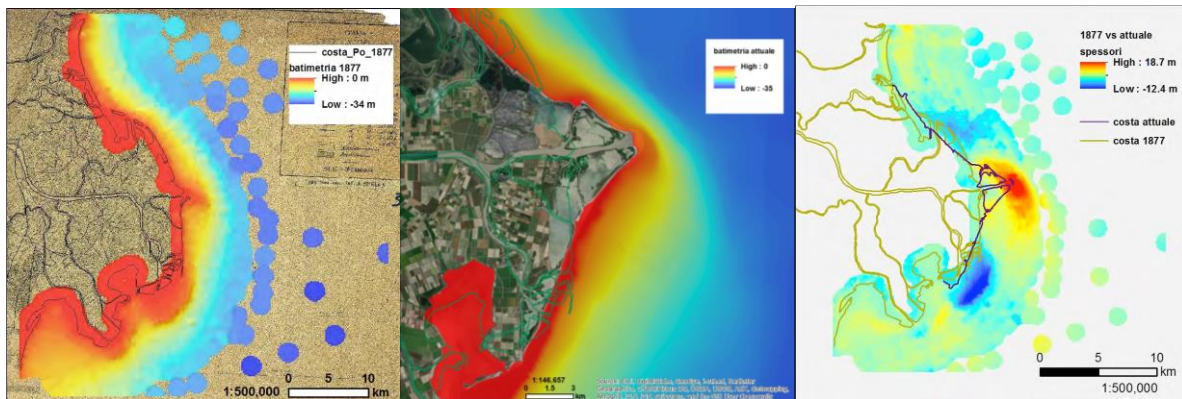


Figure 3-78: **left** DTM created on georeferenced Ing. Stella Map of 1886. **center** : actual bathymetry from singlebeam and multibeam data. **right**: result from difference between modern and historical bathymetry.

To better appreciate the variations in the three most significant sections, the morphobatimetric profiles obtained from the two DTM were compared. (Fig. D) 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.

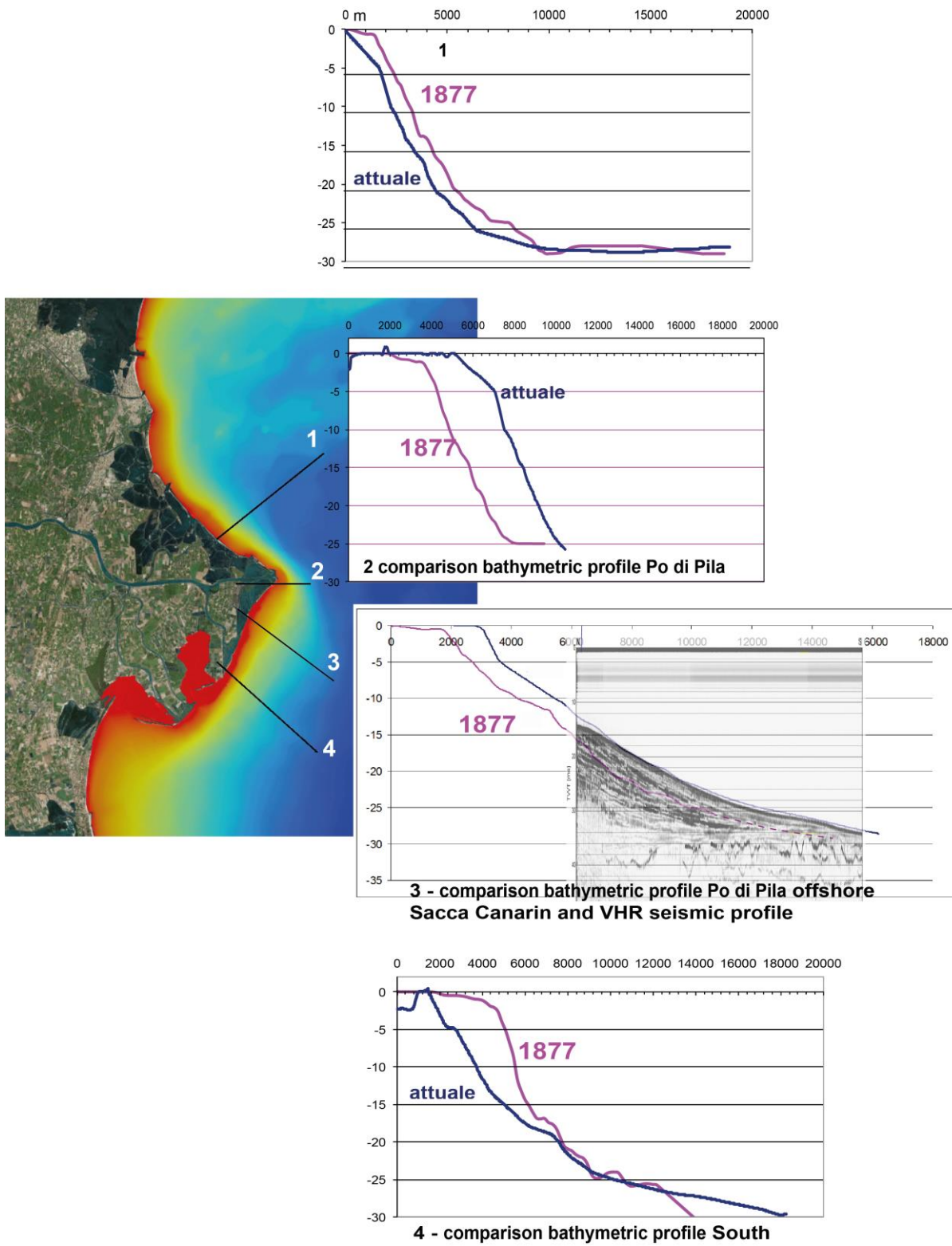


Figure 3-79: Comparison between 4 morpho-bathymetric sections obtained from the two DTM 1877 and current.

### 3.5.4.2. Tectonics and lithology

The principal structural element that characterizes the Po Plain basin is the presence of the buried fronts of the Southern Alps and the Apennines, with remarkable structural differences between the fronts and the foredeep basins of the two belts (Bresciani et al. 2014).

From a lithological point of view, sand and silt are commonly observed in correspondence of fluvial ridges and ancient shoreline. Silt clay sediments, characterized by a high organic content, are mostly located in depressed areas that in the past were prone to swamping. Sometimes even peat can be detected in areas that are below the sea level. In the transitional regions, between elevated and depressed areas, sandy silts are prevalent (Figure 3-80).

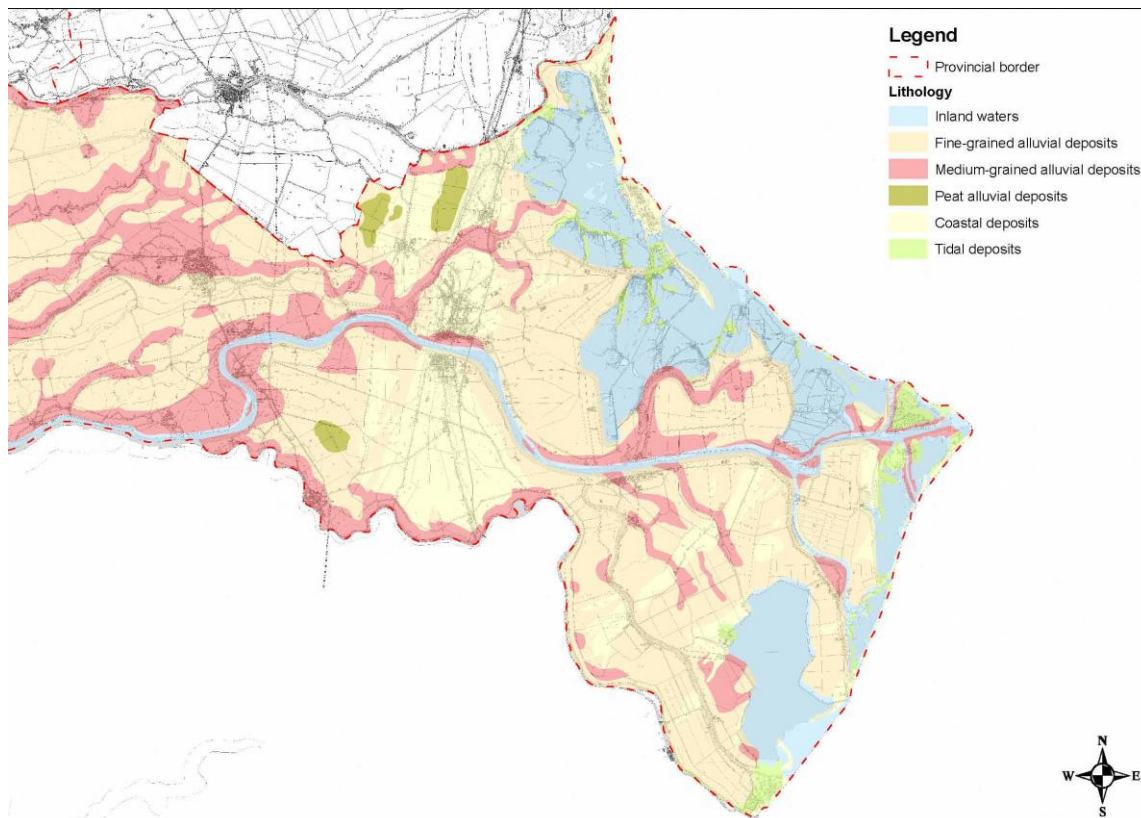


Figure 3-80: Lithology in the most part of the Po Delta Region. Source: IDT Veneto Region, <https://idt2.regione.veneto.it/>

The thickness of the deposits dating back to the Pliocene and Quaternary is remarkable, reaching sometimes 2000-2000 m, being dependent to the tectonic and subsidence processes occurred during the time. The material composing the quaternary deposits of the Delta derive from the crumbling of rocks transported from the Alps and Apennines to the sea (clay, fine sand with clay, black clay, fine sand). On the other hand, the Pliocene formation at the base of the Quaternary deposits is primarily composed of grey clays, with sand intercalations and bioclasts. Other distinct sedimentological successions can be

recognized in the whole area, belonging to specific geological phases and comprising sand, clay, peat and sometimes conglomerate.

The sedimentary deposits in the Po Delta region contain large aquifers of fresh water and important amount of gas, which has been deeply exploited especially in the past.

#### 3.5.4.3. Geomorphological setting of the lagoon systems (Sacca del Canarin and Goro)

From a morphological point of view, considering the lagoon environment of the two focus areas (Sacca del Canarin and Goro), some particular elements can be recognized (according to Reclamation consortium Po Delta):

- Sub-lagoon canals: they define a subaqueous network, connecting the lagoon to the mouths at the sea. At the beginning of the high tide (phase), the seawater starts flowing into the lagoon through these channels, with a velocity depending on the balance of forces between the lagoon waters and the sea variations. Water current in these canals is responsible for the erosion or deposition of important amounts of sediments, such as sand, silt and clay.
- *Velme* or tidal flat: they are submerged structures originated from the deposition of sediments along the sub-lagoon canals. They seldom emerge during the low tide phase.
- *Barene* or salt marsh: they are flat-marsh island and they can be seen as consolidated *velme*, which become vegetated inducing a stronger process of sediment trapping and deposition. They tend to remain emerged, above the average level of the ordinary tides. They become stable during time thanks to the presence of vegetation.
- *Ghebbi*: water ways between *velme* and *barene*, connecting the internal areas to the channels
- *Scanni*: they are elongated structures, called also mouth bar. They are of primary importance to protect the lagoon from the intrusion of salty water. Their origin relies on the deposition of sediments from the river, and their reworking from the forces of the sea currents. For these reason “scanni” are usually very mutable structures, sometimes showing parallel bars that testify the advancement of the line coast. They are usually located between the lagoon and the coast.

Summarizing, the lagoon is defined by the presence of a network of main channels, which connect the inland areas with the mouths at the sea, going through a network of secondary channels and peripheric canals (*ghebi*) and a system of *barene* and *velme*. The alternance between deep and shallow areas is a dominant element, as well as the alternance of areas with higher and lower salinity.

The grain size distribution tends to finer diameters departing from the sea, with clay deposits far from the mouths. The organic matter is widely present in the lagoon and it possesses a characteristic black colour due to the oxidation processes.

- **Sacca del Canarin**

The first picture of the Delta lagoon comes from the GAI flight in 1954, before the subsidence and the hydraulic works that were carried out in the area. In that period the sea water came only from an opening at the *scanno*, while the fresh water from the other two sides. Reeds were present on the river side. Nowadays, the morphological setting of Sacca del Canarin can be described by three main features, whose evolution is described in the paragraph 3.5.4.3

1. An inlet to the sea, called Bocca del Canarin, from which the lagoon exchanges salt water with the sea. The mouth also constitutes the access for the sediments coming from the sea and the river (Busa di Scirocco). In the north it is protected by several small reefs that were built from the beginning of 2004 by the “Reclamation consortium Po Delta”, together with a sediment tank filled with the material dredged by the canals. On the other side, the south part is exposed to the action of the storm surges. The current depth of the bottom of Bocca del Canarin is 3-4 m b.s.l in the innermost part, while it decreases towards the sea. Here the DTM (2018) shows an elongated bar parallel to the coast with a depth of 1.0 b. s. l. This bar, which can be classified as an ebb tidal delta, reduces the hydraulic exchange with the sea and holds the fresh water coming from Busa di Scirocco, both during moderate flows and floods.
2. The absence of a structured network of channels and morphological features such as barene and islands. Unlike other lagoon systems in the Po Delta region, in fact, Sacca del Canarin is characterized by a uniform and shallow bottom, with a mean depth of 0.85 m b.s.l (according to the most recent DTM of 2018). The only morphological features that can be recognized is the relict of an old littoral bar (Costà d’Avanzo) that develops parallel to the internal bank in the western part of the lagoon. According to Verza et al. (2015), here some *barene* emerge during low tide, when *velme* and oyster formation are well visible
3. Scanno, between Busa di Scirocco and Busa Storiona, which protects the lagoon from the intrusion of salty water.

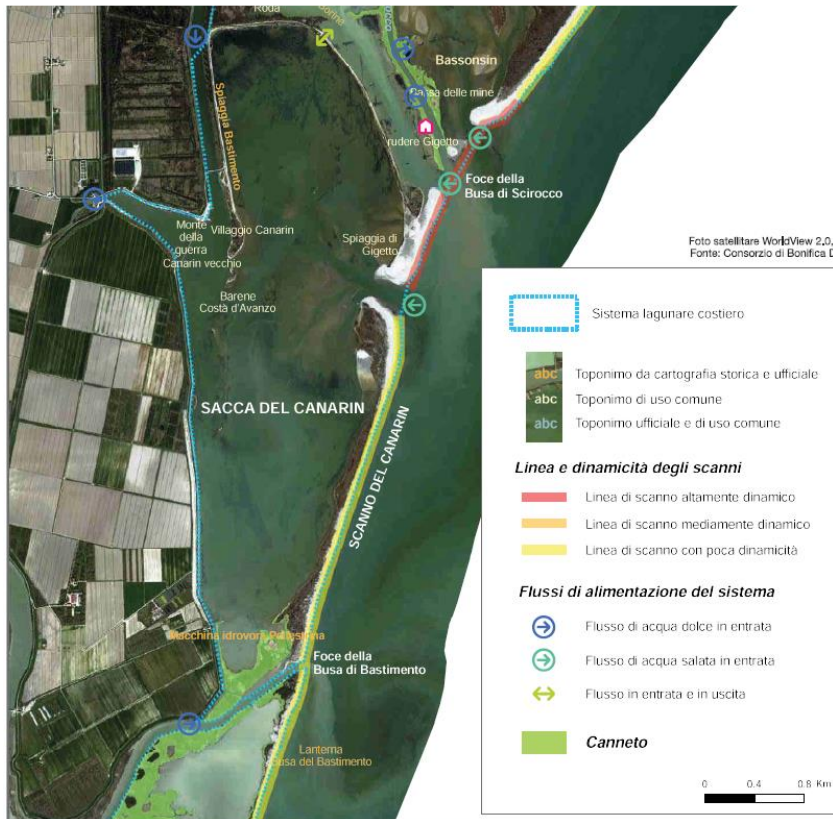


Figure 3-81: Bassona-Canarin system, Tav 1.3.5. c, page 194, Atlante lagunare costiero del Delta del Po.

## - Sacca di Goro

### Methods

The reference datum for the analysis of the current status of the geomorphological features is the digital terrain model that assembles the most recent surveys carried out in the pilot area. Since there is not a single topo-bathymetric survey (Figure 3-84) that simultaneously covers the lagoon surface and the external portions of the Scannone di Goro (Figure 3-82 and Figure 3-83), a DTM was created (DTM2012) (Figure 3-83) as mosaic of the 2008-2010 Lidar data and the 2012-2013 single-multibeam data.

DTM2012 allows to appreciate the morphological conformation of the area, highlighting the main characterizing elements; however, in a such dynamic environment it is necessary to update the measures that are now dated. In this regard, the new data of the topo-bathymetric survey carried out by RER in 2018 will be integrated in the future.

### Geomorphological description

The pilot area is characterized by the sandy spit (Scannone di Goro) on the right of the mouth of the Po di Goro. It is about 6 km long and has a maximum width of about 800 m, with a narrow fan shape; it forms the barrier that limits the lagoon southward (Sacca di Goro).



The lagoon is in communication with the sea through an inlet about 3000 meters wide which is been incised and deepened in the Lido di Volano nearshore in order to allow the transit of the boats. The lagoon shoreline is mainly artificial with banks up to 5 meters high that protect depressed areas of the hinterland and the urban centers of Goro and Gorino.

The bottom of the lagoon shows an average depth of 1.5 meters and is furrowed by tidal channels, some of which are excavated by man up to 1-2 meters deep. In the lagoon sector enclosed between the spit and the Po di Goro embankment, the shoreline is natural (unprotected) and sparse banks (barene) develop, with height close to zero and small areas emerged.

An extended bank present at the inlet is the vestige of an old portion of the Scannone that has been dismantled.

The spit is an extremely dynamic morphological element characterized by poorly developed dunes (maximum altitude about 2.5 meters), beaches and bars that can be observed on the nearshore and locally weld to the shoreline; the oblique bars characterize the sea-bottom up to a depth of about 3 meters and have a maximum longitudinal length of about 800 m and a transverse one of 200 m with a maximum height of about 1.5 meters from bottom to the crest. In the western sector the Sacca di Goro is closed by the ancient delta of the Po di Volano, characterized by ancient dune complexes and by the littoral spit that opens like a fan northward and closes southward, next to the Lido delle Nazioni.



Figure 3-82: Aerial photo (2011) of the pilot area of Sacca di Goro

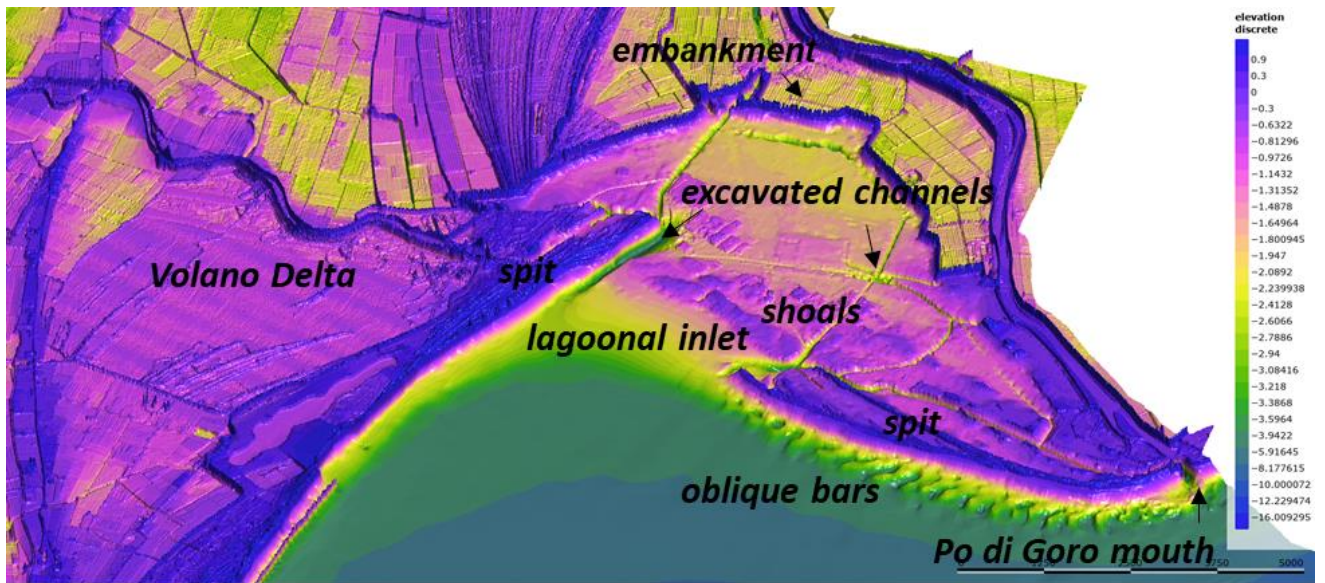


Figure 3-83: DTM2012 of the pilot area of Sacca di Goro

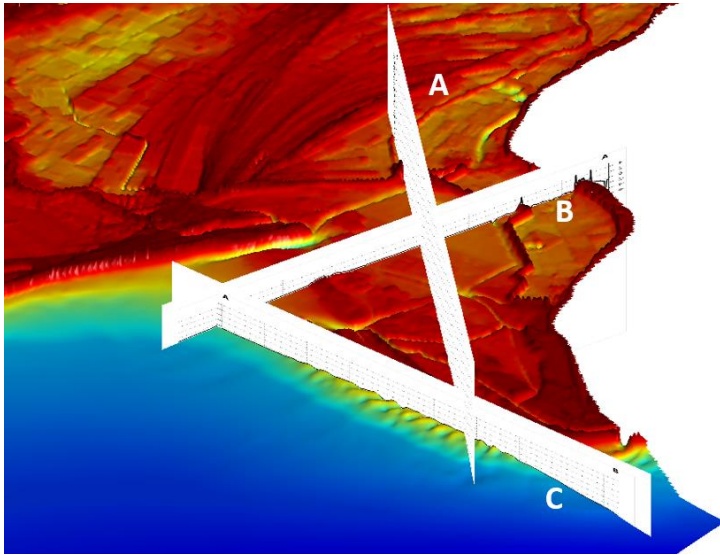


Figure 3-84: Locations of topo-bathymetric profiles

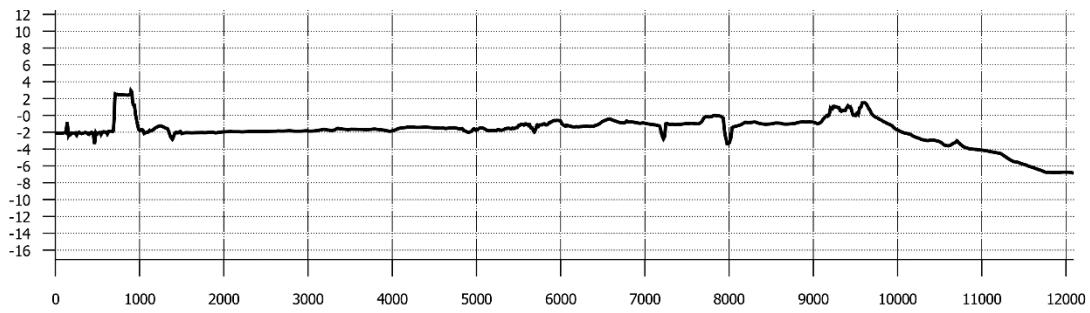


Figure 3-85: topo-bathymetric profile A

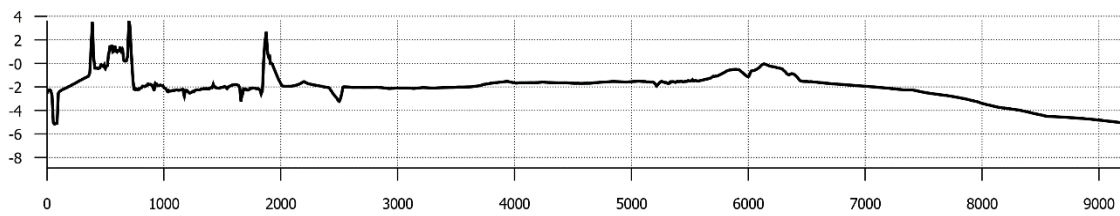


Figure 3-86: Topo-bathymetric profile B

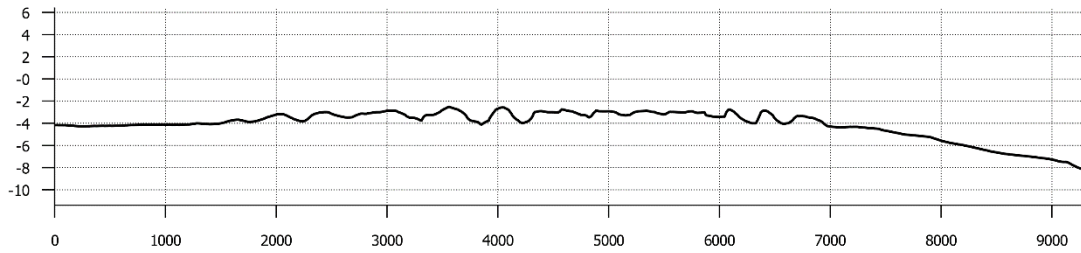


Figure 3-87: topo-bathymetric profile C

### **3.5.5. Analysis of recent trends of the geomorphological processes (methods, discussion and maps of evolutionary trend)**

#### **3.5.5.1. Geo-morphological evolution**

<sup>4</sup>The whole area has undergone important changes during the time, leading to alternate progradation and regression phases of the shoreline and consequently of the Po mouth. The shape of the Po Delta has varied due to multiple factors, such as the collision between the Africa-Eurasian plates (with the consequent formation of the Alps and Apennines), the subsidence, and the sea-level variations and, in general, the erosion and deposition processes.

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<sup>4</sup>The geological description of the Po Delta region has been mainly retrieved from Correggiari et al. 2005, Amorosi et al. 2008, Verza et al. (2015) cited in the references

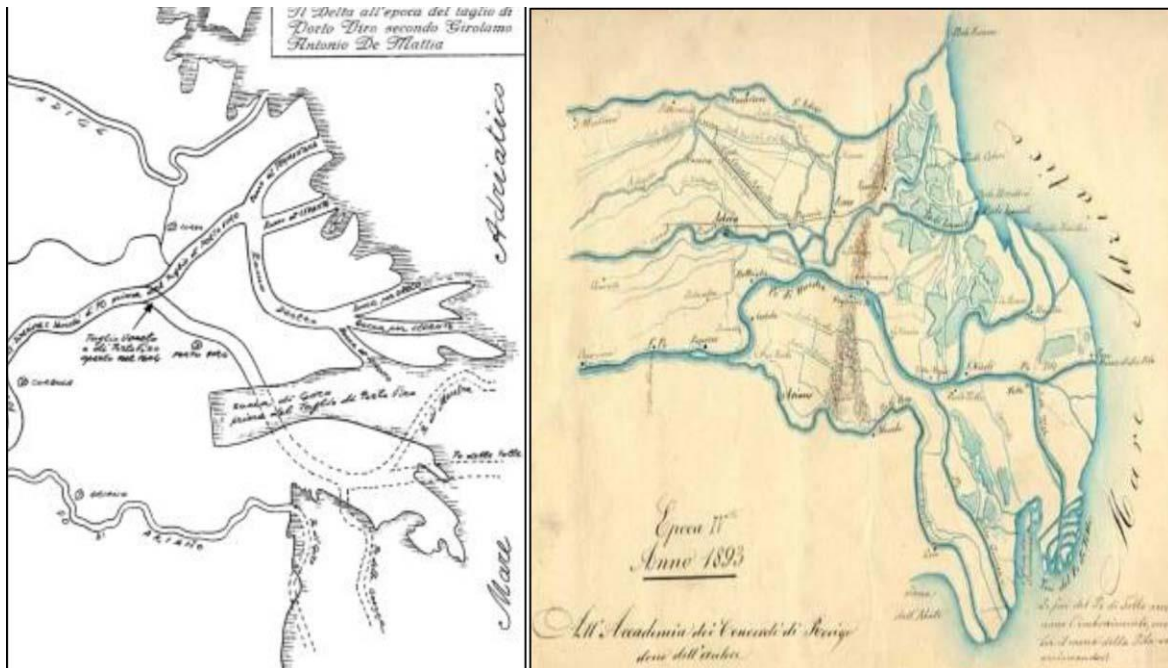


Figure 3-88: The Po Delta before and after the Porto Viro cut, image source: <https://www.bonificadeltadelpo.it/02-header-menu/la-storia-del-territorio/la-formazione-del-delta-del-po/>, originally present in the thesis of geol. Stefano Paganin.

The late Holocene Po delta formed during the sea-level High Stand that followed the Last Glacial Maximum, and it is combined with the submarine pro-delta that developed as an extensive mud wedge that downlaps on the maximum flooding surface. The evolution of the Po Delta area has been extremely complicated during the time, with profound changes in the mouth location, extension of the shorelines, presence of the marshlands.

The current configuration of the Po Delta region descends from two main historical events: the Ficarolo avulsion in 1152 and the Porto Viro cut in 1604, which triggered two consecutive diversions of the Po River, producing consequently the growth of the modern delta. The first event caused the abandonment of Primaro delta lobe, and the northward shifting of the major Po distributary channel, while the second deviated again the Po towards south, leading to the outbuilding of the modern Po Delta. The Porto Viro cut was operated by the Venice Republic to prevent the infilling of Venice Lagoon, and it marked an intense progradational phase of the delta that developed under a strong anthropogenic forcing.

After 1600 the Po Delta system has been supply-dominated, although the progradation of individual dominant lobes often caused the retreat of others. The whole system advanced synchronously for several decades, with local variation in the proportion of sediments delivered by each active branch. Therefore, it developed as a composite system resulted from the growth of individual lobes, each characterized by different histories and discharge regimes (see previous paragraphs).

The modern Po Delta, a multiple-lobe, supply-dominated system, is the result of increased sediment flux in the last few centuries, derived from climatic change 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, in fact, 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 multibeam surveys were organized in 2013, 2014 and 2016 (red, blue and green area in left Figure 3-89). In 2014 a survey was also carried out to acquire seismic Chirp profiles, white tracklines in Figure 3-90.

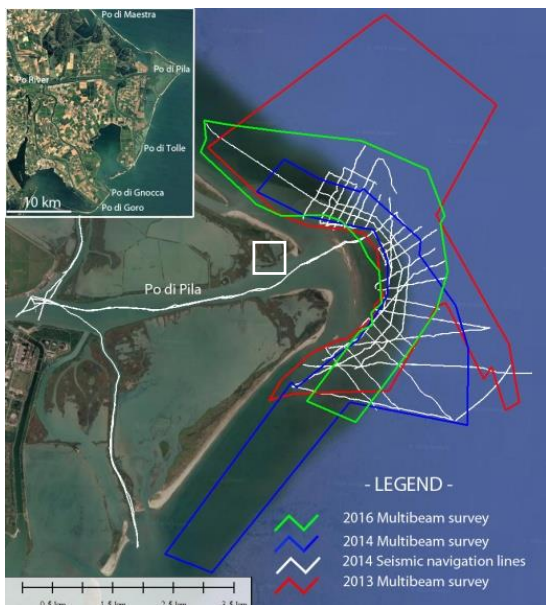


Figure 3-89: Map of the surveys on Po della Pila area. From Bosman et al 2020.

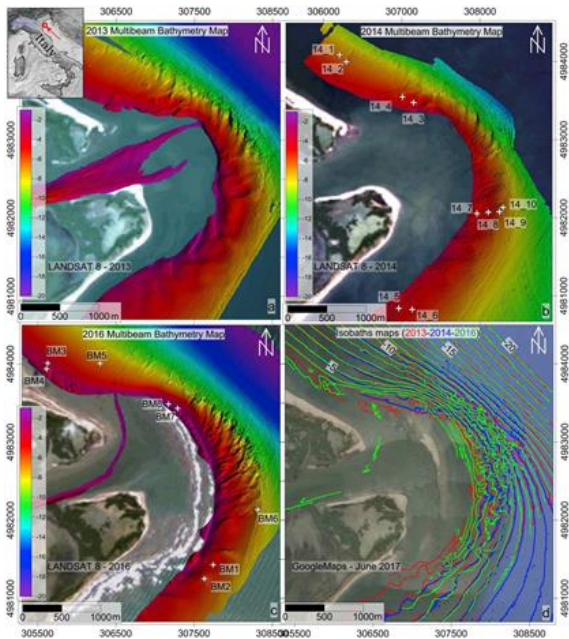


Figure 3-90: Example of map of bathymetric data. From Bosman et al 2020

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 3-11) 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; Figure 3-91) 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 3-91). 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 3-91) 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. Here local positive residuals are related to the obliteration of collapse depressions and other morphological lows (Figure 3-91).

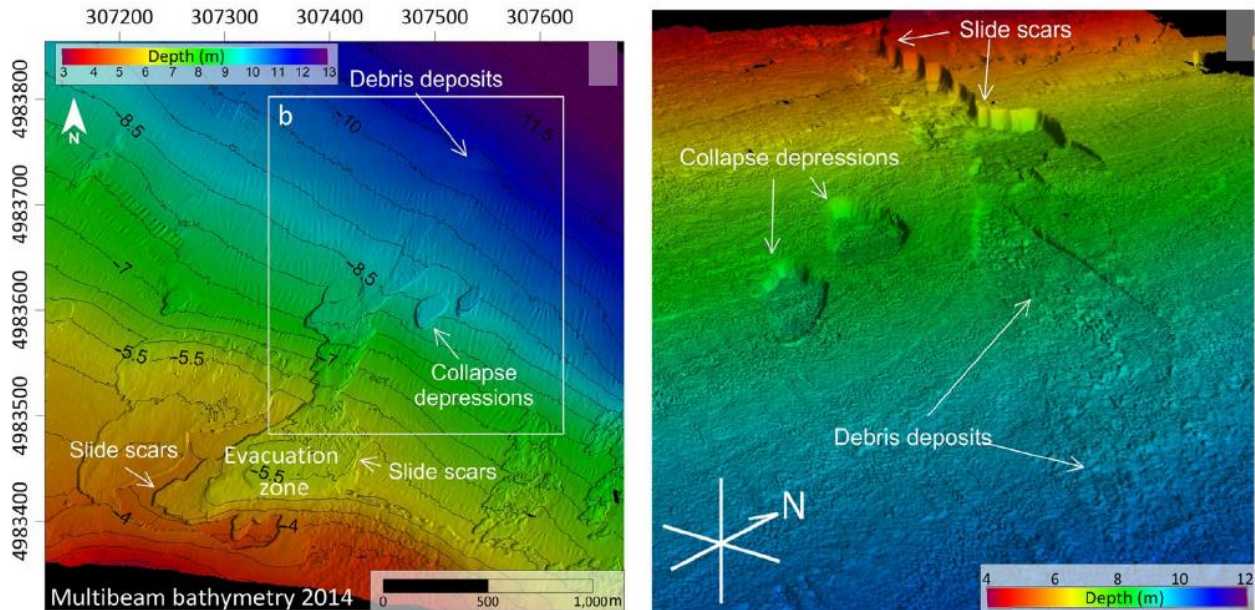


Figure 3-91: Submarine landslides scars and associated deposits located on the upper part of the prodelta slope and small collapse depressions from the 2014 survey. Trincardi et al (2020)

### 3.5.5.2. Coastline evolution

A historical evolution of the Po Delta region is available from Correggiari et al (2005), who also estimated the accretion rates and directions starting from 1600 until 1900:

- 1694 – 1750: The Po Delta grew mainly towards south at 86 km/year
- 1750 – 1820: The Po di Goro – Gnocca moved towards south-east at 129 km/year
- 1811– 1840: the Po di Maistra moved towards north at 60 m/year
- 1840 – 1886: the fluvial lobes elongated, and Po di Tolle became dominant growing at 60 m/year.
- From 1886 Po di Pila became the most dominant and grew at 47 m/year.

During the twentieth century, between the 1900 and 1996, the morphological evolution of the whole Po Delta coast followed three different phases as consequence of the changes in the sediment and water fluxes of the Po River (Simeoni et al. 2000):

1. A first period from 1900 to 1944, when the Po Delta area was influenced by the high amount of sediments transported by the Po river. The average load of the suspended sediments between 1918 and 1944 was estimated equal to 15.5 Mt/year, with a minimum between 1942 and 1943. In this period there was a general progradation of the Po Delta, as visible in **Annex 2: Po Delta – Coastline evolution**.
2. A second period from 1945 to 1983, when there was a decrease of the sediment fluxes due to the excavation activities, which started in 1950, with a peak during the 80's. The sediment shortage accelerated the subsidence, which led also to the submergence of vast portions of the Po Delta.



3. A third period, from 1984 to 1996, when the sediment supply continued to decrease. However, since the subsidence rates were lower than the previous period thanks to a series of Government's intervention, the Po Delta did not exhibit relevant changes.

Therefore, until the beginning of 2000, due to the sediment shortage, part of the Po Delta was in a phase of erosion and it was dominated by the sea processes. This has caused its typical shape of a cusp, as the sea-currents continued to remove and disperse the accumulated sediments.

The changes in the Po delta coast of the last 80 years can be derived and visualized clearly by the analysis of multi-temporal aerialphotogrammetric survey carried out from 1933 to 2018 on the delta area.

The results were obtained by integrating the coastlines extracted by Fabris et al. (2012) with the elaborations of the 2018 lidar flight conducted by the Veneto Region. They show distinctly that the most relevant changes occurred between 1933-1977, when a large portion of territory was submerged as mentioned before. In that period vast areas of the Po Delta, including mainly valleys and lagoons, went underwater due the subsidence that reached its maximum intensity in the '60s. With the sinking of the ground's surface, many embankments were destroyed or damaged, while other defense works stopped working properly, exposing thus the littoral regions to the sea and fluvial waters.

In the last period (1977-2008), the emerged surfaces are comparable to the submerged ones and little changes occurred in the last 10 years (2009-2018). The most relevant variations have involved the frontal lobe, in correspondence of the Pila mouth, which has exhibited an accretion rate of almost 20 m/year according to Ruol et al. (2016).

A curved bar has also merged in front of this lobe (Ninfo et al. 2018), favoring its progradation and accretion. Regarding the other regions, the southern part of the Po Delta is more dynamic in comparison to the northern portion, where the touristic activities have imposed the implementation of diffusive measures to control the coastal evolution.

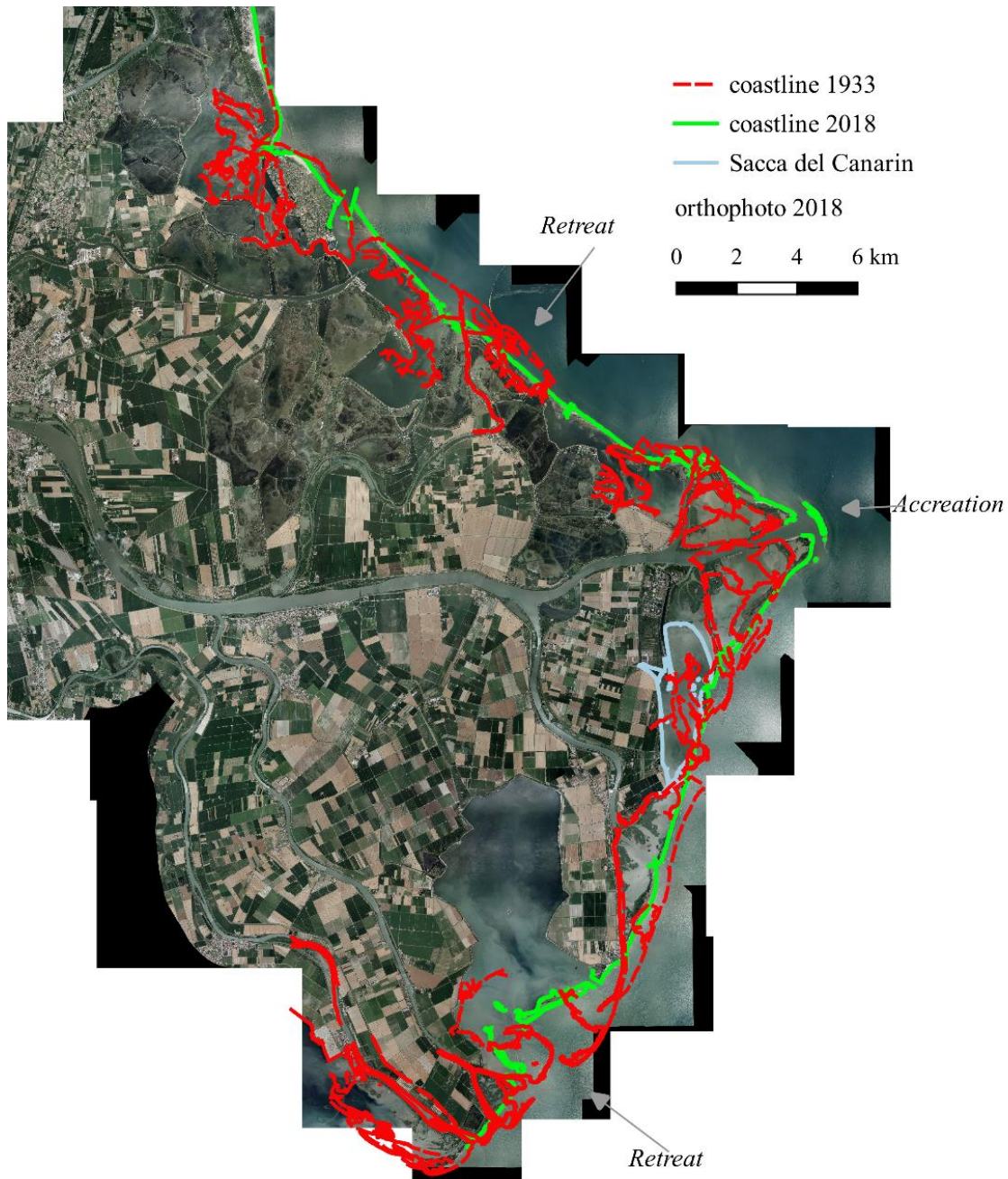


Figure 3-92: coastline evolution in the Po Delta area: 1933-2018

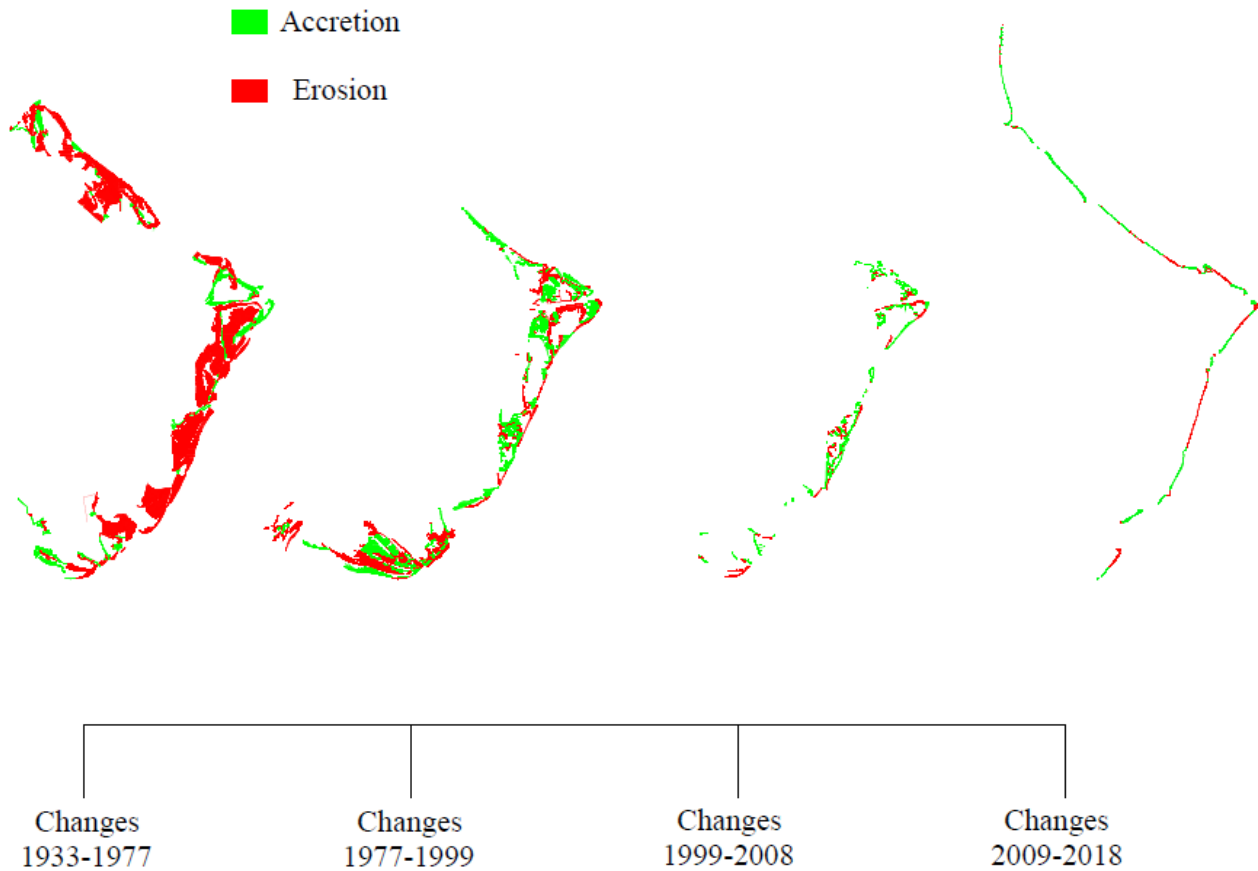


Figure 3-93: Po Delta coast changes from 1933 to 2018

### 3.5.5.3. Subsidence evolution

The subsidence refers to a slow areal lowering of the ground surface, and its rate and distribution have been analysed in several works, such as the Monitor project, the paper of Tosi et al. (2016), as well as in the works of Bondesan et al. (2015) and Ruol et al. (2016).

According to these authors, natural causes induce a subsidence rate in the Po Delta region of approximately 5 mm/year and they are represented by:

- Compaction, due to the presence of recent deposit constituting the delta plain. They are subject to consolidation processes, with the expulsion of the interstitial water and grain compaction
- Deep tectonic
- Sea level rise (eustasy), occurring since the last glacial maximum and recent climate change

Man induced subsidence has a higher rate and is due to:

- Drained reclamation: the reclamation for agriculture purposes causes a compaction of the soils due to the expulsion of the water from the inter-granular voids.
- Peat oxidation: especially in the areas subject to remediation, where the organic matter gets exposed to air and undergoes fast oxidation processes.
- Fluid extraction (methane and water)
- Lacking of new sedimentation due to dam construction and mining activities upward of the river mouths
- Artificial loads.

The **Monitor project** (2007, (**Annex 3: Po Delta – The Monitor project**)) has shown that the largest displacements are located along the mean part of Po di Goro river course; at the margins of Sacca Scardovari; along the past shoreline crossing the Municipality of Pila; and in the northern coast, between Po di Maistra and Porto Caleri. Near the coast, the deformation rates due to the subsidence reach values of -20 mm/year, but they tend to decrease towards the inland

Regarding the closest areas to Sacca del Canarin, the most recent analysis carried out in Ruol et al. (2016) reported a subsidence between -2 mm/y and 0 in the internal part between Busa di Scirocco and Busa Storiona in the period 1992-2000, with a maximum rate of -5mm/y closer to Busa Storiona. The trend is confirmed and even reduced afterwards, between 2002-2010.

- **Sacca del Canarin**

The lagoon environment is a very dynamic system, controlled by the flux and reflux of the tides and river discharge, while quick changes derive by storm surges, events of very high tides and floods. Sediments and water interact constantly changing the lagoon setting.

Three main natural, morphological trends can be identified in the features described in 0:

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. Therefore, during the years several interventions have been carried out, by dredging the section of the inlet.
2. Flattening and raising 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*. According to Ruol et al. 2016, the surrounding area of the *scannois* 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. The Enel power plant has affected for long time the area of Girotti, which only now is returning to its natural setting.

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.

According to Verza et al. (2015), several interventions have been carried out at Sacca del Canarin

4. A stone ballast and a sediment tank have been recently built at the south part of the Basson, resulting into an increasing flux of salt water in that side. The ingression of fresh water from Busa di Scirocco has been furtherly limited by building a new ballast
5. Deep canals have been dredged from the mouth to realize sediment tanks behind the scanno di Canarin and increase its stability. A fence was built at the border with the lagoon to dampen the sediment dispersion. The survey in 2014 showed that the area was slowly being vegetated and populated by birds.
6. Some of the dredged sediments have been used to nourish the velme.
7. Recently a stony groyne was built in the sea to limit the ingression of fresh water in the lagoon



Figure 3-94: Interventions in Sacca del Canarin WorldView 2.0, 2011, taken from Atlante lagunare costiero del Delta del Po, page 308. In blue the dragged canals



Figure 3-95: Evolution of Sacca del Canarin 2006, 2011, 2014, from *Atlante lagunare costiero del Delta del Po*, page 298.



Figure 3-96: Ballast at Busa di Bastimento mouth. Page 299, *Atlante lagunare costiero del Delta del Po*,

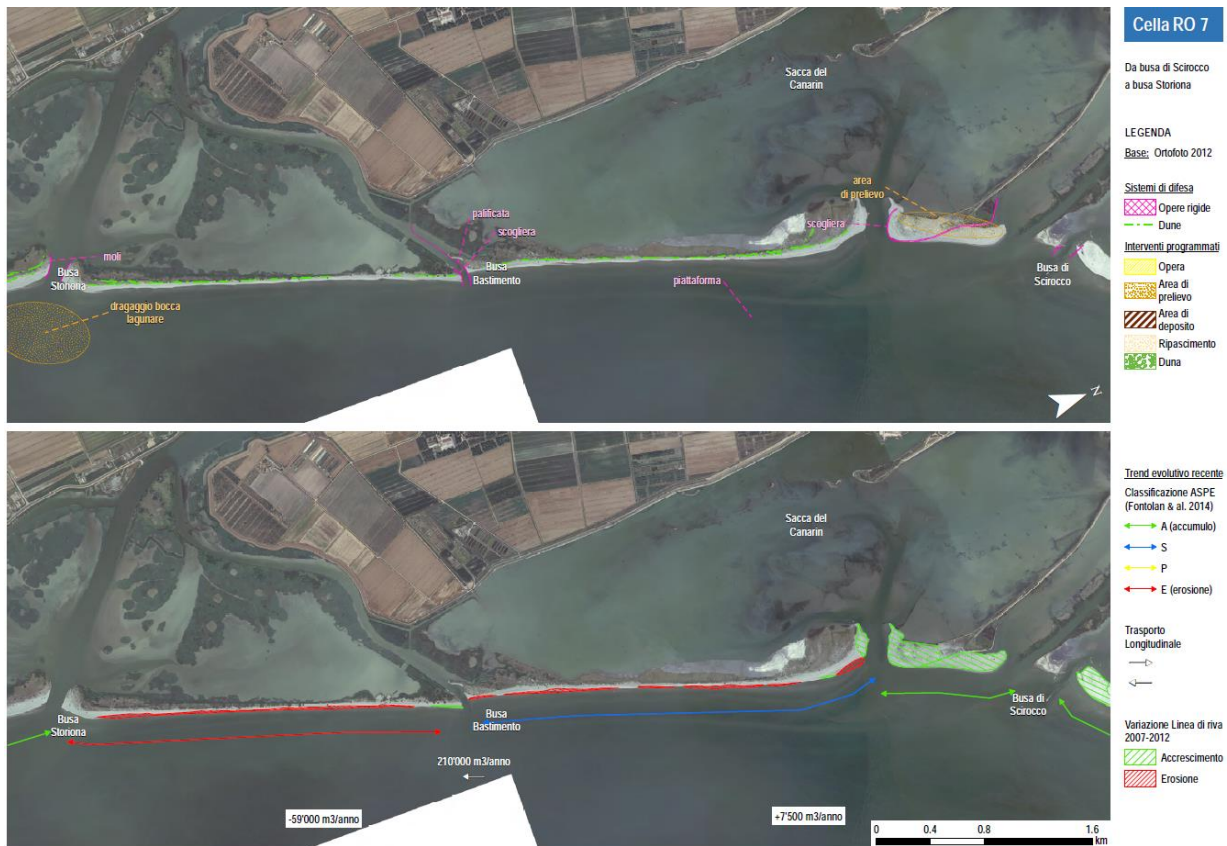


Figure 3-97: Evolution of the shoreline near Sacca del Canarin, from *Gestione integrate della zona costiera*, page 281

## - Sacca di Goro

### Multidecadal analysis

The geomorphological evolution of the pilot area can be reconstructed with extreme detail since the nineteenth century through the study of historical maps and remote sensing (aerial and satellite images) starting from the second half of the twentieth century. These data show the birth of the Sacca of Goro as a consequence of the fore-stepping of the mouth of the Po di Goro and the progressive dispersion of the sandy deposits of the delta front towards the west and the growth of the littoral spit. At the same time, in the western coast, the Volano spit has developed on the ancient delta of the Volano since the 19th century. In more recent times it is interesting to note the growth stages of the Scannone di Goro and the impact that some anthropic interventions have had on its morpho-dynamic evolution.

A detailed analysis from the XVIII to XXI is presented in **Annex 6: Po Delta – Sacca di Goro**, historical evolution.

### Geomorphological maps



Four different geomorphological maps of the area were available (<https://geo.regione.emilia-romagna.it/geocatalogo/>) for the 1943-45, 1982, 1998 and 2005 year respectively (Figure 3-98-Figure 3-101).

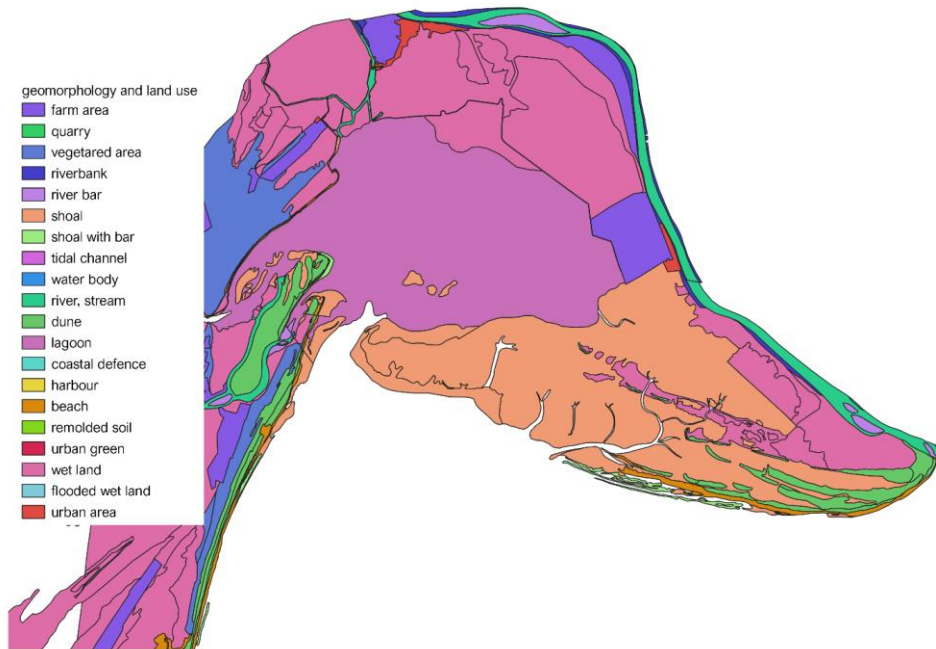


Figure 3-98 Geomorphological map for the 1943-44year.

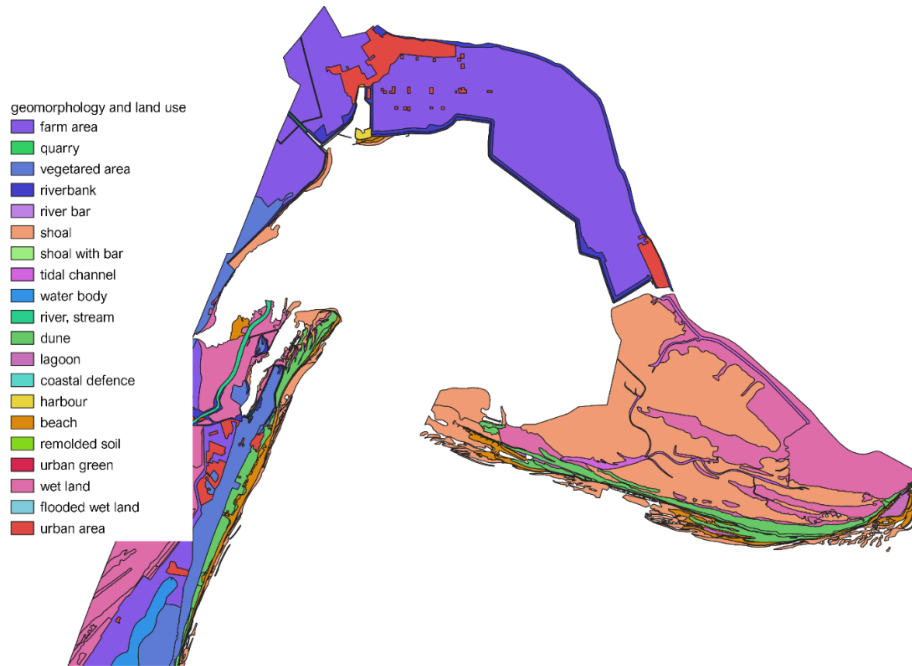


Figure 3-99 Geomorphological map for the 1982 year.

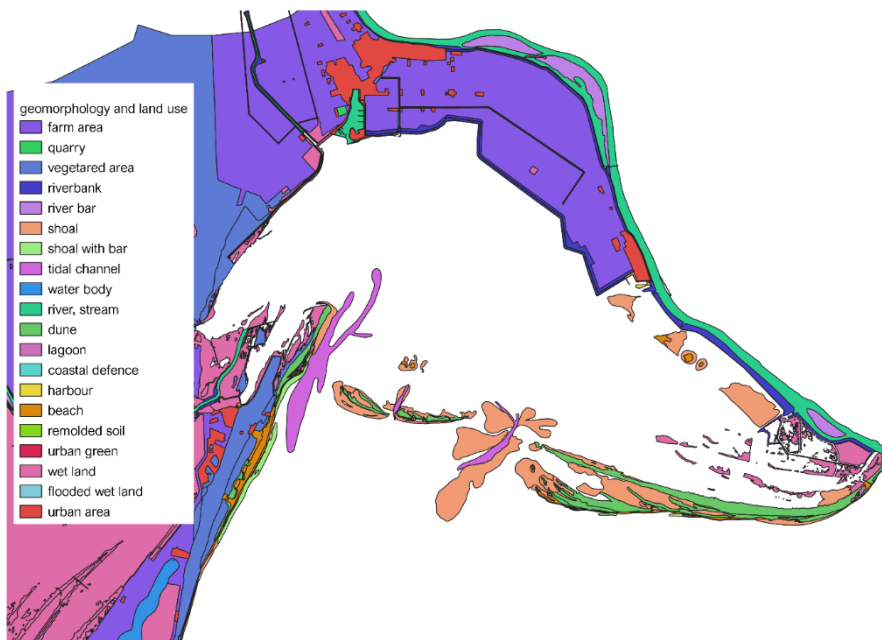


Figure 3-100 Geomorphological map for the 1998 year.

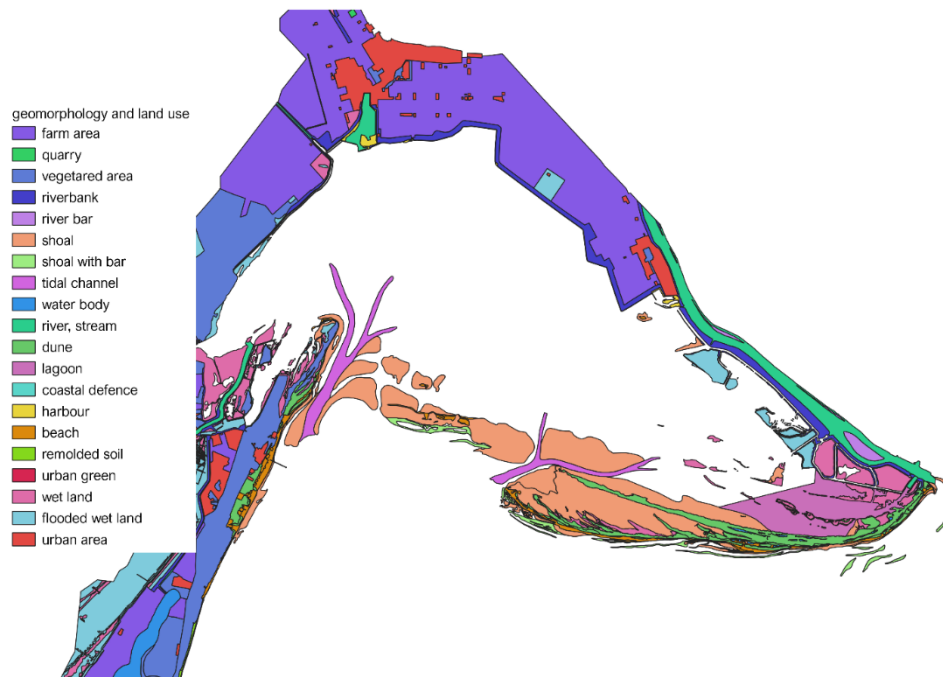


Figure 3-101 Geomorphological map for the 2005 year.

### Geomorphological trend

The collected data allow highlighting a first step characterized by the progressive closure of the gulf on the right of the prograding Po di Goro mouth and thus the creation of the lagoon (XVIII-XIX centuries).

A second step started when the decrease of the river supply stopped the mouth migration and a westward dispersion of delta front deposits began. During this period the Scannone was abundantly fed and grew considerably. In particular, the Scannone shows three stages of development: in a first stage it still advances towards the sea, leaving behind the oldest and abandoned spit and testifying that the mouth still provides an important sedimentary supply (first half of the twentieth century); subsequently the Scanno stabilizes and grows in length; after this phase the spit is fragmented, thinned and partially submerged, probably due to the predominance of erosive phenomena over the depositional ones with respect to the previous phases.

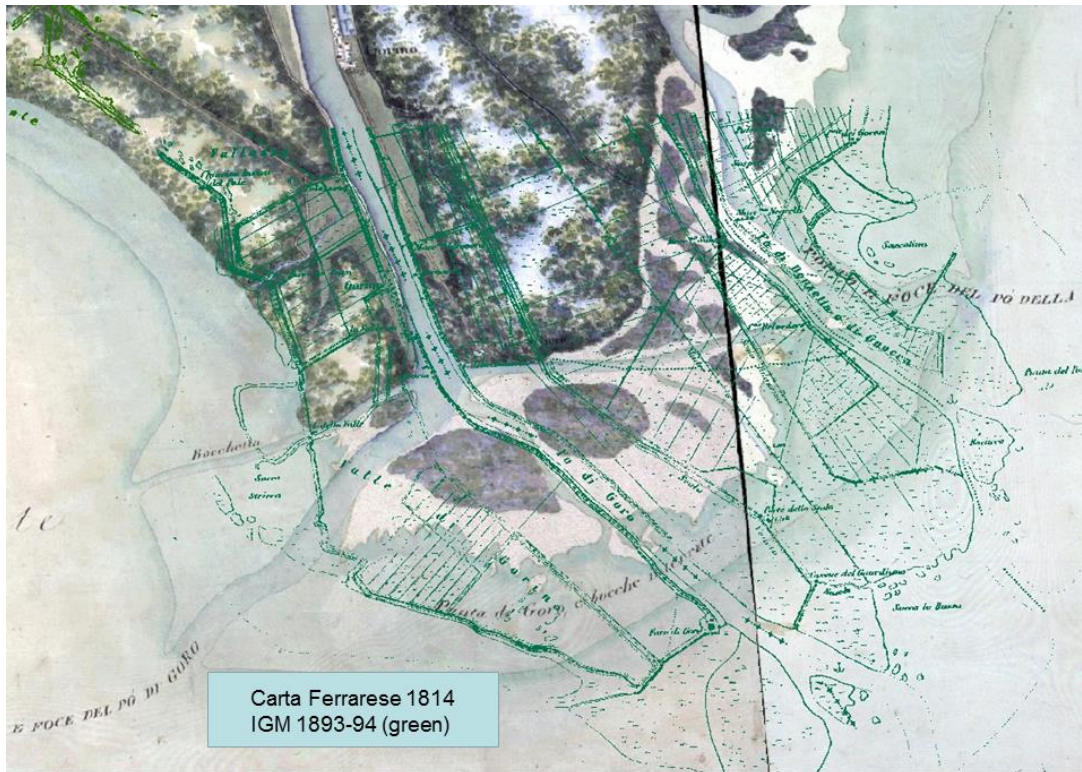


Figure 3-102: Historic maps testify the progradation of the Po di Goro mouth: in this case, in 80 years it advanced about 1 km.

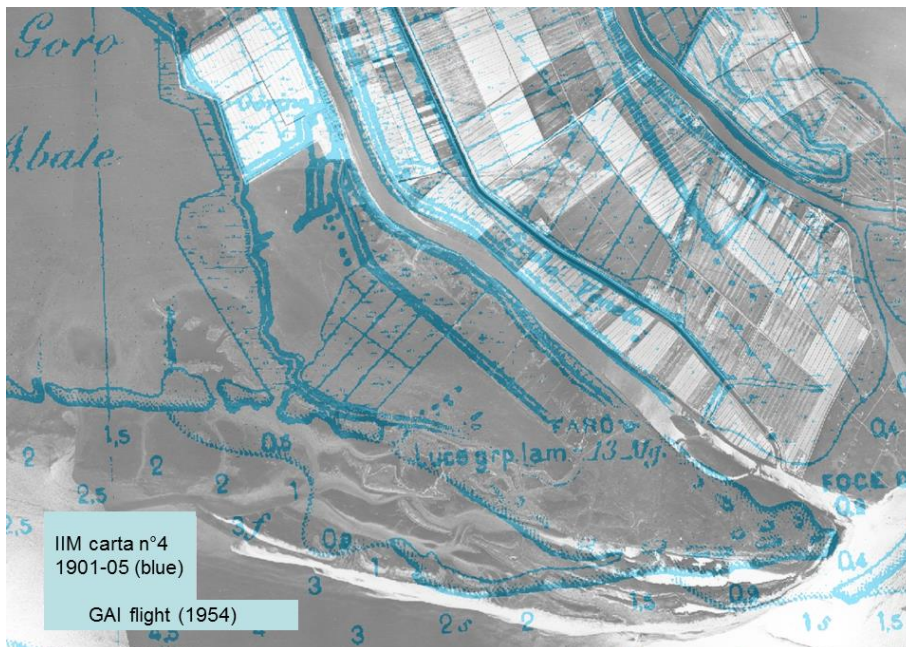
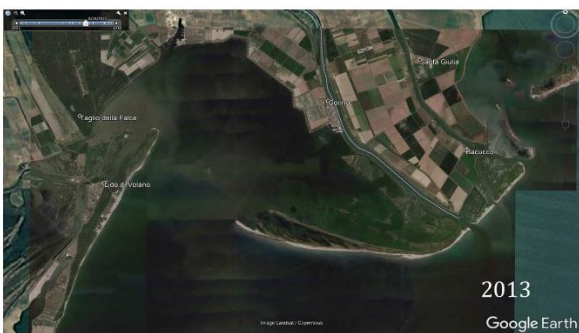


Figure 3-103: Comparison between historic topo-bathymetric map (IIM 1901-05) and aerial images (GAI flight, 1954): ancient spits as a growing trend are evident.



*Figure 3-104: Comparison between aerial images (GAI flight, 1954 and IT2000 flight, 1998): river mouth is stable whereas spit shows new branches in distal portion and islands.*



*Figure 3-105: Sequence of satellite images from 2004-2018 (Google Earth, Maxar Technologies): at this scale the submergence of the banks located west of the Scannone and the extreme variability of the sedimentary dynamics of the lagoon highlighted by the shoals, channels and suspended deposits can be observed*



*Figure 3-106: Comparison between satellite image of 2018 and 2003 coastline (yellow line) and 2013 coastline (red line): the figure shows the loss of the island in the west sector and regression in several points.*

The bathymetric evolution was also investigated, in order to understand the morpho-depositional trend of sea bottom. The digital bathymetric models available are of 1901-05, 1953, 2000 and 2012 years.

The cross-section perpendicular to the mouth of the Po di Goro (figure xx) shows that already in the first half of the twentieth century most of the proximal delta front deposits were removed and partly redistributed in the deeper portions of the seabed; in the second half of the twentieth century the seabed underwent a generalized lowering and in the more recent period there is still a depletion of the nearshore portion with accumulations at depths greater than 6 meters. The longitudinal section of the Scannone (Figure 3-107) shows that in the first half of the twentieth century the seabed has risen, thanks to the contribution of the deposits eroded by the mouth, therefore the profile stabilized in the second half of the twentieth century with evidence of a mild deposition in the western sector.

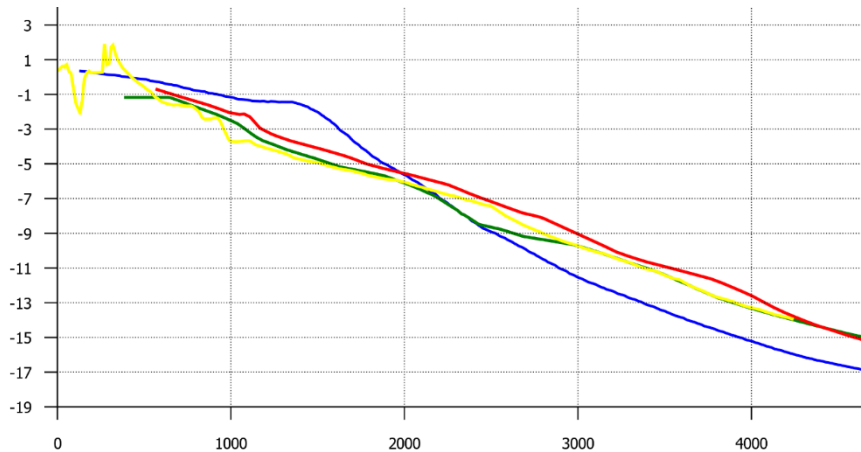


Figure 3-107: comparison between bathymetric profiles of 1901-05 (blu line), 1953 (red line), 2000 (green line) and 2012 (yellow line); the cross-section is perpendicular to the river mouth

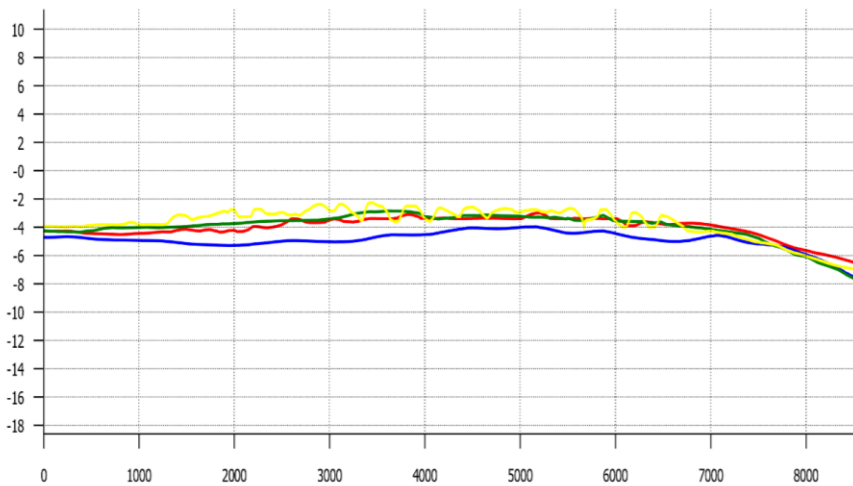


Figure 3-108: comparison between bathymetric profiles of 1901-05 (blu line), 1953 (red line), 2000 (green line) and 2012 (yellow line); the cross-section is longitudinal to the Scannone di Goro

### 3.5.6. Conclusion

#### 3.5.6.1. Problems and solutions

The analysis of historical and recent data has shown that the Po Delta is a highly dynamic area, exposed to the concurrent actions of multiple natural and anthropic alterations.

Its evolution has been dictated by the changes of the sediment and water fluxes at the catchment scale and its current configuration has been shaped by the sea currents and marine processes. Additionally,



modifications in land use, freshwater management, and hydraulic protection works have interfered with natural alterations. Numerous studies have focused on the Po Delta by analyzing the past modifications with the aim of disentangling the effect of the natural factors from the anthropic ones and predicting future trends in a changing climate.

The analysis 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.

Subsidence has played an important role in defining the emerged and submerged lands of the Po Delta.

Another aspect that has emerged, is the growth of the salt intrusion that has reached worrying proportions in the entire area of the Po Delta, especially due to the decreasing water discharges measured in the Po River and its tributaries. Lagoon environments have shown to be fragile environments, whose existence depends on the preservation of the spits that protect them from the sea, and on the maintenance of the internal circulation.

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**

Sacca del Canarin is a shallow-water lagoon, whose economy relies deeply on fishing and touristic activities. In the past the lagoon experienced problems of eutrophication that were associated to the reduced hydraulic circulation within the water body. The recharging time of Sacca del Canarin (time spent to have a complete change of the water in the lagoon) is quite high and varies according to the vicinity to the river or to the sea. In fact, it is lower close to the mouths where the water exchange is strong, while it is high in the central part, where the circulation is practically null.

For this reason, important works of vivification of the lagoon are planned, and they are intended at reducing the freshwater flux from the river mouth and the pumping stations, while increasing the saline flux from the sea. They can be divided in three groups according to “Studio di fattibilità degli interventi per il riequilibrio morfologico ambientale della Sacca del Canarin”:

- A. Short-term works: 1) maintenance of the inlet and adjacent channels; 2) reinforcement of the *scanno* in the north; 3) reinforcement of the northern embankment; 4) bounding of the discharge water from the Pellestrina pumping station
- B. Medium-term works: 1) dredging of the internal channels and realization of *barene*; 2) reinforcement of the *scanno* in the south; 3) realization of a biotope/wet area in the discharge basin of the Boscolo pumping station; 4) reduction of the channel that connects the lagoon with Busa del Bastimento.

- C. Long-term works: i) opening of a second mouth in the south; 2) dredging of the channel around the new mouth; 3) realization of barene and reinforcement of the scanno; 4) integration of the channels with the waterways in the coast.

- **Sacca di Goro**

The rich historical documentation available allows to reconstruct the different stages of the geomorphological evolution of the Sacca di Goro. In particular, it is possible to go back to the eighteenth century thanks to historical maps to observe the early stages of its formation and follow the complex morpho-depositional dynamics of the spit in recent decades through the sequence of remote sensing images. The systematic topo-bathymetric surveys, carried out from the beginning of the twentieth century, allowed the construction of digital models of the sea bottom which highlighted the morphological changes in the submerged portion.

The results of this analysis highlight different development phases, fundamentally influenced by the activity and solid transport of the Po di Goro: in the first phase, over-feeding led to a strong advancement of the mouth, a progressive closure of the Sacca and the accumulation of sandy deposits in the delta front, in a second phase the morpho-dynamic marine processes, such as long-shore transport to the west, became dominant, causing the erosion and remobilization of the delta front deposits and the continuous modifications of the spit. Anthropogenic interventions have often overlapped this general trend, amplifying or triggering new sedimentary processes at local scale.

The geomorphological and morpho-dynamic peculiarities of this depositional system have direct effects on the use of the territory and resources. In particular, two topics are strategic in this territory: shellfish farming and the identification of sandy accumulations to be used for the nourishment of beaches.

It is a fact that the sedimentary dynamics, that determine the conformation of the spit, the lagoonal inlets and the tidal channels, as well as the movement of the sediments inside the lagoon, can influence the environmental status of the areas used for the growth of mollusks. Furthermore, the presence of sandy depositional areas, especially in the western margin of the Scannone, identifies potential reserves for mining.

Interventions on this complex and fragile depositional system, however, can have their risks, especially for the fact that it is extremely difficult to predict how it will react in the medium and long term to alterations that are imposed to obtain immediate results. It is also necessary to deepen the studies and knowledge of this morpho-depositional system, both in qualitative terms, identifying the sedimentary processes that are currently taking place, and in quantitative terms, defining the volumes of the deposits of interest.

The assessments for the exploitation of sandy accumulations, for example, should take into account the overall sedimentary dynamics, also considering the sectors with sediment deficit or erosion and correlating the evolution of the Sacca di Goro to that of the southern sector of the entire Po Delta.

In this regard, the bathymetric surveys of the delta branches of the river Po have been carried out. These new data will improve the general knowledge framework and will provide valuable information on the riverbed morphology and possibly on sediment supply to the sea.

#### 3.5.6.2. Analysis of data quality

Regarding the analysis of the coastline evolution, according to (Ruol, Martinelli, & Favaretto, 2016) there are some uncertainties and inhomogeneities regarding the data, such as:

8. The interphase between land and water is not clearly identifiable from the orthophotos and it is affected by the run-up and tide condition at the time of the flight. The uncertainties here is of the order of magnitude of 2 m.
9. The orthophotos gave information of the planar evolution of the coastline, but they cannot say anything regarding the temporal deepening of the seabed and eroded/deposited volumes at the coastline.
10. For the Lidar surveys the coastline is identified as the isoline defined as +0.25 m a.s.l.. Different procedure has been followed to define the coastline from the DTM 2008, considering alternatively the furthest border between land and water. Therefore, this datum has not been considered in the overall analysis.
11. The orthorectification and homogenization of the reference system are crucial elements for the reliability of the analysis.

Regarding Sacca di Goro

The analysis of the geomorphological evolution of Sacca di Goro is based on already existing data archived in regional and other databases. These databases are, in most cases, reachable and accessible through webpages from which it is possible to directly view or download the data. For the geomorphological analysis, the Information System of the Sea and the Coast of the Seismic Geological Service and Soils of the Emilia-Romagna Region was fundamental.

All the available data have been integrated with each other and have offered valuable basic documents for understanding the geomorphology of the study area. Historical maps, aerial image sequences and digital models of land and sea surfaces have proven to be of basic importance for this purpose. The survey of the riverbed of the Po delta branches as part of the Change We Care project will be elaborated and archived into this regional database.

In this case, the high quality of the data was consequent to the possibility of visualizing more or less clearly the morphological characteristics of the territory, also using GIS and 3D modelling software. The fact that from these data a detailed evolution over the long and short term was reconstructed is their intrinsic importance.

The same importance must be given to interpretation thus to experts who have been able to extrapolate the most useful information to the needs of the community, giving greater value to the data acquired. This role has been played by university, research centers and regional services and has not yet been exhausted.

In this direction, the Seismic and Soil Geological Service of the Emilia-Romagna Region and the CNR-ISMAR of Bologna have been collaborating for several years for the acquisition and interpretation of new data, also in the pilot area.

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119. [http://www.pianificazione.provincia.rovigo.it/nqcontent.cfm?a\\_id=2438](http://www.pianificazione.provincia.rovigo.it/nqcontent.cfm?a_id=2438)
120. <https://idt2.regione.veneto.it/>
121. <https://www.regione.veneto.it/web/vas-via-vinca-nuvv/vinca>
122. <http://sgi2.isprambiente.it/mapviewer/>

## 5. ANNEXES

### Annex 1: Mula di Muggia – additional maps

A summary of the most important changes in the six-time intervals is presented in the text that follows.

#### 1. First Period (1822-1894)

The evolution of the littoral is derived from

- Carta di cabotaggio del mare Adriatico (1822-24) (Figure 5-1)
- Carta Corografica del Catasto Franceschino (1830 Figure 5-2, Figure 5-3)
- Carta Franzisco – Josephinische Landesaufnahme (1869-1887 Figure 5-4, Figure 5-5, Figure 5-6)
- Carta topografica del Militargeographisches Institut (1894) (Figure 5-7)

The most important evidences and changes are (Figure 5-8, Figure 5-9,3Figure 5-10:

- The littoral is not urbanized, apart the small town of Grado.
- The mouth of Grado is un-jettied and therefore there are no obstacles to the longshore transport to the west even beyond the town of Grado.

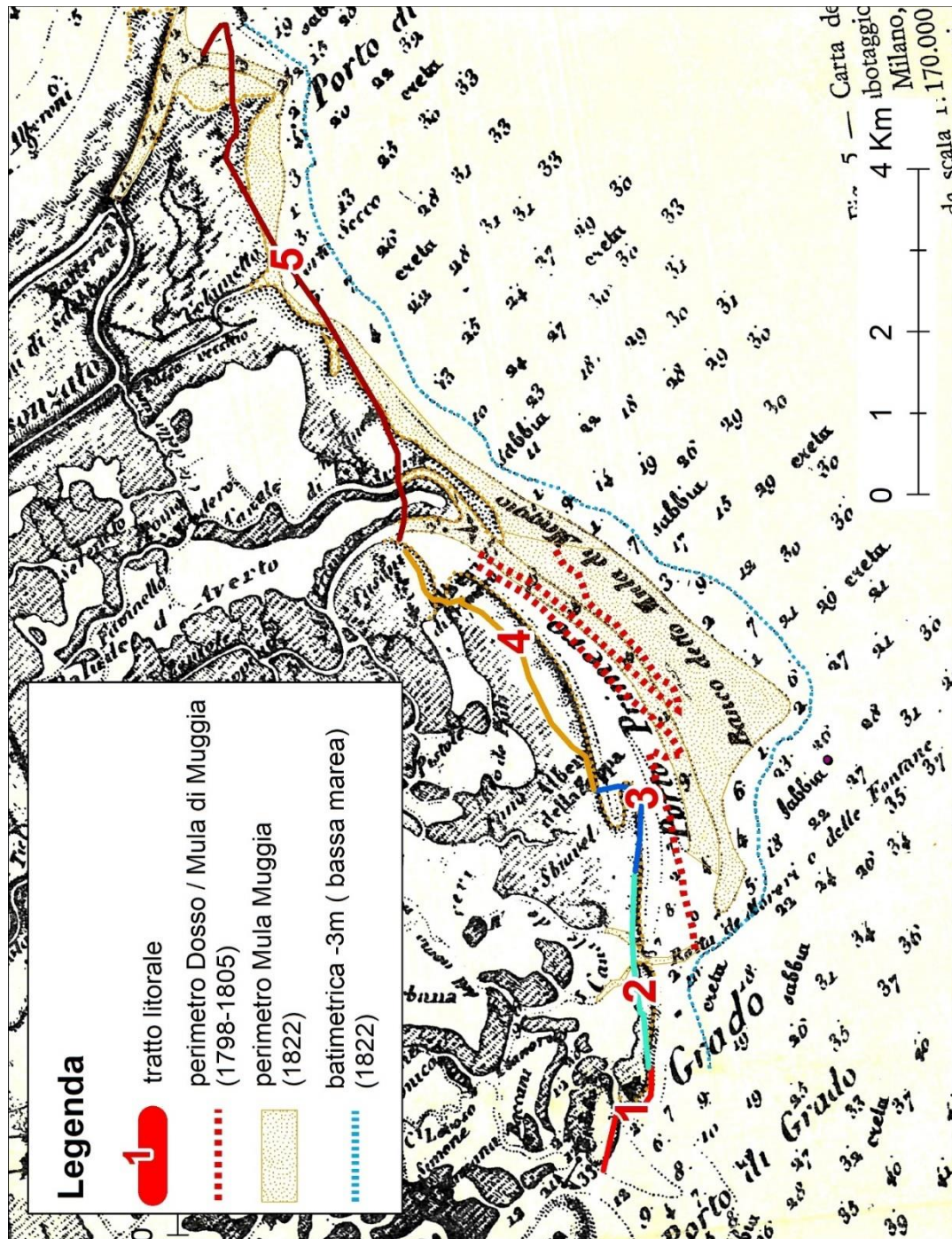


Figure 5-1: Part of the *Carta di cabotaggio del mare Adriatico (1822-1824)* with, overlaid, the today conformation of the littoral (see introduction to the study area for the location of the coastal stretches).

- First reclamation and embankment of fish farms behind the position of the today small town of Grado Pineta.
- First stabilization of the coast with embankments behind the beach and closure of some lagoon mouths (RottadeiMoreri).
- The Primero channel is parallel to the shoreline toward the west; only since 1887 a new breach has formed directly to the see in a north - south direction (the origin is unknown).
- The Mula di Muggia bank is in continuity with the eastern banks and has a strongly elongated shape towards the west.
- The Avertò channel and the Ara della Rotta channel flow into the Primero channel.
- Since 1830 an important erosion of the coasts began, above all at the Grado beach and at the Primero inlet.
- The Isonzo river flows into the Sdobbba mouth and its solid discharge feeds the entire stretch of coast.



Figure 5-2: Part of the Carta corografica del Catasto Franceschino for the area between Grado and Primiero (from Archivio di Stato di Trieste), on MAPIRE The Historical Map Portal (<http://mapire.eu>) (Timar et al. (2006)).





Figure 5-3: Part of the Carta corografica del Catasto Franceschino for the littoral near the Isonzo mouth. (from Archivio di Stato di Trieste), on [MAPIRE The Historical Map Portal \(http://mapire.eu\)](http://mapire.eu) (Timar et al. (2006).

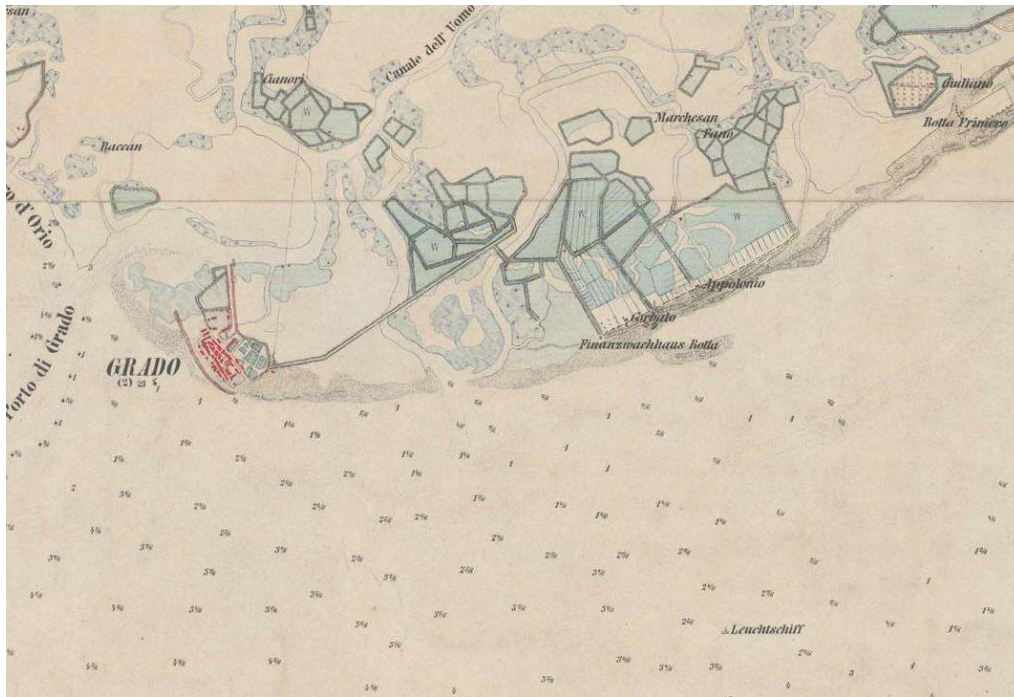


Figure 5-4: Carta Franzisco – JosephinischeLandesaufnahme (1869-1887) Carta Franzisco – JosephinischeLandesaufnahme (1869-1887) from <http://mapire.eu> alla voce *The Third Military Survey* (Molnar & Timar, 2009).

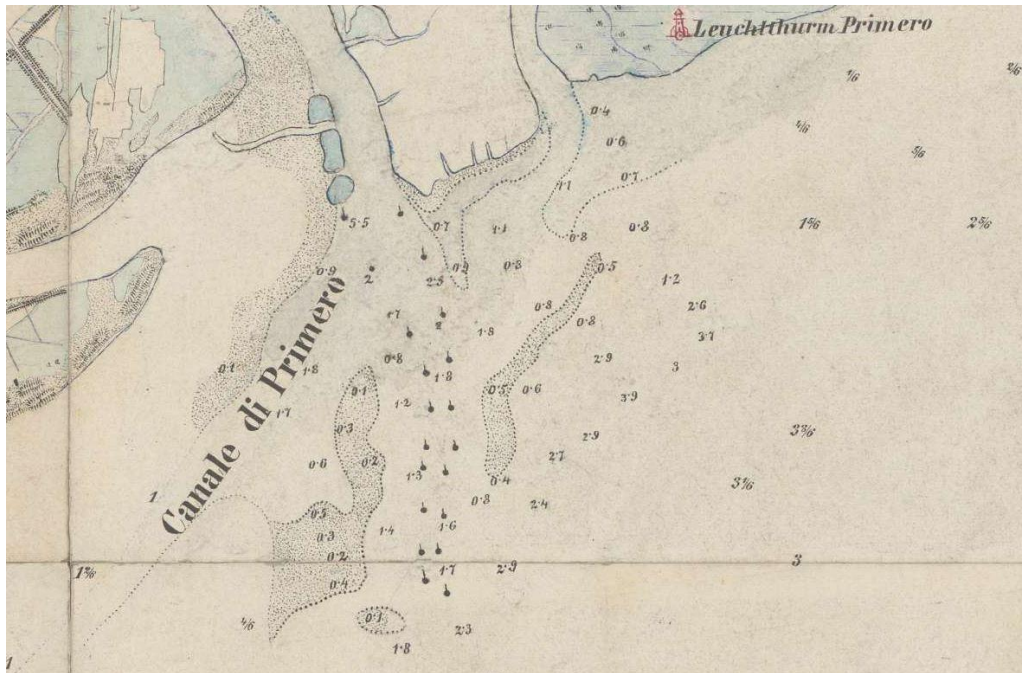


Figure 5-5: Carta Franzisco – Josephinische Landesaufnahme (1869-1887) from <http://mapire.eu> under heading The Third Military Survey (Molnar & Timar, 2009).



Figure 5-6: Carta Franzisco – Josephinisch eLandesaufnahme (1869-1887) from <http://mapire.eu> under heading The Third Military Survey (Molnar & Timar, 2009).

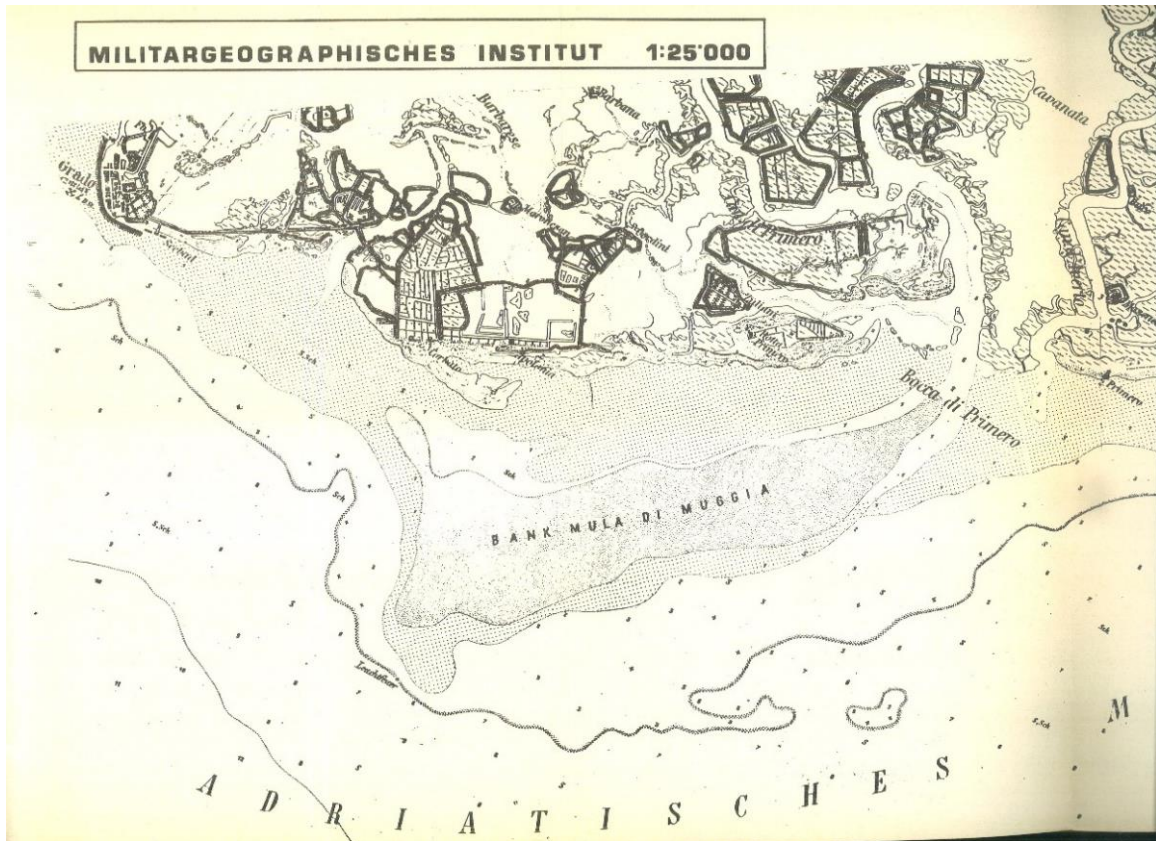


Figure 5-7: Topographic map by MilitargeographischesInstitut reported in Studio Volta (1979).

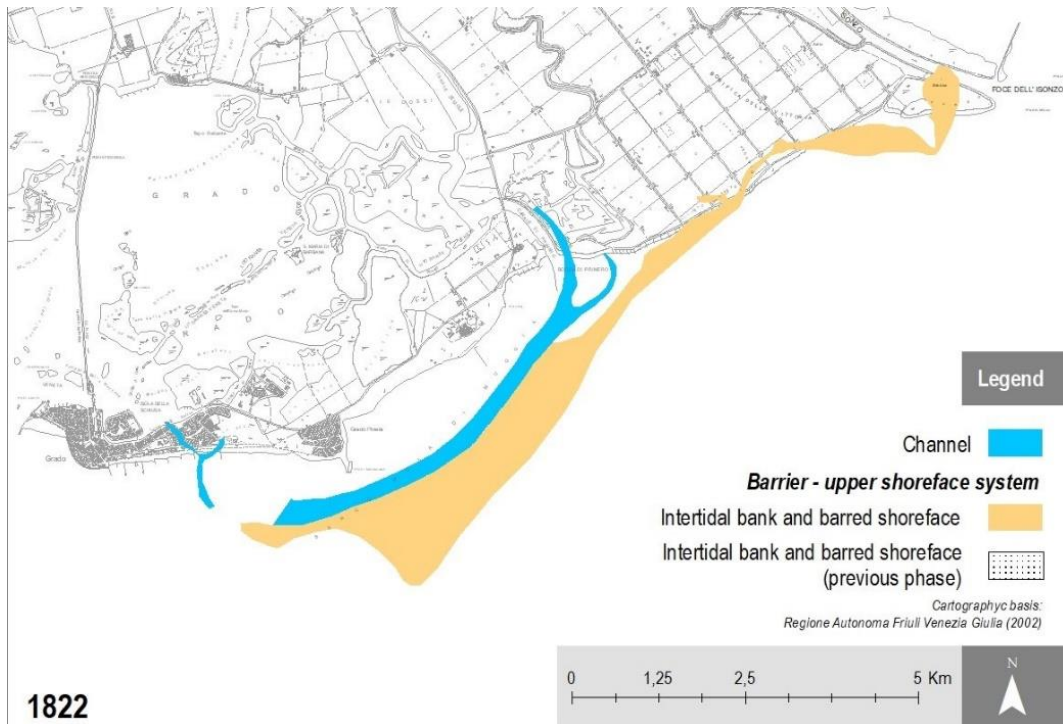


Figure 5-8: Schematic synthesis of the morphology of the area (1822).

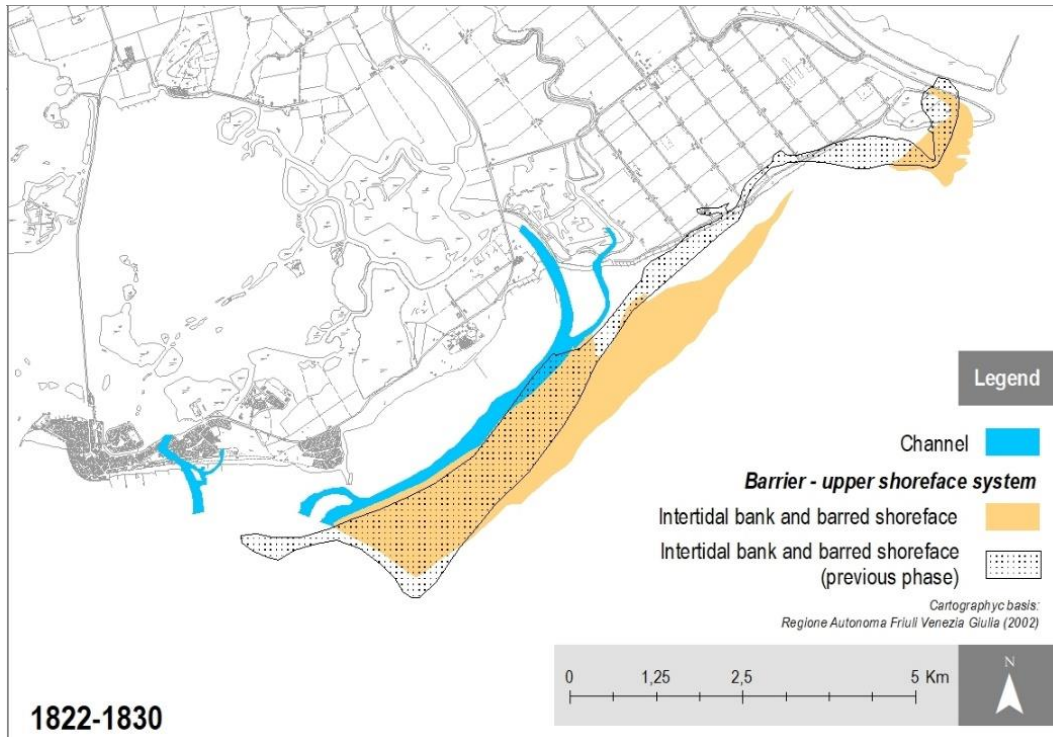


Figure 5-9: Schematic synthesis of the morphology of the area (comparison 1822-1830).

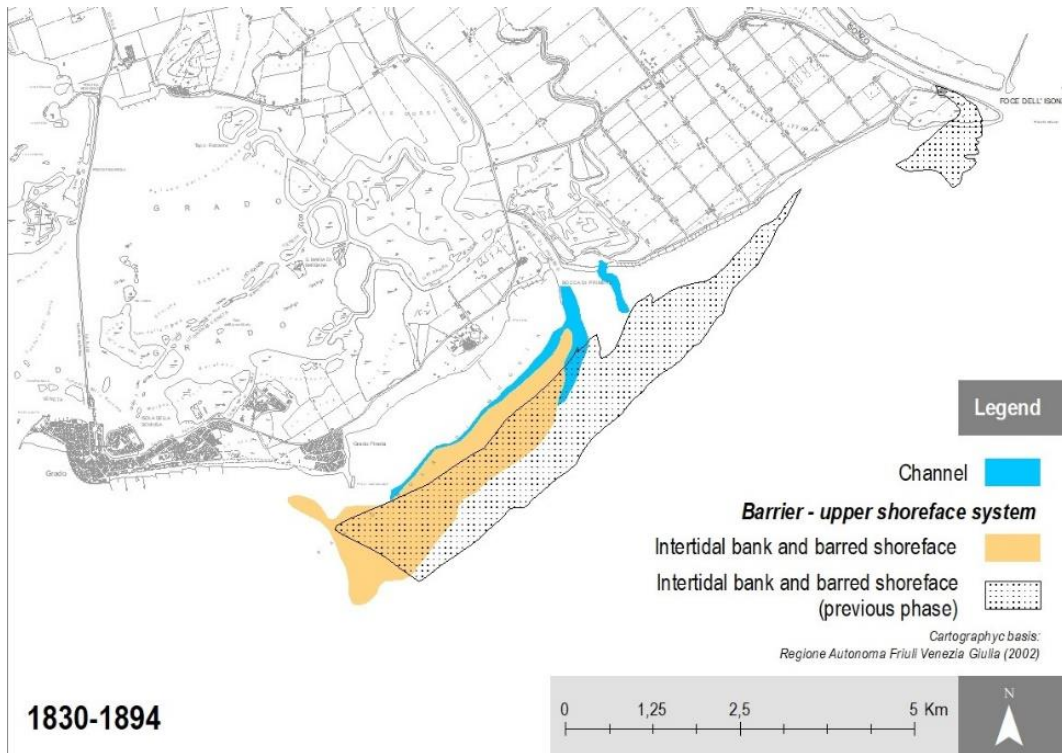


Figure 5-10: Schematic synthesis of the morphology of the area (comparison 1830-1894).

## 2. Second period (1894 – 1954)

The evolution of the littoral is derived from:

- Carta topografica del Militargeographisches Institut (1894)
- Carta topografica IGM 40IISE e 40IIIS (1915-1917)
- Carta IGM 40IISE (1927)
- Carta I.I.M. (Marina di Grado)
- Carta IGM 40IISE 1938 and 40IIISO 1938 (3.37)
- Carta I.I.M Marina di Grado (1939)
- Carta IGM 40IISE (1949) and 40IIISO (1949)
- Aerial photo 1954, GAI flight (Figure 5-11 and Figure 5-12)

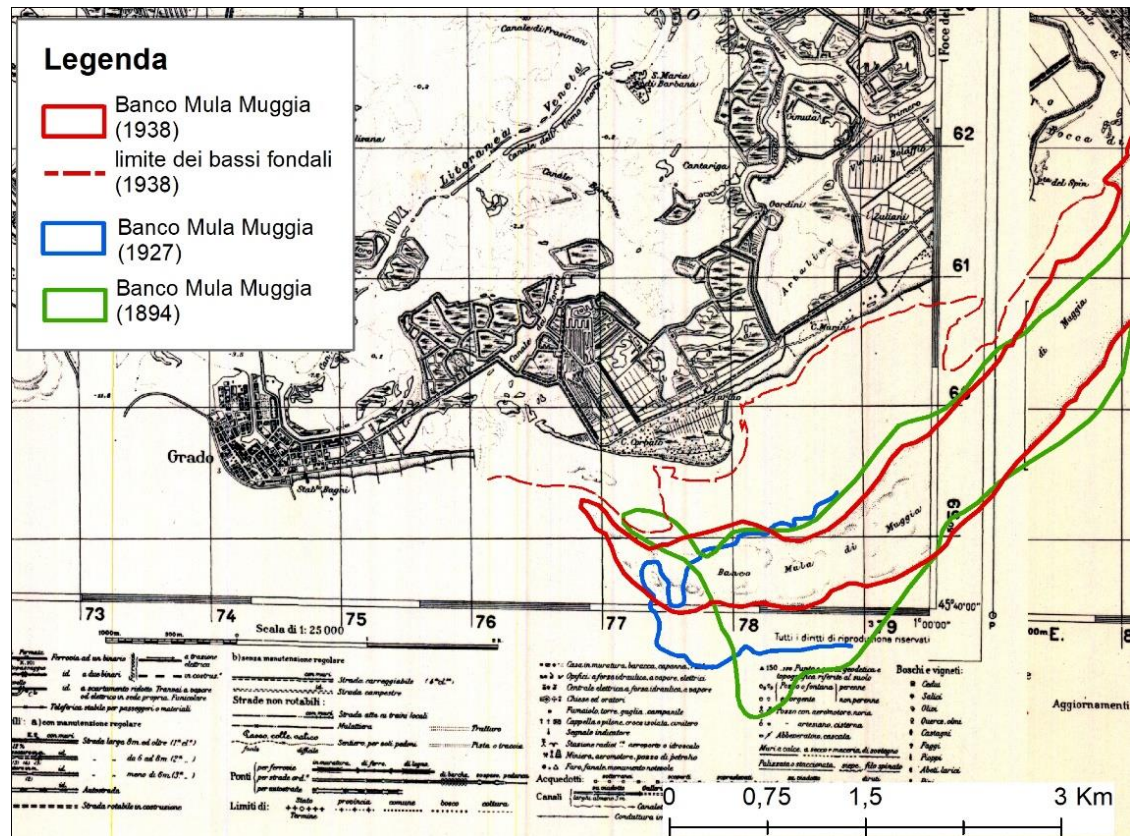


Figure 5-11: Topographic map I.G.M. from 1938 (40IISE1938) with, superimposed, some elements from the 1894 and 1927 cartography.

The most important evidences are (Figure 5-14 and Figure 5-15):

- Following the construction of the Bocca di Grado dams (built between 1927 and 1934), the Costa Azzurra beach in Grado began to form due to the interception of longshore sedimentary transport.
- Beginning of the tourist - seaside development of Grado city.
- Complete stabilization of the beach from Grado to Grado Pineta with massive extraction of sand from the adjacent seabed and from the Banco della Mula di Muggia.
- Extensive land reclamation works between Grado Pineta and the Isonzo river mouth.
- The Primero and the Avertò have two separate mouths.
- Closure of the Ara della Rotta channel
- The Primero new outlet to the sea becomes the most important, the original channel loses hydraulic efficiency and tends to silting up.
- The Banco della Mula di Muggia migrates landward and westward.
- Massive sand mining on the Banco della Mula di Muggia and on the banks adjacent to the mouth of the Isonzo.



- The Isonzo principal mouth is the Quarantia branch and the coast is deprived of the Isonzo sedimentary supplies; the mouth will be brought back to the Sdobbba in 1937.

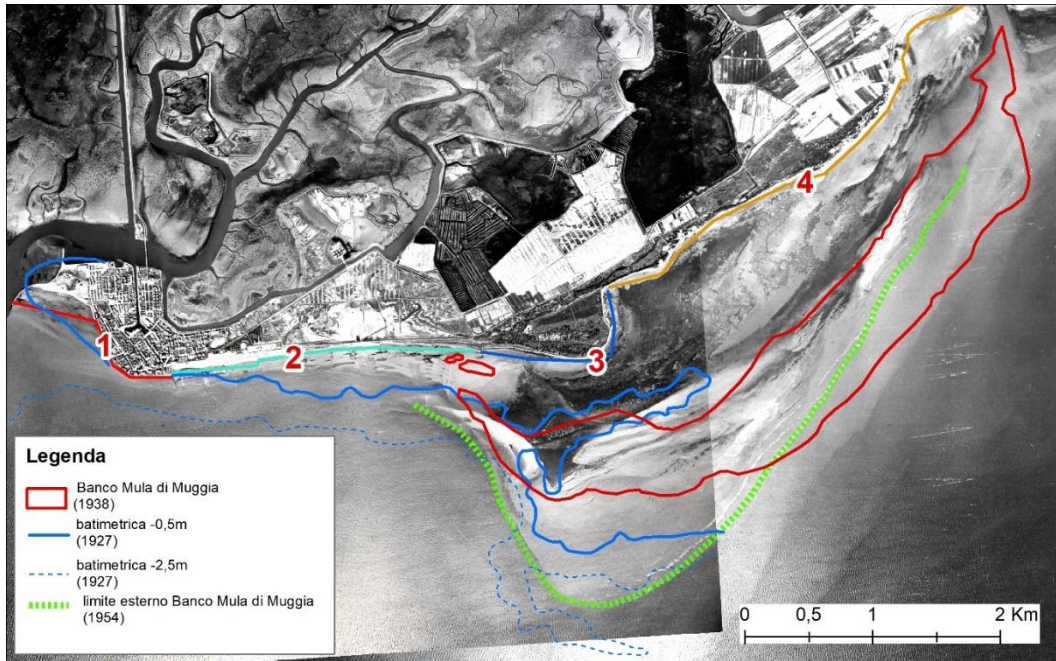


Figure 5-12: Aerial photo of 1954 with, overlaid, the today conformation of the littoral (see introduction to the study area for the location of the coastal stretches) and with some elements of the maps from 1927 (blu line) and 1938 (red line).

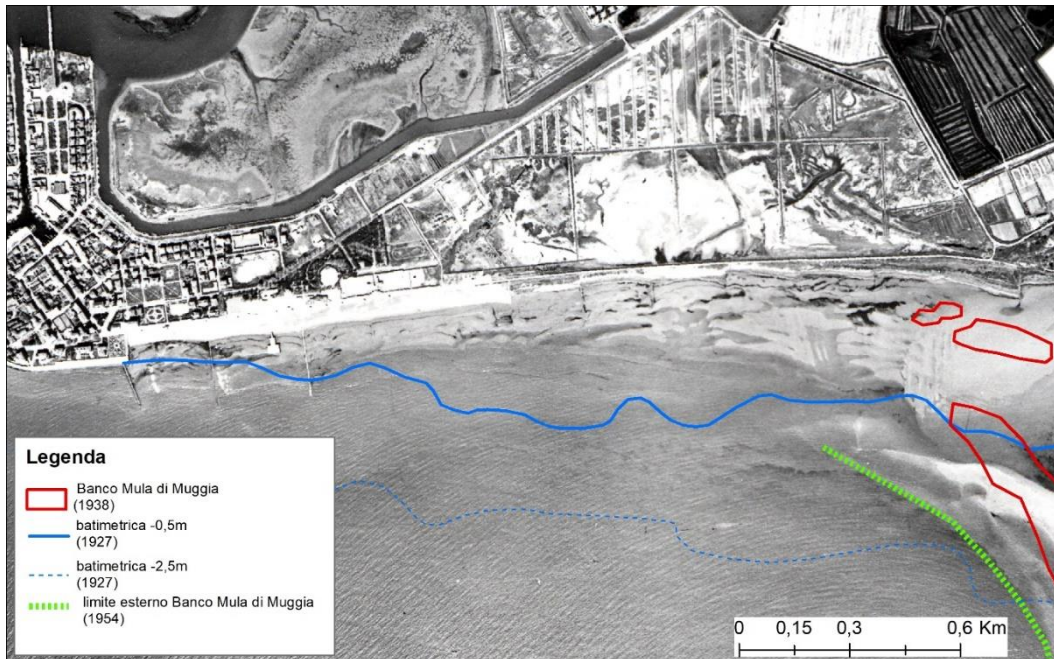


Figure 5-13: - Aerial photo of 1954 with some elements of the maps from 1927 (blu line) and 1938 (red line).

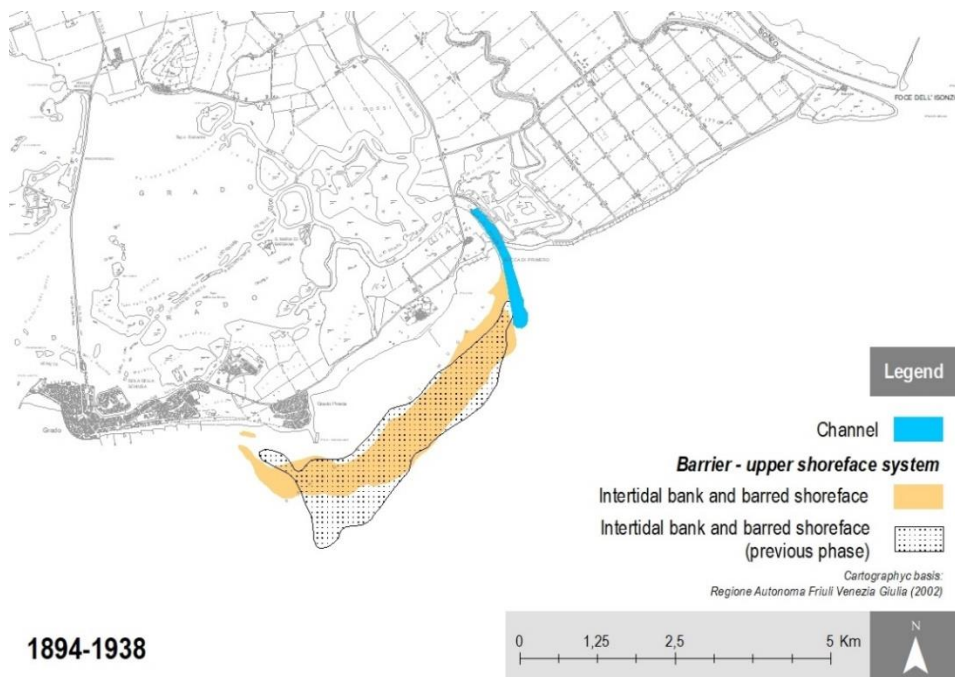


Figure 5-14: Schematic synthesis of the morphology of the area (comparison 1894-1938).

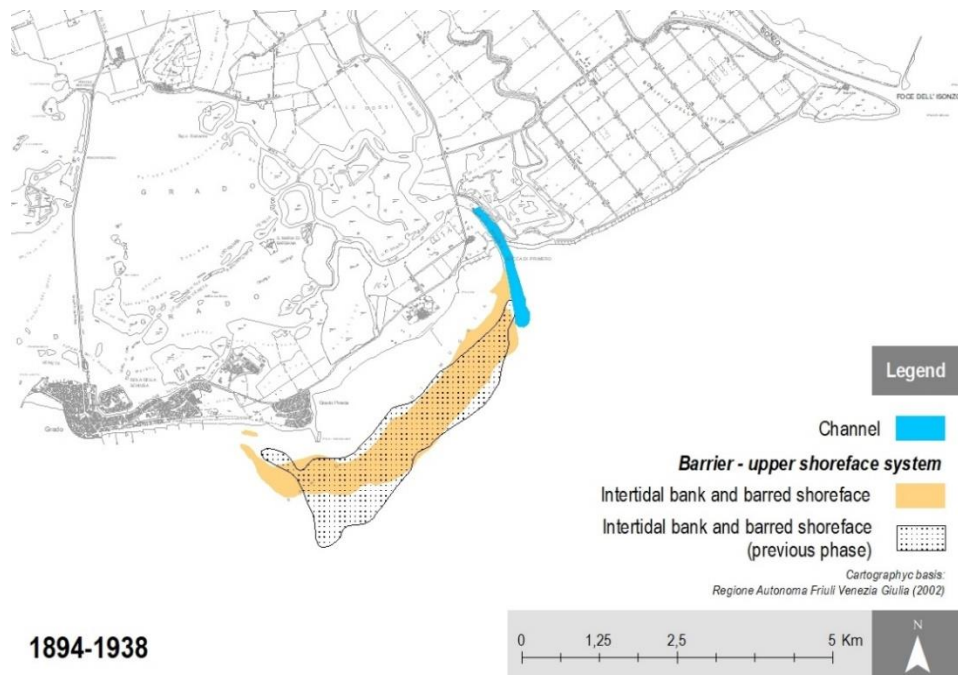


Figure 5-15: Schematic synthesis of the morphology of the area (comparison 1938-1954).

### 1. Third period (1954 -1978).

The evolution of the littoral is derived from:

- Aerial Photos – GAI flight (1954)
- Aerial Photos – CNR flight 1978 (Figure 5-16, Figure 5-17 and Figure 5-18)
- First topo - bathymetric surveys of the coast, several campaigns not always well comparable with each other (1968, 1972-73, 1978).

The most important evidences are (Figure 5-19):

- The complete reclamation of the hinterland constrains the degree of freedom of the coastal system.
- - Continuous prograddation of the Costa Azzurra beach.
- Tourist development and urbanization of the coast (Grado Pineta, new campsites), construction of the promontory of Punta Barbacale with strong modification of the hydraulic circulation of the back barrier area called "baroso".
- - First excavation of little canals and "swimming hollows" in the "baroso" area.
- Intensive tourist development of the beaches with continuous sand leveling and nourishment.
- Finger bars develop on the eastern side of the bank.

- The apex of the bank becomes stabilized while the western limit continues its migration.
- The internal limit of the bank has a stable position and the extent of seagrass increases.
- The mouth of Sdobba shows an accumulation of sediments on the seabed.

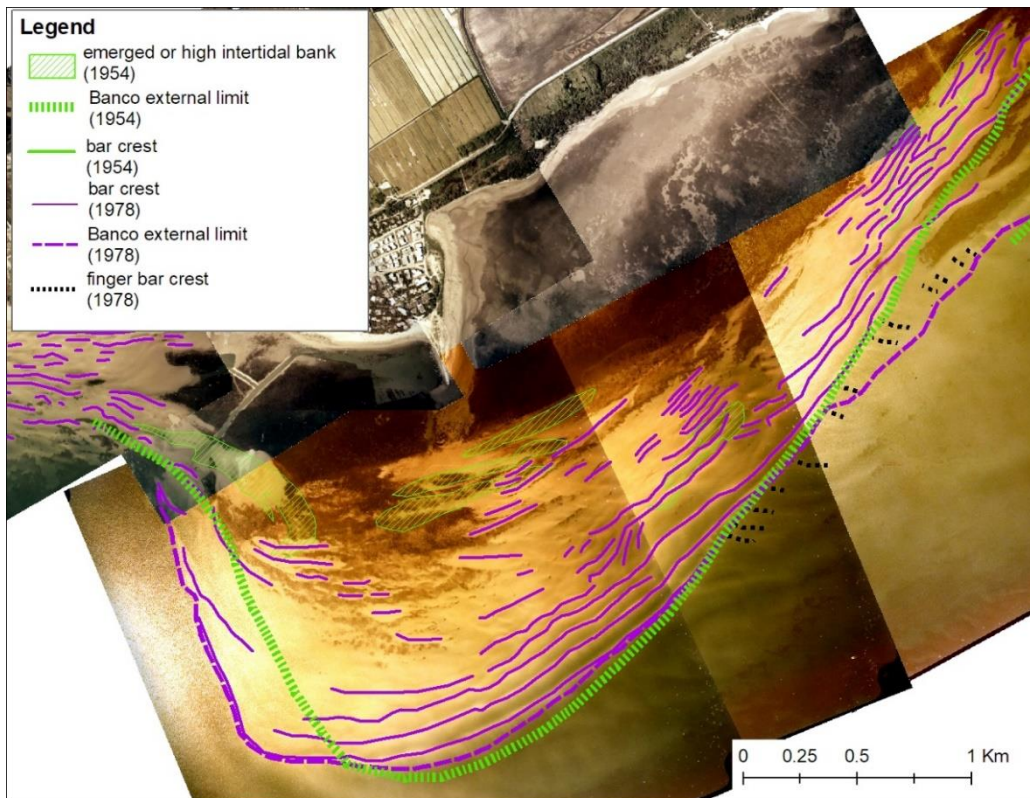


Figure 5-16: Aerial photo from 1978 with, superimposed, some morphological elements from 1978 and 1954.

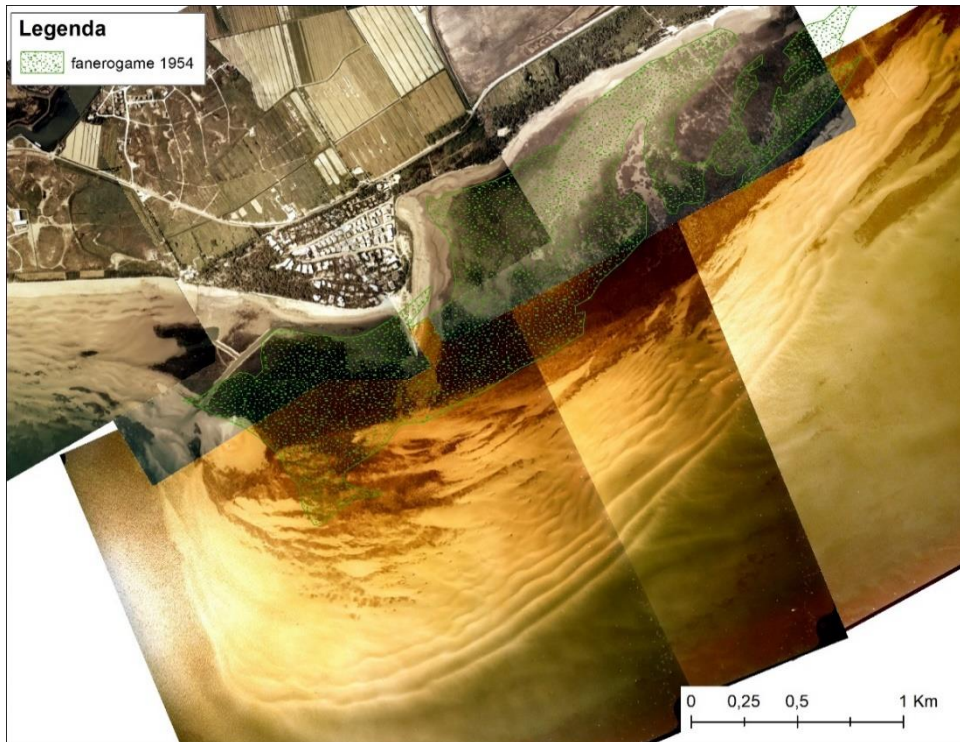


Figure 5-17: Aerial photo from 1978 with, superimposed, seagrass areas from 1954 (green areas).

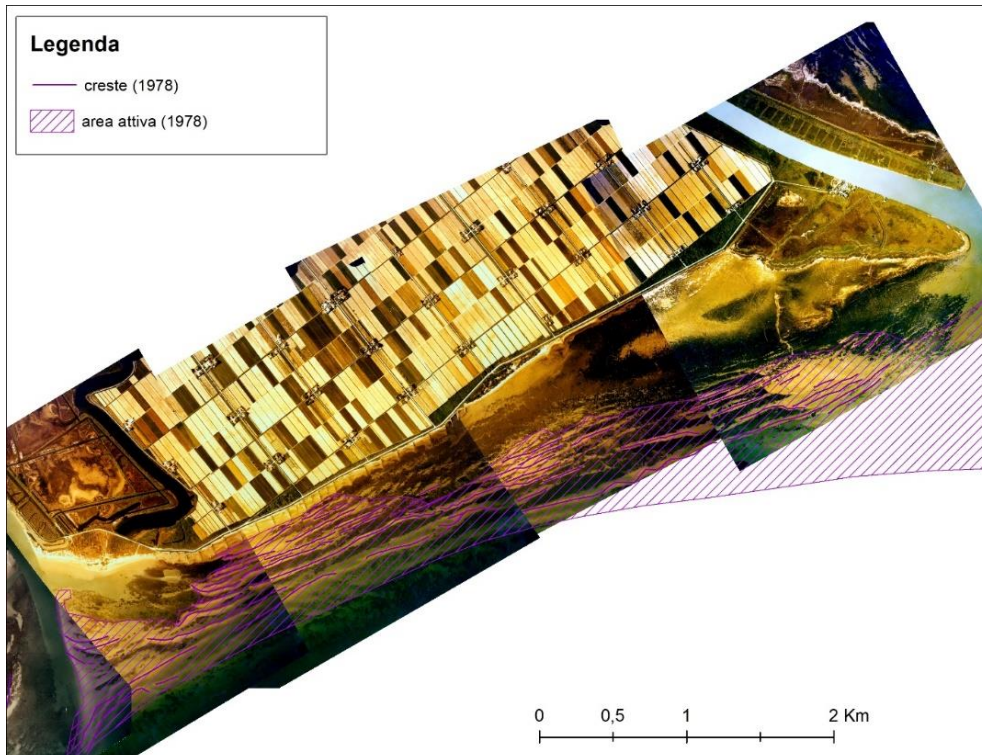


Figure 5-18: Aerial photo from 1978 with, superimposed, some morphological elements.

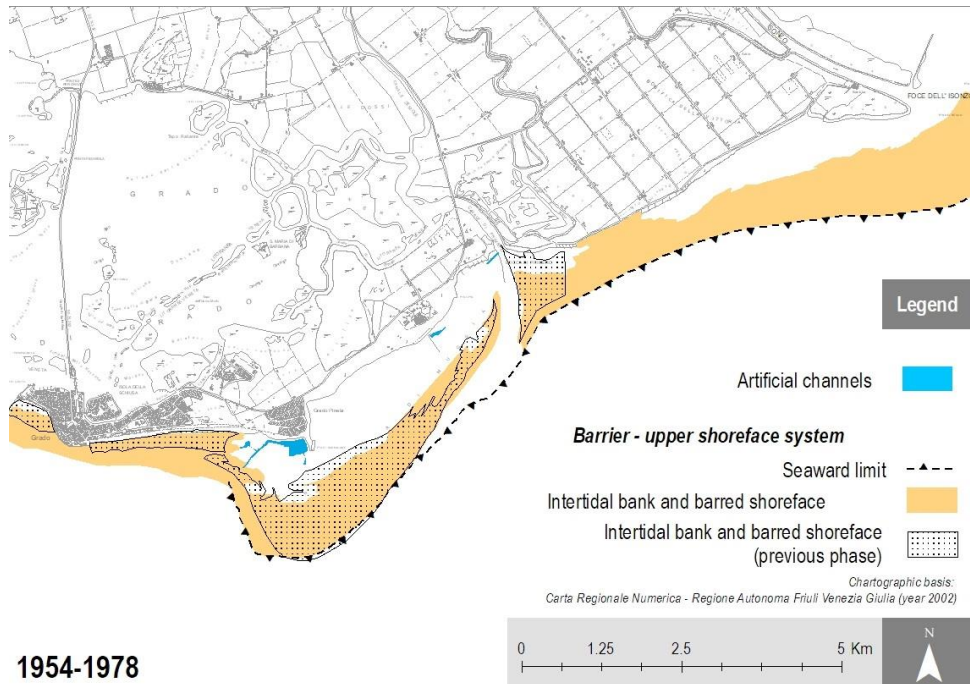


Figure 5-19: Schematic synthesis of the morphology of the area (comparison 1954-1978).

## 2. Fourth period (1978 – 2007).

The evolution of the littoral is derived from:

- Digital orto-photo 2007 (<http://www.pcn.minambiente.it/mattm/servizio-wms/>) (Figure 5-20).
- Topo - bathymetric surveys (1985 and 2007).



Figure 5-20: – The Banco della Mula di Muggia in the aerial photo from 2007.

The most important evidences are (Figure 5-21, Figure 5-22, and Figure 5-23):

- The growth of the Costa Azzurra beach continues.
- Further extensive inland urbanization.
- Redevelopment of the coast of Grado Pineta with nourishment of the beach, cutting of the artificial promontory of Punta Barbacale and excavation of a new channel, which, however, in 2007 appears to be occluded towards the sea by the migration of sand bars.
- Dredging of small artificial channels, “swimming hollow” and small artificial beaches on the coast between Grado Pineta and Primero.
- Seaward of the mouth of Primero there is an evident bypass corridor with finger bars which tend to connect at the edge of the sand bank to the west.
- The apex and the eastern limit of the Banco do not undergo conspicuous changes.
- On the western edge of the Banco, growth continues with the formation of new sand bars (Figure 5-24).
- The eastern part of Grado beach begins to be directly influenced by the Banco with the extension of the submerged sand bars and the formation of an emerged one near. It tends to isolate about 800 m of beach from swell action, favoring settling of fine sediment (Figure 5-24).
- Seagrass colonize extended sectors of sand bars and troughs in the internal part of the bank.

- Increase of seagrass extension also occurs for the area between the Primero inlet and the Isonzo mouth, where there are extensive growths of the seabed with the formation of new bars towards the sea.



*Figure 5-21: - Zoom of the aerial photo from 2007 in the area of maximum migration of the sandbanks. Red line represent the emerged part of the bank.*



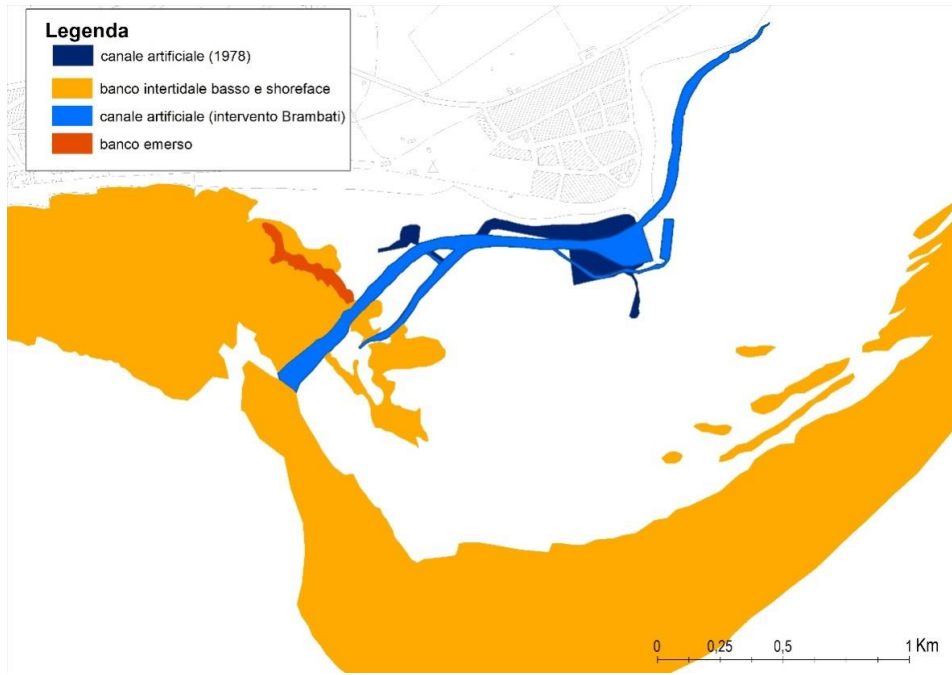


Figure 5-22: Situation in 2007 of the artificial channels dredged from 1978 to 2007.



Figure 5-23: The Banco della Mula di Muggia in the aerial photo from 2007, superimposed are the seagrass area from 1978.

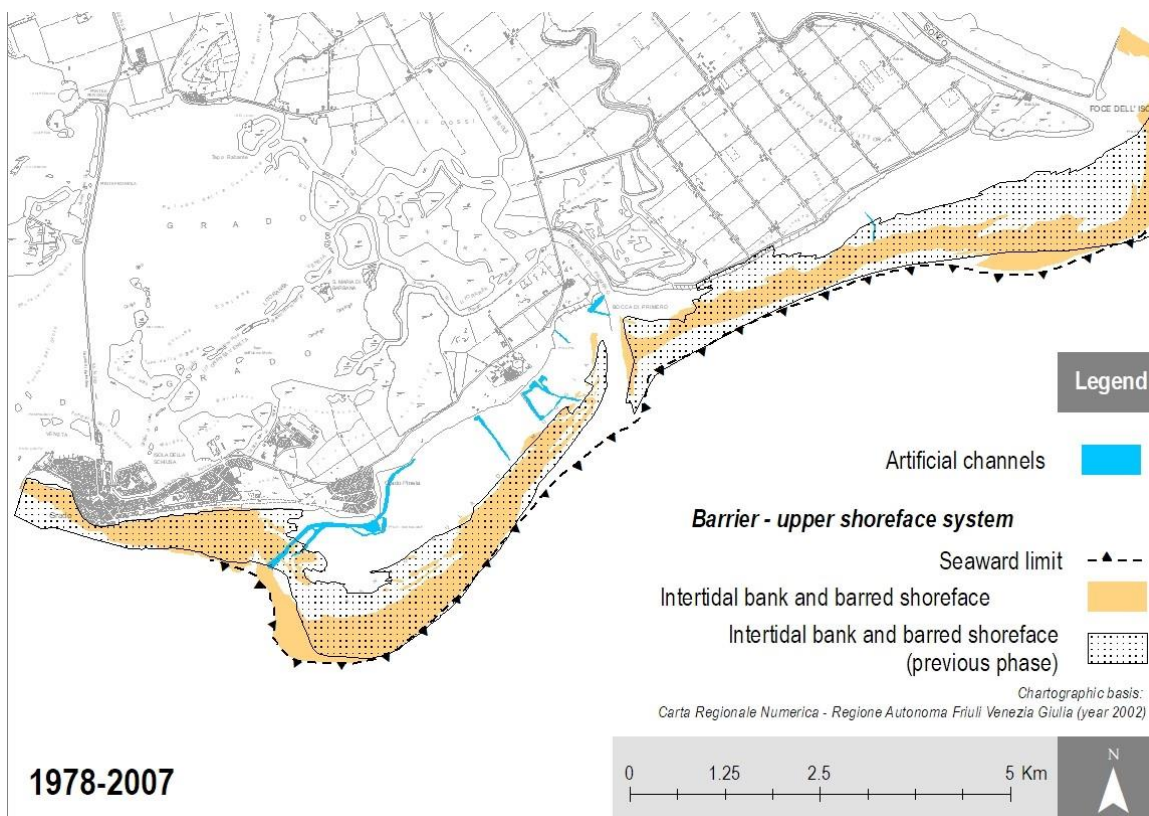


Figure 5-24: Schematic synthesis of the morphology of the area (comparison 1978-2007).

## 5- Fifth period (2007- 2019)

The evolution of the littoral is derived from:

- Digital orto-photo 2007 (<http://www.pcn.minambiente.it/mattm/servizio-wms/>).
- Digital Ortophoto 2014 AGEA (Agenzia per le Erogazioni in Agricoltura) Regione Autonoma Friuli Venezia Giulia
- Topo - bathymetric surveys (2007 and 2019).

The most important evidences are (Figure 5-25):

- The Costa Azzurra beach is stable.
- Increase in seagrass surfaces in the back barrier area.
- The eastern limit of the Banco and the apical part keep their position roughly.
- The westward growth of Banco's sand bars continues and the small emerged bar expands, migrating in part to the north-west, isolating a further portion of the tourist beach.

- The bar and trough beds between Primero and the Isonzo mouth are maintained and show evidences of migration towards the west, in the direction of the prevailing longshore currents.

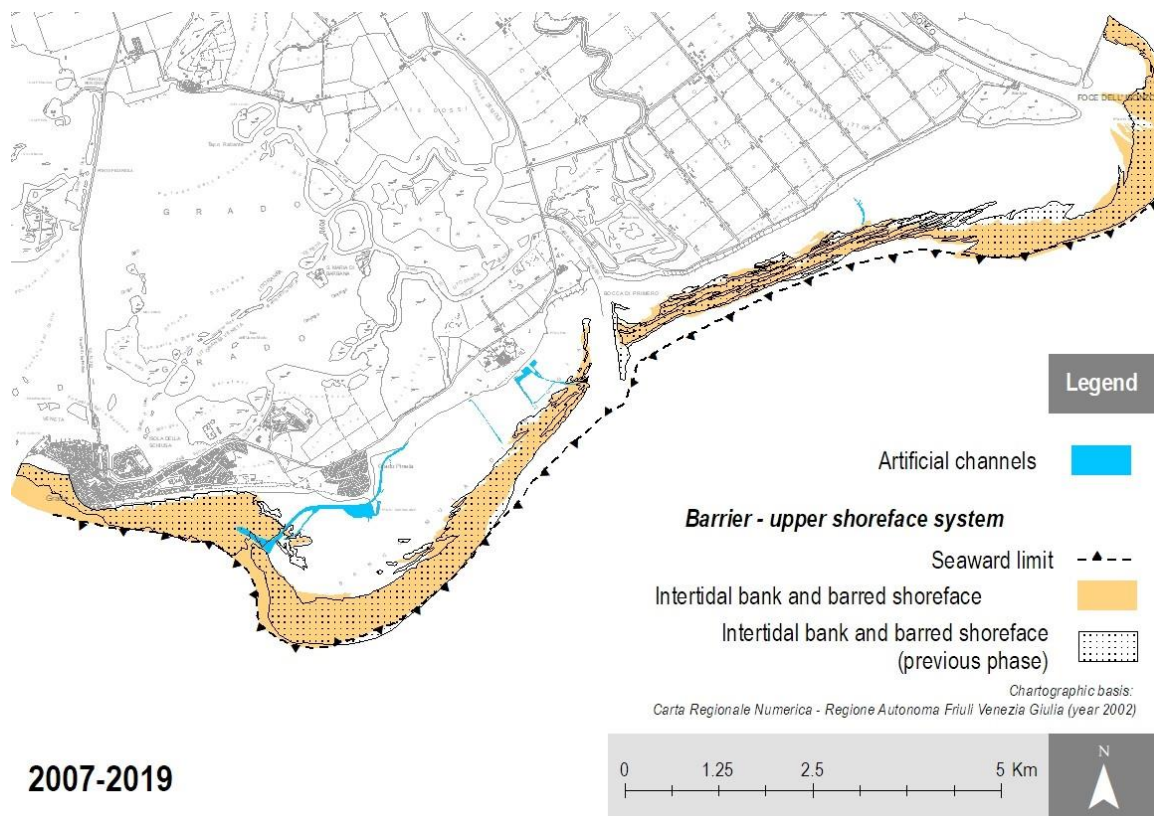


Figure 5-25: Schematic synthesis of the morphology of the area (comparison 2007-2019).

### Geomorphological maps

Thanks to the multidecada lanalysis, we obtained 3 geomorphological maps for the recent past of the area: 1954, 1978 and 2007 (Figure 5-26, Figure 5-27 and Figure 5-28).

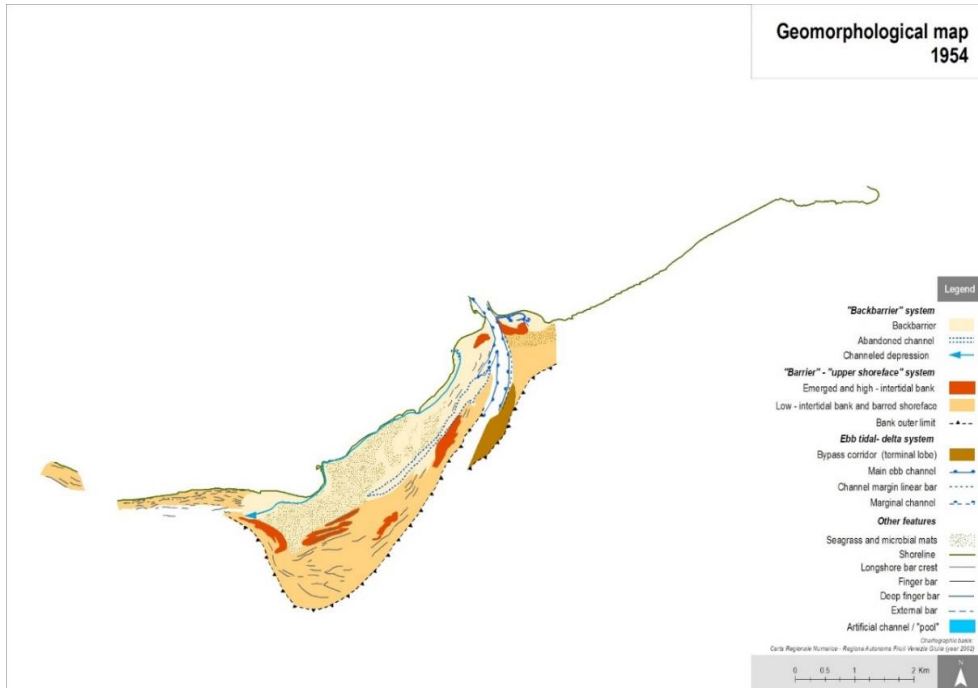


Figure 5-26: Geomorphological map for the year 1954.

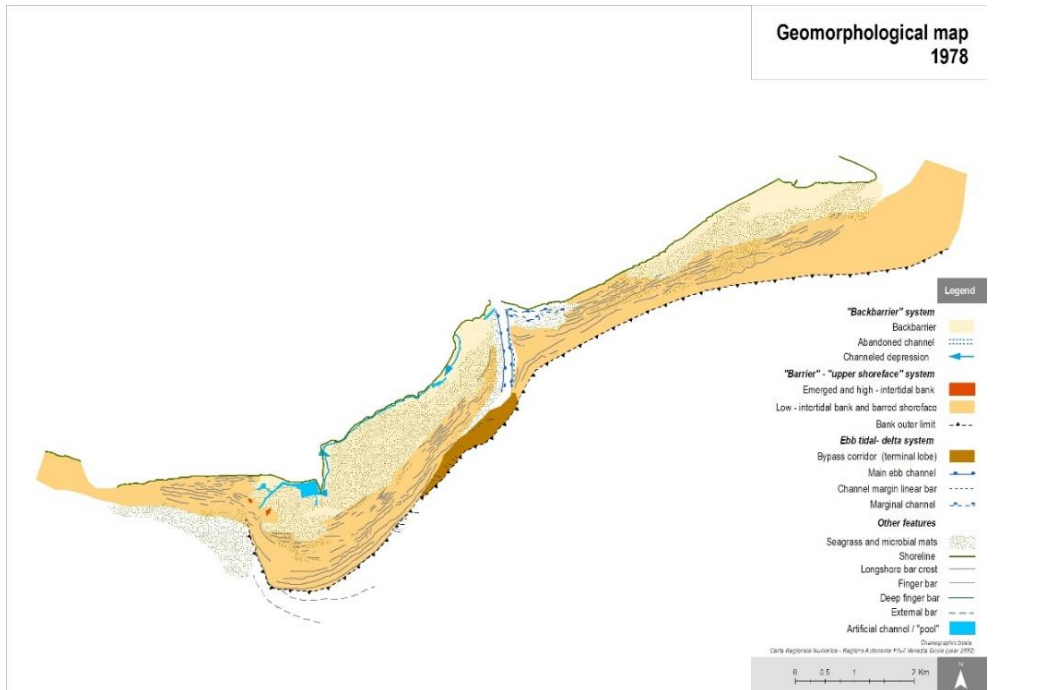


Figure 5-27: Geomorphological map for the year 1978



Figure 5-28: Geomorphological map for the year 2007.

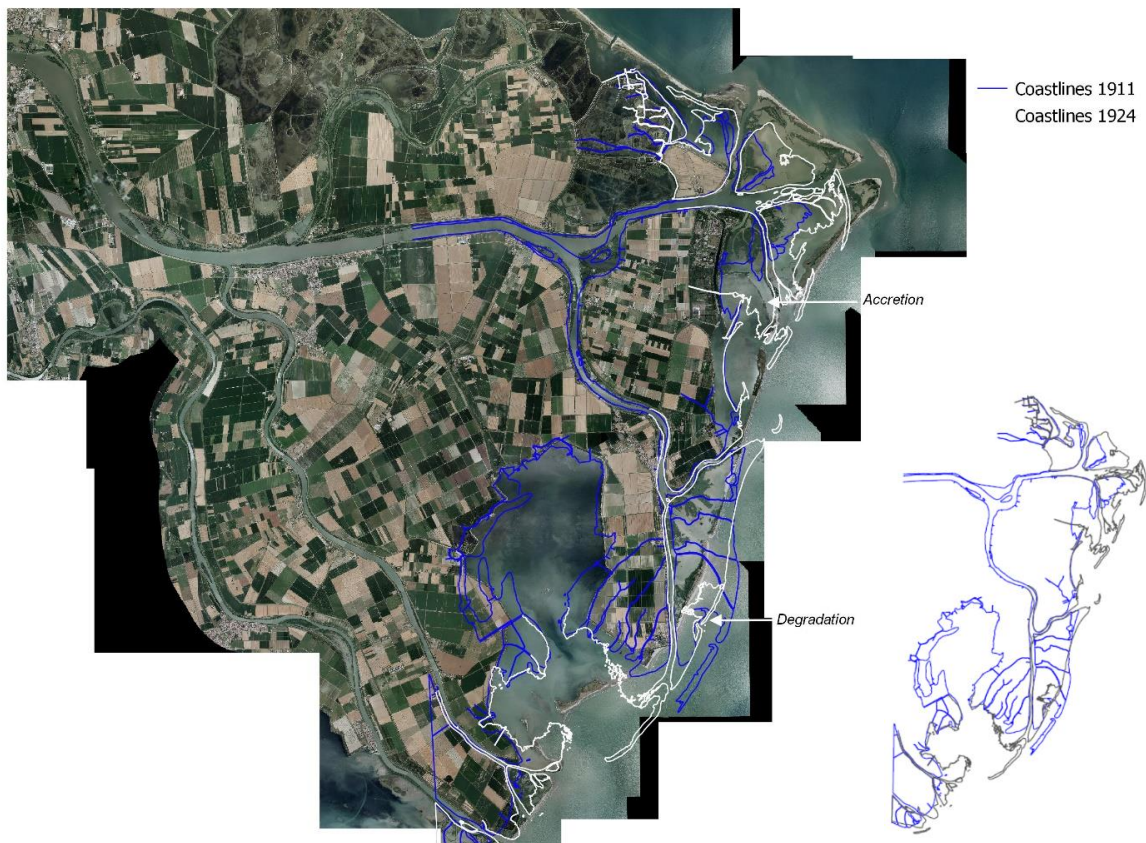


## Annex 2: Po Delta – Coastline evolution

The maps on the planimetric variations of the Po delta coast are based on the study of "Analysis of coastal erosion in the Po Delta from 1933 to 2008 by means of multi-temporal aero-photogrammetry". The work was carried out by UP SIT and Cartography of the Veneto Region together with the Surveying and Geomatics Laboratory, DICEA of the University of Padua.

The acquisition of the geographical<sup>5</sup> data from surveys of different years allowed for the creation of historical comparison maps of the evolution of the coastlines for the years 1911, 1924, 1933, 1955, 1944, 1955, 1977, 1999, 2008 and 2014, as shown below<sup>6</sup>.

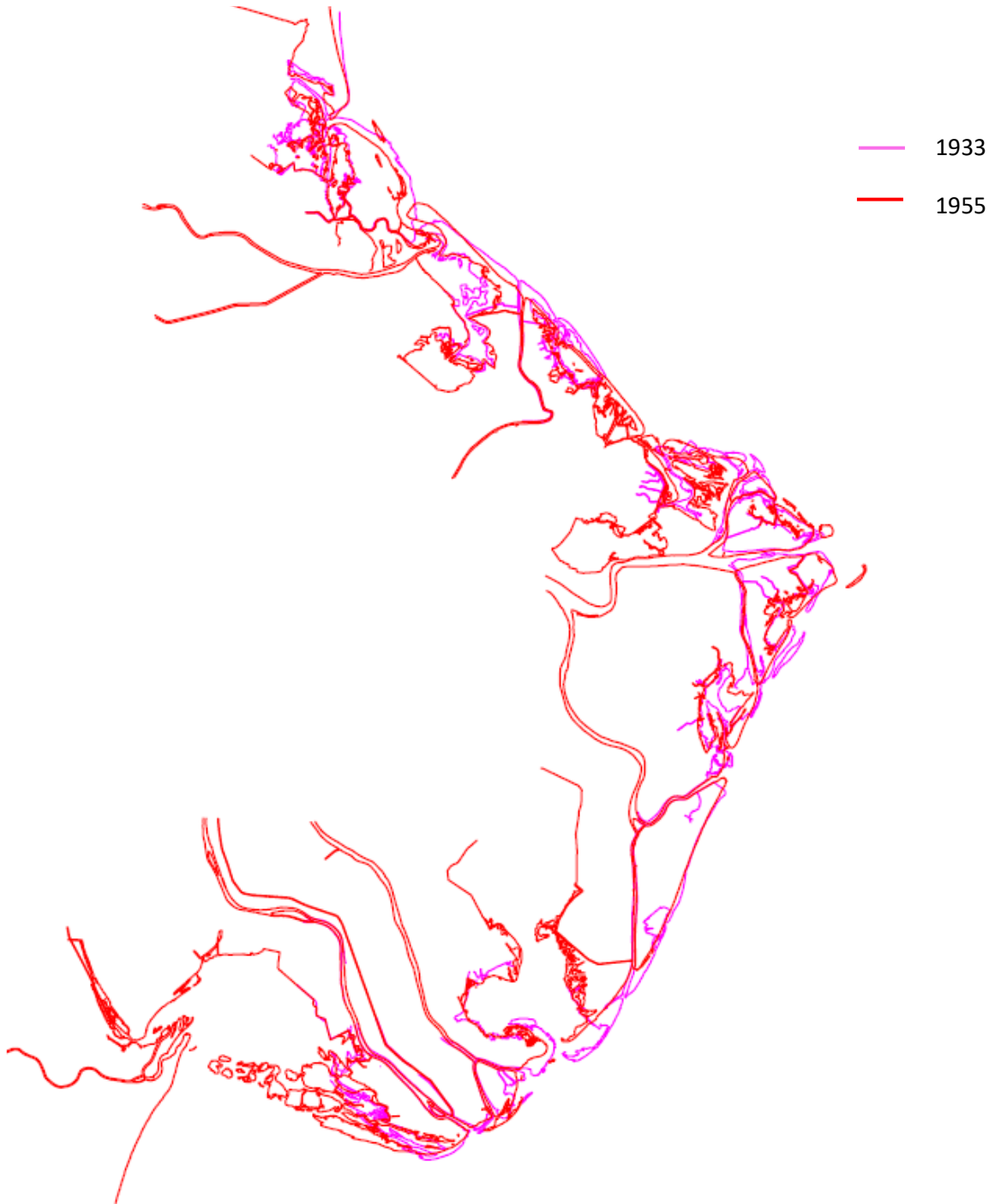
### Evolution of the coastline years 1911 and 1924



<sup>5</sup> Analysis of coastal erosion in the Po Delta from 1933 to 2008 by means of multi-temporal aero-photogrammetry and Giscoste of Genio Civile di Rovigo.

<sup>6</sup> Veneto Region Environmental Directorate, Change we care Project.

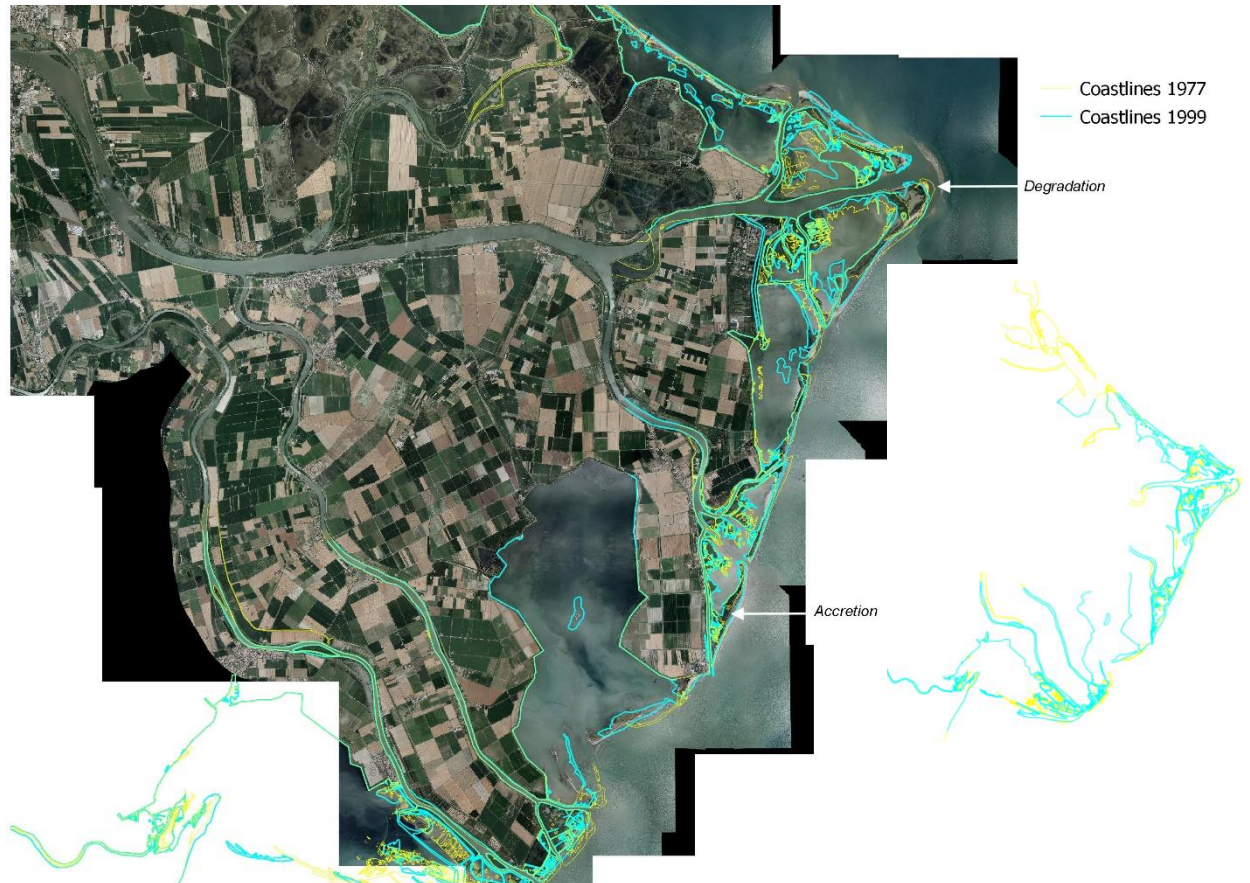
### Evolution of the coastline years 1933 and 1955



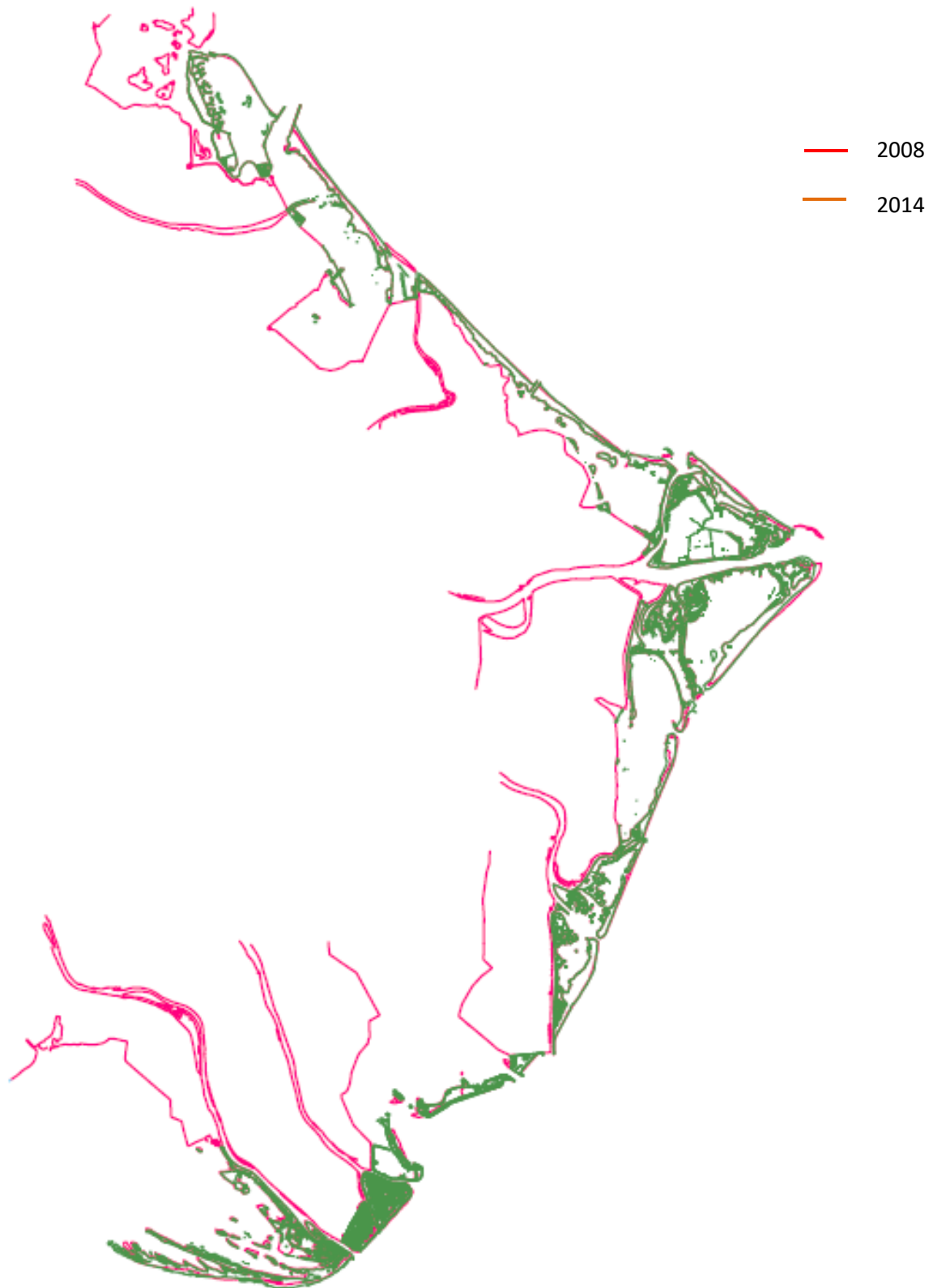




## Evolution of the coastline years 1977 and 1999



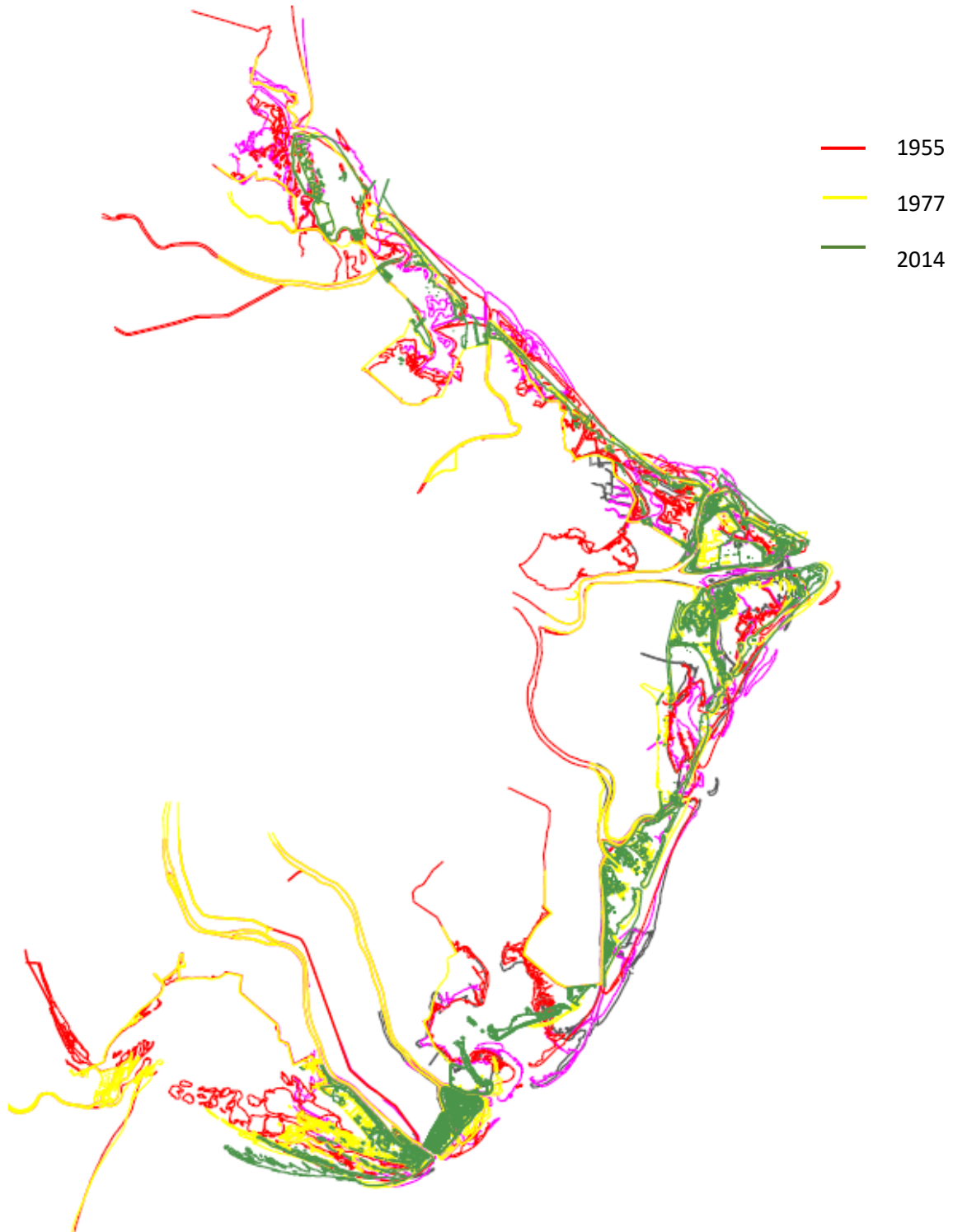
## Evolution of the coastline years 2008 and 2014









### Evolution of the coastline years 1955, 1977 and 2014



Based on the variation of the coastlines in the considered years, it was possible to create analysis maps referring to the progression and erosion of the Po Delta coast, as illustrated below<sup>7</sup>.

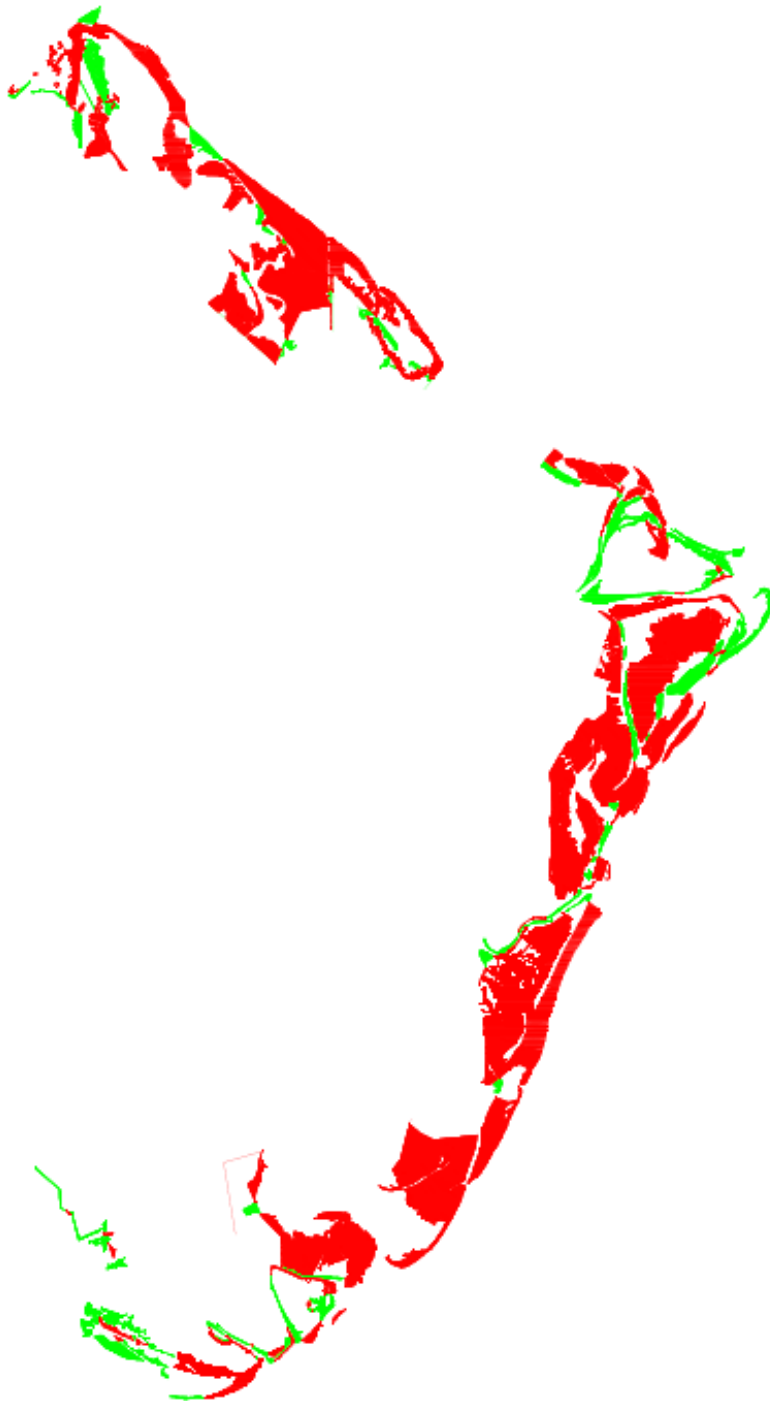
### **Progradation and accretion coastline between 1933 and 1977**

 Accretion

 Erosion

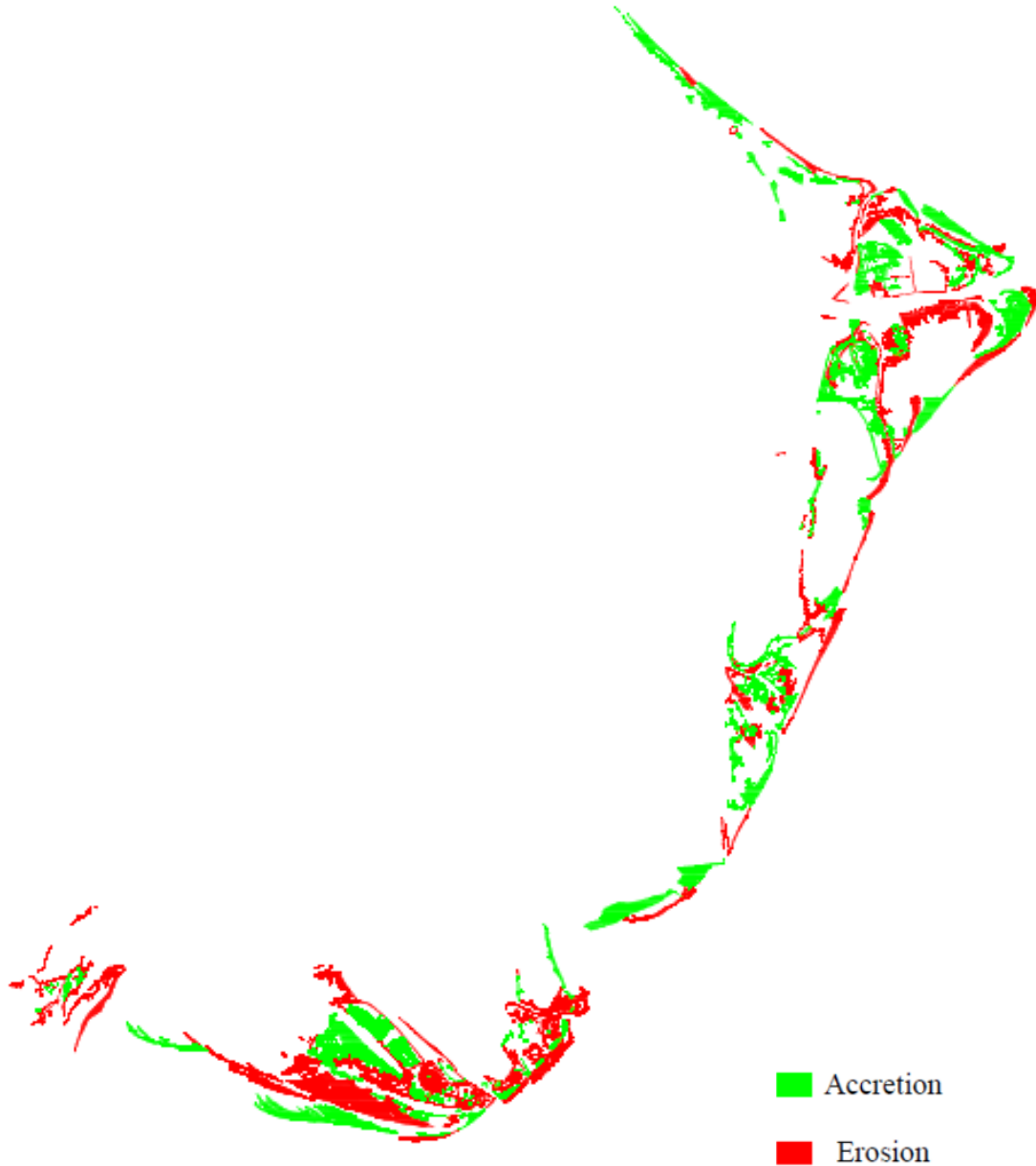
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<sup>7</sup> Veneto Region

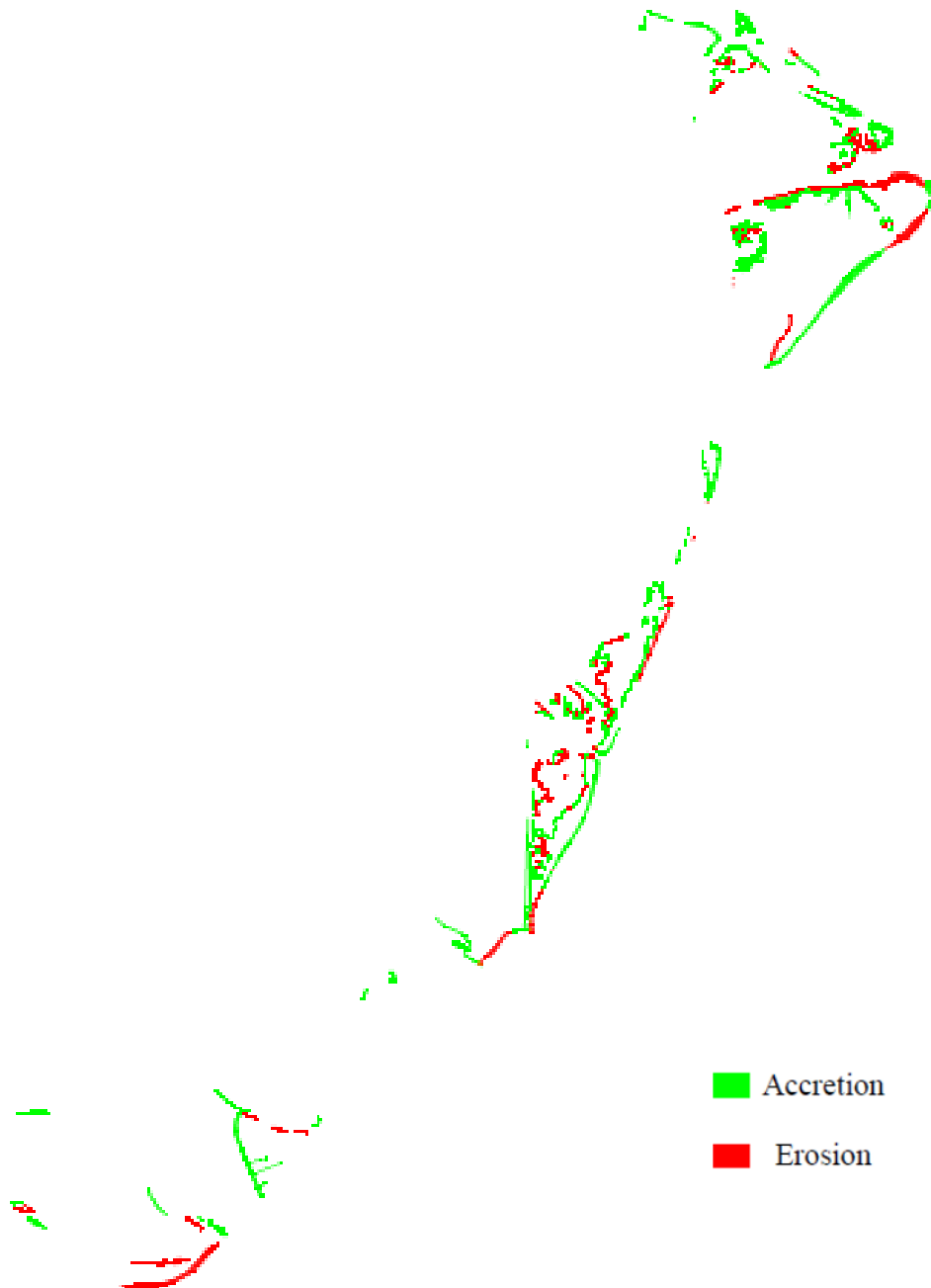


**Progradation and accretion coastline between 1977 and 1999**

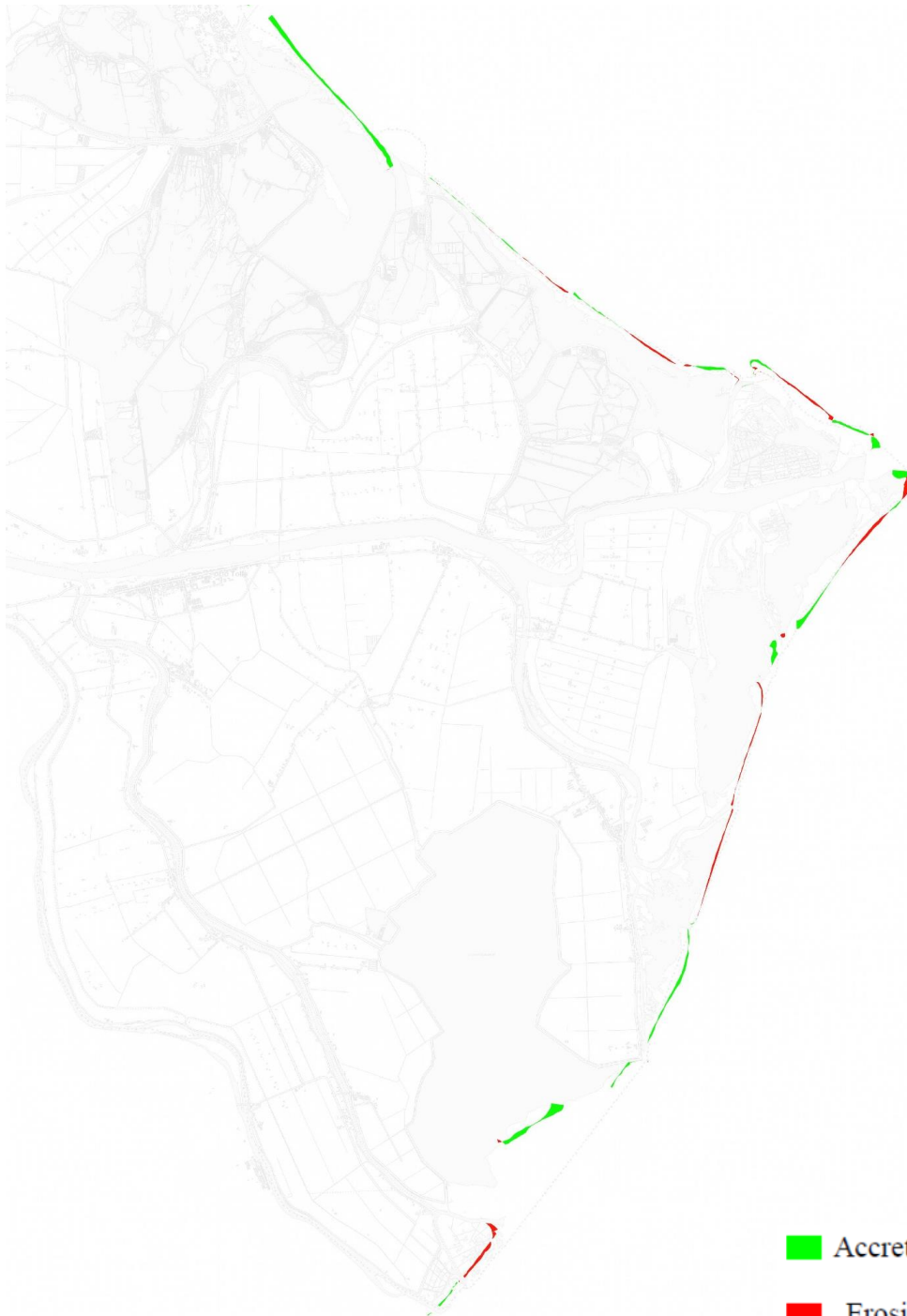






### Progradation and accretion coastline between 1999 and 2008



## Progradation and accretion coastline between 2009 and 2018



 Accretion

 Erosion

## Annex 3: Po Delta – The Monitor project

### Map realized during the Monitor project: changes of morphologies between 1954-2003

The MONITOR Interreg project: “Hazard Monitoring for Risk Assessment and Risk Evaluation” was financed through community and regional funds and it had as lead partner the Austrian Federal Ministry of Agriculture, Forestry, Environment and Water resources, while the Veneto Region took part to the project with its Geological Service.

The project aimed at the monitoring of natural risks and at the protection of the territory.

In particular, the main goal of the project was the integration of the management activities of the risk at different levels with interdisciplinary approaches, in order to support the planning and management of the emergencies. The improvement of the methodologies for the analysis and communication of the risks was an additional objective.

The Veneto Region considered two pilot areas for this project: one of these was the Po Delta, which was analyzed considering the hydraulic and geological hazards existing in the area. Alternative techniques were tested to monitor the geological processes in the region, and specifically the INSAR methodology was employed to analyze the subsidence comparing the results with the precision levelling surveys.

At the same time, the project investigated other geological and geomorphological aspects of the Po Delta, producing the “geomorphological map of the Po Delta”<sup>8</sup>, which reconstructed the evolution of the Po River course and the hazard element relative to the features of the area.

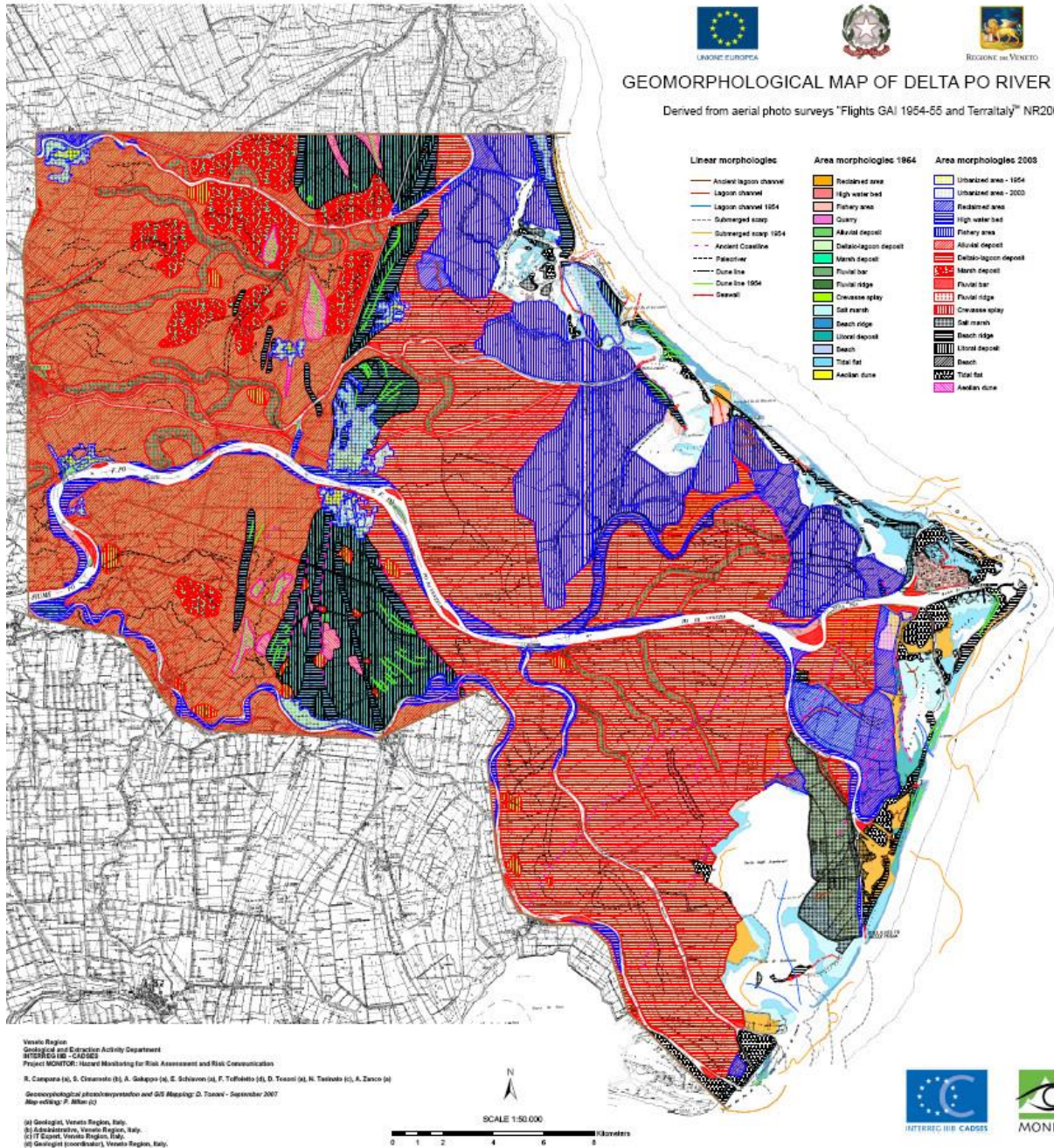
The analysis of the geomorphological and geological evolution of carried out during the “MONITOR” project has provided some useful elements for the “Change We Care” project. Therefore, the final project presentation is reported here.

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<sup>8</sup> Derivata dalle foto aeree (“Voli GAI 1954-55 e Terraltaly™ NR2003”) e studi precedenti

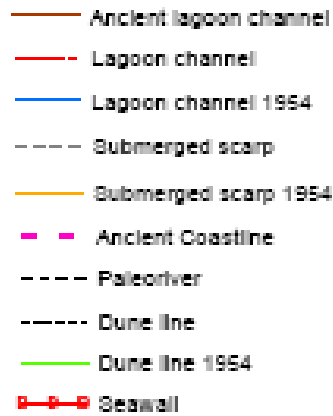
### GEOMORPHOLOGICAL MAP OF DELTA PO RIVER AREA

Derived from aerial photo surveys "Flights GAI 1954-55 and Territaly" NR2003"



- full colors: morphological elements observed in ancient photos (1954)
- superposed colored patterns: morphological elements observed in recent photos (2003)

### Linear morphologies



### Area morphologies 1954



### Area morphologies 2003







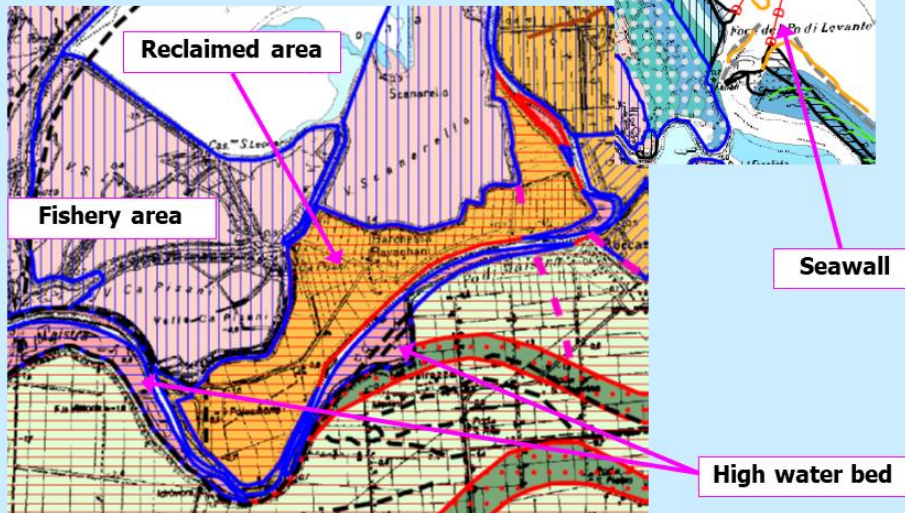
## Principal geomorphological elements in the map

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Venice, 19-20 settembre, 2007

### • Anthropogenic forms



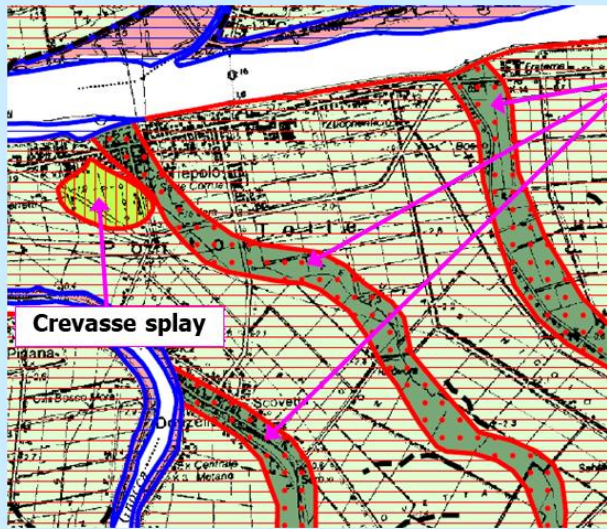
## Principal geomorphological elements in the map

workshop 06



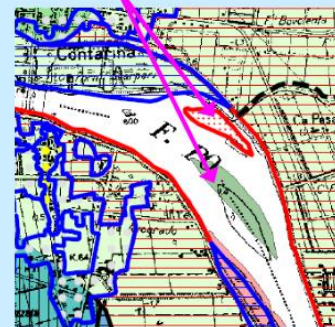
Venice, 19-20 settembre 2007

### • Fluvial forms



Fluvial ridge

Fluvial bar



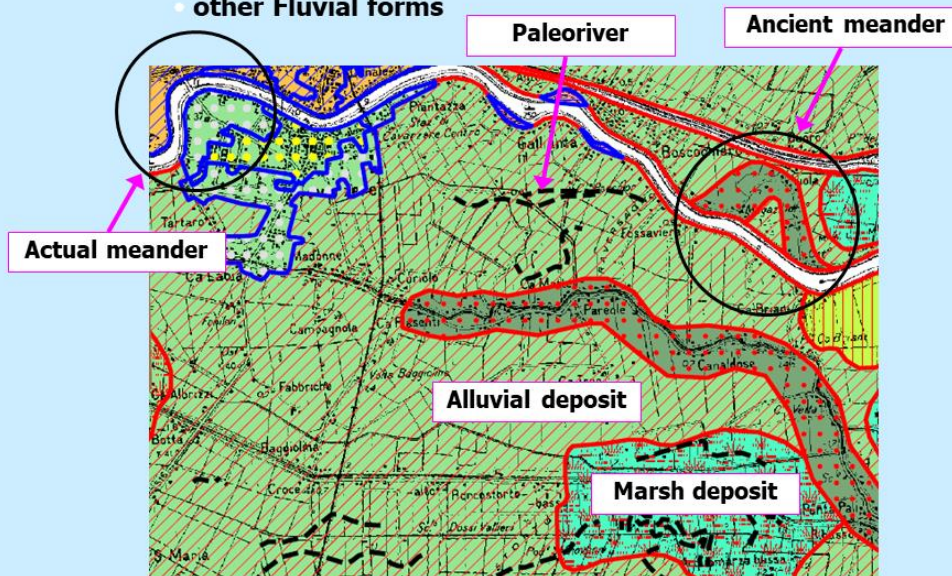
## Principal geomorphological elements in the map

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### • other Fluvial forms



Paleoriver

Ancient meander

Actual meander

Alluvial deposit

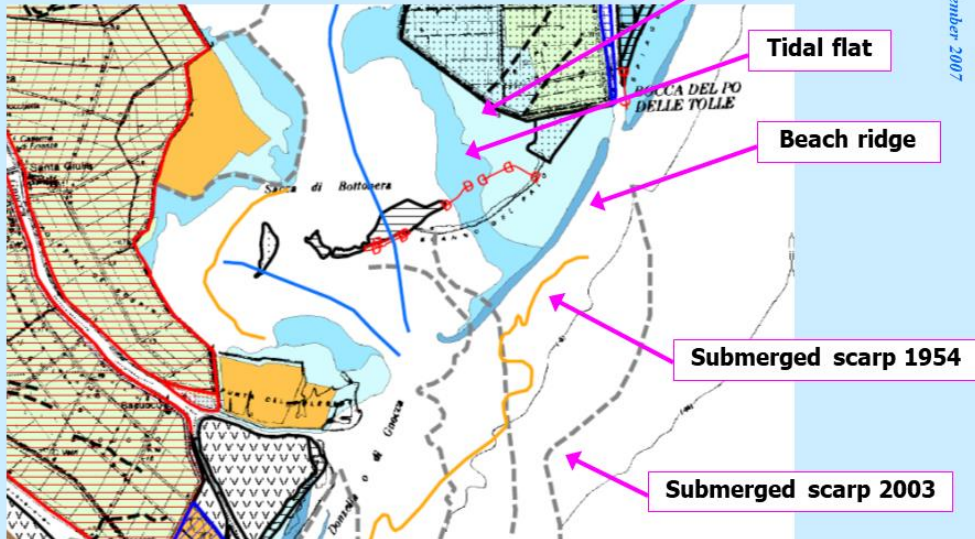
Marsh deposit

## Principal geomorphological elements in the map

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### • lagoon and litoral forms

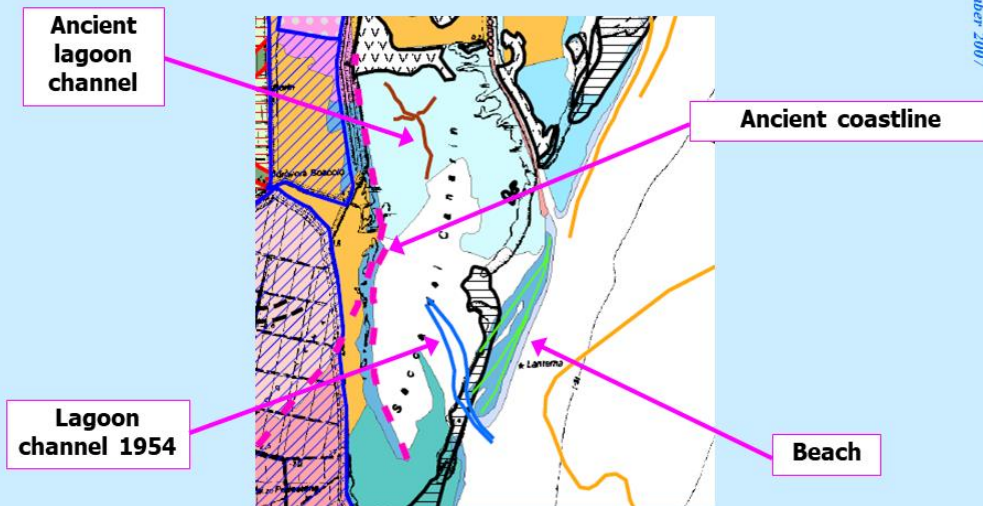


## Principal geomorphological elements in the map

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- other lagoon and litoral forms



## Principal geomorphological elements in the map

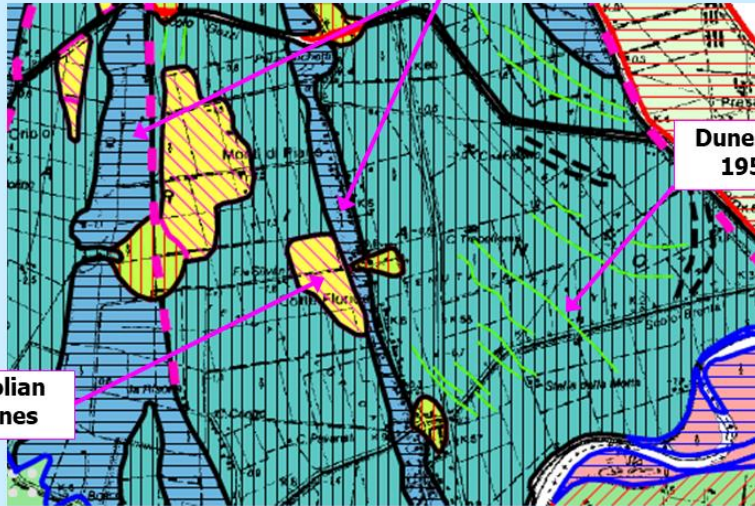
workshop 06



Venice, 19-20 september 2007

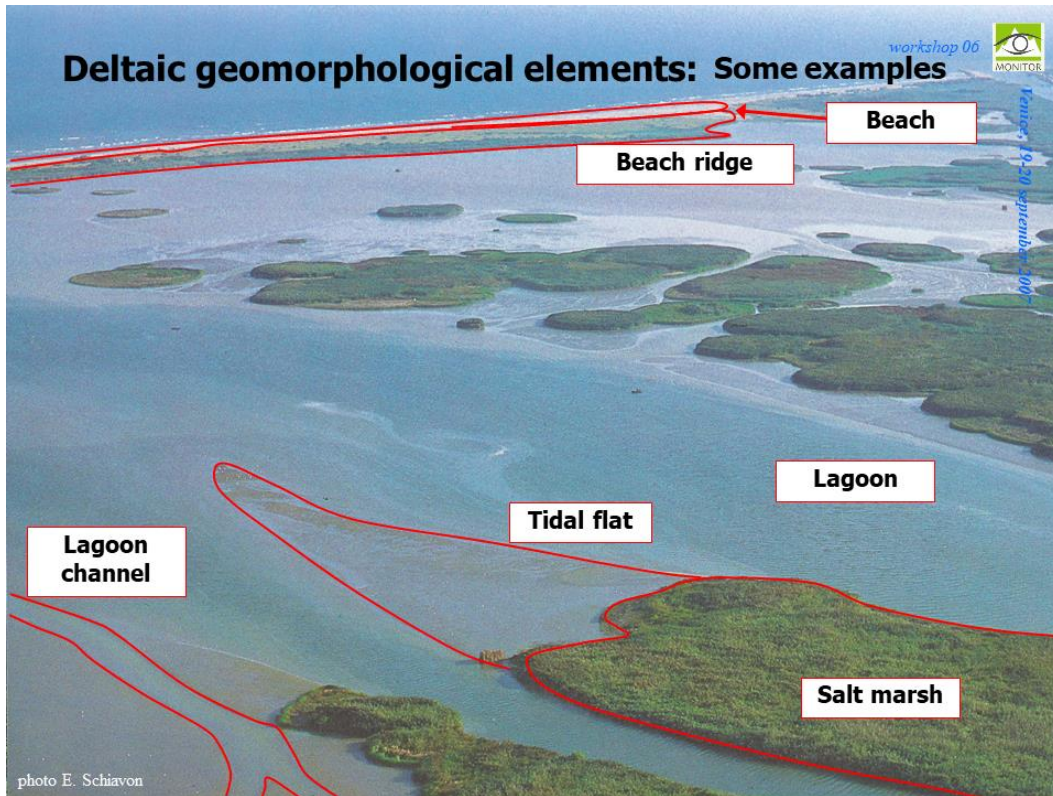
- aeolian forms

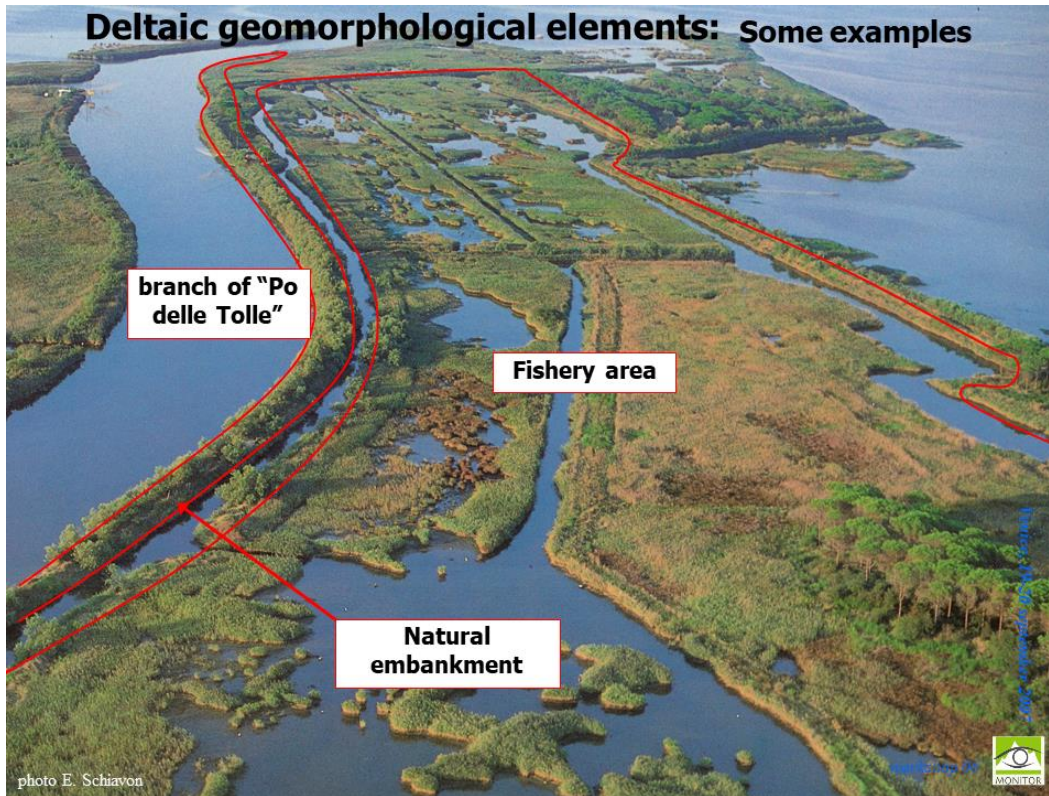
Ancient Beach ridges

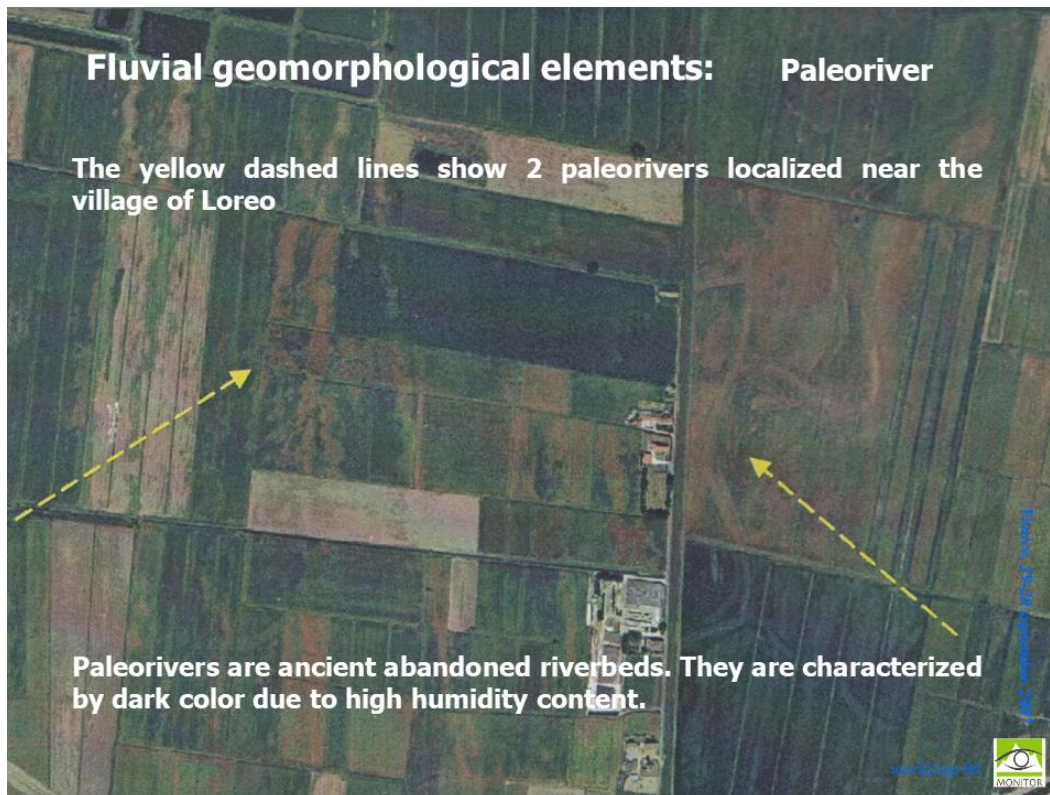


Aeolian dunes

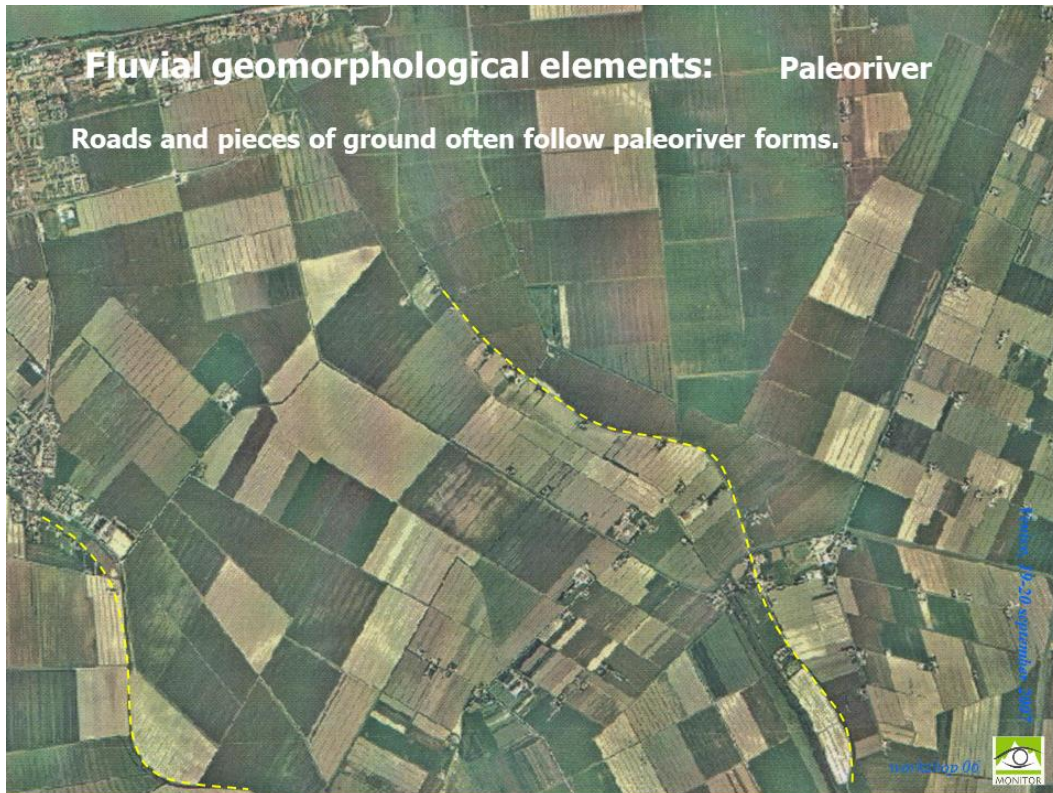
Dune line  
1954

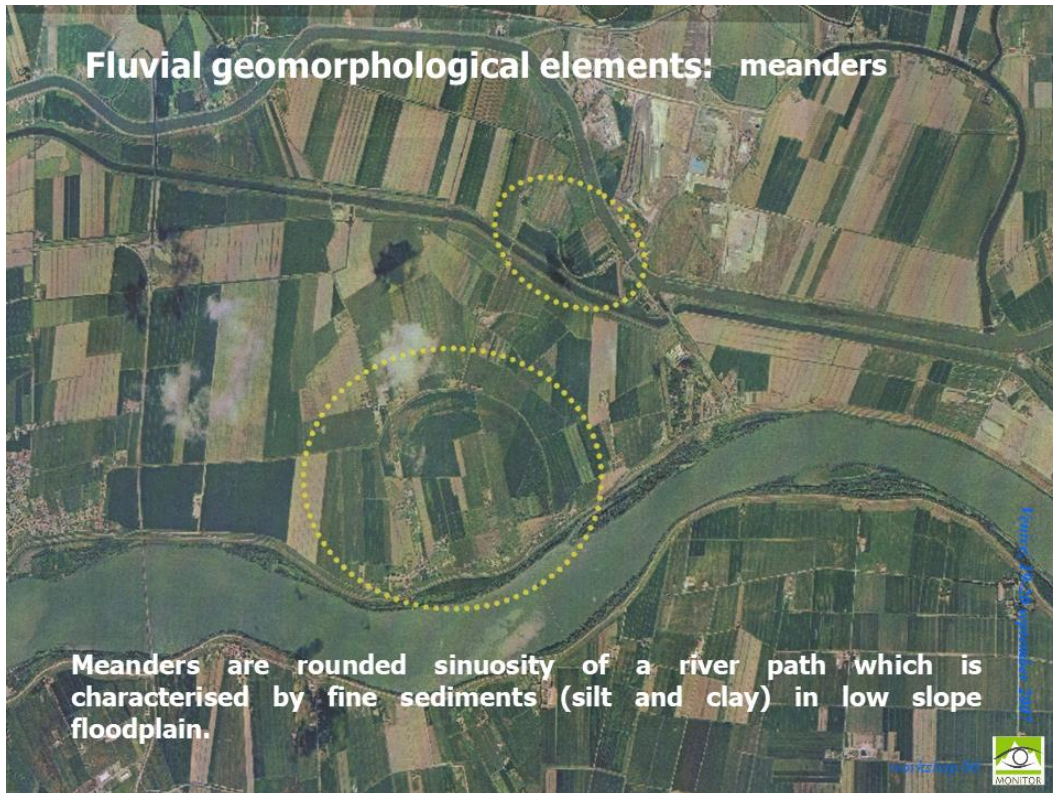


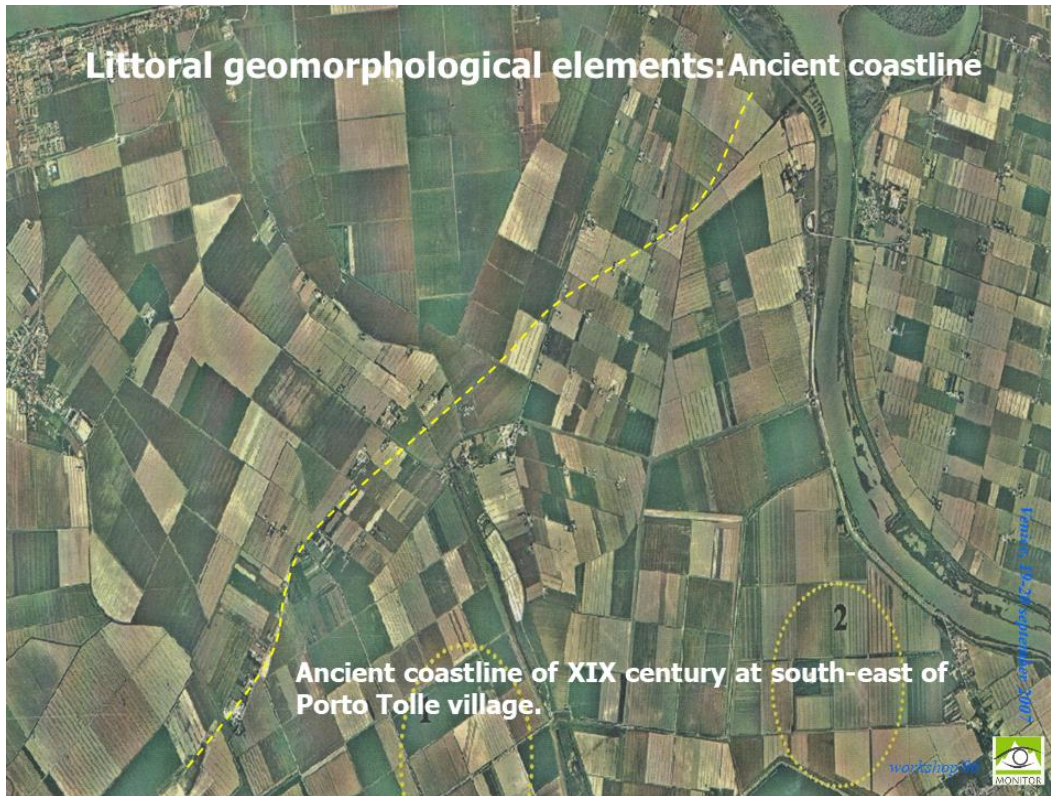


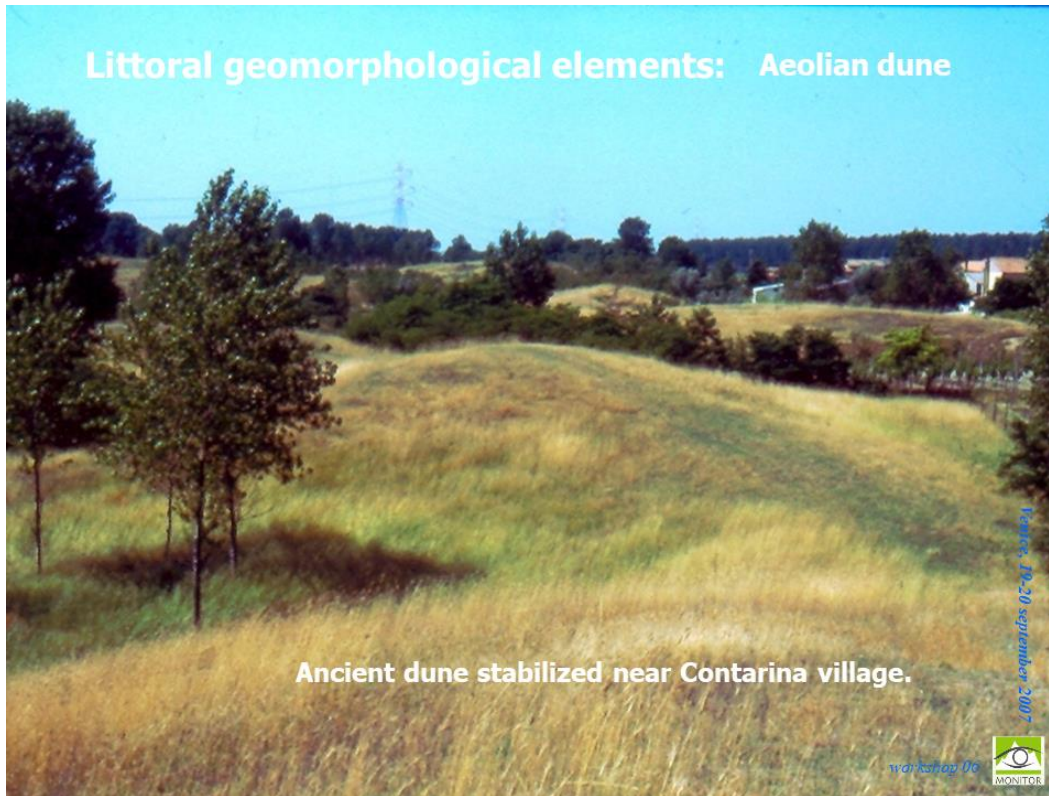








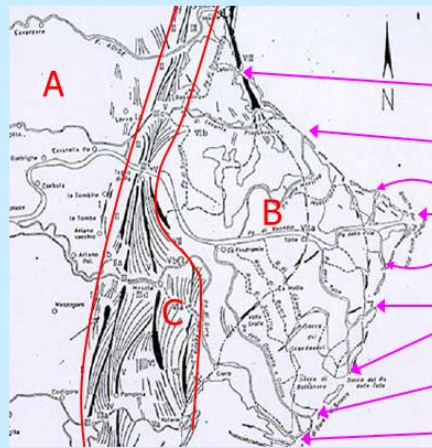




## Geomorphological setting of the Delta Po river

In the delta Po river area there are two different parts.

- before *taglio di Porto Viro* (1598 – 1604) - A
- modern delta after *taglio di Porto Viro* - B
- beach ridge systems divide these two parts - C



Six different branches form the Po Delta

Po di Levante

Po di Maistra

Po della Pila

Po delle Tolle

Po di Gnocca

Po di Goro

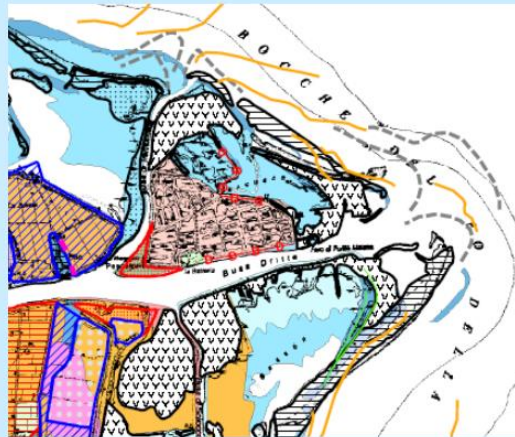
## Evolution of Delta Po river between 1954 and 2003

Three kinds of morphological variations:

- **VARIATIONS OF COASTLINE**  
depending on  
**SUBSIDENCE**  
**DECREASE OF SEDIMENT TRANSPORT**
- **VARIATION IN FLUVIAL PATTERN**  
**ABANDONED MEANDER**  
**MIGRATION and MODIFICATION OF FLUVIAL BARS**
- **ANTHROPIC MODIFICATIONS**  
**RECLAIMS**  
**URBANIZATION**

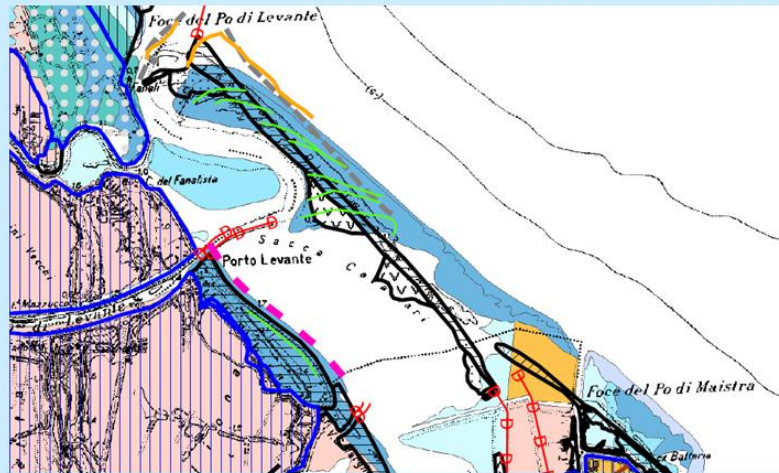
## Variation of coastline

More than 65 % of sediment load is located in the *Po della Pila* producing, as consequence, the projection of this Po branch



## Variation of coastline

The decrease of sediment transport and the subsidence cause the coastline withdrawal along all the other Po branches.  
At Porto Caleri the withdrawal reached 250 meters.





## Variation of coast line : **SUBSIDENCE**

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The subsidence phenomena is caused by:

- sediment transport decreasing
- over-exploitation of the gas-bearing water
- natural compaction of the young delta terrains

The example of "Po di Pila"



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## Subsidence

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branch of "Po delle Tolle"

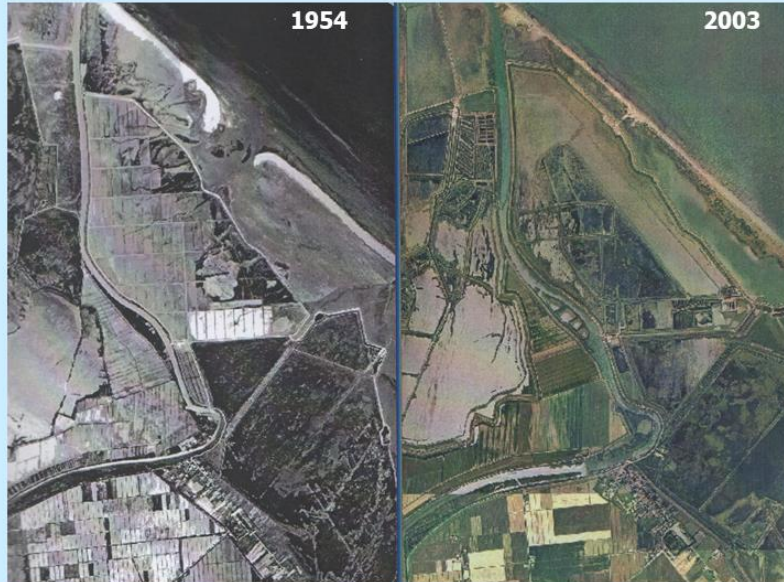


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## Subsidence

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### branch of "Po di Maistra"



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## Subsidence

branch of "Po di Gnocca"

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Variation of fluvial pattern: **ABANDONED MEANDER**

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East side of  
Cà Vendramin



2003

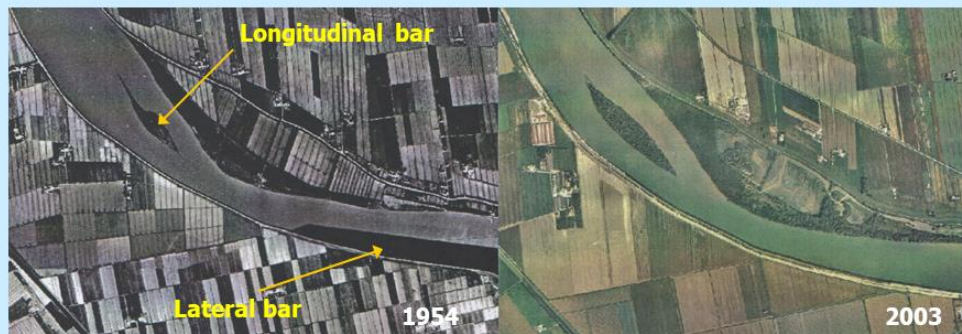


1954

The meander was abandoned  
between 1955 and 1971

## Variation of fluvial pattern: **FLUVIAL BARS**

Here we can observe the variation of longitudinal bar at the centre of the fluvial channel and the disappear of the right lateral bar.



*Po di Venezia near village of Villareggia*

## Anthropic modifications:

**Polesine Station.**      **Camerini**      **Power**

## STRATEGIC INFRASTRUCTURES

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## Anthropic modifications:

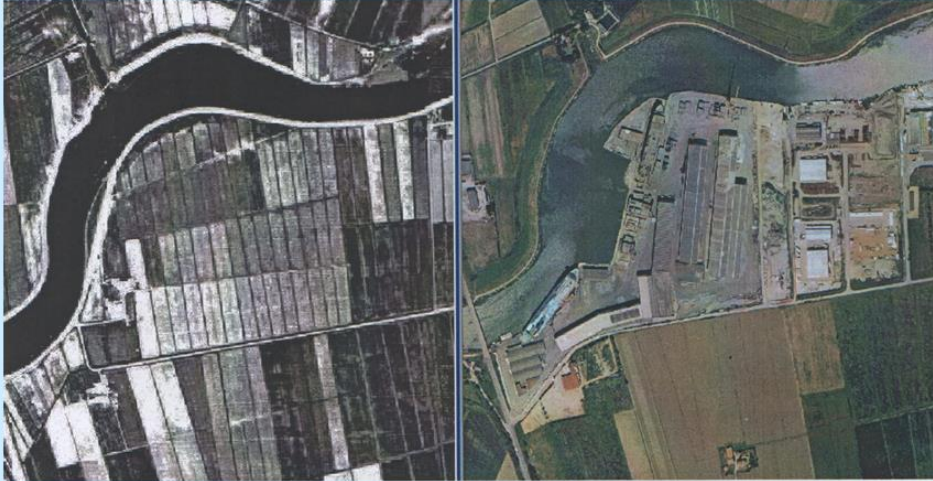
## STRATEGIC INFRASTRUCTURES

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### Shipyard at Rosolina

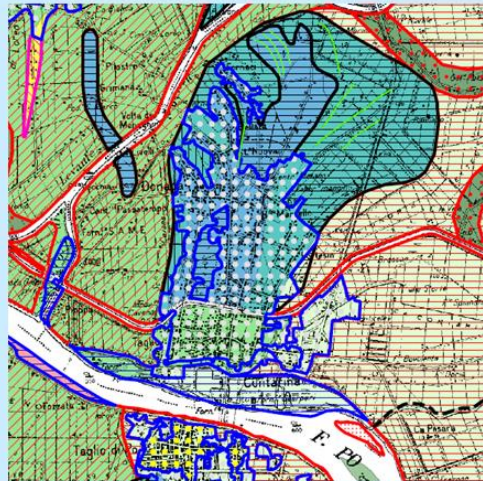
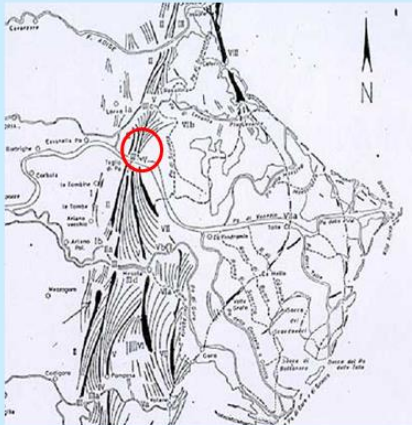




## Anthropic modifications:

## URBANIZATION

This is the example of the village of Contarina at the centre of the Delta  
 Urbanization has deleted a large part of the beach ridges belonging to the ancient coastline (before the *Taglio di Porto Viro*).



## Annex 4: Po Delta – Canarin, historical images

Below are the historical photos of Sacca del Canarin from 1949 to 2014, showing the anthropic and geomorphological changes due to the sediment accumulation and erosion







ORTOFOTO - 1977





ORTOFOTO - 1983

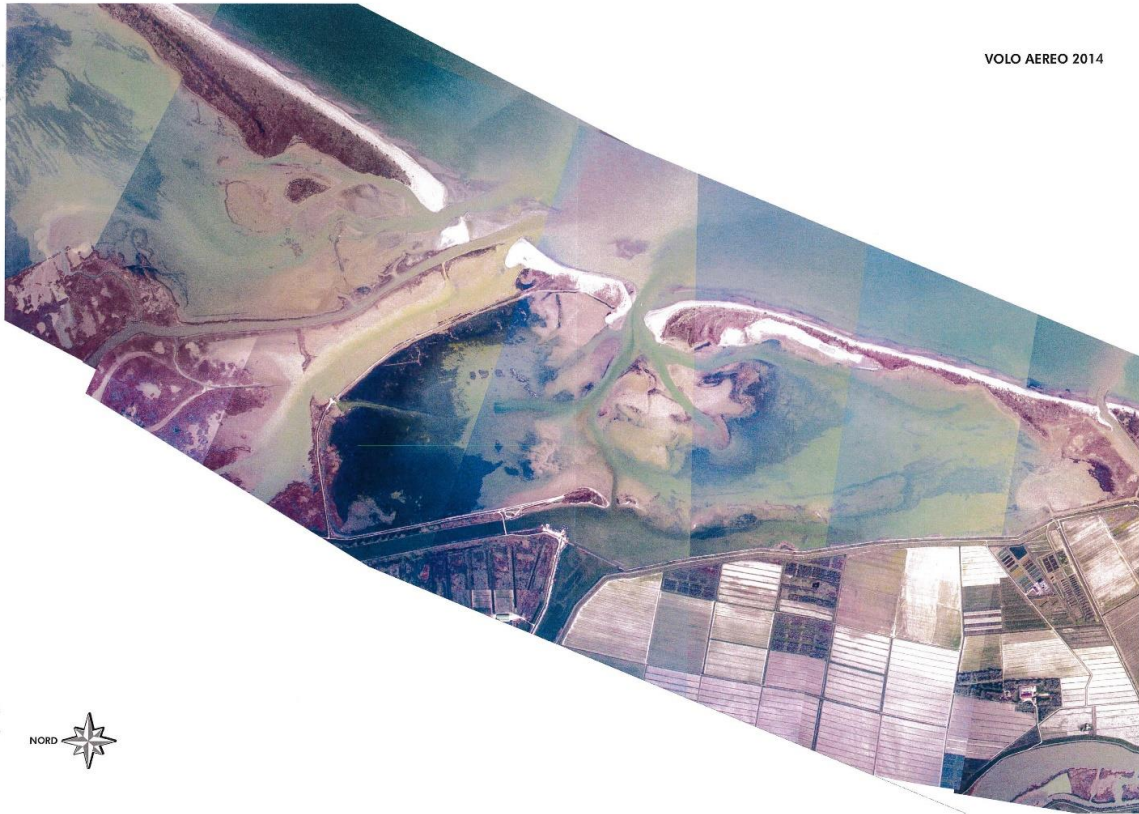












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## Annex 5: Po Delta – Sacca di Goro, Manila Clam

### Manila Clam management

Manila clam rearing has led to great productive, commercial and social opportunities with the start of affirmation of numerous cooperatives of clam farmers and other related activities, such as clams depuration, packaging and trade. Over the past thirty years, the Goro clam production has established itself at the national level, with shares equal to 50-60% of the total production, and internationally, as the most important European producer.

Currently, approximately the 33% of the surface of the Sacca di Goro is licensed for the Manila clam cultivation, to about a thousand farmers, associated in thirty-six cooperatives, with registered office mainly in the municipality of Goro. These data are certainly relevant and gives the idea of their absolute extent, if we consider that the municipality of Goro has less than 4,000 residents. Most of the cooperatives have a few tens of members, one cooperative has 100, while 540 are the members of the largest cooperative, the Consorzio Pescatori di Goro.

After the introduction, the Manila clam farming has had an unpredictable development and today all the local economy is based almost entirely on the exploitation of this resource, with an annual production ranging between 10,000 and 15,000 tons. If from the production prospect, this monoculture represents a fragile system which needs diversification, from that of the conservation of natural resources, it certainly represents a great realized opportunity. Indeed, it's a fact that the income obtained from this, highly sustainable, form of rearing, has made less or not attractive at all the traditional fisheries, both in the lagoon and in the adjacent coastal sea, so that to decrease the fishing effort and thus related impacts on the lagoon and marine ecosystem. All steps of rearing, such as cleaning the sediment, seeding, clams transferring from one area to another during the growth cycle, and harvesting, take place only within the licensed areas. Consequently, only focusing to the Sacca di Goro, the remaining two thirds have seen a decrease or disappearance of fishing pressure with a benefit for their role as breeding and nursery areas for several fish species and other protected organisms.

With respect to the ecosystem management of the Sacca di Goro, recently, through the Life Project AGREE, on the basis of monitoring results, a substantial change has been adopted. Two water gates between the Po di Goro and the Valle di Gorino have been opened almost permanently with the aim of increasing the freshwater inflow and favoring restoration of reed stands in the eastern part of the lagoon. At the same time, negotiations have started with clam farmers, to move some of the rearing areas from internal zones of the lagoon to offshore areas, located right in front of the Scannone di Goro. This action was undertaken mainly to avoiding further the risks related to seaweed blooming but at the same time, it has brought a further decrease of human presence and relative impacts within the lagoon.

These actions, as recently pointed out in an integrated analysis of Ecosystem Services (ESs), performed by Gaglio and co-authors (2019), rely on the involvement of stakeholders and information sharing on multiple benefits derived from restoring of degraded habitats and diversification of economic activities. This solution may harmonize the different needs and uses, such as habitat conservation and aquaculture activities, while restoring regulating, supporting, and cultural ESs that contribute to achieving sustainable goals. Specifically, the more rational use of the lagoon is expected to support the local economy under a blue growth strategy, by maintaining clam farming productivity and promoting ecotourism initiatives. Moreover, the improved hydrodynamic conditions of the lagoon and, to a lesser extent, the benefits in terms of phytodepuration of restoring reed stands, are expected to reduce the risks of anoxic events and algal blooms, thus favouring the possible recovery of submerged vegetation in the process. Presently, the most important disturbance to these habitats is due to agricultural activities, both at the scale of the whole Po basin and locally, in the Province of Ferrara. In particular, small coastal basins that discharge drainage water directly into the lagoon (Castaldelli et al. 2013; Viaroli et al. 2018) are areas particularly prone to nutrient leaching (Aschonitis et al. 2013). For this reason, the restoration of vegetated buffer areas represent the most effective measure to reduce eutrophication and related effects.

#### Sacca di Goro - Manila Clam management

## Annex 6: Po Delta – Sacca di Goro, historical evolution

*XVIII-XIX centuries: birth of the Sacca di Goro*

At the end of the sixteenth century, the Sacca di Goro did not exist and the area was occupied by the open sea which faced a straight coastline. After the river diversion at Porto Viro (1604) the southern delta branches were more nourished and the mouth of the Po di Goro began to migrate south-east creating a gulf (Figure 5-29) which would evolve in a lagoon, already at the end of the XIX century (Figure 5-30). The Scannone was formed as a small sandy bank in this period while the Volano spit already had a prominent shape (Figure 5-31).



*Figure 5-29: Historical Map 1570 (Carta del Pasi): the area of the Sacca di Goro corresponds to the open sea between the two Po River mouths (Po di Volano to the south and Po di Goro to the north)*

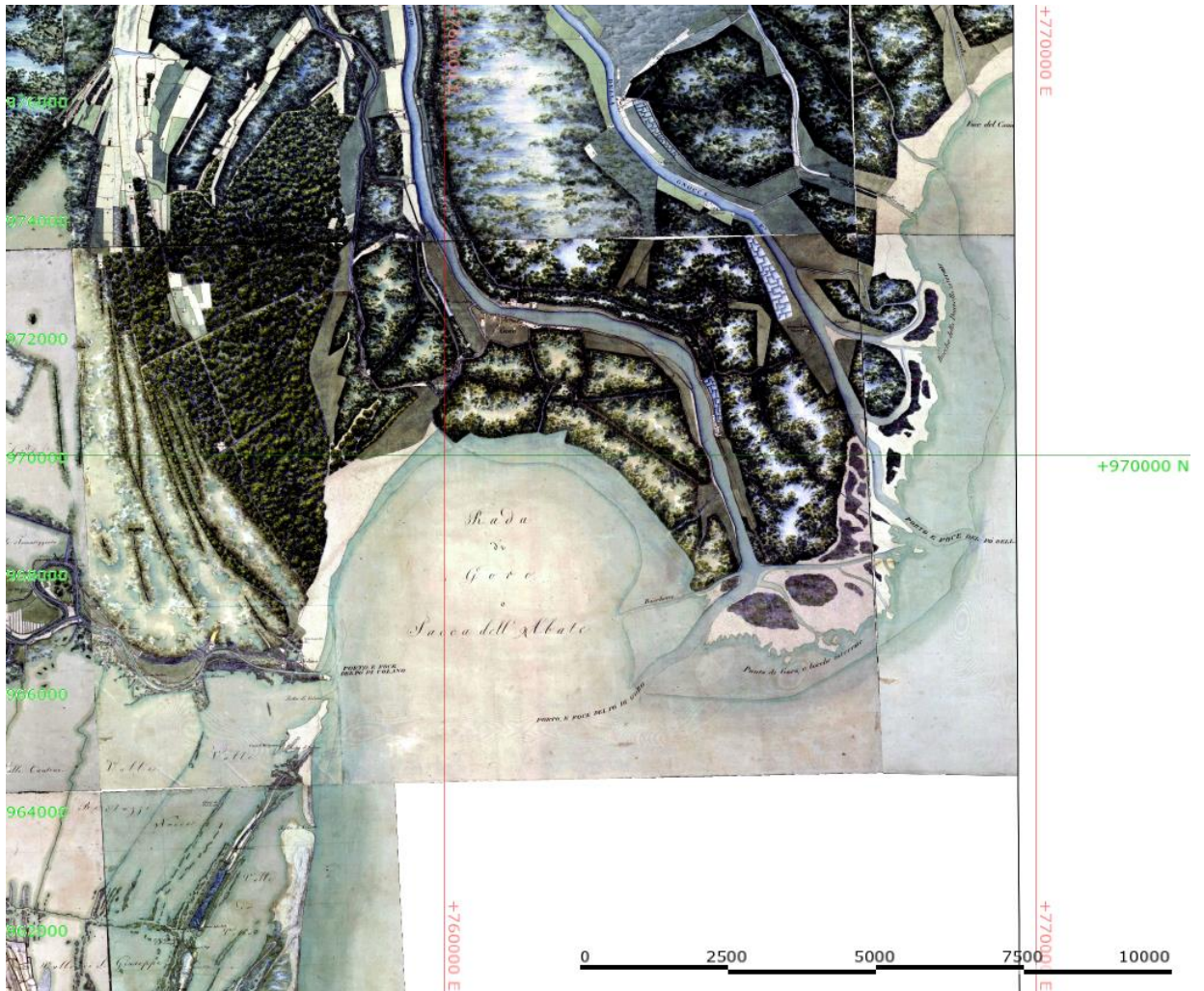


Figure 5-30: Historical map of 1814 (Carta del Ducato di Ferrara): the Sacca di Goro is a gulf, the Scannone and the Volano spit are not present.



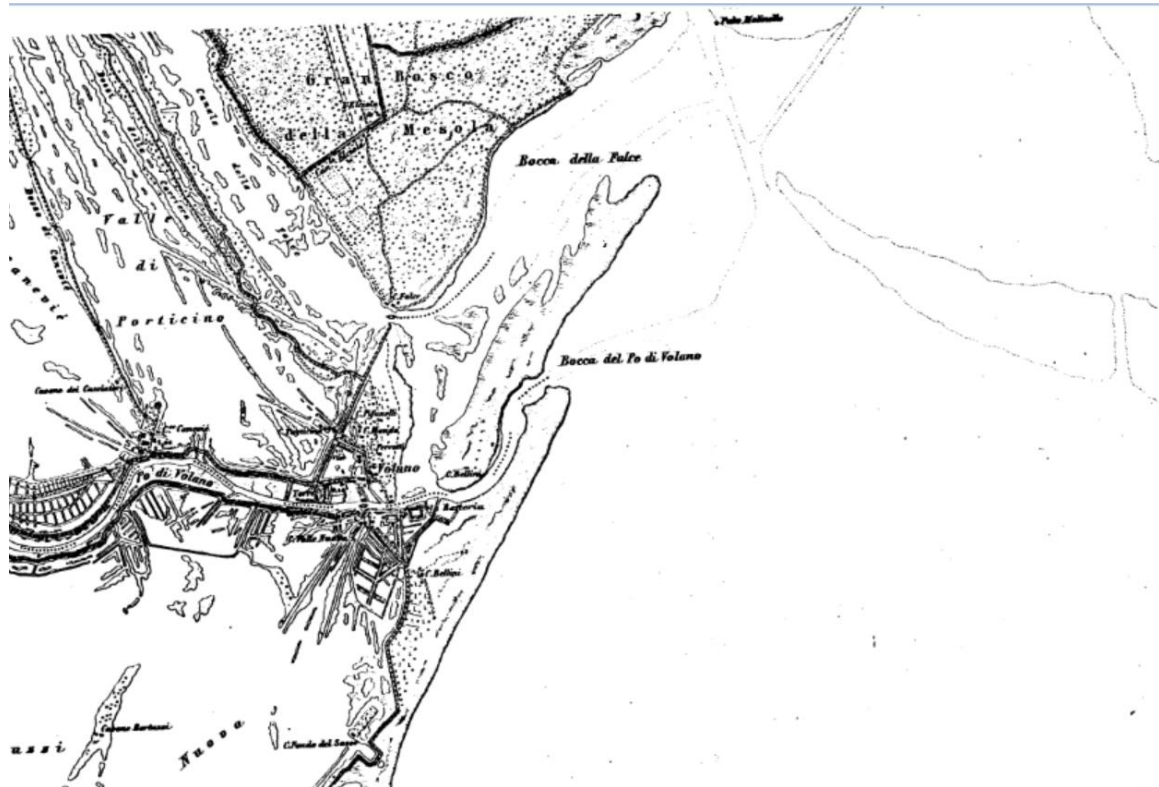


Figure 5-31: Topographic map of 1893-94 (IGM): The lagoon begins to take shape, the Volano spit is already formed (image below) while the Scannone is embryonic as a small emerged mouth bar (image above)

#### *From the 19th century to today: growth and evolution of the Scannone di Goro*

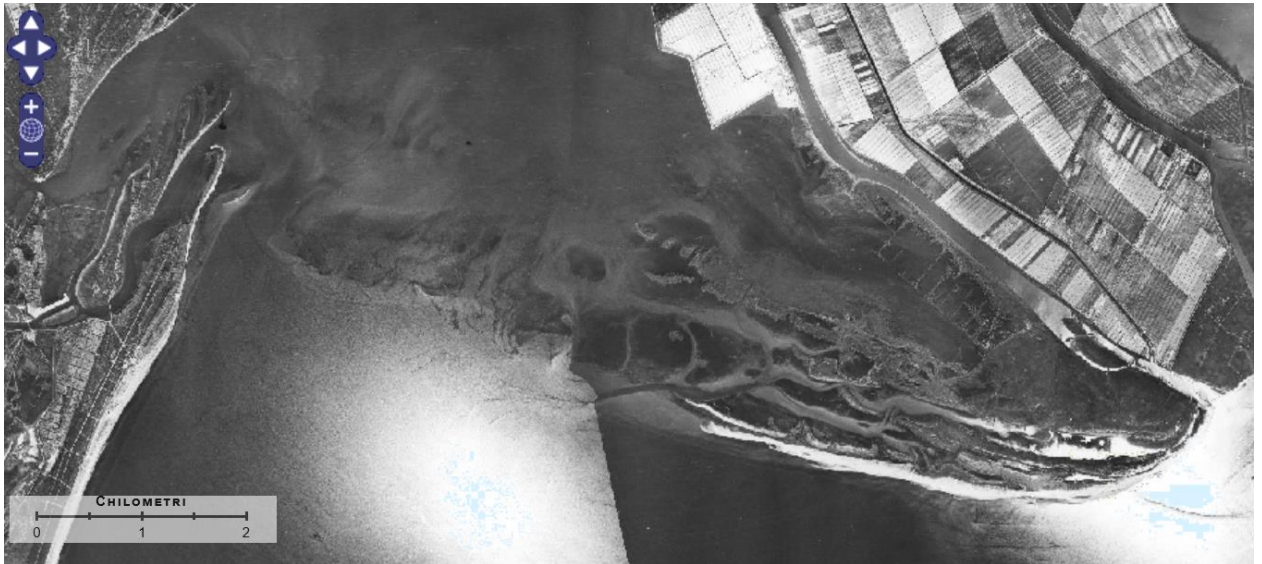
In the 1940s the Scannone was already formed as an articulated sand bank. The mouth of the Po di Goro had advanced strongly until the previous decade when the redistribution of the delta front sands became predominant (Simeoni et al, 2000). From this moment, the dynamics of the Scannone have been rather complex both for natural reasons, being an extremely changeable sedimentary system, and for anthropic causes. The evolutionary history, in fact, was influenced by processes that took place in the hinterland, as a consequence of the works for regulating rivers, the reclamation and extraction of water and hydrocarbons from the subsoil, and by morpho-dynamic processes triggered by anthropic interventions directly on the banks of sand (extraction and excavation).

The most important phases of the morphological evolution of the Scannone can be summarized in the following points:

- progressive growth in length of the spit up to the 90s, fed by the deposits of the delta front that are gradually eroded and transported to the west (Figure 5-32 and Figure 5-33)



- incision and development of a new lagoon mouth which determines its fragmentation and the formation of an island in the west portion and the reduction of the spit (Figure 5-34)
- dismantling and partial submerging of the island and erosion of the Scannone near the mouth (Figure 5-35)



*Figure 5-32: 1954-55 flight (GAI): The Scannone di Goro was already formed, relict banks from previous spit are visible*

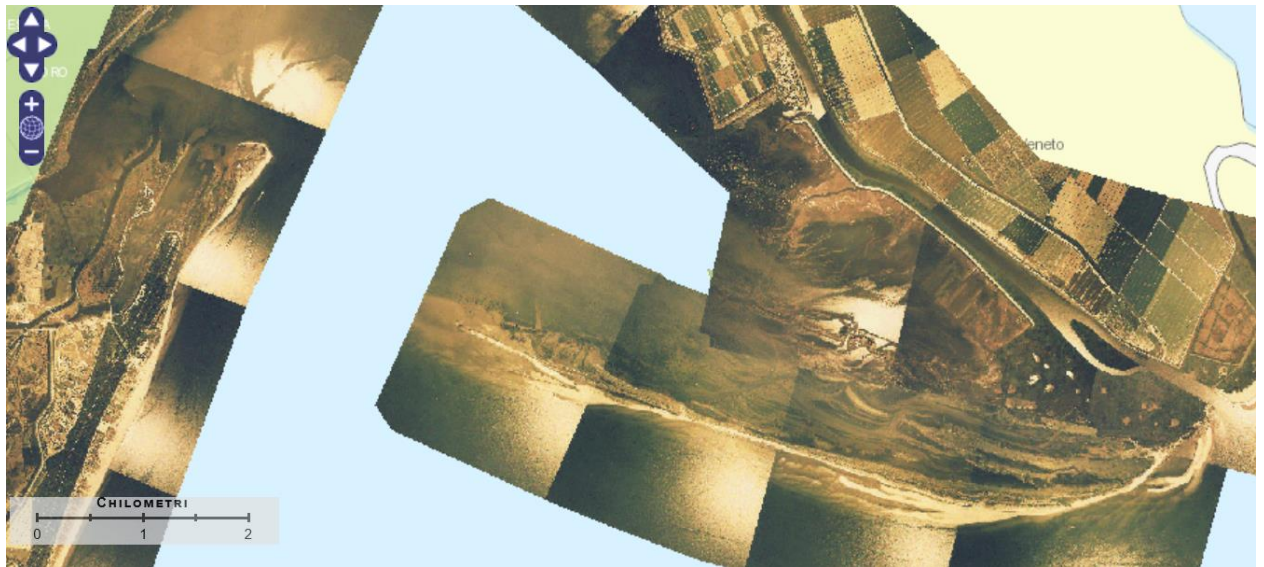


Figure 5-33: 1982 flight (RER): In these years the spit reaches its maximum length; littoral bars that weld to the beach are visible, the further growth of the Volano spit is also evident.



Figure 5-34: The spit is truncated by a new lagoonal inlet and a wide emerged sand bank is isolated between the reduced Scannone and the Volano spit.



*Figure 5-35: 2018 satellite images (Google Earth, Maxar Technologies): The Scannone appears rather stable with evidence of retreat near the river mouth; the island was completely flooded.*