Università degli Studi di Padova
Dipartimento di Ingegneria Civile, Edile e Ambientale
Department of Civil, Environmental and Architectural Engineering

Corso di laurea magistrale in Environmental Engineering

Tesi di laurea

Coastline changes in Veneto Region (Italy) from 2012 to 2018 by means of multitemporal orthophotos

Relatore:
Prof. Ing. Massimo Fabris

Laureanda:
Annachiara Vincenzi
2010612

Anno accademico 2021-2022

Abstract

Coastline, which represents the boundary between land and the water surface, has a very dynamic nature. As a matter of fact, coastlines are continuously changing in shape and position due to both natural and anthropogenic causes.

Change of coastline has great importance, therefore it is needed to detect this variations and take precautions. The area of interest is the Veneto Region coast. The main characteristic of the coastal strip of the Upper Adriatic Sea is its continuous evolution and its variability of land uses and alternation of ecosystems. The shallow depth of the seabed, exchanges with the waters of the lagoon, contributions from the numerous rivers that carry agricultural, civil and industrial discharges to the sea, meteorological and hydrodynamic variability, and pressures from maritime traffic, fishing and tourism, make the coastal marine environment extremely sensitive and subject to sudden changes in chemical, physical and biological characteristics. Added to this is the erosive phenomenon and the works implemented to remedy it (groins, breakwaters, and beach nourishment), as well as other defensive works.

The aim of this thesis is the study of the Veneto Region coastal changes from 2012 to 2018. Multitemporal orthophotos from the years 2012, 2015 and 2018 were used to and the restitution of the ground-sea transition was performed.

Coastline change analysis related to these years is provided with the help of QGIS software. QGIS is a Geographical Information System application that supports viewing, editing and analysis of geospatial data. The software made it possible to calculate this changes both with distances (between two coastlines drawn from multitemporal orthophotos) and with areas. The comparison between year 2012, 2015, 2018 coastlines made it possible to observe which zones are subjected to deposit and which to erosion phenomenon.

In a particular environment such as the North Adriatic basin, coastal zone monitoring is an essential task in sustainable development and environmental protection.

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1. Introduction

A coastline is defined as the line of contact between the land and a body of water [1]. It is a unique and complex feature and has been recognized as one of the most important linear features on the earth's surface, which displays a dynamic nature and is an indicator for coastal erosion and accretion [2]. Coastal erosion is the process of removal of material at the shoreline which leads to loss of land as the shoreline retreats landward whereas accretion is the product of deposition of material at the shoreline which leads to gain of land as the coast advances seaward [3].

The morphology of coastal areas is influenced by both natural phenomena and anthropic activities. The increase of anthropic activity along the coasts has damaged the equilibrium, accentuating the dynamics of erosive—progradation. The coastal erosion affecting the entire North Adriatic coast puts at risks local infrastructure, environment and the tourist economy [4].

The location and attributes of coastlines are highly valued by a diverse user community, as they have never been stable in either their long-term or short-term positions. Human life, cultivation and natural resources are affected by the processes of erosion and accretion along the coast, and rapid coastline changes can create catastrophic social and economic effect along these regions [2].

Coastal areas need continuous monitoring as a support for human intervention to reduce the hazard [5]: plan efficient maintenance work, sand refill and engineering structures to avoid coastal drift [4]. Ground deformation areas can be monitored with geomatic methodologies such as global positioning system and differential, satellite images, classical topographic measurements and geometric levelling, LiDAR with airborne laser scanning approach and aerial digital photogrammetry [6].

The aim of this thesis is the study of the Veneto Region coastal changes from 2012 to 2018 by means of digital orthophotos.

The area under investigation is the coastline of the Veneto Region, which extends for about 160 km, between the mouth of the Tagliamento River and the mouth of the Po di Goro [7]. A description of the Venetian coastal area is provided in the next chapter.

Then, in chapter 3, materials and methods used in order to detect coastal variations are presented. Multi-temporal digital orthophotos were used to study the evolution of the Veneto Region coastline from 2012 to 2018. The QGIS software made it possible to plot the ground-sea transition line from 2015 and 2018 digital orthophotos and to calculate erosion and deposit distances and areas.

Furthermore, figures, results and data are presented in chapter 4 and 5 in order to appreciate the variations of the Veneto Region coastline. It was decided to subdivide the venetian coastline into 20 morphologically homogeneous cells, following the example given by the report "*Studio e monitoraggio per la definizione degli interventi di difesa dei litorali dall'erosione nella Regione Veneto*" written by the Piero Ruol, Luca Martinelli and Chiara Favaretto in collaboration with the University of Padova. For each cell, deposit and erosion areas, together with other descriptive information are given.

The knowledge of the coastline is the basis to overcome coastal problems, to measure and characterize land and water resources such as the area of the land and the perimeter of the coastline. Monitoring the evolution of the coastline is an essential task in the environmental management of the entire coastal zone [8].

2. Description of the area under study

The Italian coastline is about 8300 km long. Italian beaches are generally wide (several tens of meters), found mainly on the Adriatic front. Emilia-Romagna and Veneto have the widest beaches.

The coastal environment is a dynamic ecosystem in which natural and anthropogenic processes add up and interact, modifying its geomorphological, physical, and biological characteristics, and sandy shorelines are the most vulnerable territories, where said evolutions are most apparent [9].

2.1 The Veneto Region coastline

The area under investigation is the coastline of the Veneto Region (Figure 1), which extends for about 160 km, between the mouth of the Tagliamento River and the mouth of the Po di Goro [7]. The Venetian coastline can be divided, in the direction of North-South, into two main parts:

- Northern part, from the mouth of the Tagliamento River to the mouth of the Adige River (province of Venice) for a total of 98.7 km. This part comprehends the municipalities of San Michele al Tagliamento, Caorle, Eraclea, Jesolo, Cavallino-Treporti, Venezia and Chioggia;
- Southern part, from the mouth of the Adige River to the southern branch of the Po Delta called Po di Goro (province of Rovigo) for a total of 56.8 km. This part comprehends the municipalities of Rosolina, Porto Viro, Porto Tolle and Ariano nel Polesine.

The main characteristic of the flat coastal strip of the Northern Adriatic is its continuous evolution and its variability of land uses and alternation of ecosystems; it is in fact characterized by a system of mouths (Tagliamento, Livenza, Piave, Sile, Brenta, Adige and Po) and lagoons (Baseleghe, Caorle, Venice and further south the countless lagoons of the Po delta) [7].

Figure 1 Venetian coastline, the stretches belonging to Venezia and Rovigo provinces are highlighted. Municipalities in the province of Venice are indicated with magenta, while those is province of Rovigo are green. (Source: Regione del Veneto)

The Veneto region coastline is morphologically characterized by sandy shorelines north and south of the Venice lagoon. The coastal marine environment is extremely sensitive and subject to sudden changes in chemical, physical and biological characteristics. This is due to the shallow depth of the seabed, the exchanges with the waters of the lagoon, the contributions from the numerous rivers that carry agricultural, civil and industrial discharges to the sea, the meteorological and hydrodynamic variability, and the pressures from maritime traffic, fishing and tourism. In addition to this, there is the erosive phenomenon and the works implemented to remedy the phenomenon itself (groins, breakwaters and the nourishment of beaches), as well as the complementary works at the inlets planned as part of the interventions to safeguard Venice from the phenomenon of high water [10].

A particular aspect of the Venetian seabed is the presence of rocky irregularities, called Tegnùe, particularly sensitive environments of great importance from a biological and naturalistic point of view. From Tegnùe to algae, from sea turtles to dolphins, each of these is fundamental to the others and to the balance of the marine habitat.

2.1.1 The province of Venice

The coastlines of the province of Venice consist of 100 km of low sandy coastline belonging to deltaic and barrier island systems, whose sediments originate from the rivers that flow into this part of the North Adriatic (Tagliamento, Piave, Sile, Brenta, Adige) [11].

A general erosive trend of the shoreline is observed here with retreats caused by natural and anthropogenic factors, including the reduction of solid transport of rivers (dams, excavations), urbanization of the coast [7].

The conditions of wave energy and tide cause these shorelines to be characterized by the development of long littoral arrows ("spits") and barrier islands (known as lidos) to enclose well-characterized lagoons from a morphology, connected with the sea through a series of tidal inlets. The evolution of these beaches depends on a precarious balance between the transgressive marine regime, due to rising sea level of the sea and the fluvial input, which has been decreasing over time [11].

Figure 2 Left: Lido of Venice. Right: Jesolo beach. (Source: Veneto.info)

The beach is an open system in which there are continuous inputs and outputs of sediment attributable to different causes. The origin of the materials that constitute beaches is generally quite varied; in the case of the Veneto, it is mostly sands from rivers and distributed by currents along the shore. They originate due to waves reaching the shoreline with oblique fronts and are responsible for the transport of sediment along the shore. Only in rare cases there are contributions of sands that result from ongoing erosion, such as on relict dunes that are dismantled by the action of the sea and whose material becomes part of the beach balance (Punta Tagliamento area, for example).

Instead, beach nourishment operations have become quantitatively significant in recent decades, with of beaches with artificial contributions of sands mainly from underwater quarries (shorelines of Pellestrina, Cavallino, Jesolo) (Figure 2).

2.1.2 The province of Rovigo

The section of coast belonging to the province of Rovigo extends from the Adige mouth to Po di Goro mouth (about 60 km) and consists of a succession of shores, sandbars and emerging islands, characterized by sandy beaches with a weak slope (Figure 3).

The evolution of the coastline and the seabed in front of it, over the past 50 years, has been conditioned by the concomitant presence of the subsidence phenomenon and the decreased solid input of the Po and Adige. As a result, there has been a generalized retreat of the coastline and deepening of the seabed with a progressive thinning of the sandbars that perform the function of natural defense of the back lagoons. The deltaic hinterland lies almost completely below sea level [7].

Figure 3 Left: Barricata beach. Right: Rosolina beach. (Source: Veneto.info)

The most interesting environment is the Po River Delta (PRD), which covers about 400 km^2 in the northern Italy and was formed by the deposit of sediments carried by the Po, the largest river in Italy that runs west–east for about 690 km from the Monviso Mont before flowing into the northern Adriatic Sea; the geology of the delta is mainly composed of terrigenous sediments up to 2000 m thick, and it is a complex multi-aquifer freshwater system [12].

Nowadays, the effects of the great land subsidence that occurred in the last century are evident: most of the PRD now lies below the mean sea level and is characterized by the lengthening of the deltaic branches, anthropogenic stabilization of the hydrographical network, elevated borders seawards (levees, flood protection structures), and a significant depression in the center [12].

Due to great ecological and economic value, high populations, and extensive agriculture, constant monitoring of deformations throughout the complex ecosystem of the PRD is necessary to provide information about displacements in order to implement territorial defense systems against flooding [5].

2.1.2.1 Subsidence in the Veneto coastal area

The areas of the Venetian coast mainly subject to subsidence phenomena are those of the lagoon of Venice and the Po delta, see Figure 4.

The phenomenon of subsidence consists of a slow movement of lowering of the land surface. The main causes of this phenomenon are related to natural processes and/or with increased anthropogenic pressure. Ground deformations in the PRD are mainly due to land subsidence of different origin: tectonic, sediment compaction, and artificial (anthropic). The actions of man that can induce subsidence phenomena are generally related to the extraction of fluids and solids from the subsurface and from the excavation of materials for the creation of underground tunnels [7].

Long-term subsidence is mainly the result of deep tectonics, glacial isostatic adjustments, and geodynamic movements that provide a maximum rate of 2.5 mm/year [5].

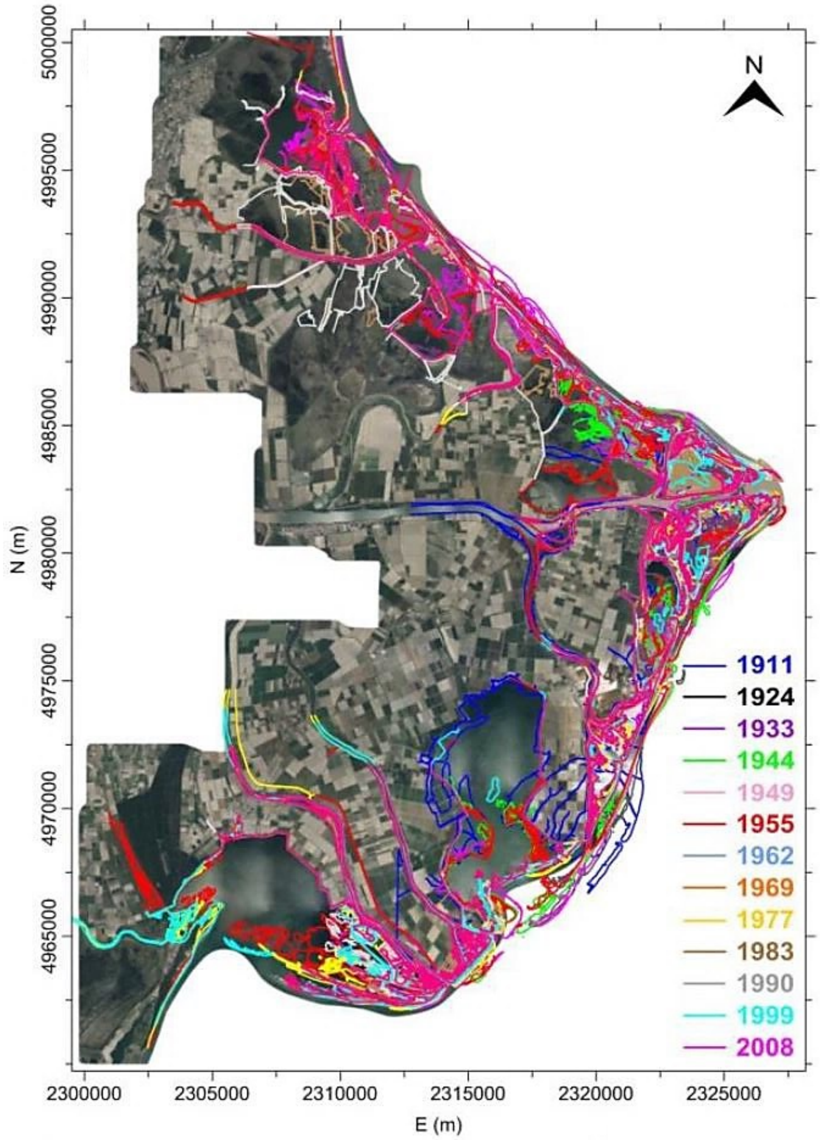

Figure 4 Rovigo coastline restitution from year 1911 to year 2008. (Source: Coastline evolution of the Po River Delta (Italy) by archival multi-temporal digital photogrammetry, M. Fabris)

2.1.3 Coastline protection methods

A good understanding of the coastal environment of a determined site is an essential prerequisite to assessing the ability of a coastal defense option to perform as it is intended. A complex interaction exists between the various elements defining the coastal environment. The introduction of coastal protection works will invariably modify nearshore processes in some way and it is important to account for that feedback effect. Coastal morphology at any location is the result of erosion and accretion patterns which, in turn, depend on the interaction of wave climate, currents and tides with this morphology. The causes and effects of coastal features must always be considered when dealing with works which affect littoral movement [13].

There is a wide range of coastal works that might be employed to tackle a particular situation, each of which may perform a number of different functions. The first important distinction is between hard coastal protection structures and soft coastal protection operations [13], which is represented in the scheme reported in Figure 5.

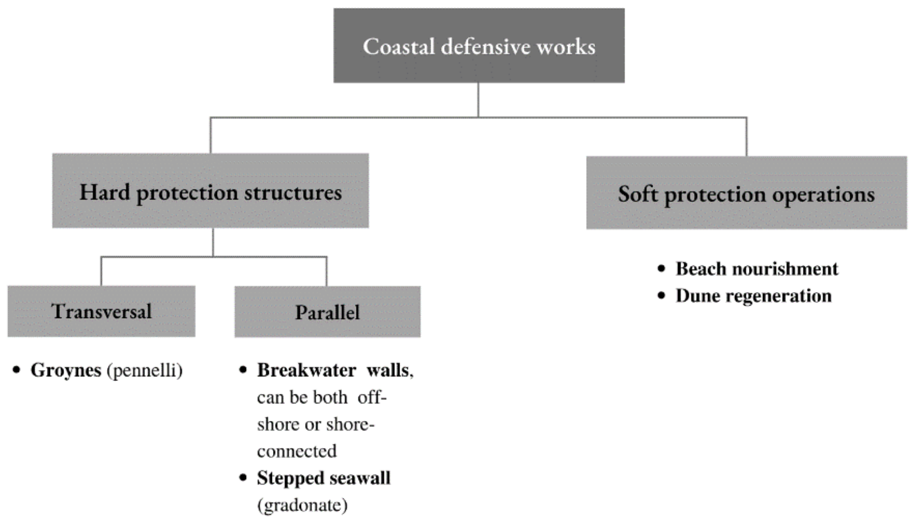

Figure 5 Coastal defensive works categories. (Source: G. Fontolan)

2.1.3.1 Hard engineering for coastal protection

The rigid or hard protections structures are actual artificial, man-made structures used to protect coastlines against erosion. They could be sub-divided into transversal and parallel defensive works.

2.1.3.1.1 Transversal defensive works

Transverse works are all those works that run transversely to the coastline (Figure 6). Transverse rigid defenses intercept longshore solid load, trapping sediment on the upwind side. Groins are real proper defenses of the shoreline.

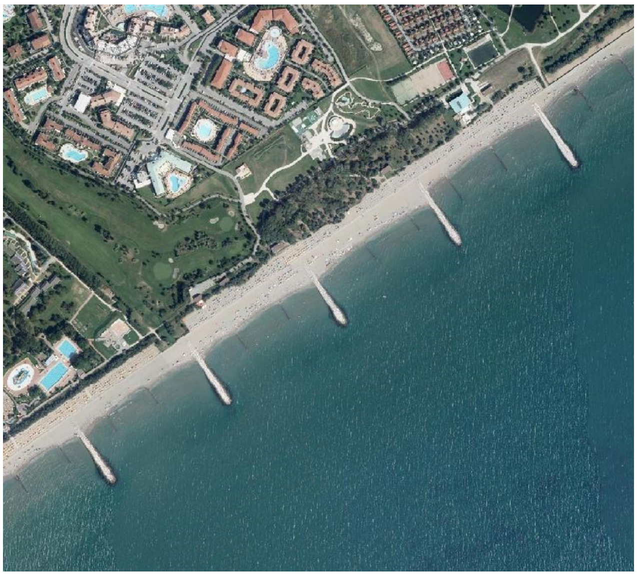

Figure 6 Transversal defensive work in Duna Verde. (Source: 2018 orthophotos, Regione del Veneto)

Groins are structures that extend from the beach into the water, see Figure 7. They help counter erosion by dissipating wave energy and by trapping sand from the current. Groins accumulate sand on their up drift side, but erosion is worse on the downdrifts side, which is deprived of sand. Usually such works are made in groups and are effective in areas where transport parallel to the shoreline is high in one direction.

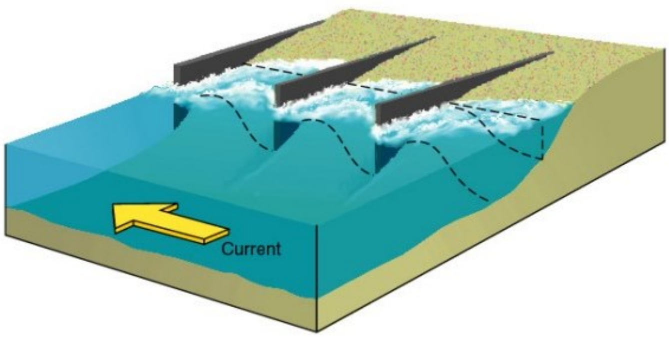

Figure 7 Groins sketching. (Source: G. Fontolan)

2.1.3.1.2 Parallel defensive works

Parallel rigid defenses are structures to dissipate the wave motion. If placed in adherence they defend an artifact radically, even to the detriment of beach formation or restoration; in a detached position they allow for variable levels of protection along frontage.

Shore-connected breakwater walls

This type of breakwater acts as a barrier to prevent erosion and flooding. Breakwater walls are works arranged parallel to the shoreline, whose function is to dissipate the energy of the incident wave motion, protecting the area behind and resulting in sediment accumulation between the barrier and shore (Figure 8). If the solid transport parallel to the shore is not zero, the sediment deposition effect can be exerted against both the upstream and downstream beach.

Figure 8 Parallel defensive works located at Bibione lighthouse. (Source: Regione del Veneto)

The geometry of such a work is expected to slightly change the shoreline trend, generating a salient to the back of the barrier itself, but providing partial continuity of littoral solid transport.

Stepped seawall

Figure 9 Defensive sloping at Eraclea shoreline. (Source: Regione del Veneto)

Stepped seawalls are designed to enable waves to break to dissipate wave energy and to repel waves back to the sea (Figure 9). These works are used to protect areas behind the beach from the action of wave motion waves; they can be made of reinforced concrete, metal sheet piling, boulders or concrete blocks [7].

Improper use often results in severe localized erosion and negative repercussions on adjacent shorelines, both by the reflection phenomena that this type of defense causes under storm surges, and by the concentrations of flow that are realized close to it.

2.1.3.2 Soft engineering for costal protection

Importing sand to a beach is considered the best response to erosion, it increases the distance of wave travel which reduces erosion.

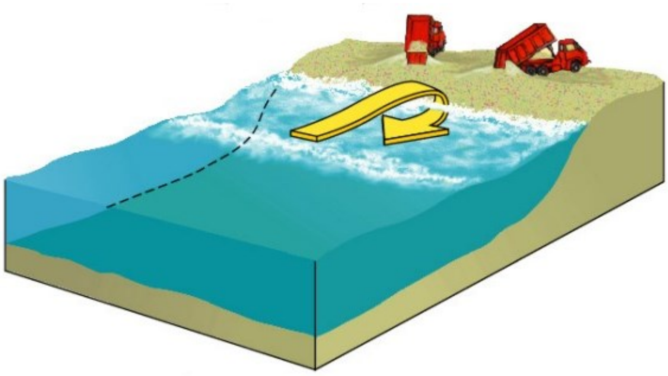

Figure 10 Beach nourishment sketching. (Source: G. Fontolan)

Beach nourishment (Figure 10) is an intervention that involves an artificial contribution of suitable material (by grain size, mineralogy, chemical-biological composition) to a coastal area that has a sediment deficit, with the aim of reconstructing and maintaining the beach, ensuring sufficient width and height to provide effective protection against storm surges, and/or creating a recreational-tourist area.

The technologies that can be employed depend essentially on the characteristics of the borrow area, the site to be repaved, and the volumes involved. In the case where materials are not available locally, marine quarries are increasingly being used, which guarantee native-like material in high quantities but which, especially for small-scale or maintenance-type interventions, turn out to be expensive [7].

3. Materials and methods

The aim of this thesis is to study the Veneto Region coastal changes from 2012 to 2018 by means of multitemporal digital orthophotos.

In this chapter the data and materials used in order to perform the study are presented, together with the software and the methodologies adopted.

3.1 Orthophotos

An orthophoto (also known as a orthophotograph) is an aerial image that has been geometrically corrected (ortho-rectified) so that the image is uniform from edge to edge. Orthophotos are corrected to remove terrain effects (what happens when you take a 3D surface and make it into a 2D product) and distortions that result from the camera's lens and the angle the photo was taken from the plane. The goal of ortho-rectification is to create an image where distance measurements are the same across the entire image [14].

An orthophoto has a geographic reference to the Earth, such as a UTM or State Plane coordinates, so each pixel in the photo can be accurately located.

As for the study of the Veneto Region coastal changes, the reference system is the Italian Gauss-Boaga projection, zone West.

3.1.1 Reference systems

3.1.1.1 Geographic reference system

The Earth's surface is approximated by a mathematically very complex geometric figure, the geoid, which in turn is approximated by a simpler figure, the rotational ellipsoid [15].

A point on the Earth's surface is identified by two angular coordinates (latitude and longitude) that give its position on the ellipsoid, plus a linear measure that is the elevation information.

More than one rotational ellipsoids exists, each with its own characteristics (length of semi-axes and polar flattening) and different from the others. There is Bessel ellipsoid (1841), Helmert's (1906), Hayford's (1910), International (1924), WGS72 (1972), WGS84 (1984) and others. Over time each nation chose the ellipsoid that best suited its territory.

The Italian system Roma40, is based on the International ellipsoid oriented at Roma Monte Mario, the European system, ED50, is still based on the International ellipsoid but oriented in Germany, at Potsdam.

3.1.1.2 Cartographic reference system

In order for a small piece of an ellipsoid to be displayed on a plane (on paper or on a screen) it must be projected onto it. Projecting a curved surface onto a plane involves quite a few problems, and for years cartographers have struggled with the associated distortion problems.

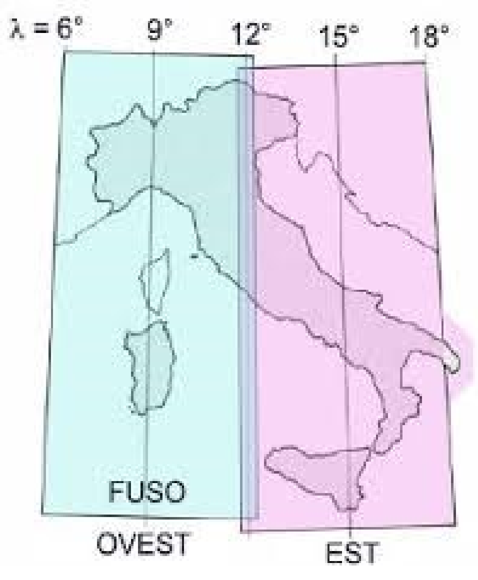

Figure 11 Gauss-Boaga projection. (Source: Regione del Veneto)

Points on the earth's surface are subjected to projection algorithms that convert latitude and longitude into a Cartesian coordinate pair with metric units, X and Y (also referred to as North and East). Many projected reference systems have adopted "false origins" to avoid negative coordinates.

In Italy, the International Ellipsoid of the Rome 40 system is projected onto the plane using the inverse projection of Mercator or Gauss. The Italian cartography derives from the Gauss conformal with some modifications made by Giovanni Boaga (Figure 11). The two zones have false origins of 1500 km and 2520 km.

3.1.2 Digital Orthophotos AGEA 2015 and 2018

The orthophotos used for the restitution of the coastlines of year 2015 and 2018 are provided by the Veneto Region [16].

The aero photogrammetric image is produced and provided in orthophoto sections, each covering an area of about 30 km^2. The four-band ortho-images are available in RGB color. The image definition is 1Pixel=20 cm.

AGEA provides the Veneto Region with aero-photogrammetric products and in particular high-resolution orthophotos according to a three-year flight plan.

The aerial photos, from which the examined orthophotos were derived, are all taken at central times of the day, an element that ensures a fairly homogeneous assessment of shoreline position [11].

3.2 Veneto Region Coastline of 2012

The *Laboratory of Survey and Geomatics* of the University of Padova provided the coastline restitution related to the orthophotos of year 2012. The tracing of the coastline was done by a student of the University of Padova as part of a bachelor’s civil engineering thesis in the academic year 2014-2015. The software used was ArcGIS.

3.3 QGIS Software

The software implemented in order to manually plot the Veneto Region coastline on the orthophotos of year 2015 and year 2018 is *QGIS version 3.18*.

QGIS is a user friendly Open Source Geographic Information System (GIS) licensed under the GNU General Public License. QGIS is an official project of the Open Source Geospatial Foundation (OSGeo) [17]. It is a geographic information system (GIS) application that supports viewing, editing, printing, and analysis of geospatial data.

The first GIS software emerged in the second half of the 1980s from the integration of other computer programs belonging to four categories [18]:

1. Database Management Systems (DBMS)
2. Systems for processing vector graphic information (CAD: Computer Aided Design)
3. Systems for processing raster maps (image processing)
4. Systems for statistical analysis of alphanumeric data (statistical software).

The power of GIS lies in bringing together the features of these programs and handling various types of data in an increasingly integrated way, as no other software can do.

The software is able to manage different types of geographic information:

1. spatial information (vector and raster)
2. non-spatial information.

ESRI vector formats (shapefiles) are the ones that have most characterized GIS software. The shapefile is a vector data storage format capable of recording location, shape and attributes of spatial entities.

Another important issue when working with QGIS software is the choice of the reference system (Figure 12). In the QGIS context, the reference systems are called CRS (Coordinate Reference System) or SRS (Spatial Reference System) or more simply SR, which can be classified into two basic categories:

1. Geographic (or non-projected) SRs, in which each point on the earth's surface is located based on the angular values of latitude and longitude;

2. Projected SRs, in which the location of each point on the earth's surface is the result of a projection resulting in a two-dimensional Cartesian system in which each point has a coordinate pair X,Y.

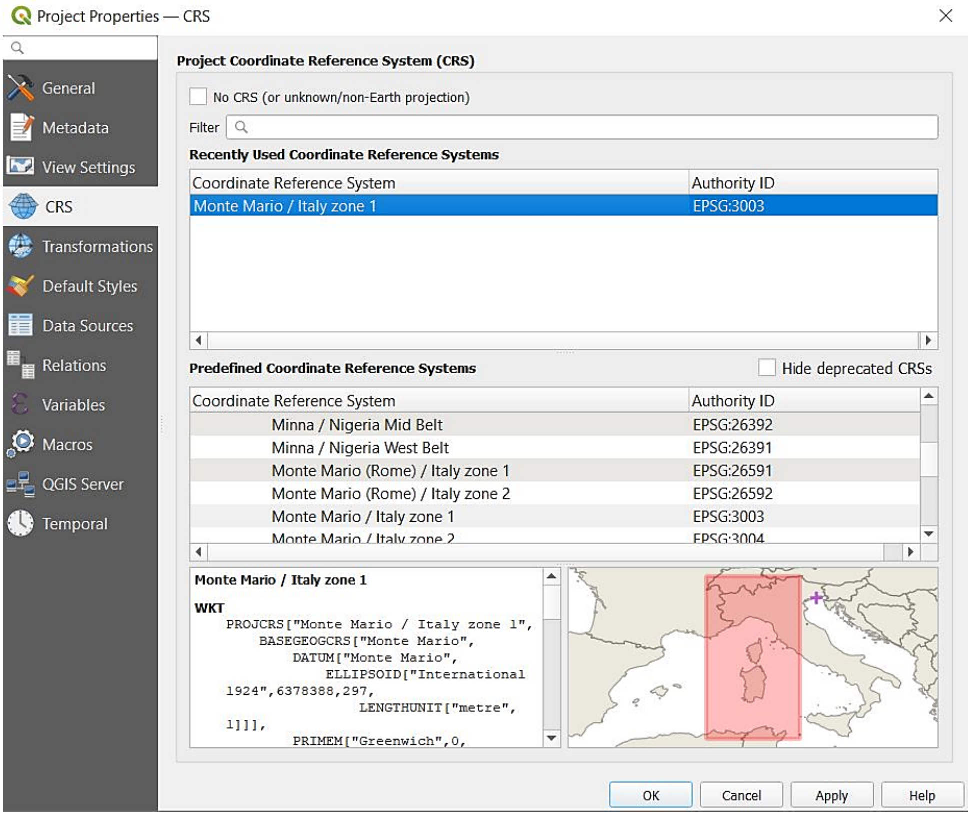

Figure 12 QGIS “Project Properties” window.

Reference systems and their transformation parameters have been codified in registries maintained by global organizations. Of all these registries, the most widely used is the European Petroleum Survey Group (EPSG) registry currently maintained by the Geodetic Committee of the International Association of Oil and Gas Producers (OGP).

EPSG codes are now recognized as the standard for the classification of Reference Systems worldwide.

The reference system used to operate the restitution of the Veneto Region coastline in this thesis is EPSG 3003 (highlighted in red in Figure 13).

DATUM	PROIEZIONE	CODICE EPSG	ALIAS
Roma40	Gauss-Boaga	3003 (fuso Ovest)	Monte Mario / Italy zone 1 (fuso O)
		3004 (fuso Est)	Monte Mario / Italy zone 2 (fuso E)
ED50	UTM	23032 (zona 32 N)	ED50 / UTM zone (32)N
		23033 (zona 33 N)	ED50 / UTM zone (33)N
		23034 (zona 34 N)	ED50 / UTM zone (34)N
WGS84	UTM	32632 (zona 32 N)	WGS84 / UTM zone (32)N
		32633 (zona 33 N)	WGS84 / UTM zone (33)N
		32634 (zona 34 N)	WGS84 / UTM zone (34)N
ETRS89	UTM	25832 (zona 32 N)	ETRS89 / UTM zone (32)N
		25833 (zona 33 N)	ETRS89 / UTM zone (33)N
		25834 (zona 34 N)	ETRS89 / UTM zone (34)N
RDN2008	UTM	6707 (zona 32 N)	RDN2008 / UTM zone (32)N
		6708 (zona 33 N)	RDN2008 / UTM zone (33)N
		6709 (zona 34 N)	RDN2008 / UTM zone (34)N

Figure 13 Most used reference systems in Italy with indication of EPSG codes. (Source: openoikos.com)

3.3.1 Restitution of the Veneto Region coastline of 2015 and 2018 using QGIS software

Regarding the restitution of the coastline on orthophotos, it was chosen to return the land-sea transition line. All returns were performed by the same operator (the thesis' author) under the same conditions.

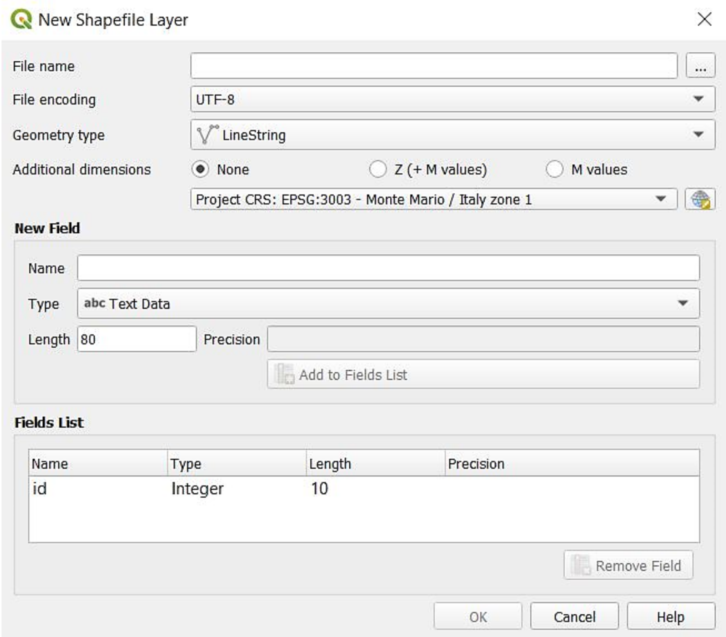

Figure 14 QGIS "New Shaperfile Layer" window.

First, the orthophotos provided by the Veneto Region (.ecw) are inserted in QGIS 3.18. Then the process of tracing the land-sea transition line can start by selecting *New Shapefile Layer* (Figure 14).

An example of restitution of the coastline of Bibione beach (province of Venice) is provided below.

In order to start tracing the coastline, the correct layer must be selected from the Layer Panel, then to edit it we will select *Toggle Editing* > *Add Line Feature* (Figure 15).

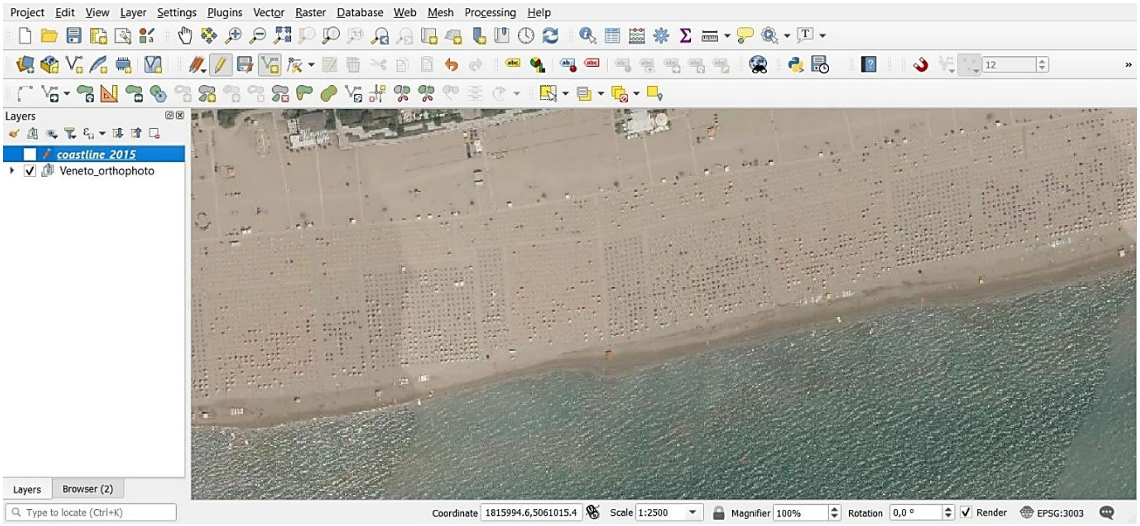

Figure 15 QGIS user interface.

While tracing the land-sea transition line is very important to be coherent and accurate. This means that if we choose to consider as "land" a particular sand color or element, then we must maintain the choice along the whole area of interest.

The restitution process involves the operator placing a series of points along the coastline that are automatically joined to form a line (Figure 16).

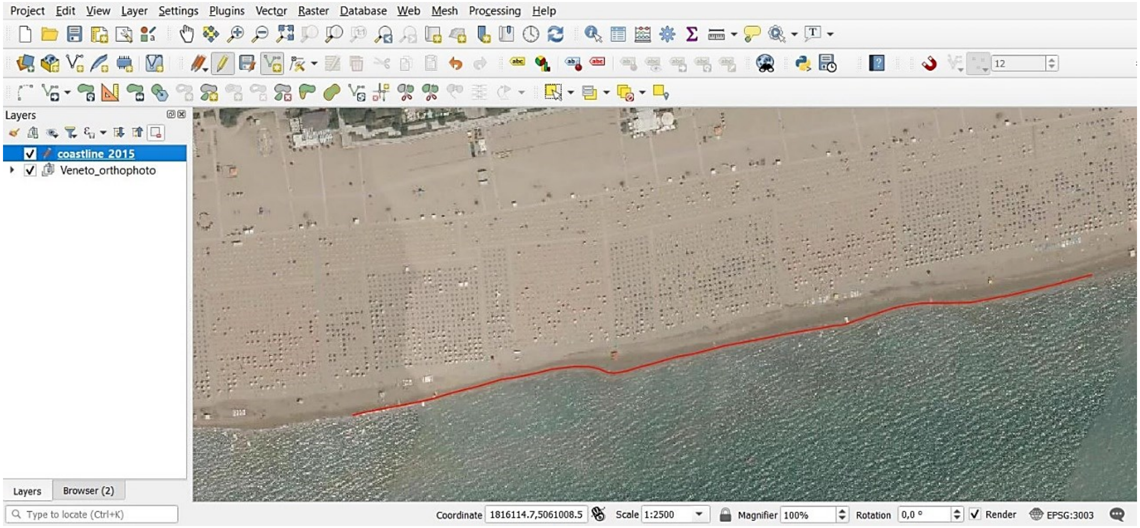

Figure 16 QGIS restitution of coastline.

As mentioned before, the coherence is very important while choosing where to place the points. Some examples are shown below in Figure 17.

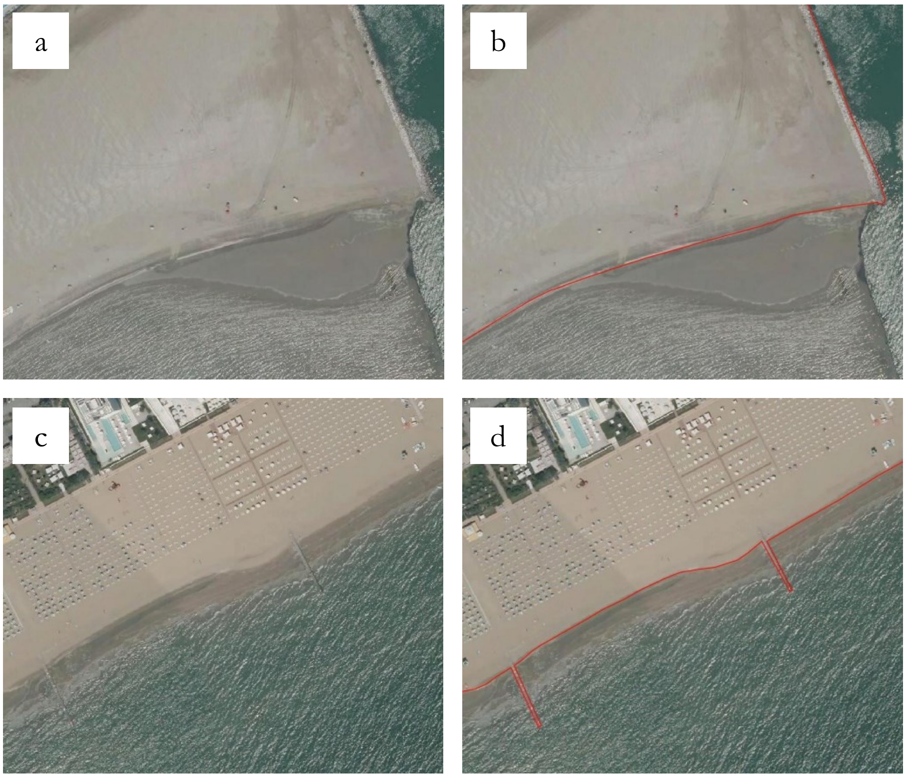

Figure 17 Examples of coastline restitution on 2015 orthophotos.
Figures a, b: Caorle beach (VE). Figures c, d: Jesolo beach (VE).

During the tracing of the transition line, the structures orthogonal and parallel to the shore, as docks and transverse defensive works, were represented as an integral part of the coastline (Figure 18).

Figure 18 Orthogonal structures are considered part of the coastline (Eraclea, VE).

When the transition line is completed, it’s important to save the work. QGIS, for each shape file saved, creates 5 different files which are associated to it:

- .shp: the file that contains the geometry for all features;
- .shx: the file that indexes the geometry;
- .dbf: the file that stores feature attributes in a tabular format;
- .prj: the file that contains information on projection format including the coordinate system and projection information. It is a plain text file describing the projection using well-known text (WKT) format;
- .cpg: the file used to specify the codepage for identifying the character set to be used. These are stored in plain text file format and contains information about the encoding applied for creating the shapefile.

When you work with a shapefile, you must keep all of the key associated file types together.

The same procedure is applied again to plot a new coastline on 2018 digital orthophotos.

3.3.2 Detection of coastal changes using areas with QGIS software

When the restitution of both coastline is completed, the following step is studying the coastal changes between 2012 and 2015 and also between 2015 and 2018.

In order to study the coastal variations, it is possible to analyze the areas of deposit and erosion. To do so, QGIS provides the necessary instruments: *Union*, *Poligonize* and *Clip* processing tools.

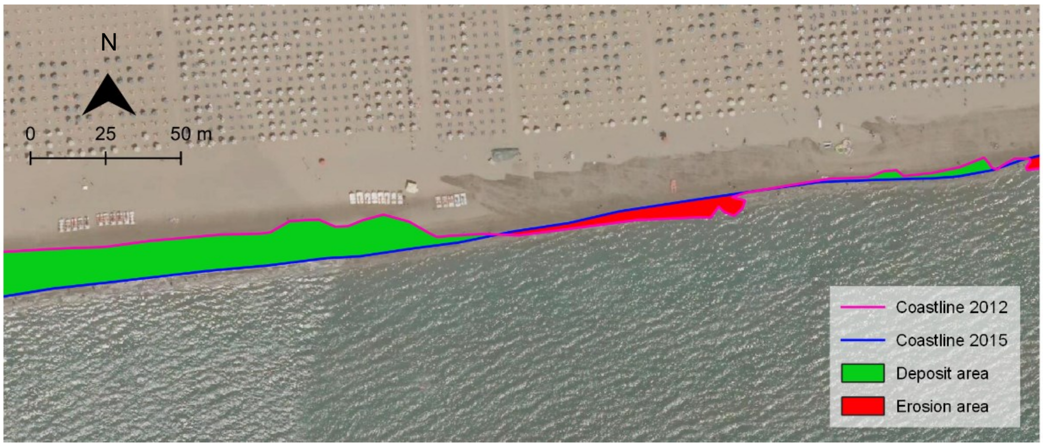

Figure 19 Coastal variations from 2012 to 2015 (Bibione, VE). The orthophoto on the background is taken in 2015.

The result obtained with the software QGIS is shown in Figure 19. Green areas are deposit areas, while the red ones are erosion areas. It's also possible to select one or more than one areas and open the *Attribute Table* or the *Statistical Summary* to see all information about them (Figure 20).

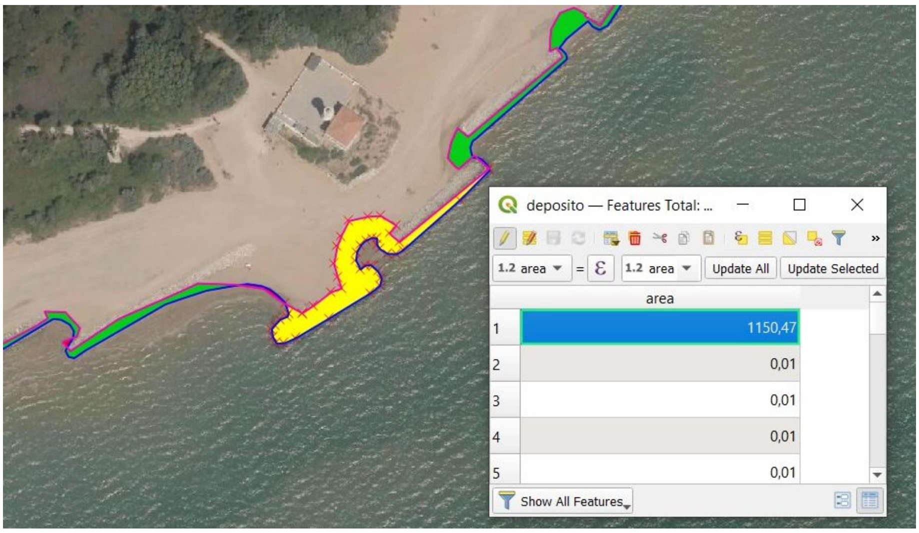

Figure 20 Attribute Table associated with the selected yellow area (deposit area).

3.3.3 Detection of coastal changes using distances with QGIS software

In order to study the coastline variations, the analysis based on the areas is not the only option, we can also use the shortest distance between two coastlines.

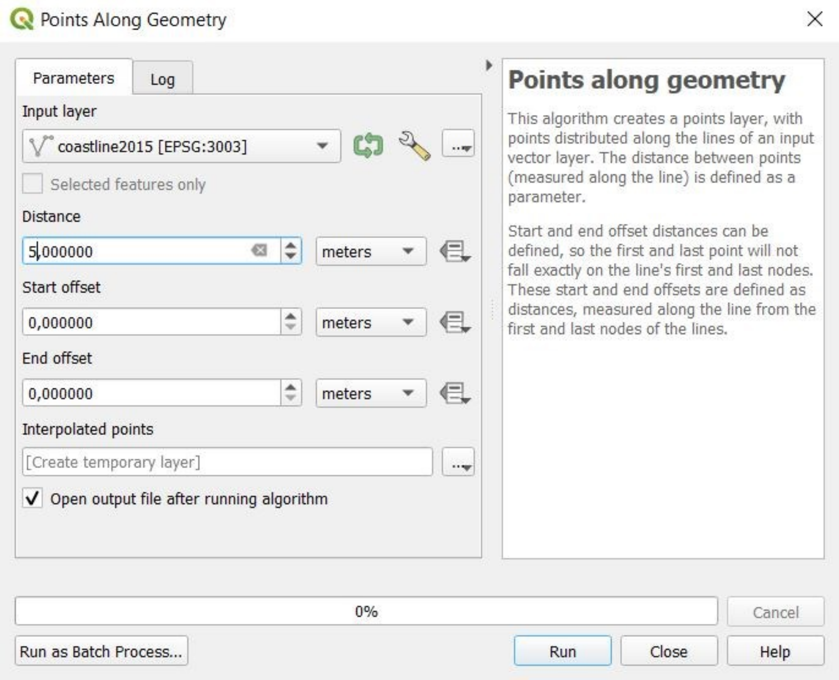

Figure 21 QGIS “Points along geometry” window.

Considering the comparison between 2012 and 2015 coastlines, the procedure starts by placing points on the 2015 coastline, from the menu bar: *Processing > Toolbox > Points along geometry* (Figure 21).

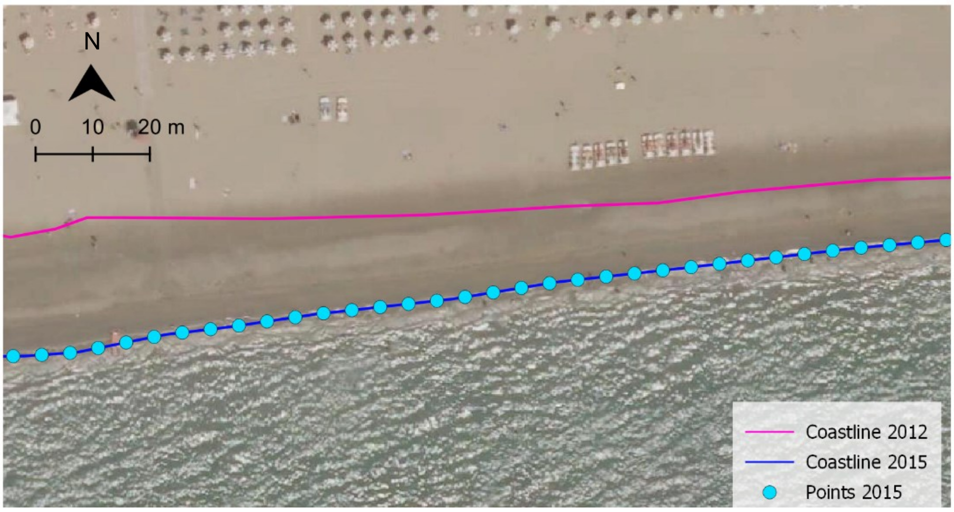

Figure 22 Points placed every 5 m on coastline 2015 (Bibione, VE).
The orthophoto on the background is taken in 2015.

At this point (Figure 22), we are ready to calculate the perpendicular distances between the points we just created and the 2012 coastline. We select the layer just created *Points 2015* and, in its *Attribute table*, we open the *Field calculator*. With the expression shown in Figure 23, QGIS calculates the Linestring for each point reporting the line of minimum distance.

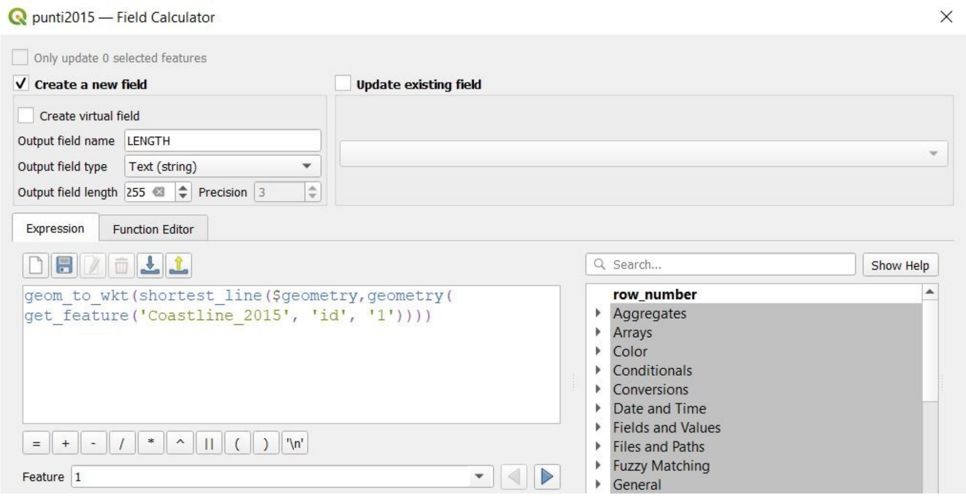

Figure 23 QGIS Field Calculator. Calculation of Length.

But we are interested in the distance value, to do this, from A*ttribute table* we open the F*ield calculator* and create a new field set as shown in Figure 24. We have thus calculated all the perpendicular distances.

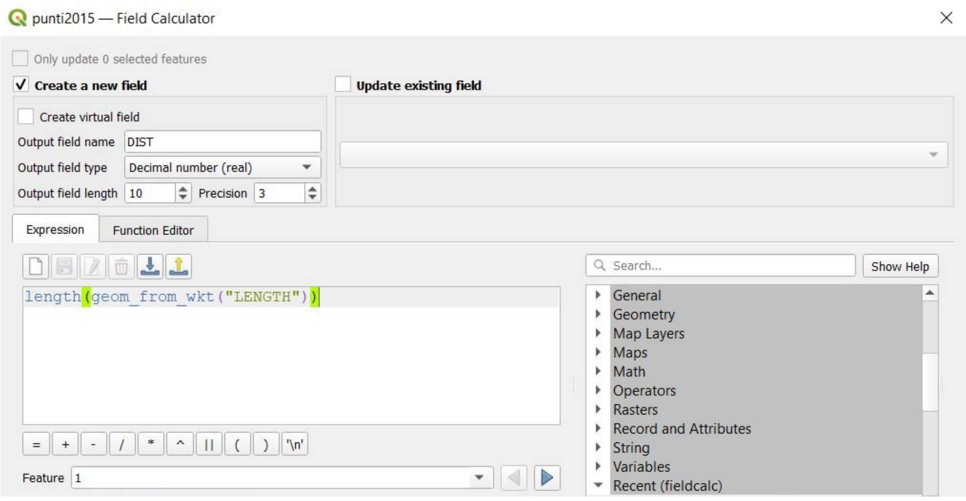

Figure 24 QGIS Field Calculator. Calculation of Distance.

If we want to view the perpendicular distances on screen, we export the point file and save it in delimited text format (.csv). Then we import the file using *Data Source Manager > Delimited Text.* At this point, the perpendicular distances will be visible on QGIS, as shown in Figure 25.

Selecting an area on QGIS is then possible to view the *Statistical Summary* about the distances contained in the selection (mean, maximum and minimum value, etc.).

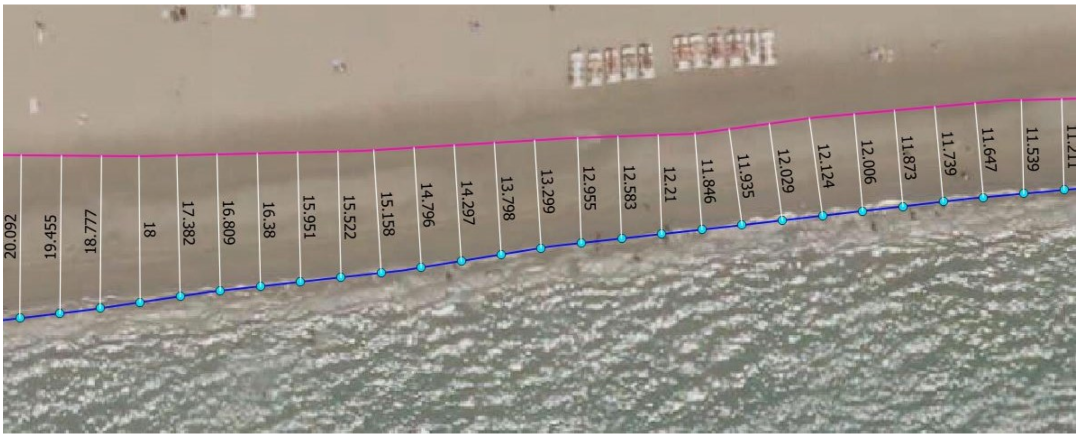

Figure 25 Distances between coastline of 2012 (pink) and 2015 (blue) on QGIS.

The analysis with perpendicular distances is not as good as the one carried out with areas. In fact, the software presents some problems when the two coastlines are not parallel to each other. Below, in Figure 26, two examples are presented.

Figure 26 Left: example of good calculation of perpendicular distances between coastlines (Bibione, VE).
Right: limits of QGIS application for the calculation of perpendicular distances between coastlines (Bibione, VE).

It is also possible to give different colors to the points along the coastline of 2015, in order to better visualize if they fall behind the 2012 coastline (erosion zone) or ahead the 2012 coastline (deposit zone). An example is provided in Figure 27.

Figure 27 Points along 2015 coastline are colored in order to highlight deposit (green) or erosion (red) zones.

4. Results

In this chapter, the overall results obtained from the comparison of the coastlines of years 2012, 2015 and 2018 are presented. The analysis has been performed using QGIS software with the methodologies described in the previous chapter.

The study involves the comparison between the coastline of year 2012 and that of 2015 and then between those of 2015 and 2018. The table below (Table 1) summarizes the results obtained in terms of areas of deposit and erosion in the two time intervals for the province of Venezia and Rovigo.

		2012 - 2015	2015 - 2018
Venezia	Deposit area	1107687 m^2	249913 m^2
	Erosion area	149270 m^2	439226 m^2
Rovigo	Deposit area	737859 m^2	510289 m^2
	Erosion area	669283 m^2	555930 m^2

Table 1 Veneto Region coastline changes.

In this thesis it was decided to subdivide the venetian coastline into 20 morphologically homogeneous cells, following the example given by the report “Studio e monitoraggio per la definizione degli interventi di difesa dei litorali dall’erosione nella Regione Veneto” of 2016 written by the Piero Ruol, Luca Martinelli and Chiara Favaretto in collaboration with the University of Padova.

A morphologically homogeneous cell, or littoral cell, means a stretch of coastline included within morphologically notable, such as river mouths, lagoon inlets, harbor dams, etc. Within it, sediment movements are relatively free and conditioned by the characteristics of individual storm surges.

For the coasts of Veneto, notable morphological elements delimiting littoral cells are identified as follows: mouth of the Tagliamento River, Mouth of Porto Baseleghe, Mouth of Falconera, mouth of the Livenza River, mouth of the Piave River, mouth of the Sile River, Bocca di Lido, Bocca di Malamocco, Bocca di Chioggia, mouth of the Brenta

River, mouth of the Adige River, Bocca di Caleri, Bocca di Porto Levante, mouth of the Po di Maistra, Busa di Tramontana, Busa Dritta, Busa di Scirocco, Busa Storiona, mouth of the Po of Tolle, mouth of the Po di Gnocca, mouth of the Po di Goro. It was determined to number these cells starting from north to south by assigning the abbreviation of the province (VE/RO) to them. Thus, 10 cells were identified in the province of Venice and as many in the province of Rovigo [7].

Cell	Position	Cell	Position
VE1	Tagliamento mouth – Porto Baseleghe	**RO1**	Adige mouth – Bocca di Caleri
VE2	Porto Baseleghe – Falconera mouth	**RO2**	Bocca di Caleri – Bocca di Porto Levante
VE3	Falconera mouth – Livenza mouth	**RO3**	Bocca di Porto Levante – Po di Maistra mouth
VE4	Livenza mouth – Piave mouth	**RO4**	Po di Maistra mouth – Busa di Tramontana
VE5	Piave mouth – Sile mouth	**RO5**	Busa di Tramontana – Busa Dritta
VE6	Sile mouth – Bocca di Lido	**RO6**	Busa Dritta – Busa di Scirocco
VE7	Bocca di Lido – Bocca di Malamocco	**RO7**	Busa di Scirocco – Busa Storiona
VE8	Bocca di Malamocco – Bocca di Chioggia	**RO8**	Busa Storiona – Po di Tolle mouth
VE9	Bocca di Chioggia – Brenta mouth	**RO9**	Po di Tolle mouth – Po di Gnocca mouth
VE10	Brenta mouth – Adige mouth	**RO10**	Po di Gnocca mouth – Po di Goro mouth

Table 2 Veneto Region cells coding.

Table 2 identifies the code for each of the twenty cells and its boundary elements, while Figure 28 shows where the cells are located and gives a first schematic graphic division of the area of interest of each cell.

In the following part of this chapter, all the previously mentioned cells from the province of Venice and those from the province of Rovigo are analyzed, respectively. A brief analysis containing the main general information is presented for each cell, followed by the areas of deposition and erosion and some significant portion of orthophotos showing the changes of coastlines over time.

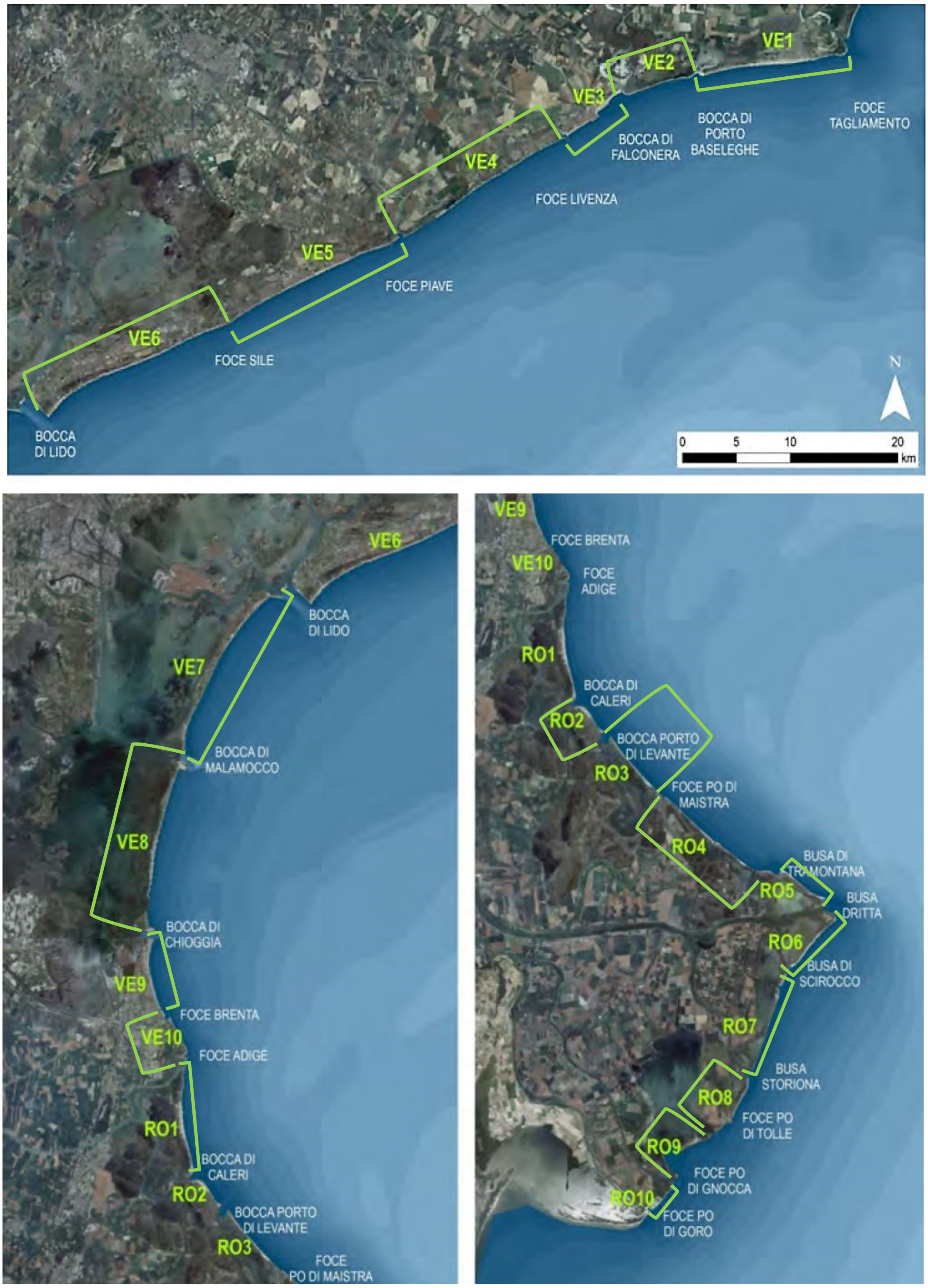

Figure 28 Morphologically homogeneous coastline cells. (Source: P.Ruol et al.)

When comparing multi-temporal orthophotos and the coastlines of years 2012, 2015 and 2018, it is important to consider what may be inaccuracies and errors.

First, the co-registration accuracy of the data. Even if the reference system is the same for both orthophotos, it is possible to observe that edges of building or other easily recognizable points do not match.

There might be another problem, a parameter which can't be controlled: if one of the flights (2012, 2015, 2018) was done at low tide, the coastline the user plots will be shifted towards the sea; if, on the other hand, the flight was done at high tide, the coastline returned will be shifted towards the hinterland. It is understandable that, when comparing the two coastlines, it could results in significant values of deposit or erosion but these values are actually fictitious, since they are due to the different tidal height during the flights.

In addition, errors may be attributable to the sensitivity of the user who drew the line (line tracing error), the accuracy of the orthophoto (pixel size) and the georeferencing of the image in the software.

For the purpose of this thesis, these errors can be accepted since the extent of the area of interest is very large, as previously stated the Veneto coast is 160 km long, and for this thesis it is intended to make a general study of shoreline changes.

VE1 – from Tagliamento mouth to Porto Baseleghe

The coastline between the mouth of the Tagliamento River and the mouth of Baseleghe harbor (Figure 29) extends for a length of about 10 km and belongs to the municipal territory of San Michele al Tagliamento, Bibione (VE).

2012 - 2015

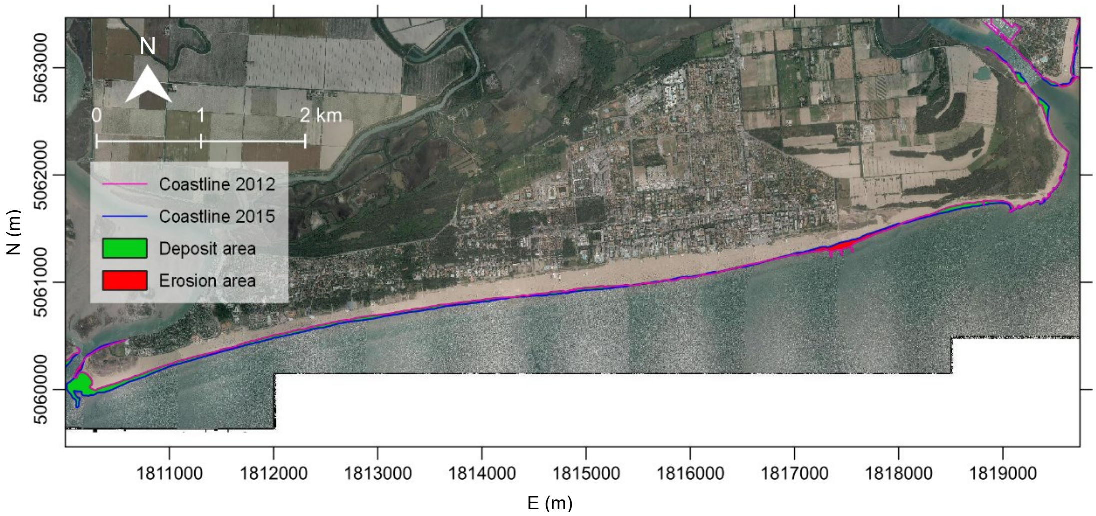

Figure 29 Cell VE1, 2015 orthophoto.

Erosion area = 40408 m^2

Deposit area = 211587 m^2

The northern part of the mouth of Tagliamento River (Lignano, UD) shows mainly deposit phenomenon. The medium value of the rate of deposit is +5.3 m/yr and for some areas it was more than +11.3 m/yr (Figure 30).

In the first stretch of coastline on the right at the Mouth of the Tagliamento River (Figure 31), some discontinuous adhesion barriers were first constructed (in the late 1990s). Today the mouth appears to be completely fenced by rigid works in adherence, carried out in the years 2008 – 2010. It is possible to observed that the first stretch of shoreline in front to the lighthouse, defended with barriers parallel to the shore, has undergone a heavy accumulation of sands.

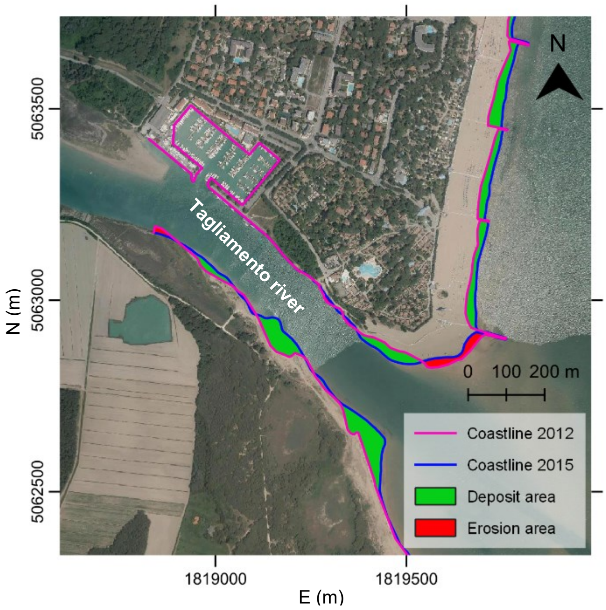

Figure 30 Tagliamento mouth, 2015 orthophoto.

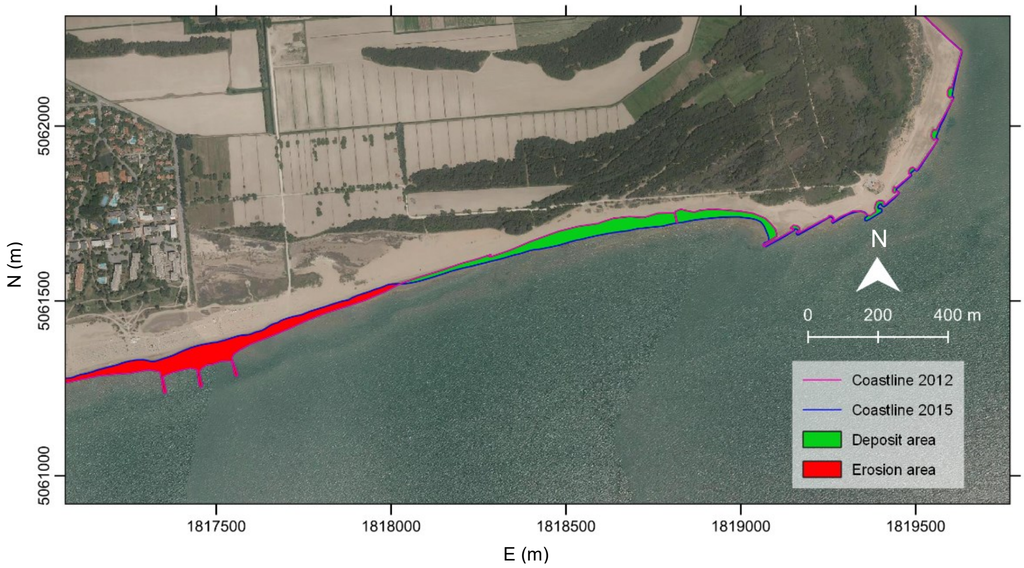

Figure 31 Bibione lighthouse, 2015 orthophoto.

The orientation of the coast between Bibione and Porto Baseleghe (Figure 32), gradually less inclined from west to east, means that this stretch of coastline is increasingly balanced, being fed by the sands delivered to the sea by the Tagliamento River, by those from the erosion of the delta and from the migration of fill sands. Getting close to Porto Baseleghe, the prevailing trend is accretion. Medium distance between the two coastlines is +17.42 m.

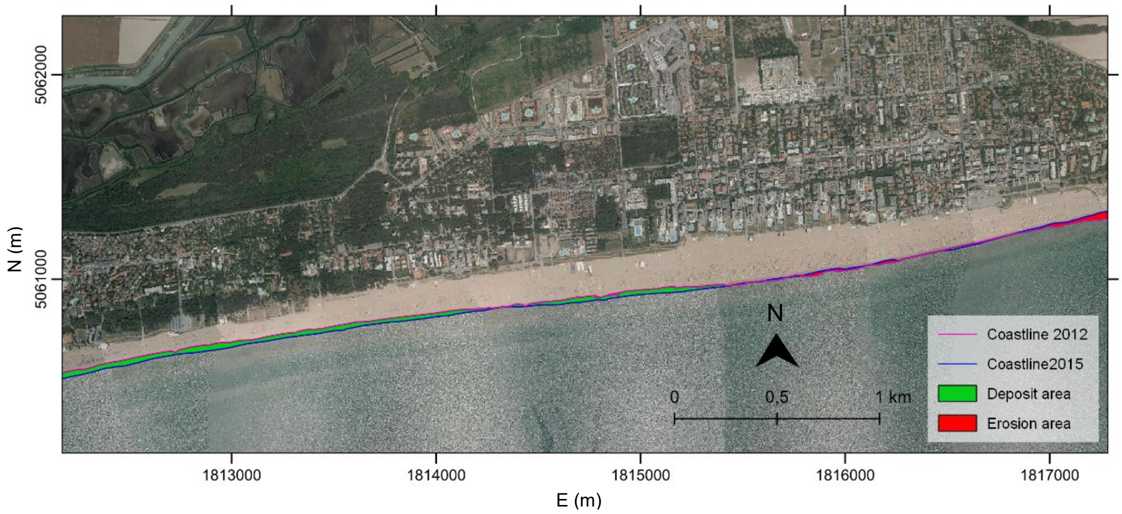

Figure 32 Bibione, 2015 orthophoto.

Considering the Bocca of Porto Baseleghe, the longest distance between the 2012 and 2015 coastlines amounts of +140 m (Figure 33).

Figure 33 Porto Baseleghe, 2015 orthophoto.

In the years 2006-2007, an experimental work called "sand trap" was carried out to intercept the sands before they deposited in the Port of Baseleghe. The sands intercepted by this work, made of overflowing metal sheet piles (long approximately 100 m with head at an elevation of -2.0 m), are periodically brought back upstream (in terms of solid transport littoral, that is, toward Bibione).

2015 - 2018

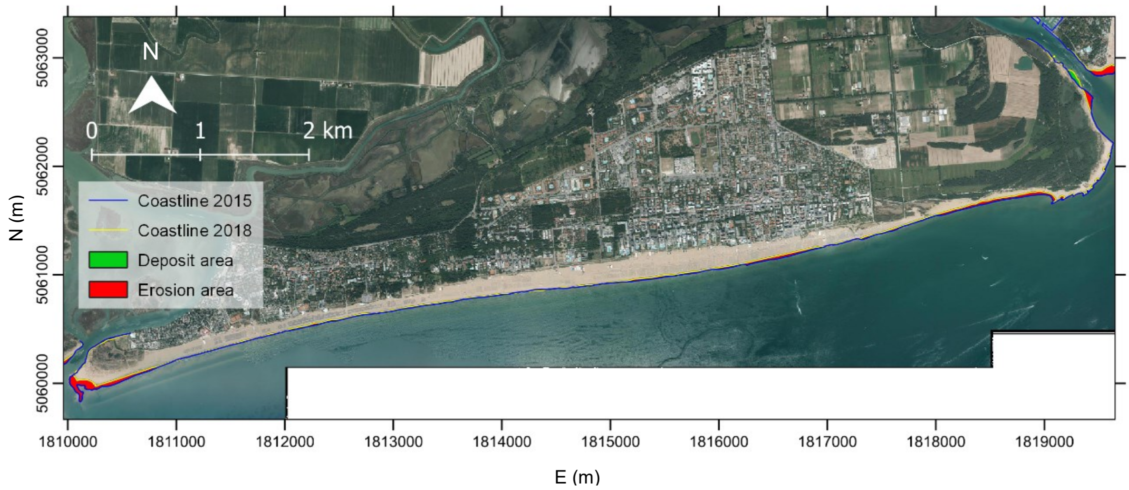

Figure 34 Cell VE1, 2018 orthophoto.

Erosion area = 142078 m^2

Deposit area = 8600 m^2

The trend changes respect to years 2012-2015 (Figure 34). Showing a medium rate of erosion of -1.5 m/yr but with picks of -24 m/yr.

The first stretch of coastline on the right at the Mouth of the Tagliamento River (Figure 35) manifests a significant tendency to retreat, reflecting the fact that the fluvial solid input is insufficient to maintain the current configuration of the river delta.

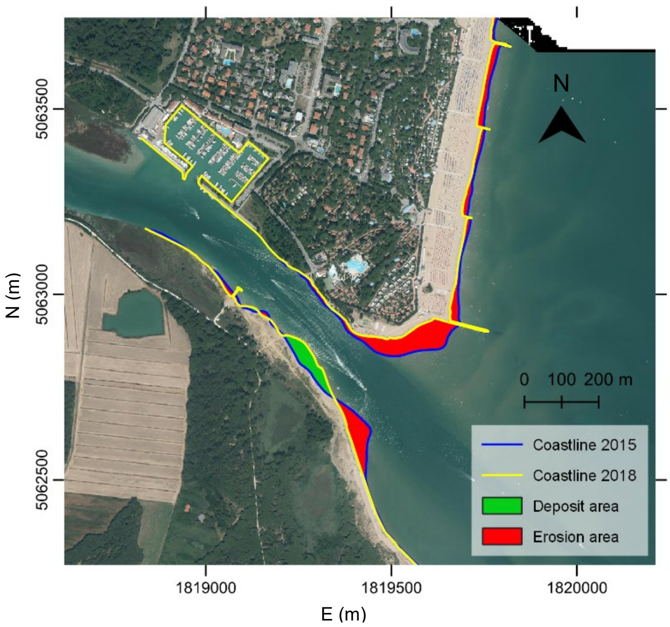

Figure 35 Tagliamento mouth, 2018 orthophoto.

Erosion prevails also going South toward Bibione and Porto Baseleghe. With a maximum retreating distance of -29 m. Medium distance value is -10.79 m. The coast located on the mouth of Canale dei Lovi (Figure 37) shows a completely different behavior respect to the previous years 2012-2015. Same thing happened in proximity of the Bibione lighthouse (Figure 36). Periodic artificial beach nourishment is carried out in the area.

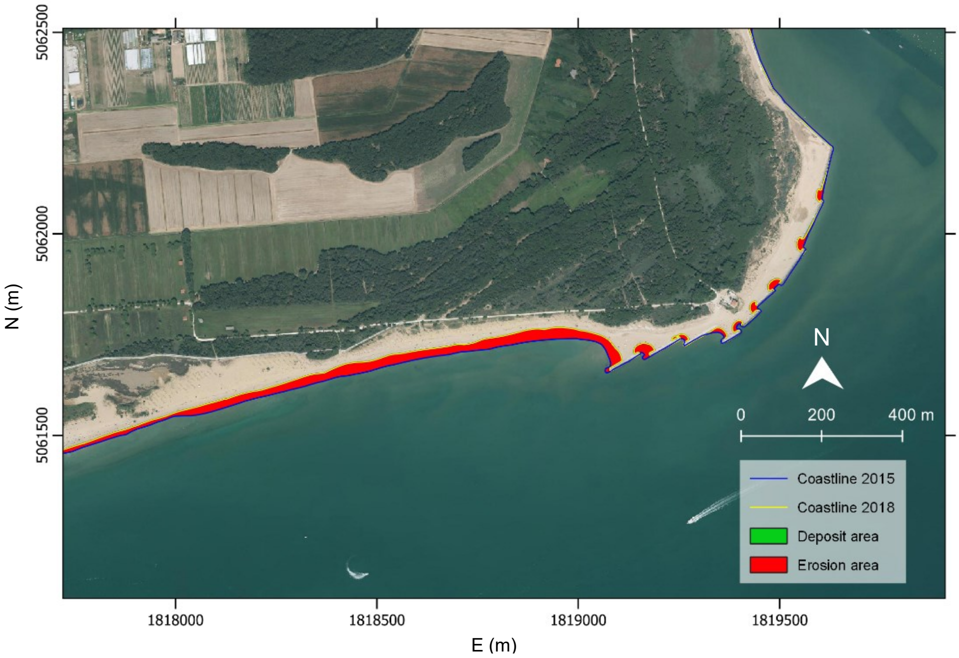

Figure 36 Bibione lighthouse, 2018 orthophoto.

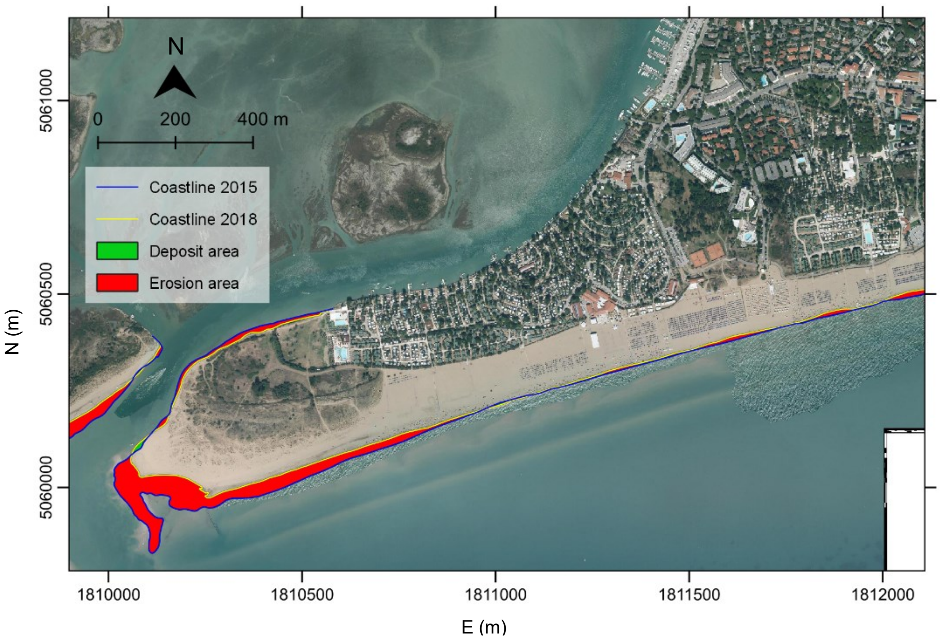

Figure 37 Porto Baseleghe, 2018 orthophoto.

VE2 – from Porto Baseleghe to Falconera mouth

The coast under consideration extends for about 5.5 km and is included in the territory of the municipality of Caorle (VE).

The lagoon of Caorle and Bibione represents the remnant of the large flood expansion basin of the rivers Livenza to the south and Tagliamento to the north and has been the subject of various reclamation interventions protracted from the early years of the century until the 1960s; as a result of these interventions, the current configuration of the lagoon area presents some closed valleys (Valle Zignago, Valle Perera, Valle Franchetti, Valle Nuova and Valle Grande, for a total extension of more than 40 km2), alternating with areas of ancient or recent reclamation for agricultural use, bordered by an extensive network of streams. The direction of solid transport is from NE to SW.

2012 - 2015

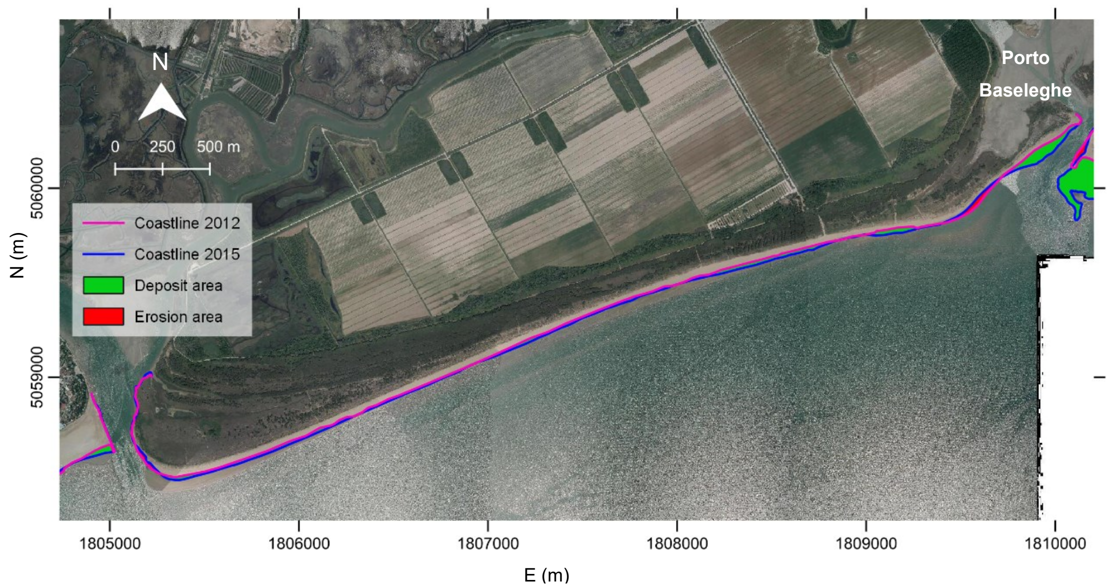

Figure 38 Cell VE2, 2015 orthophoto.

Erosion area = 8681 m^2

Deposit area = 64858 m^2

For the middle section, the sediment balance showed a longitudinal transport from cell VE1. By analyzing the evolution of the shoreline, it is possible to see that this area is substantially accretion, in fact in Figure 38 the pink line is mainly located behind the blue one.

2015 - 2018

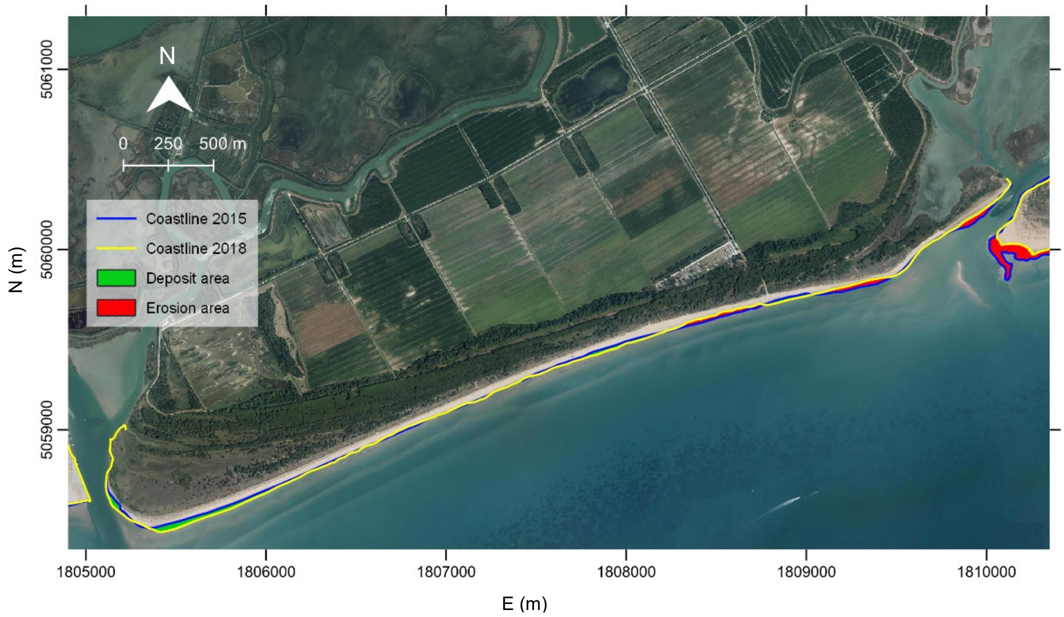

Figure 39 Cell VE2, 2018 orthophoto.

Erosion area = 28248 m^2

Deposit area = 37126 m^2

Unlike previous years, the first stretch of coastline to the right at the mouth of Porto Baseleghe (Figure 39) manifests an erosive tendency of the shoreline.

VE3 – from Falconera mouth to Livenza mouth

The shoreline under consideration extends for a length of about 5 km from the mouth of Falconera to the mouth of the Livenza River and like the previous one is part of the municipal territory of Caorle (VE).

2012 - 2015

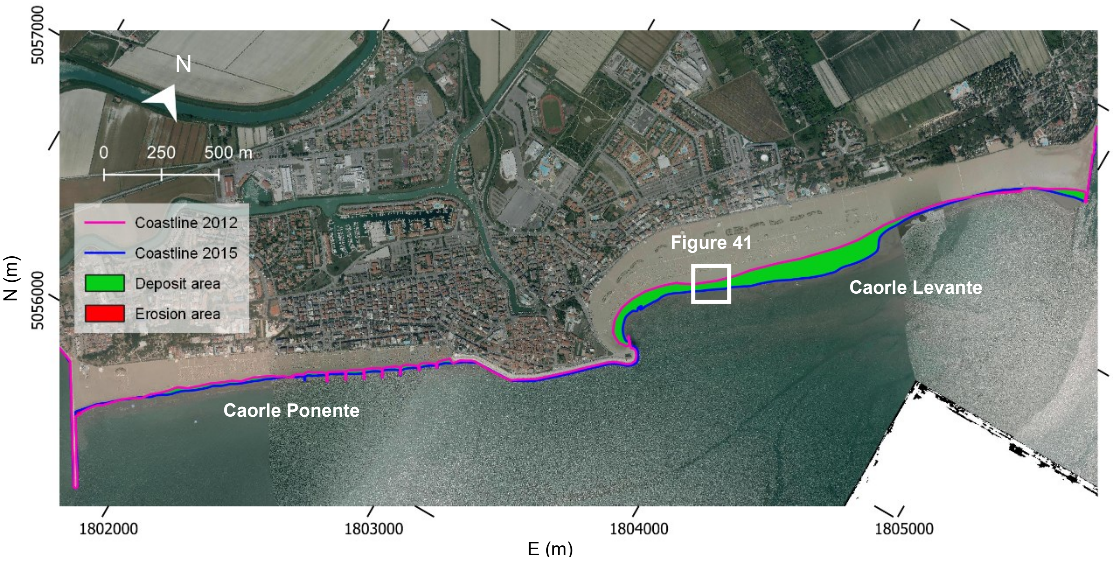

Figure 40 Cell VE3, 2015 orthophoto.

Erosion area = 3440 m^2

Deposit area = 113297 m^2

The first stretch of coastline (between Porto Falconera and the Levante beach of Caorle) has a very different orientation from the adjacent (both with respect to those further north and further south) and appears much more "vertical," the orthogonal to the shoreline is in fact oriented at 140°N and this direction almost coincides with the direction of origin of the Sirocco swells that, evidently, condition the solid sediment transport in this part of the Upper Adriatic. Consequently, the transport solid along shore that manages to cross the cusp of Madonna dell'Angelo to the south is very small. For this reason there is a constant deposition of sands, coming from the north, which remain confined here (Figure 40).

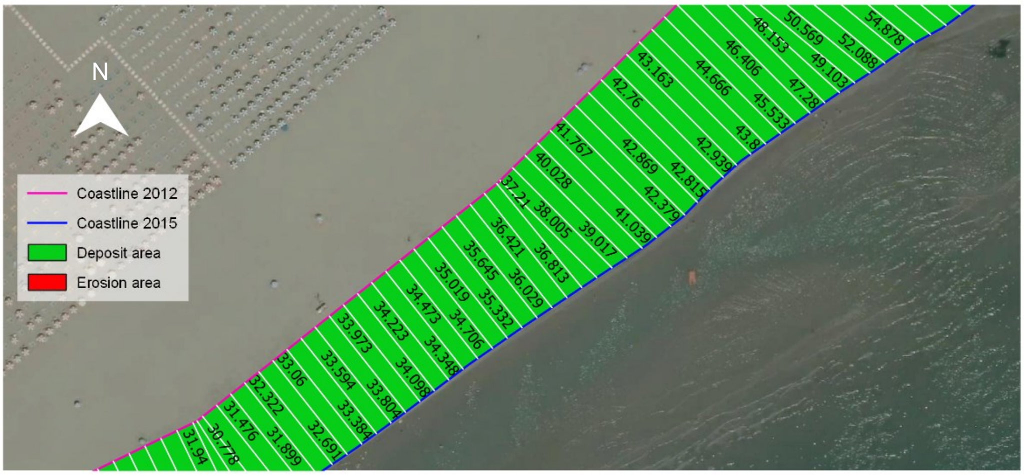

Figure 41 Caorle Levante with indication of perpendicular distances between coastlines , 2015 orthophoto.

Caorle-Levante (Figure 41) shows a medium accretion distance of +37.63 m.

About the Ponente side, the small dock seem to work well, since the average accretion distance between 2012 and 2015 coastlines is much smaller (+9 m).

2015 - 2018

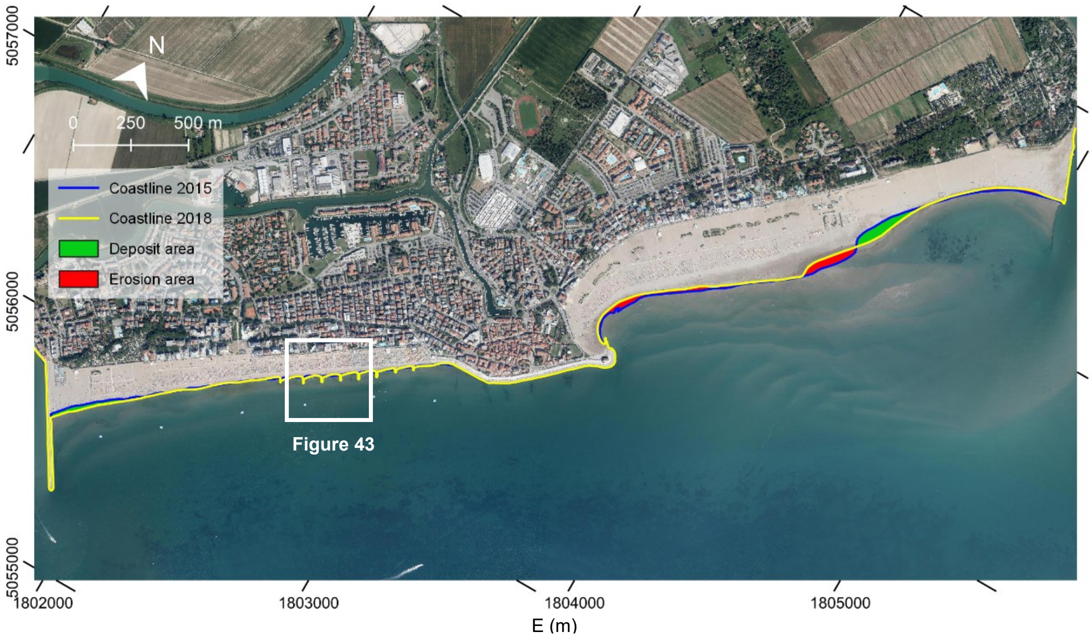

Figure 42 Cell VE3, 2018 orthophoto.

Erosion area = 26100 m^2

Deposit area = 18513 m^2

The Caorle-Levante beach consists mainly of very fine-grained sediments, with silty fractions that cause drainage difficulties and sometimes, during heavy rainfall, the formation of puddles. In this stretch the emerged beach is very wide.

In the Caorle-Ponente area, the deposit phenomenon is not as strong as in the years before. In the Figure 43, it is possible to see the recurring trend along the indentations between the docks. The northern part shows erosion, while the southern part accretion. This is probably due to the sea currents.

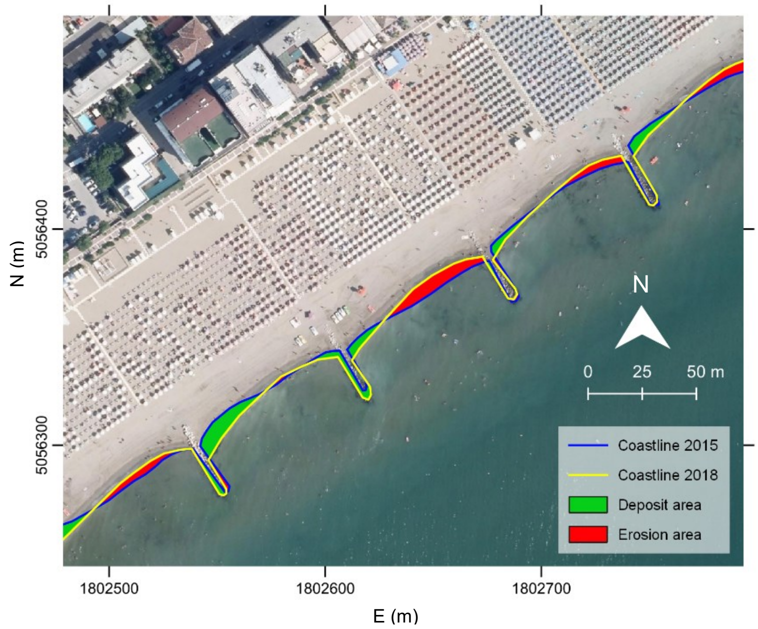

Figure 43 Caorle Ponente, 2018 orthophoto.

VE4 – from Livenza mouth to Piave mouth

The coastline under consideration extends for a length of about 12 km from the mouth of the Livenza River to the mouth of the Piave River; the territory is administratively divided by the mouth of the Laguna del Mort between the municipalities of Jesolo and Eraclea while to the northeast the territory of Duna Verde, Valle Altanea and Porto S. Margherita is under the jurisdiction of the municipality of Caorle.

2012 - 2015

Erosion area = 13179 m^2

Deposit area = 105623 m^2

The cell is characterized by the continuous presence of defense works (Figure 44): along the entire cell there is a diaphragm made of reinforced concrete, associated with groins of different types, sizes and spacing. In a large part of the cell there is also a reinforced concrete slab rampart equipped with a summit parapet wall; in particular, the rampart is present from the Livenza to Duna Verde and from Eraclea to Piave.

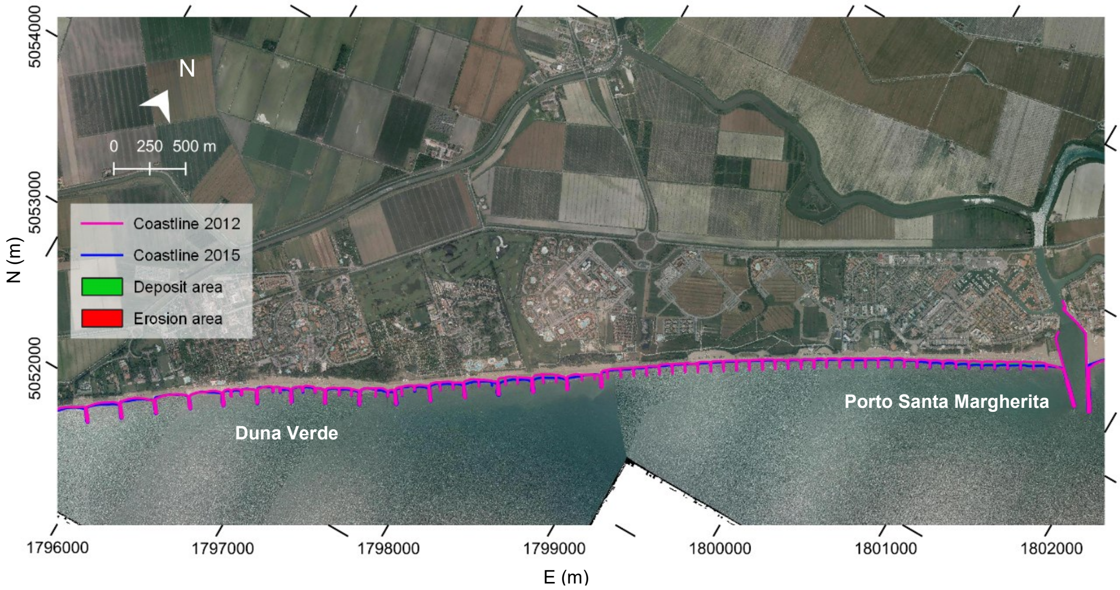

Figure 44 Northern portion of cell VE4, 2015 orthophoto.

The stretch of shoreline in front of Porto Santa Margherita (Figure 45) is characterized by the presence of stone groins, about 50 m long, some of them bypassed or submerged by wave action. The entire stretch of coastline from Lido Altanea to the "Laguna del Mort" was instead the subject of a major intervention of coastal protection that included:

the extension of every 3rd groin, the hauling of the 2 intermediate groins, simultaneous with the pouring of significant volumes of sand for artificial beach nourishment. In this area, the maximum distance between the two coastlines is +27 m.

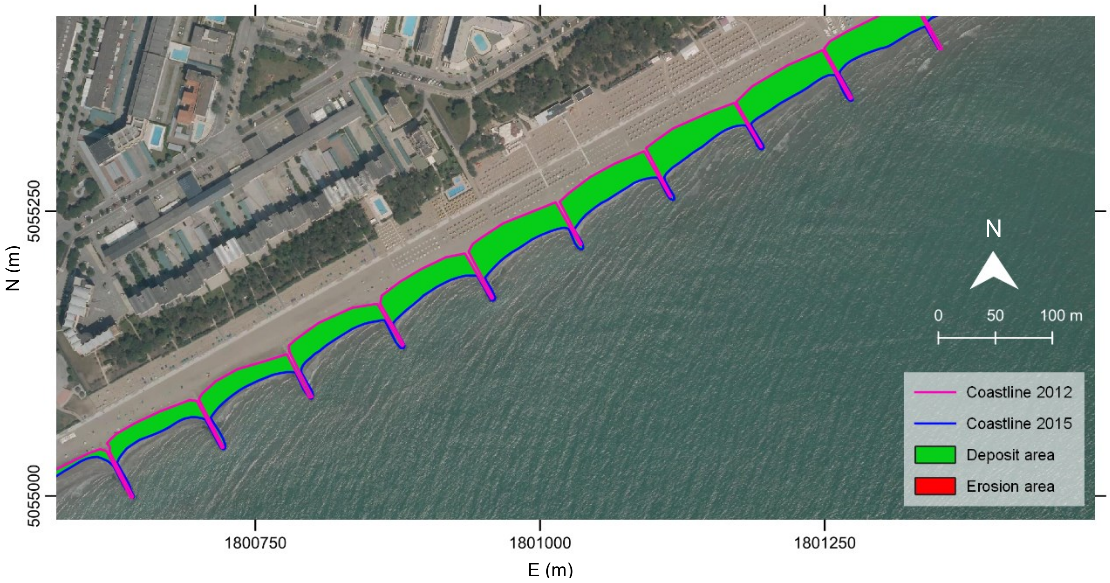

Figure 45 Porto Santa Margherita, 2015 orthophoto.

The same behavior is found in the Laguna del Mort area (Figure 46) where the accretion of the coast between the docks reaches values of +39 m.

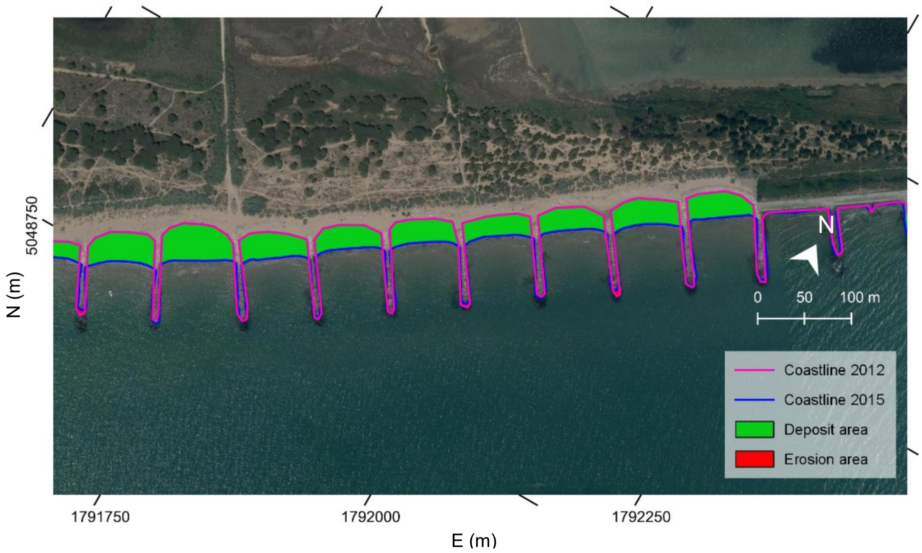

Figure 46 Laguna del Mort, 2015 orthophoto.

2015 - 2018

Erosion area = 52816 m^2

Deposit area = 35654 m^2

The stretch of beach in front of Porto Santa Margherita (Figure 47) and Duna Verde are in a clear condition of erosion, reflecting the fact that solid inputs coming from upstream (mainly from the Tagliamento River) have been reduced for a long time. If front of Duna Verde, in addition to the groins orthogonal to the shore, there is also a diaphragm wall that prevents the retreat of the shoreline.

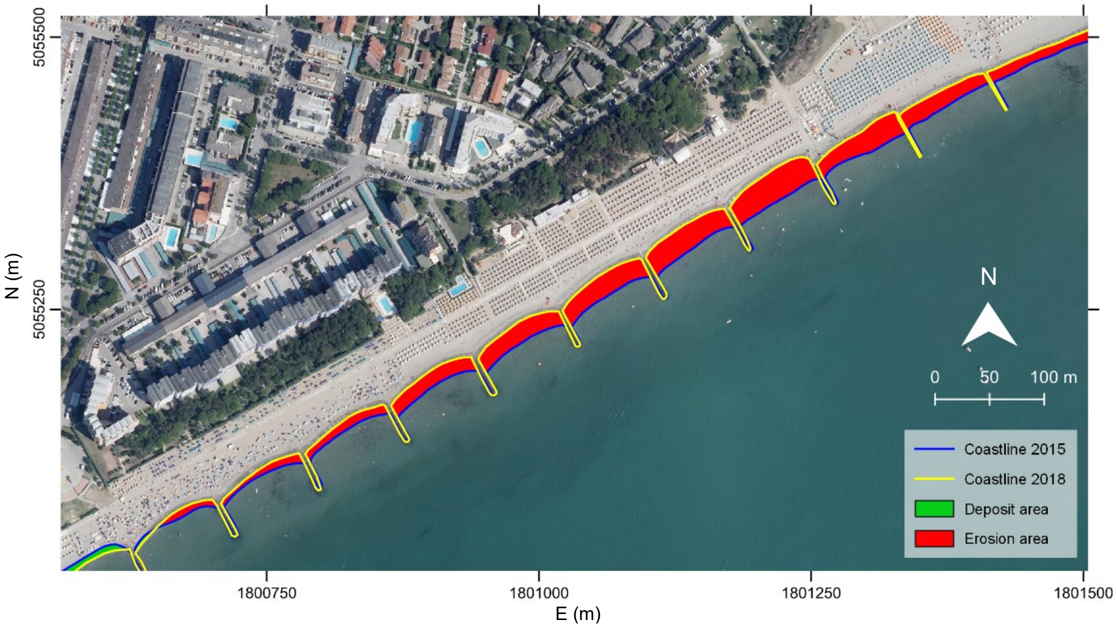

Figure 47 Porto Santa Margherita, 2018 orthophoto.

The Piave River, from the point of view of river solid transport, still delivers modest volumes of sand to the sea. Every year in the mouth about 40000 m^3 of sediment is dredged, a useful resource for beach nourishment in the surrounding areas.

VE5 – from Piave mouth to Sile mouth

The coastline under consideration, which is indisputably one of those with the greatest tourist/balneal vocation, extends for about 13 km, from the mouth of the Piave river to the mouth of the Sile river.

2012 - 2015

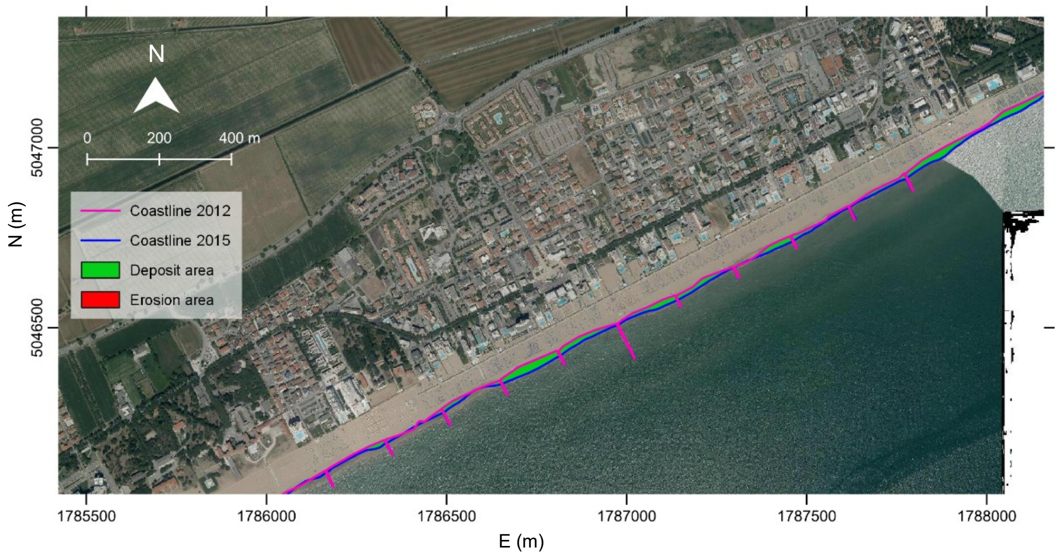

Figure 48 Cell VE5, 2015 orthophoto.

Erosion area = 10048 m^2

Deposit area = 144762 m^2

In the stretch in front of Jesolo (Figure 48), there are groins on piles that intercept only a small part of the high longitudinal transport. This area does not present serious erosive phenomena but needs however, maintenance to stabilize the shoreline following exceptional storm surges. The current management, based on periodic beach nourishments, seems entirely appropriate.

Given the high longitudinal transport, the most suitable erosion defense technique is the combination of beach nourishment and groins, possibly of the filtering type.

2015 - 2018

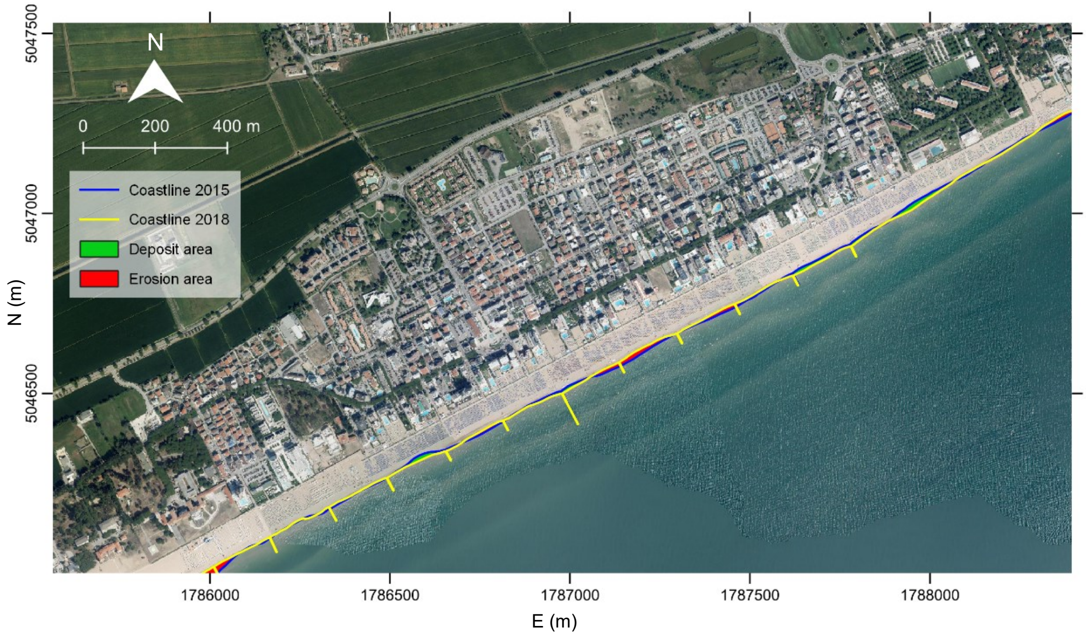

Figure 49 Cell VE5, 2018 orthophoto.

Erosion area = 38816 m^2

Deposit area = 32623 m^2

The situation looks stable (Figure 49). The defensive works present in this stretch of coast are:

- Mouth rebar at the Piave mouth
- Permeable groins
- Groins built on concrete piles

VE6 – from Sile mouth to Bocca di Lido

The Cavallino coastline, which stretches 13.5 km from the mouth of the Sile River to the northern breakwater of the Lido harbor, limits to the sea the northeastern portion of the Venice lagoon basin. The orthogonal to the shoreline has an orientation of about 150°N.

This part of the coastline is part of the municipality of Cavallino-Treporti, a seaside location with numerous presences during the summer season. There are villages and campsites along the coast, while the part of the municipality further inland is devoted to intensive agriculture.

2012 - 2015

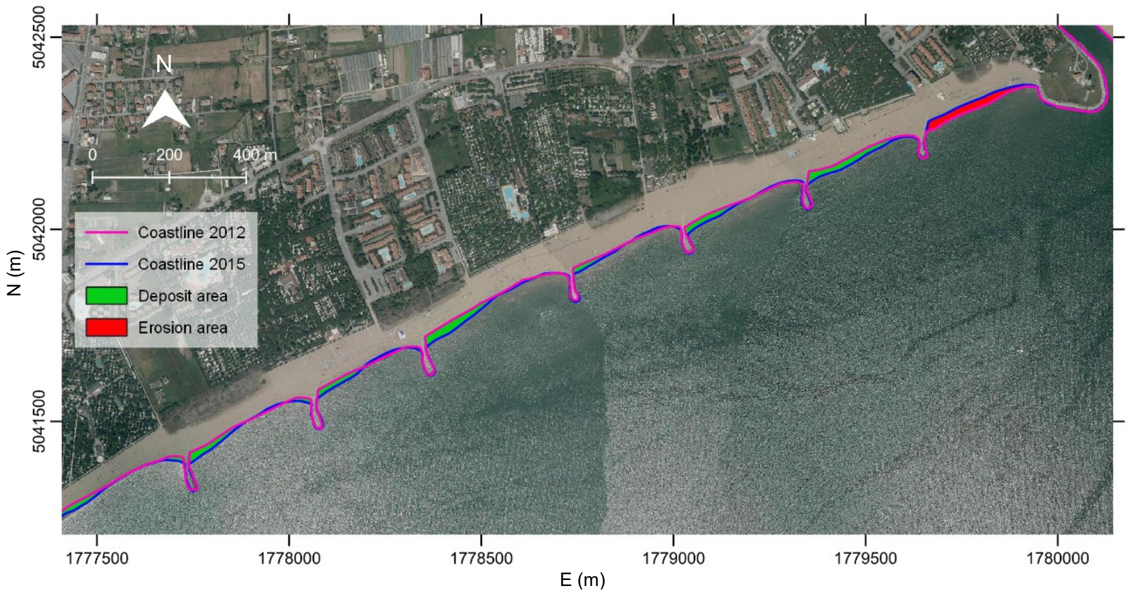

Figure 50 Cavallino beach, 2015 orthophoto.

Erosion area = 35386 m^2

Deposit area = 103589 m^2

From the recent evolution of the shoreline, it can be observed (for example in Figures 50 and 51, Cavallino coast) that after the major intervention completed in the late 1990s, the shoreline appears to be stable thanks in part to periodic maintenance nourishment.

2015 - 2018

Figure 51 Cavallino beach, 2018 orthophoto.

Erosion area = 50396 m^2

Deposit area = 45268 m^2

The shoreline in front of Punta Sabbioni (Figure 52) is characterized by an advancement, due to the presence of the armor North of the Lido harbor, which has blocked the solid transport directed toward the Venice Lido for decades.

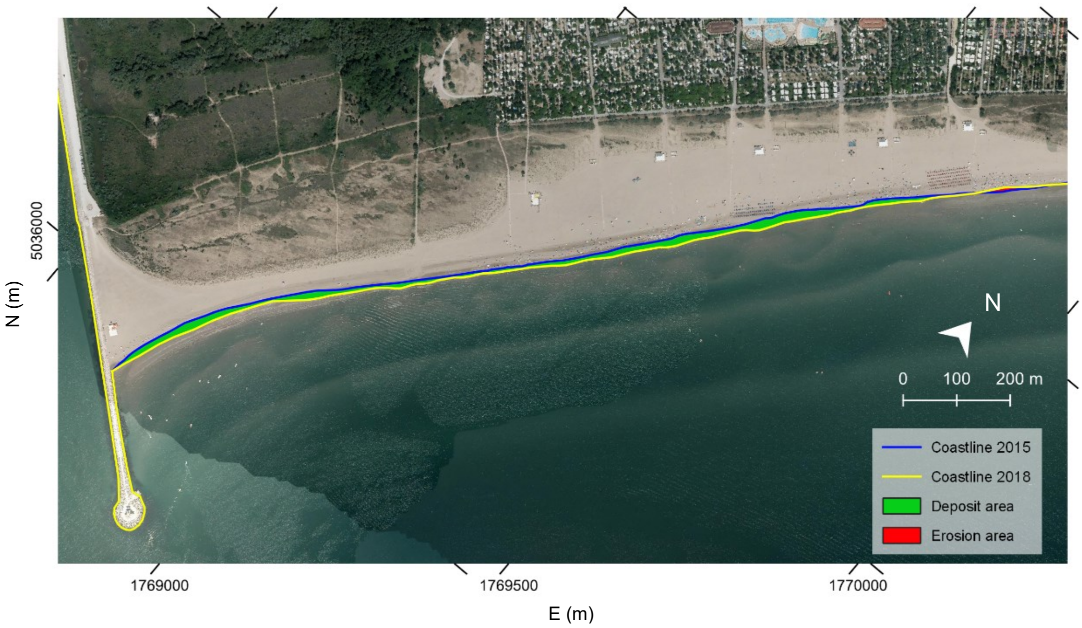

Figure 52 Punta Sabbioni, 2018 orthophoto.

VE7 – from Bocca di Lido to Bocca di Malamocco

The coastal stretch of the Venice Lido has a predominantly tourist and cultural vocation.

It presents an alternation of types of works and environments. The central area is highly anthropized and the beaches are equipped for bathing; the Lido also hosts the "Venice Film Festival" since 1932, which attracts numerous visitors to this island.

The Venice Lido shoreline, following the construction of the jetties in the Bocca di Lido to the north and Malamocco to the south, presents itself as an isolated physiographic unit, in that it receives very little nourishment from littoral solid transport from the North and from the South.

2012 - 2015

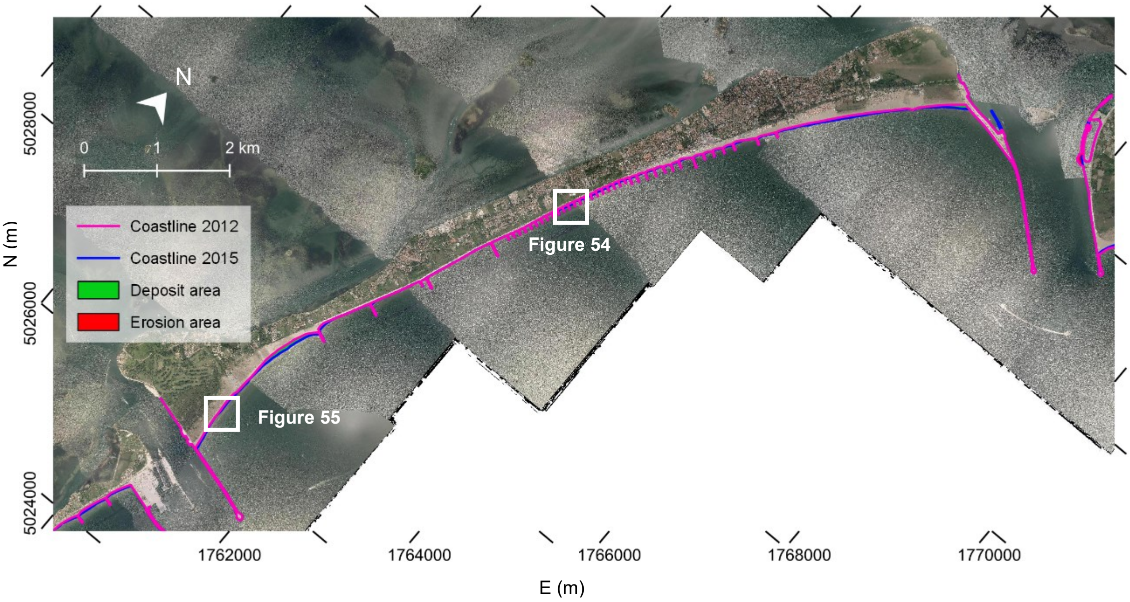

Figure 53 Cell VE7, 2015 orthophoto.

Erosion area = 9840 m^2

Deposit area = 164827 m^2

The stretch north of the Lido has a tendency to accumulate, and there are no coastal defenses except for a few short cordons of dunes. Accretion of the coast reaching values of +56 m in the southern part of the cell (Figure 55).

In the central section of the Lido(Figure 54), the sea defenses first consist of groins about 100 m long, then the "murazzi" and a submerged reef in front of the murazzi themselves and, in the area near the Marconi promenade, some small beaches contained laterally by the groins.

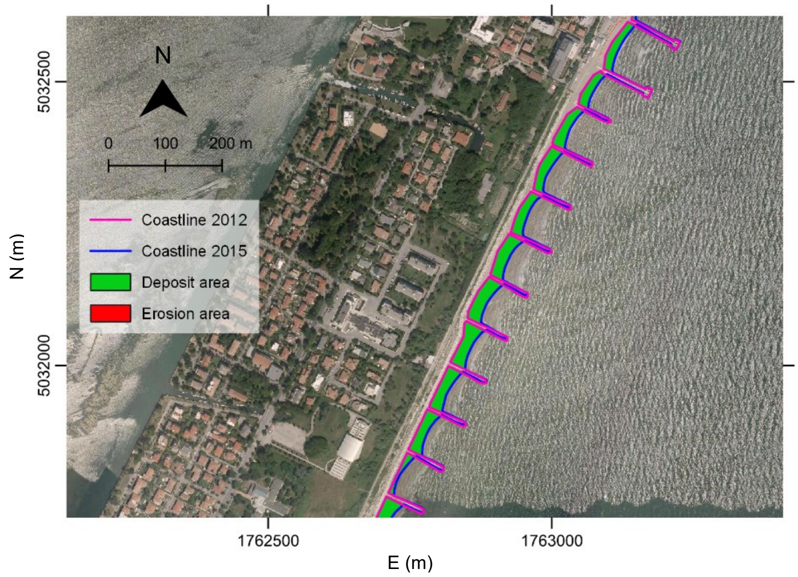

Figure 54 Central part of cell VE7, 2015 orthophoto.

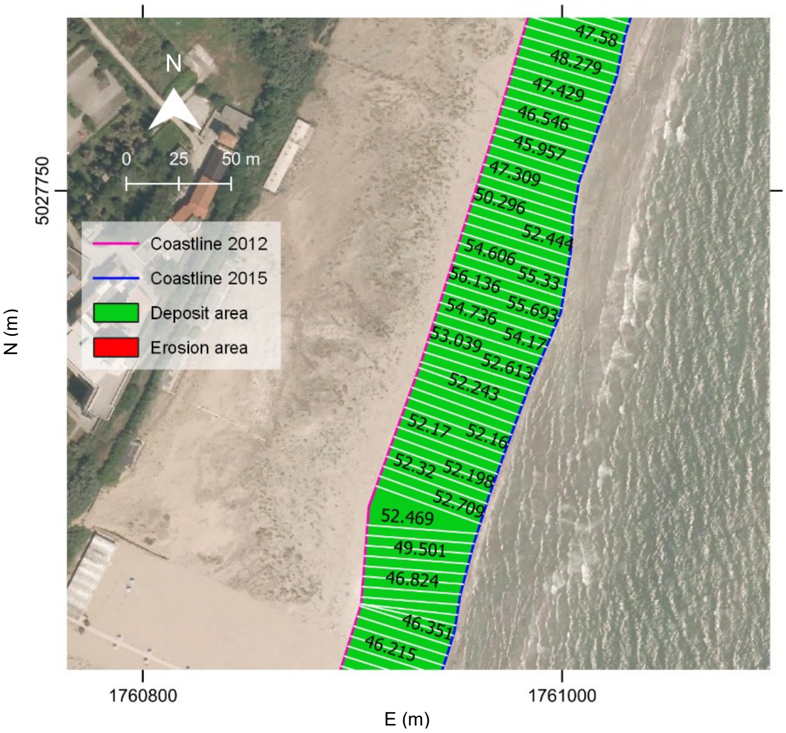

Figure 55 Southern end of cell VE7 with indication of perpendicular distances between coastlines , 2015 orthophoto.

2015 - 2018

Erosion area = 32976 m^2

Deposit area = 28619 m^2

From the point of view of sediment balance, this cell turns out to be completely isolated. There is in fact no feeding from neighboring areas, given the presence of the two long armor piers of the lagoon inlets that border the island. In fact, the volume of sediment transported by the currents is intercepted by the piers, causing erosive phenomena that are mainly concentrated in the central section of the Lido (Figure 56).

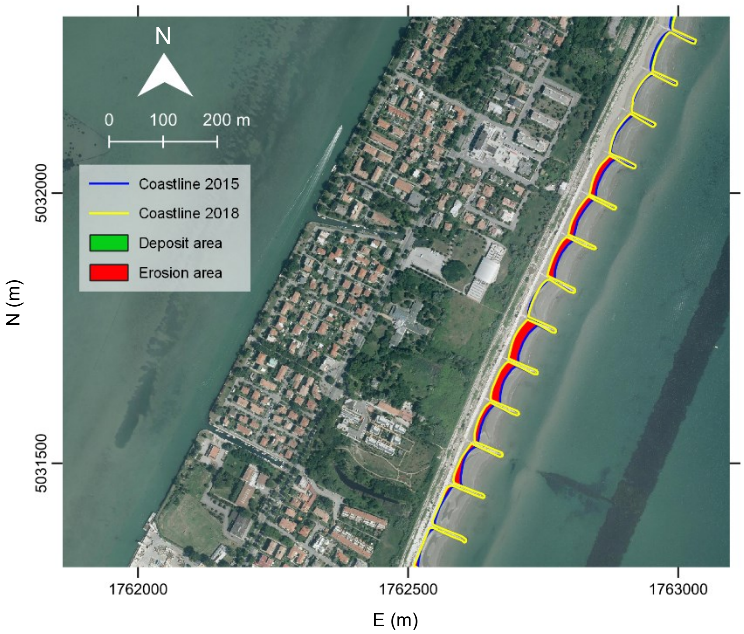

Figure 56 Central part of cell VE7, 2018 orthophoto.

Only near the two piers, namely in the area of San Nicolò and Alberoni, sediment accumulations have been created, allowing a widening of the beaches.

VE8 – from Bocca di Malamocco to Bocca di Chioggia

Similar to the Venice Lido, the island of Pellestrina is also a cell bounded by two harbors (north Malamocco and south Chioggia) and can be considered a closed physiographic unit. The jetties have in fact modified the regime of currents coastal and therefore the Pellestrina shoreline is devoid of sand inputs from either boundary. This cell is approximately 11 km long and orthogonal to the shoreline, it has an orientation of 100 °N.

The island of Pellestrina is characterized by a medium influx of tourists in the summer season and economic activities related to fishing and agriculture. The northern and southern ends of this cell are areas of great environmental value. In particular, the Ca' Roman area is an oasis that preserves, thanks to its relative isolation and the absence of excessive tourist exploitation, one of the most intact dune environments in the entire Upper Adriatic where one can find plant associations now rare and valuable animal species.

The coastline of the island of Pellestrina is, together with the Lido, the natural sea defense for the Venice lagoon. The entire coastline, with the exception of except for the southern stretch (Ca' Roman), is protected by a system of cell defenses and a "murazzo" that runs along the island.

2012 - 2015

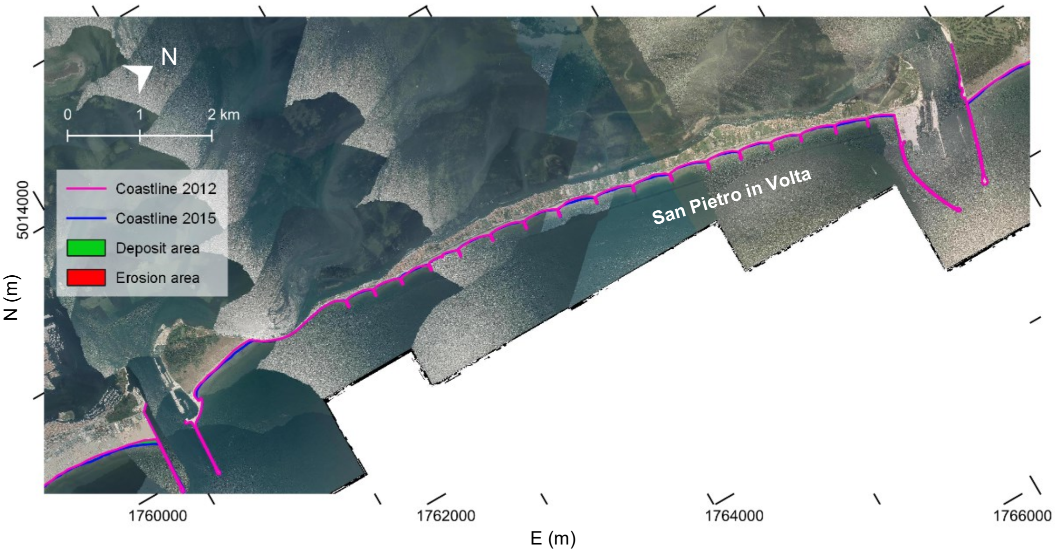

Figure 57 Cell VE8, 2015 orthophoto.

Erosion area = 6950 m^2

Deposit area = 105881 m^2

In the San Pietro in Volta area (Figure 58), the distance between the two coastlines reaches value of +35 m, the medium value is about +6 m.

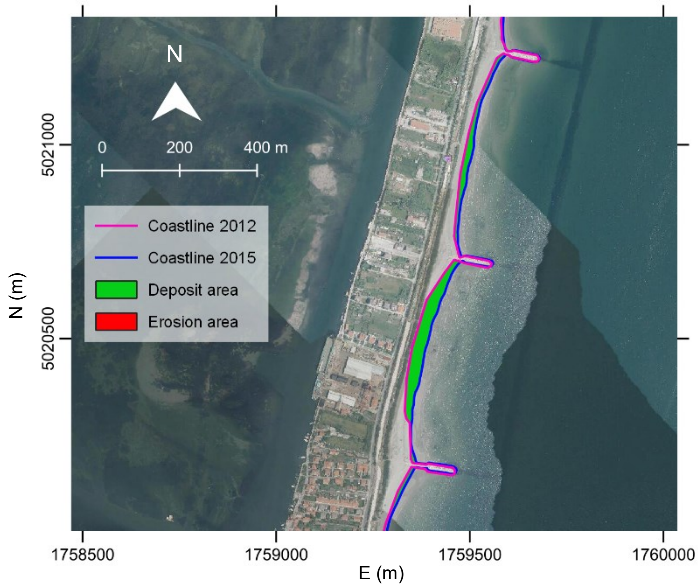

Figure 58 San Pietro in Volta, 2015 orthophoto.

The cell defense, completed in the late 1990s, was achieved by pouring over 4 million m^3 protected by a series of groins and a submerged barrier. The protection and containment works of the poured material ensured a high durability of the beach nourishment.

2015 - 2018

Erosion area = 42779 m^2

Deposit area = 14963 m^2

Regard the San Pietro in Volta area (Figure 59), there is a complete change in trend (erosion prevails) and a recurring trend between the docks. Receding of the coast reaching values of -19 m. The need for a new supply of sand is found to be necessary.

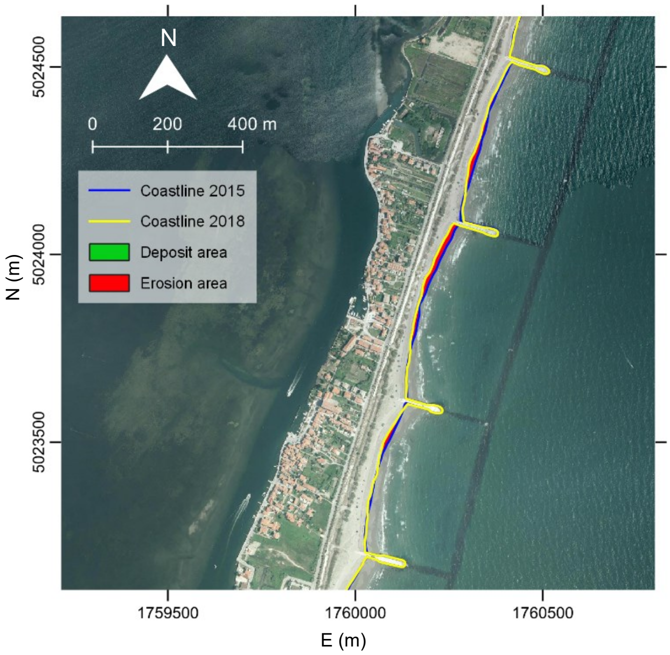

Figure 59 San Pietro in Volta, 2018 orthophoto.

In fact, it is deemed essential to beach nourishment before wave action can directly reach the murazzo resulting in increased losses to the offshore.

VE9 – from Bocca di Chioggia to Brenta mouth

The coastline of Sottomarina stretches for about 6.5 km, and the perpendicular to the shoreline has an orientation of 75 °N. This stretch of coastline represents the terminal section of a strip of land that forms the natural and first protection of the lagoon of Venice.

2012 - 2015

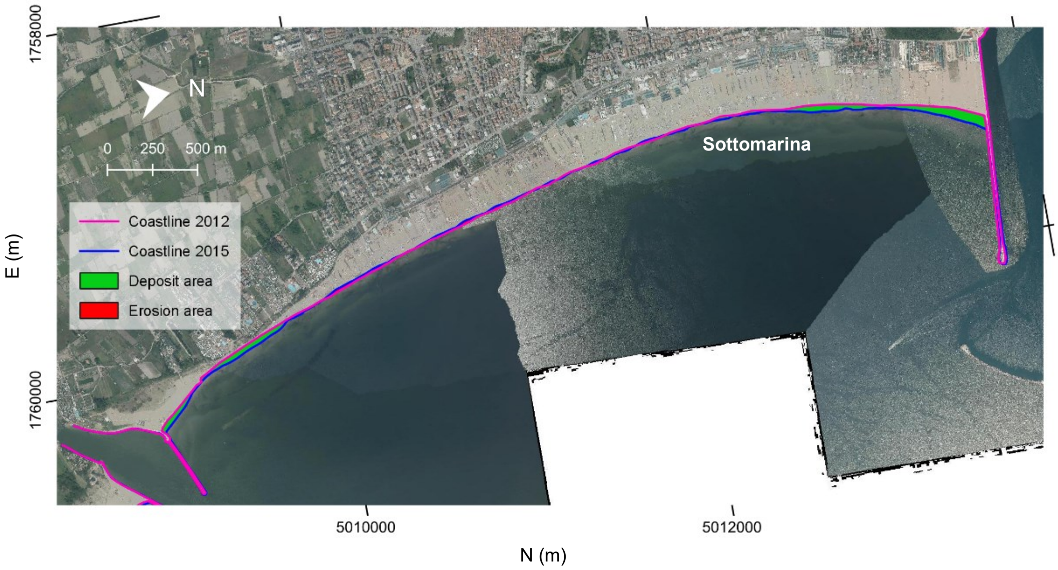

Figure 60 Cell VE9, 2015 orthophoto.

Erosion area = 14646 m^2

Deposit area = 73257 m^2

Littoral solid transport, which appears to be directed southward from cell VE1 up to VE6 and appears substantially on average zero at the Venetian shores, is directed northward at Sottomarina (Figure 60). The sediments are therefore intercepted almost entirely by the southern armor of the Bocca di Chioggia. The area on the hydrographic right at the mouth is constantly advance and the shoreline in some places reaches 300 m in width (Figure 61).

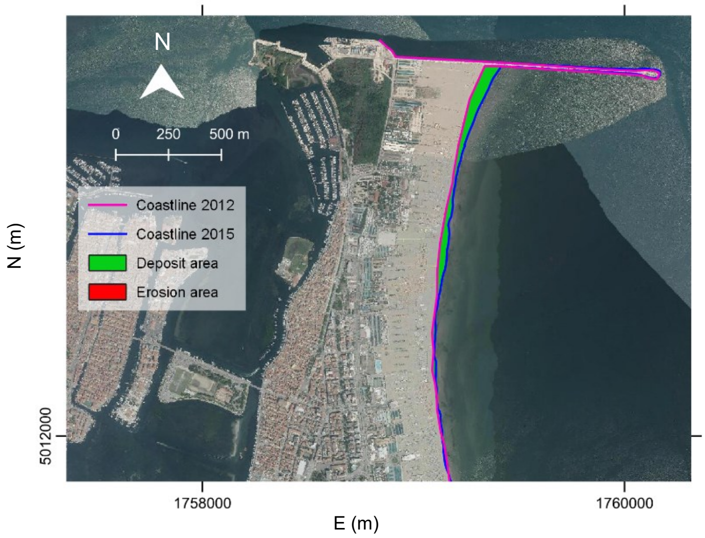

Figure 61 Northern end of cell VE9, 2015 orthophoto.

The submerged zone located close to the south pier of the mouth of Chioggia was found, following suitable verifications carried out by the Veneto Region, to be a borrow area of sand volumes useful for the realization of beach nourishment.

2015 - 2018

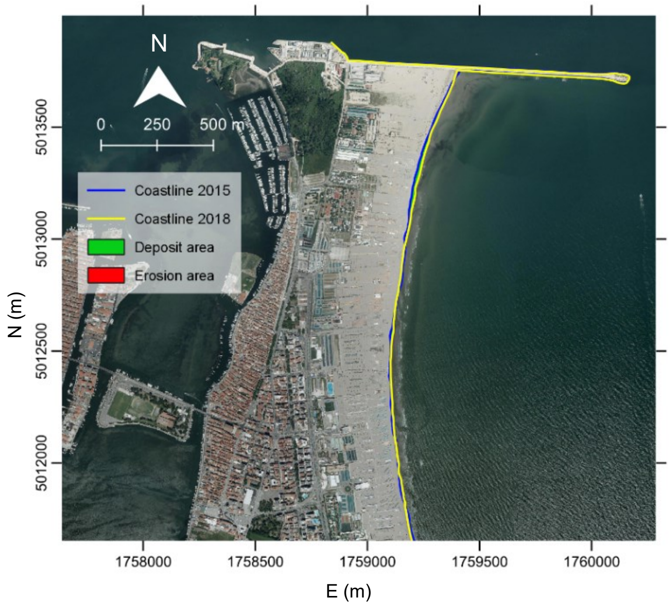

Figure 62 Northern end of cell VE9, 2018 orthophoto.

Erosion area = 15852 m^2

Deposit area = 21980 m^2

The deposit phenomenon slowed down respect to the previous years (Figure 62). The cell looks stable.

VE10 – from Brenta mouth to Adige mouth

The stretch of coastline between the mouth of the Brenta and the mouth of the Adige, called the Green Island, stretches for about 3 km.

Beginning from the 1960s the part of the island close to the beach became increasingly important for tourism, with the gradual construction of hotels, campgrounds and bathing establishments. The rest of the island is still used for agriculture.

2012 - 2015

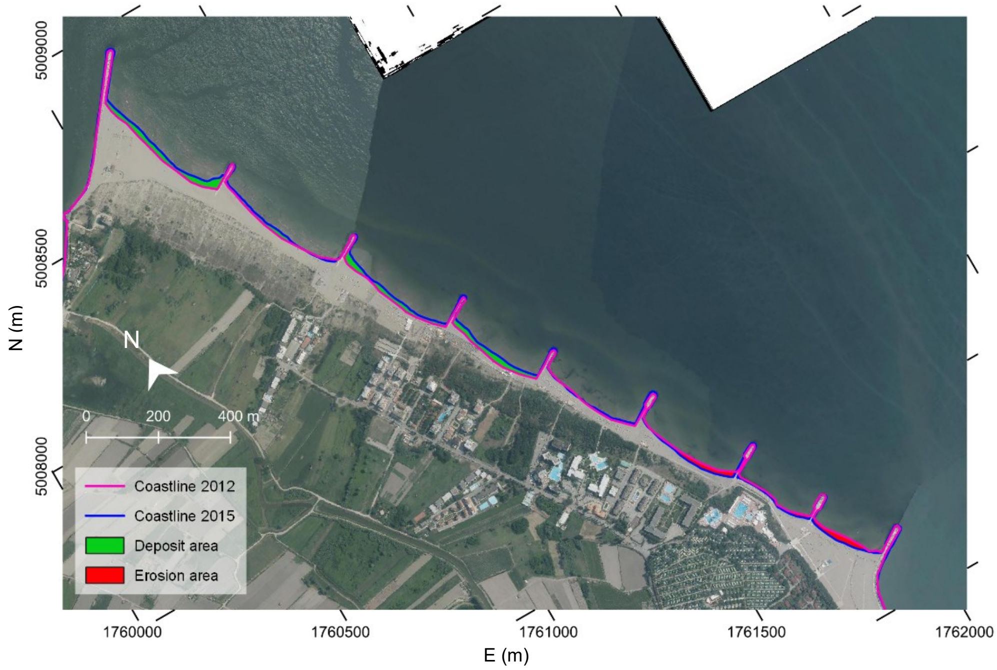

Figure 63 Cell VE10, 2015 orthophoto.

Erosion area = 6692 m^2

Deposit area = 20006 m^2

The northern part of the cell shows a prevailing growing behavior, while it can be observed the retreating trend for about 1700 m north of the Adige mouth.

2015 - 2018

Figure 64 Cell VE10, 2018 orthophoto.

Erosion area = 9165 m^2

Deposit area = 6567 m^2

The behavior of the cell coast seems to stabilize, erosion and deposition phenomena are weaker (Figure 64).

RO1 – from Adige mouth to Bocca di Caleri

The shoreline of Rosolina stretches for about 8 km, and the orthogonal to the shore has an orientation of 80 °N. The urbanized area, with some equipped beaches, affects only the first 4 km.

The last stretch to the south accommodates an area of considerable natural and environmental value.

2012 - 2015

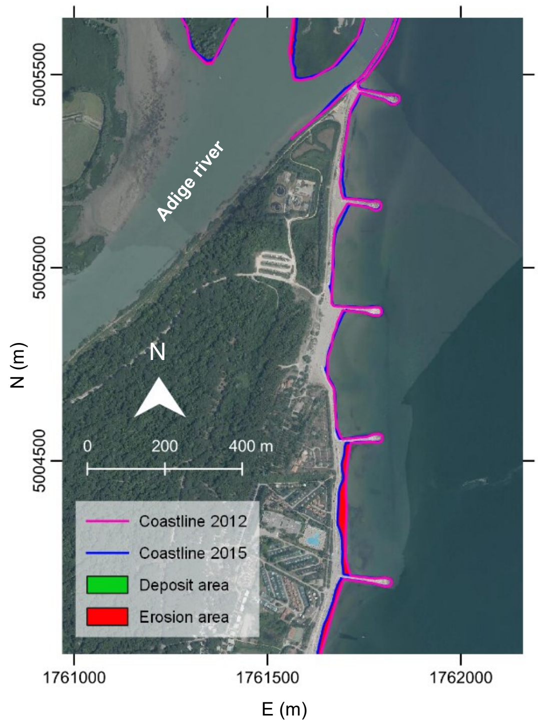

Figure 65 Northern end of cell RO1, 2015 orthophoto.

Erosion area = 71743 m^2

Deposit area = 77318 m^2

The constant retreat of the shoreline, in the northern part of the cell, evidences an erosion that is still in progress; to counteract this phenomenon, 5 stone groins (Figure 65) and a submerged reef were built immediately downstream from the mouth of the Adige to form 4 closed cells.Numerous beach nourishments are carried out in this area.

The receding of the coast reaches values of -22 m.

Moving South, the coast upstream Bocca Caleri is very unstable (Figure 66).

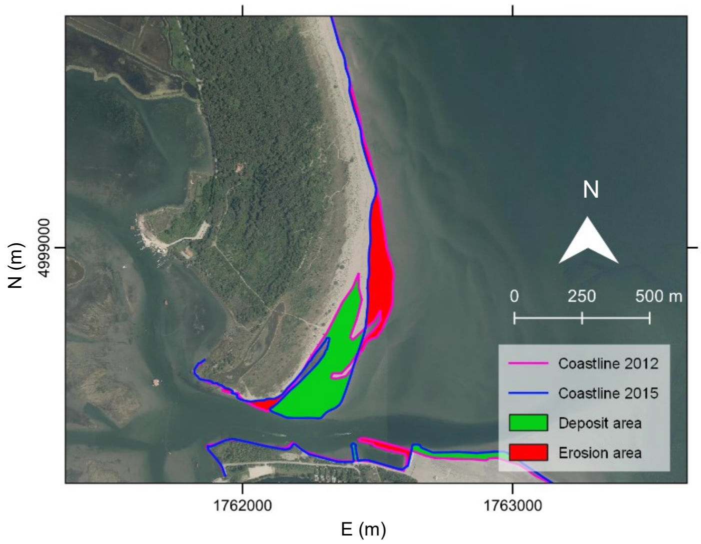

Figure 66 Southern end of cell RO1, 2015 orthophoto.

2015 - 2018

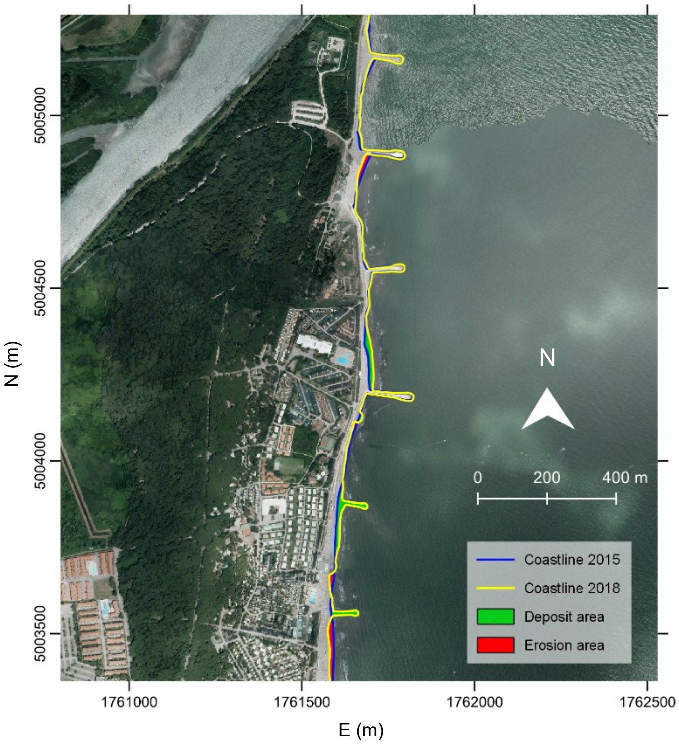

Figure 67 Northern end of cell RO1, 2018 orthophoto.

Erosion area = 50700 m^2

Deposit area = 63761 m^2

The first section to the north consists of a fragile artificial structure, sometimes overflowed by waves during the most violent sea storms, that divides the open sea from the mouth of the Adige River, closing planimetrically an old branch of the mouth. In the northern part of Rosolina Mare, erosion is still a problem. Probably for this reason, they decided to build two more docks (Figure 67). Receding of the coast seems to diminish, reaching values of -15 m.

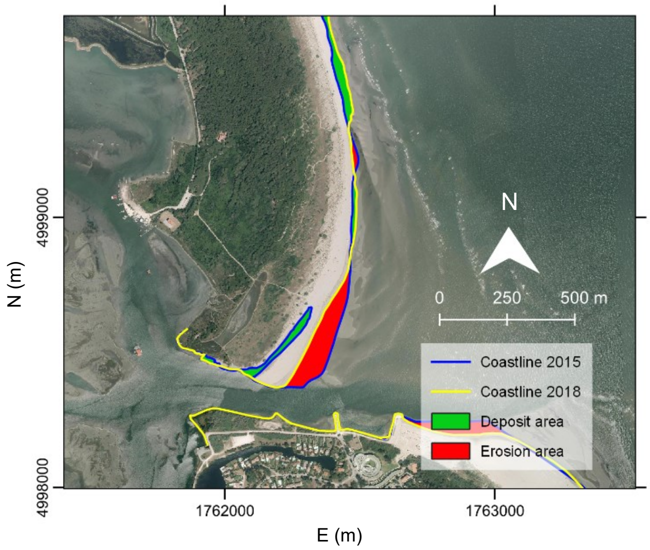

Figure 68 Southern end of cell RO1, 2018 orthophoto.

As already mentioned, the instability of the Bocca Caleri coast is confirmed (Figure 68), with maximum retreating distance of -90 m.

RO2 – from Bocca di Caleri to Bocca di Porto Levante

The 2.5 km stretch of coastline between the mouth of Porto Caleri and the mouth of the Po di Levante is the shoreline of Albarella Island. The Albarella Island (municipality of Rosolina) is a private island for tourist - seaside use and is part of the Regional Park of the Delta Po River.

2012 - 2015

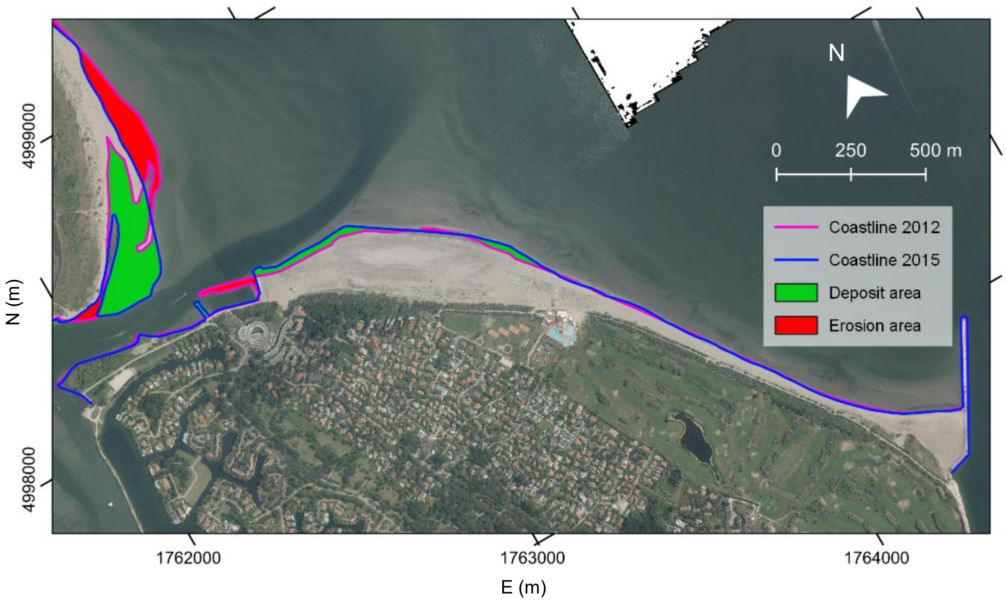

Figure 69 Cell RO2, 2015 orthophoto.

Erosion area = 9882 m^2

Deposit area = 19328 m^2

Immediately downstream of the protective reef of Porto Caleri, in the northern cape of Albarella Island, an area is observed in a condition of accumulation, where the beach has a width of about 200 m.

At the southern end of this cell the shoreline is protected by the North Pier of Po di Levante and an area of sediment deposition has formed behind it.

2015 - 2018

Figure 70 Cell RO2, 2018 orthophoto.

Erosion area = 21615 m^2

Deposit area = 3002 m^2

From the analysis of the shoreline evolution, there has always been a gradual increase of the beach in the shoreline of Albarella Island, but recently it seems to show erosive phenomena.

RO3 – from Bocca di Porto Levante to Po di Maistra mouth

The shoreline between the mouth of the northernmost branch of the Po Delta (Po di Levante) and the mouth of the Po di Maistra is a thin emerged known as Scanno Cavallari that separates the sea from the Vallona Lagoon; this stretch of beach is long approximately 5 km and the orthogonal to the shore has an orientation of about 47 °N. The Cavallari Scanno was a wide strip of land occupied by rural buildings and dwellings but, due to the subsidence of the soil and the consequent partial submersion, it was abandoned in the 1950s.

Starting from this cell and continuing southward, the coast of the Province of Rovigo takes on a predominantly natural being an integral part of the Po River Delta, so the considerations that now follow are valid for all the subsequent cells. With the exception of a few short stretches, the coastline is not anthropized and is a succession of mouths of the river Po, lagoon inlets, islands and sandbars that act as a first defense for the lagoons behind.

This area is part of the Po Delta Regional Park; it is home to complex vegetation associations, priority habitats and is an important site for nesting, migration and wintering of numerous species.

The conformation of this coastline requires different assessment, analysis, and therefore planning than the remaining Venetian coast. Being in fact an area with a strong environmental relevance and relatively little anthropization, a management that aims to maintain and enhance this character.

2012 - 2015

Erosion area = 81637 m^2

Deposit area = 99585 m^2

At the northern end of this cell the shoreline is protected by the South Pier of Po di Levante, and a stone reef was built behind it in 1985; the remaining shoreline is not protected by works parallel or orthogonal to the shore except for a section in which a soft stone reef was built. In contrast, the southern end of the cell is characterized by the presence of the reef separating the Vallona lagoon.

Such a scanno (Figure 71) protects the Vallona lagoon, which in the past was open to the sea at the mouth of the Po di Maistra; to the south of the lagoon there is a gate that favors internal circulations within it. Almost all of this stretch, on the seaward side, is in accretionary conditions due to the presence of the long dock of Porto Levante, which hinders part of the solid transport, stopping the migration of the scanno located in front of the mouth of the Po di Maistra. The maximum accretion distance is +34 m.

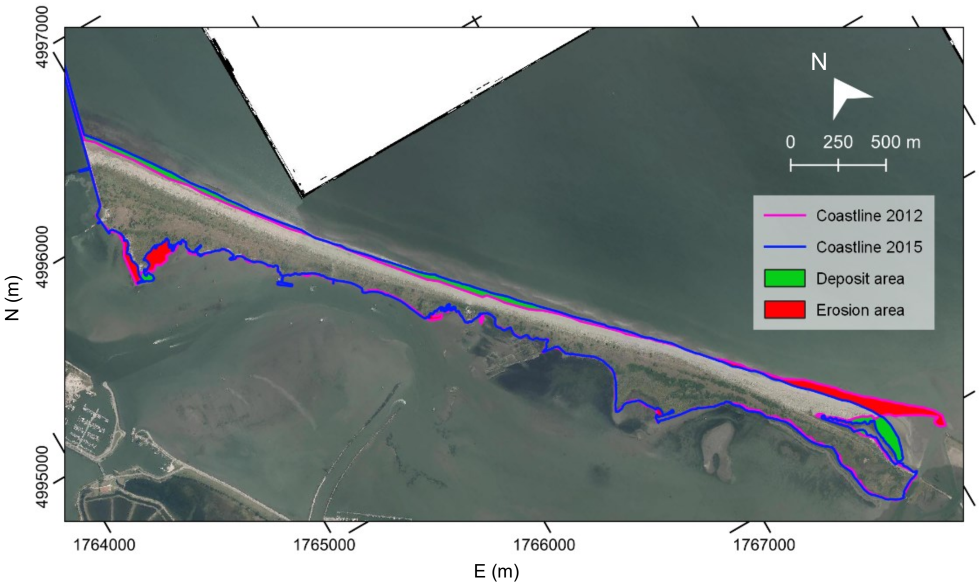

Figure 71 Cell RO3, 2015 orthophoto.

2015 - 2018

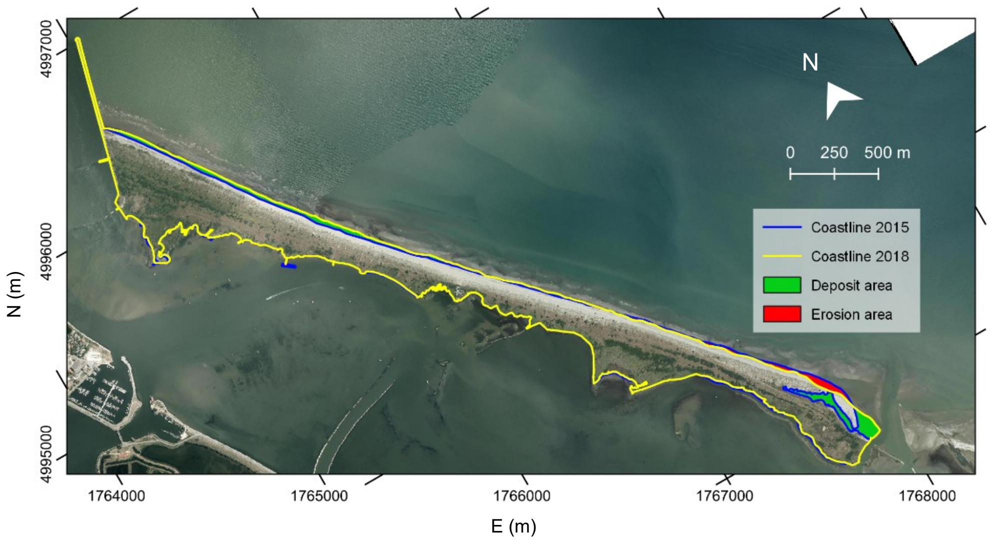

Figure 72 Cell RO3, 2018 orthophoto.

Erosion area = 35728 m^2

Deposit area = 75149 m^2

Because of its high dynamism, this coastline is, as mentioned earlier, a fragile physiographic unit, which needs to be protected to ensure defense from marine encroachment marine encroachment of the areas behind it (Figure 72). However, the Cavallari scanno has suffered, in the past decades, significant reductions in the inland side, towards the the river, and these losses of emerged surfaces have made this thin strip of land even more fragile and vulnerable. The activity economy in this area is exclusively related to shellfish farming developed in the Vallona Lagoon.

RO4 – from Po di Maistra mouth to Busa di Tramontana

The coastal cell bounded on the north by the mouth of Po di Maistra and on the south by Busa Tramontana extends for about 9 km and is also known as Lido di Boccasette. At the northern end are the protective works at the mouth of Po di Maistra, namely the reefs and a piling; on the hydrographic right at Po di Maistra there are 10 wooden groins. This scanno is the only one equipped with a beach and is interrupted in two places: the North mouth and the southern (more recent) mouth of the Barbamarco Lagoon. Both mouths are protected by short stone piers and complemented by soft barriers parallel to the shoreline.

2012 - 2015

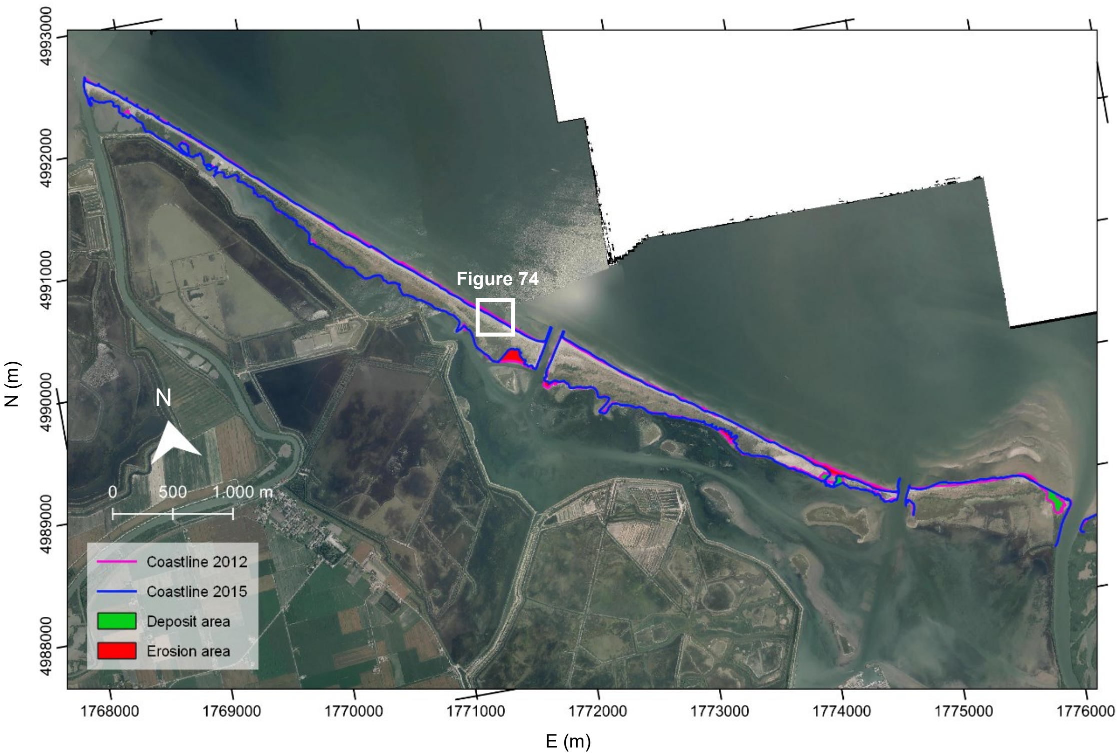

Figure 73 Cell RO4, 2015 orthophoto.

Erosion area = 73835 m^2

Deposit area = 67936 m^2

This scanno (Figure 73) performs the function of marine ingression defense for the lagoon behind it and is of great environmental significance, being part of the Po Delta Regional Park.

In the first part north of this scanno, the municipality of Porto Tolle authorizes the establishment of seasonal bathing establishments. This stretch, protected by a series of ineffective wooden groins, is eroding and annually, to ensure its usability tourism, small volumes of sand are poured. The receding of the coast reaches values of -20 m (Figure 74).

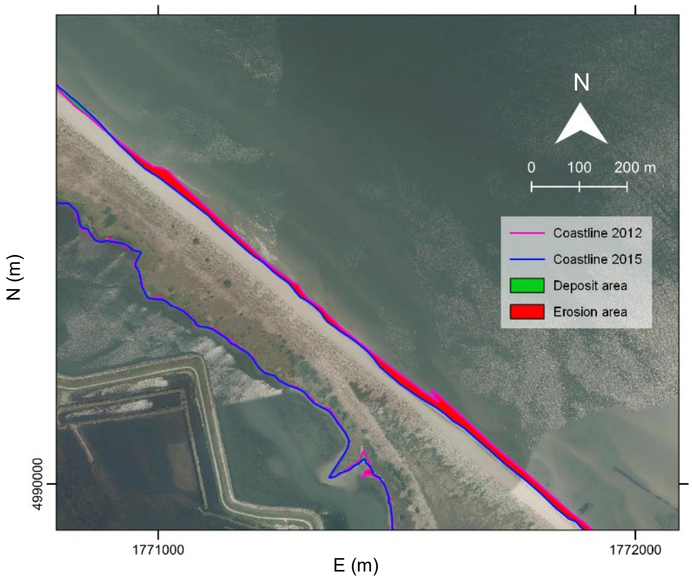

Figure 74 Northern section of cell RO4, 2015 orthophoto.

Looking at the evolution of the shoreline, it can be seen that the southern part of this cell, is growing. In particular, there is an area of sandy deposit (Figure 75).

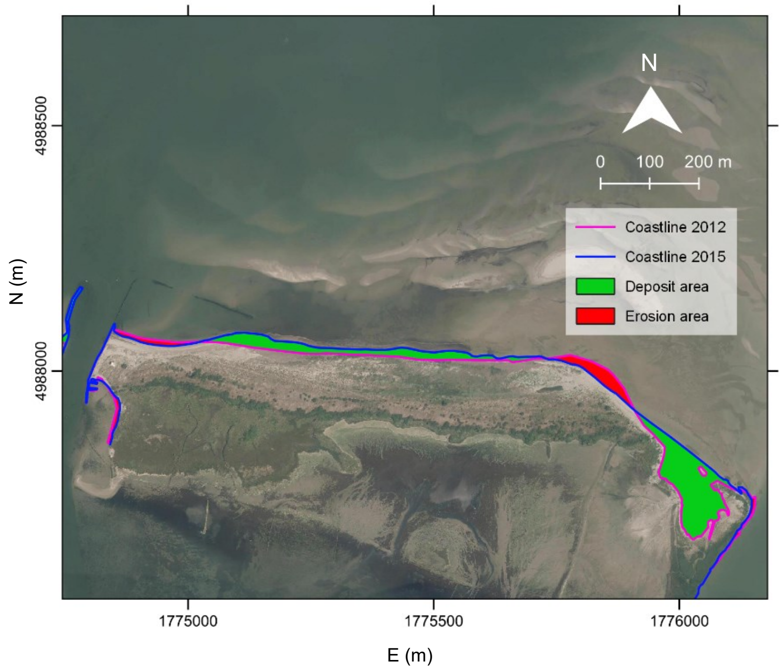

Figure 75 Southern section of cell RO4, 2015 orthophoto.

2015 - 2018

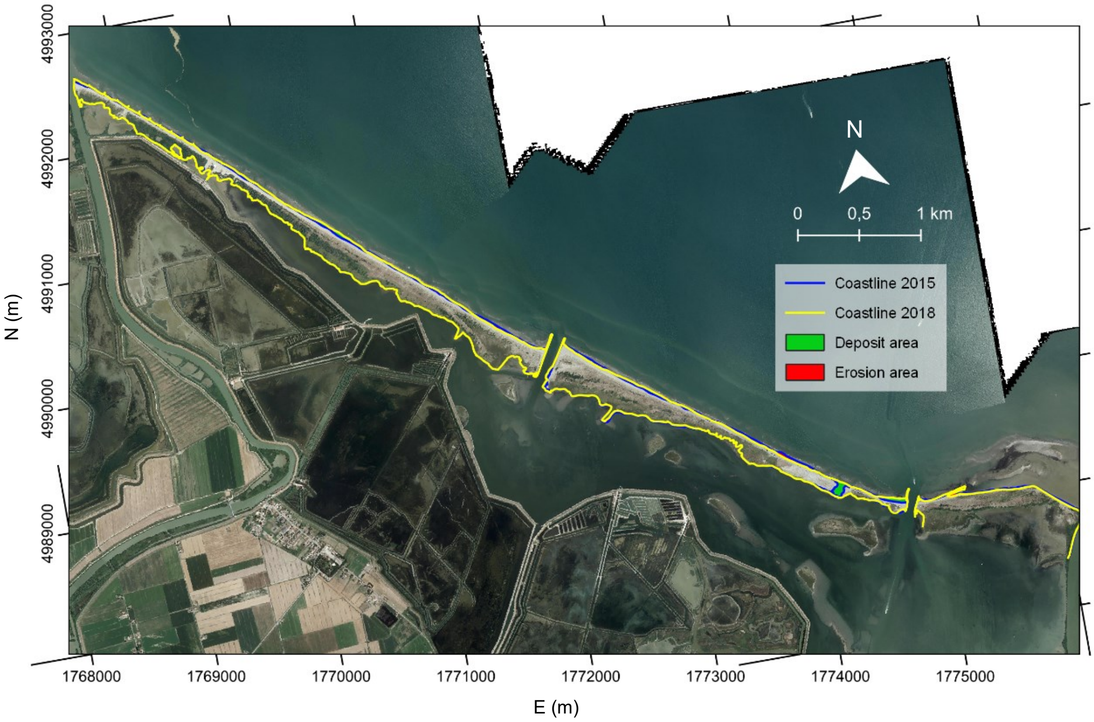

Figure 76 Cell RO4, 2018 orthophoto.

Erosion area = 51003 m^2

Deposit area = 54631 m^2

In the southern shoreline of this littoral cell is the southern mouth of Barbamarco, used as an access channel to the Port of Pila. This exclusively fishing port is very important for bluefish fishing. Given the importance of the port's activity and the size of the boats passing through it (draft of 3.5 m) the channel is regularly dredged.

RO5 – from Busa di Tramontana to Busa Dritta

The stretch of coastline belonging to this cell is bounded by two of the three branches into which the Pila Po divides, namely Busa di Tramontana and Busa Dritta. This cell turns out to be completely devoid of works and therefore very subject to the evolution natural evolution typical of the Po Delta.

This cell is a completely natural area in which it is not conceivable to think of major anthropogenic interventions, given also the high evolutionary dynamism of these scanni and barrier islands.

2012 - 2015

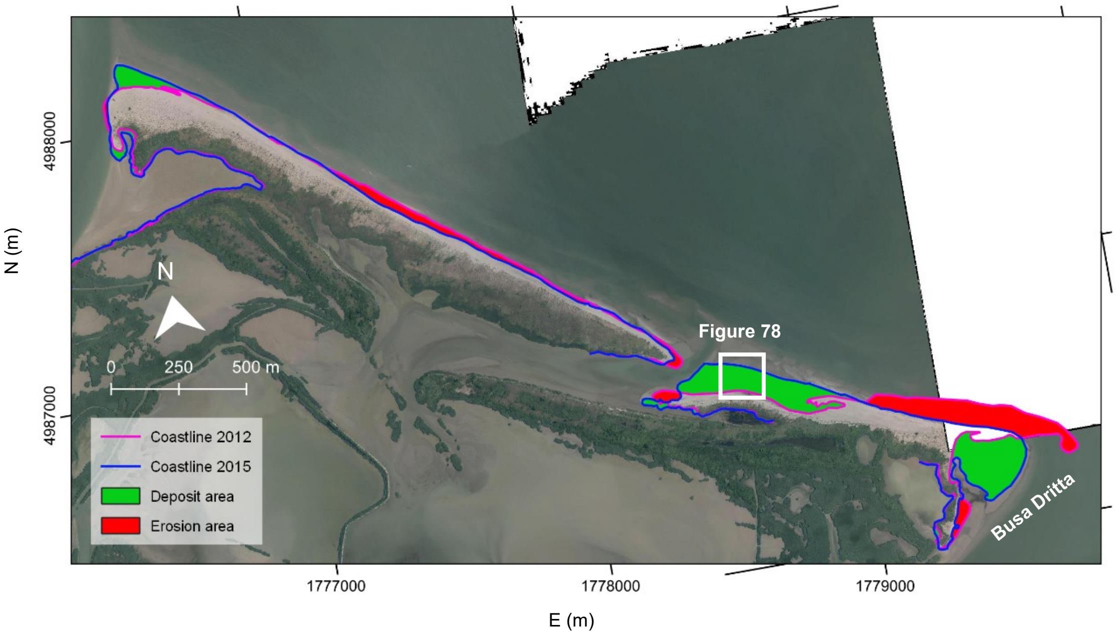

Figure 77 Cell RO5, 2015 orthophoto.

Erosion area = 89212 m^2

Deposit area = 127644 m^2

It is possible to observe a seaward advancement and thus an evolution of the delta cusp due to the fluvial solid transport of the main branch of the Po, which counteracted the erosive effects of sea action and subsidence.

The southern part of cell RO5 (Figure 78) is very unstable with accretion distance reaching values larger than +100 m and retreating distance of -90 m.

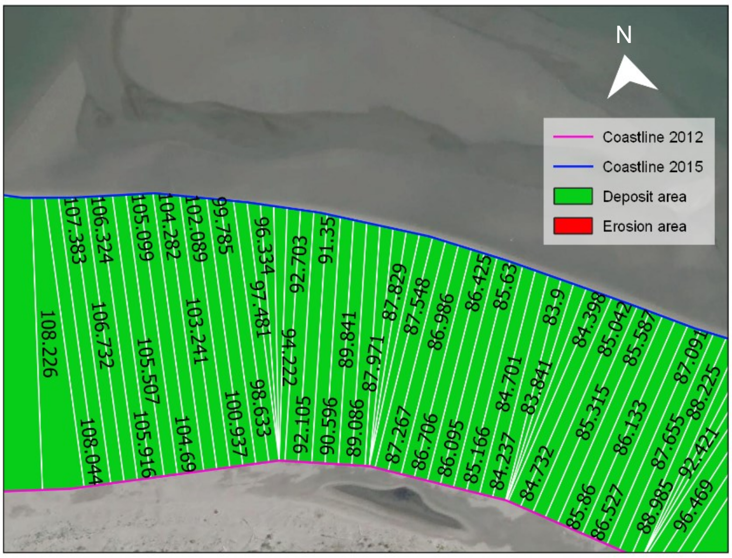

Figure 78 Southern section of RO5 with indication of perpendicular distances between coastlines, 2015 orthophoto.

2015 - 2018

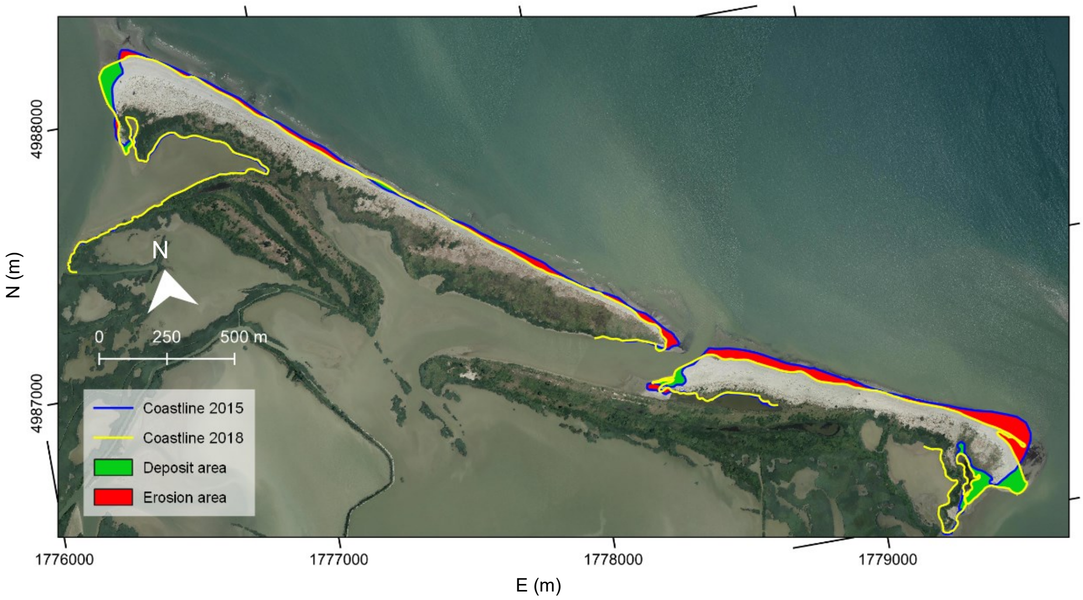

Figure 79 Cell RO5, 2018 orthophoto.

Erosion area = 72120 m^2

Deposit area = 30910 m^2

This littoral cell (Figure 79) and the following are the two scanni that delimit the cusp of the Po Delta, or Maistra mouth. They are constantly changing stretches of coastline and vary their morphology depending on littoral and especially fluvial dynamics.

As is the case near the mouths of major rivers, Busa Dritta represents a point of divergence of littoral solid transport (Figure 80). In fact, to the north it is directed northward, while to the south of it the direction is opposite.

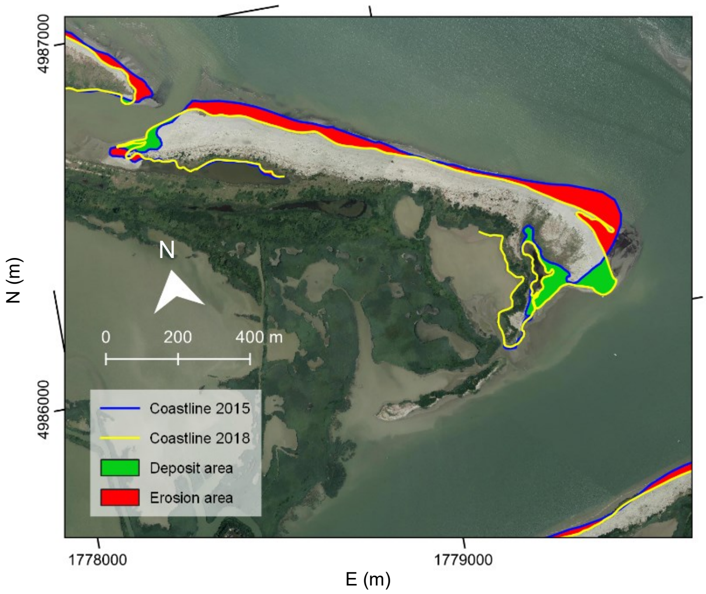

Figure 80 Southern section of cell RO5, 2018 orthophoto.

RO6 – from Busa Dritta to Busa di Scirocco

The littoral cell between two final branches of Stack Po, namely Busa Dritta and Busa di Scirocco, is characterized like the previous one by the absence of rigid works, and thus the phenomenon of Delta accretion caused by the transport riverine solid of the Po.

This scanno protects the Basson lagoon at sea, an area of high potential productivity due to its location at close to the mouth of the Po di Pila, although it is a fragile environment due to the continuous modifications induced by river branches.

Three sea outlets converge at the southern end of this stretch (in order from the north): the mouth of the Laguna of the Basson, the sea outlet of the Po di Scirocco (Busa scirocco), and the now-buried Enel drainage canal.

2012 - 2015

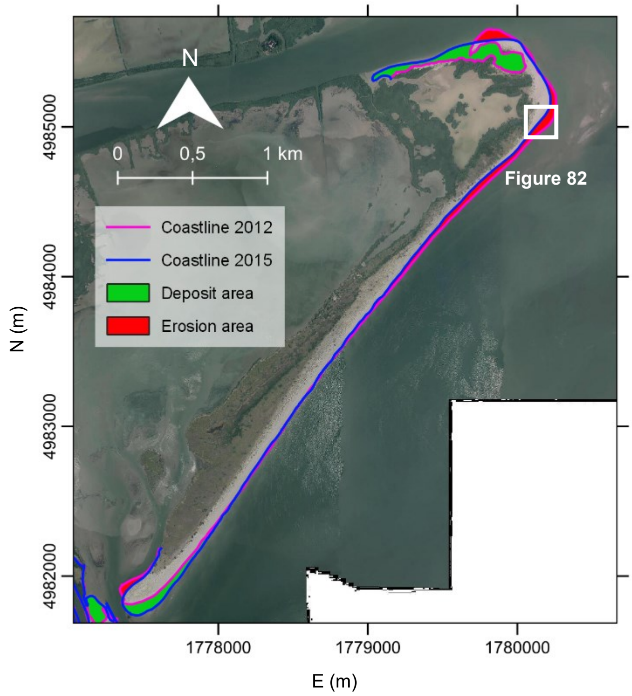

Figure 81 Cell RO6, 2015 orthophoto.

Erosion area = 92838 m^2

Deposit area = 109493 m^2

In this cell it is present a maximum retreating distance of -60 m (Figure 82) and a maximum accretion distance of + 81 m.

Figure 82 Northern part of cell RO6 with indication of perpendicular distances between coastlines, 2015 orthophoto.

2015 - 2018

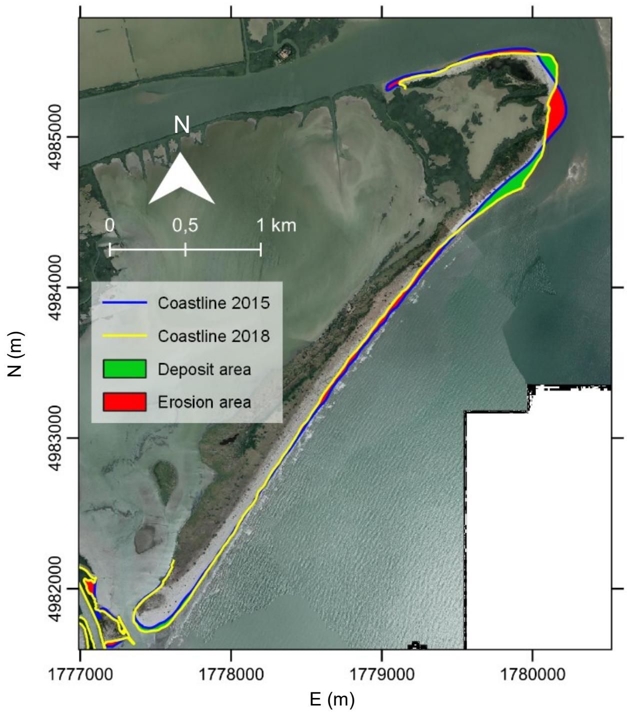

Figure 83 Cell RO6, 2018 orthophoto.

Erosion area = 96295 m^2

Deposit area = 62721 m^2

The cell shows a maximum retreating distance of -113 m in its northern part.

RO7 – from Busa di Scirocco to Busa Storiona

The stretch of coastline between Busa di Scirocco and Busa Storiona extends for about 7 km and the orthogonal to the coast has an orientation of 110 °N. The shoreline of this cell is not continuous, being interrupted by the mouth of Sacca di Canarin and the mouth of Busa del Bastimento.

On the hydrographic right at the Busa di Scirocco, a stone reef has been built by the Po Delta Reclamation Consortium, which has created a scanno to protect the Sacca del Canarin; as for the Busa del Bastimento it is protected by reefs and wooden piling. The cell is bordered to the south by the protective stone pier of the Busa Storiona.

2012 - 2015

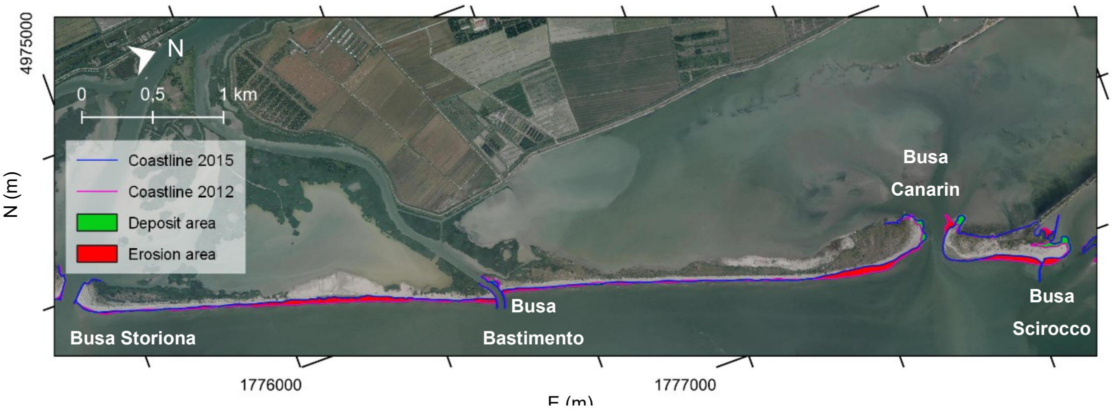

Figure 84 Cell RO7, 2015 orthophoto.

Erosion area = 110674 m^2

Deposit area = 25311 m^2

Maximum retreating distance = -50 m.

Littoral solid transport is directed from north to south, that is, it is still diverging from the Po Delta cusp. In the vicinity of Busa Scirocco, near the former Enel discharge channel, a reef has been built, completely buried in the inside and induced, on the sea side, the formation of an accumulation zone. More details will be given in chapter 5.

2015 - 2018

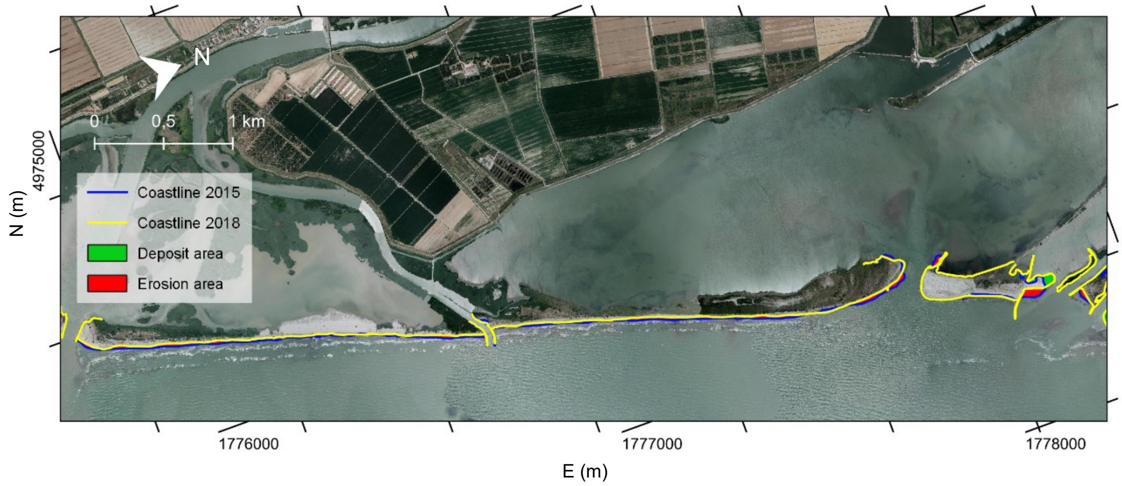

Figure 85 Cell RO7, 2018 orthophoto.

Erosion area = 95235 m^2

Deposit area = 20237 m^2

The variation of the shoreline shows erosive phenomena. In particular, there is there is a retreat along the entire littoral cell, denoting its fragility towards the risk of overtopping and marine ingression into the lagoon. The maximum coastline change rate is -8 m/yr.

RO8 – from Busa Storiona to Po di Tolle mouth

The shoreline under consideration is named Bonelli Beach and extends for about 4 km between Busa Storiona and the mouth of Po di Tolle. This scanno also performs the function of defense from marine ingression for the lagoon behind it and is of great importance from an environmental point of view, in fact it is part of the Po Delta Regional Park.

2012 - 2015

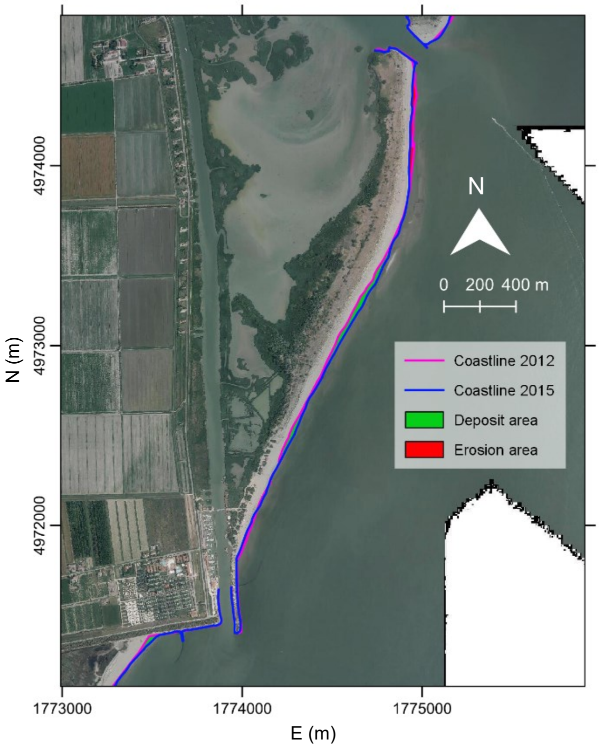

Figure 86 Cell RO8, 2015 orthophoto.

Erosion area = 15418 m^2

Deposit area = 27303 m^2

The stretch is bounded to the north by Busa Storiona (a branch of the Po di Tolle). Currently about 80% of the flow of the Po di Tolle is conveyed to the sea through this Busa. This intervention induced the accretion of the cell under investigation especially in the bottoms in front of the Busa.

In the central part, the shoreline has advanced. Maximum accretion distance is +31 m.

This cell also has, as stated earlier, a strong environmental value, and moreover, in the terminal stretch southward, sees the presence of a beach equipped for tourist/beach use (Barricata beach).

2015 - 2018

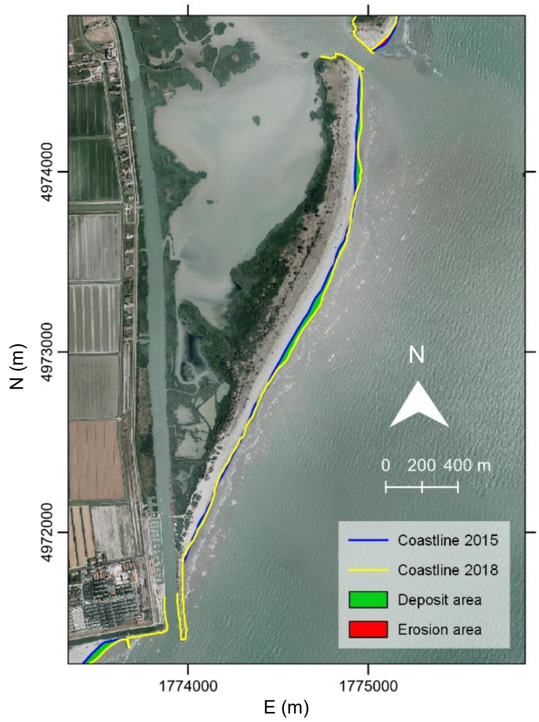

Figure 87 Cell RO8, 2018 orthophoto.

Erosion area = 3945 m^2

Deposit area = 36390 m^2

The transport is intercepted by the mouth armor of the Po di Tolle (north), consisting of a jetty and a soft barrier, which promotes the localized deposition of sediment.

The maximum accretion distance is +41 m along the coast.

RO9 – from Busa Storiona to Po di Tolle mouth

The stretch between Po di Tolle and Po di Gnocca delimits the Sacca di Scardovari from the sea; this lagoon communicated until 1997 with the Adriatic Sea through a single 1,700-meter-wide mouth, located on the hydrographic left to the Po di Gnocca. Between 1995 and 1997 work was carried out to safeguard and vivify this pocket, which included the opening of a second artificial mouth near the mouth of the Po di Tolle, protected by stone piers, and the construction of a reef made of stones to protect the scanno in front of the Po di Gnocca.

The scanno's essential function in defending the lagoon behind it, which is of great environmental importance-in fact, it is part of the Po Delta Regional Park.

2012 - 2015

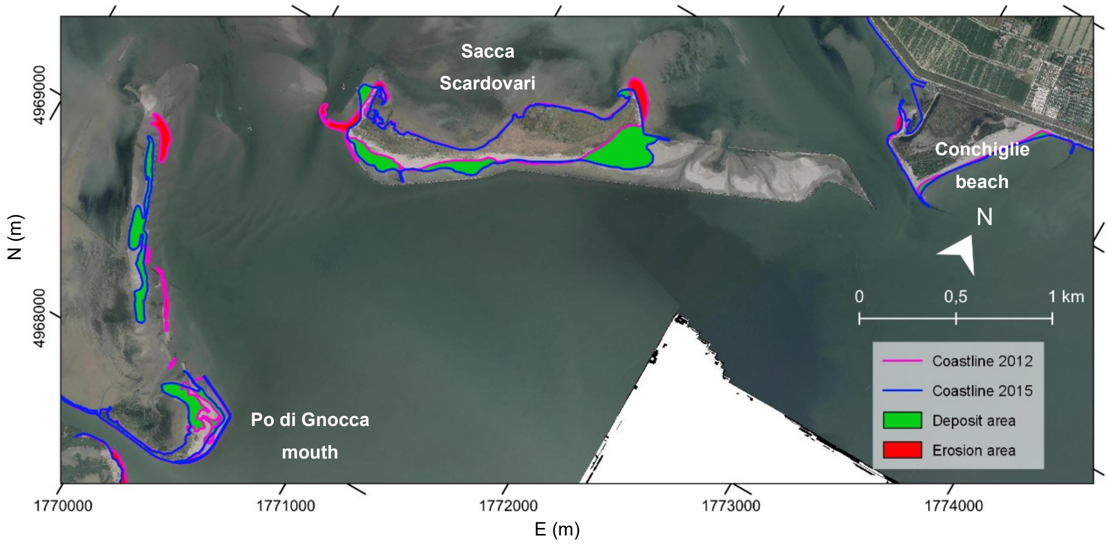

Figure 88 Cell RO9, 2015 orthophoto.

Erosion area = 56433 m^2

Deposit area = 178074 m^2

This paragraph introduces the main highlights of the cell's behavior. More details will be given in chapter 5.

The second section is the protective scanno of the Scardovari Basin, a lagoon of considerable environmental and fishing interest, where there are numerous shellfish farms. Observing the past evolution, it is evident the fragility that distinguishes this scanno, characterized by a rapid morphological evolution. From the variation of the shoreline one can observe how the island has migrated southwestward over the different years taking on different conformations, also as a result of numerous anthropogenic interventions for its mouth stabilization.

2015 - 2018

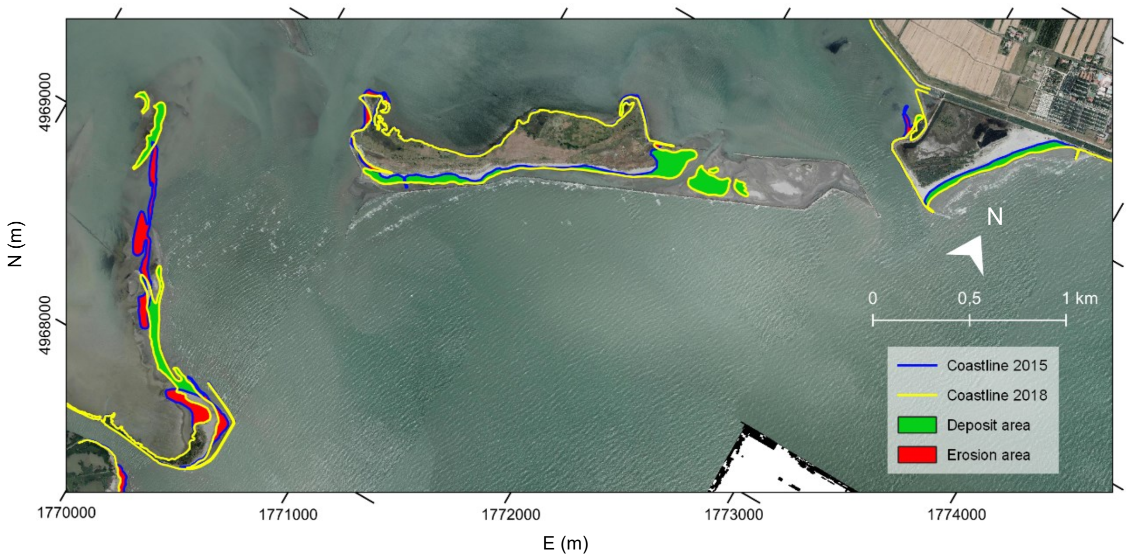

Figure 89 Cell RO9, 2018 orthophoto.

Erosion area = 78227 m^2

Deposit area = 158963 m^2

The first stretch is between the mouth of the Po di Tolle and the northern mouth of the Sacca (artificial mouth). The beach (called Conchiglie beach) is equipped for bathing use. From the analysis of the shoreline variation, a growing trend of this beach is observed.

RO10 – from Po di Gnocca mouth to Po di Goro mouth

The last cell south of the Venetian coast is the one between the mouths of the Po di Gnocca and Po di Goro, it extends for about 3 km and the orientation of the normal to the coast is 125 °N.

This scanno performs the function of defense from marine encroachment for the territories behind it and has great relevance from an environmental point of view, in fact it is part of the Po Delta Regional Park.

2012 - 2015

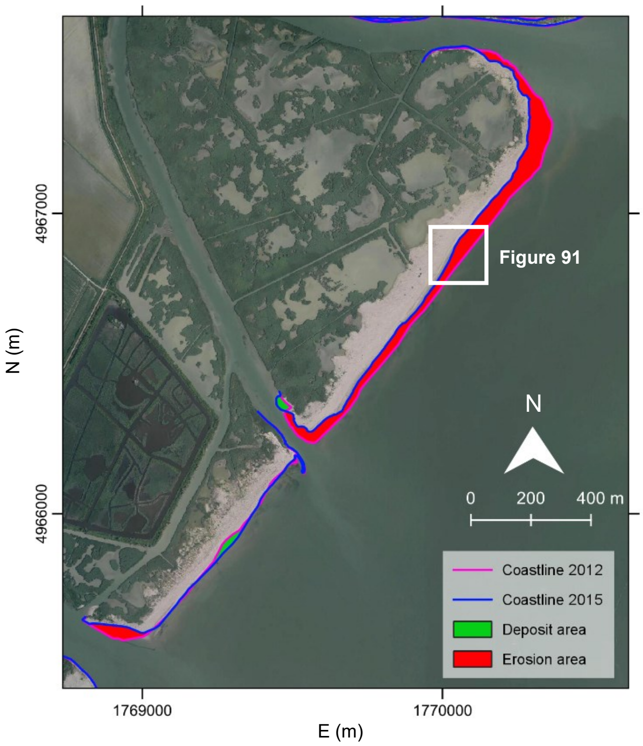

Figure 90 Cell RO10, 2015 orthophoto.

Erosion area = 67611 m^2

Deposit area = 5867 m^2

The stretch between the mouth of the Po di Gnocca and the mouth of the Po di Goro is the southern end of the Veneto coastline (Figure 90).

Figure 91 Central part of cell RO10 with indication of perpendicular distances between coastlines, 2015 orthophoto.

The evolutionary trend that characterizes this cell is strongly erosive and the shoreline shows a constant retreat (Figure 91). Maximum retreating distance = -75 m, while the mean value accounts for -27 m.

2015 - 2018

Erosion area = 51062 m^2
Deposit area = 4525 m^2

The same considerations made for the previous three-year period are valid also for 2015-2018, see Figure 92. Maximum retreating distance = -50 m

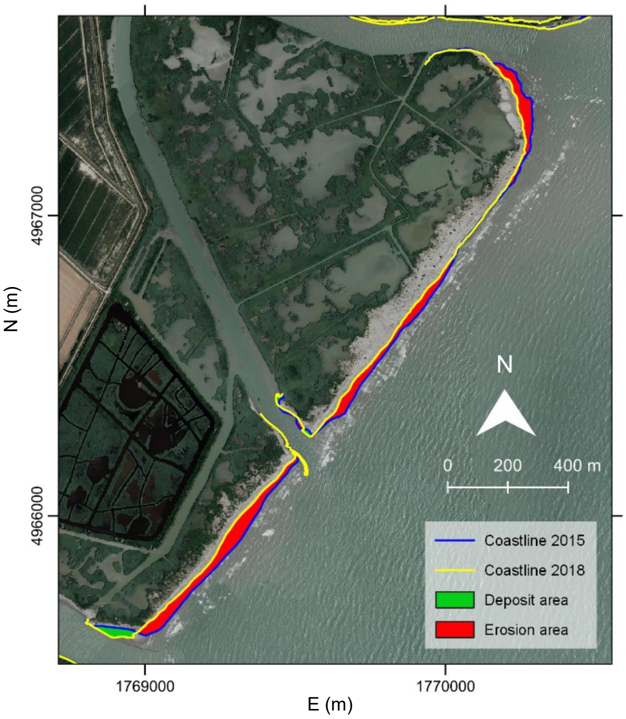

Figure 92 Cell RO10, 2018 orthophoto.

5. Discussion on the results

In this chapter, a more detailed analysis is performed with respect to the cells that presented the most interesting and significant coastal changes.

In the following table (Table 3), a summary of the coastal variations for each cell is given.

	2012 - 2015		2015 - 2018		Overall balance 2012-2018
CELL	Deposit area (m^2)	Erosion area (m^2)	Deposit area (m^2)	Erosion area (m^2)	
VE1	211587	40408	8600	142078	+37701
VE2	64858	8681	37126	28248	+65055
VE3	113297	3440	18513	26100	+102270
VE4	105623	13179	35654	52816	+75282
VE5	144762	10048	32623	38816	+128521
VE6	103589	35386	45268	50396	+63075
VE7	164827	9840	28619	32976	+150630
VE8	105881	6950	14963	42779	+71115
VE9	73257	14646	21980	15852	+64739
VE10	20006	6692	6567	9165	+10716
RO1	77318	71743	63761	50700	+18636
RO2	19328	9882	3002	21615	-9167
RO3	99585	81637	75149	35728	+57369
RO4	67936	73835	54631	51003	-2271
RO5	127644	89212	30910	72120	-2778
RO6	109493	92838	62721	96295	-16919
RO7	25311	110674	20237	95235	-160361
RO8	27303	15418	36390	3945	+44330
RO9	178074	56433	158963	78227	+202377
RO10	5867	67611	4525	51062	-108281

Table 3 Veneto Region coastline changes in terms of areas.

The cells that will be analyzed in more detail in this chapter are:

- VE1: this cell presents the maximum deposit area in the time interval 2012-2015 and the maximum erosion area between 2015 and 2018;
- RO7: this cell shows the maximum erosion area in the time interval 2012-2015;
- RO9: this cell shows the maximum deposit area in the time interval 2015-2018.

The analysis focused more on observing variations in area, since the minimum distance between coastlines does not always work correctly, see Chapter 3.

5.1 Cell VE1

Below, it is reported again a brief description of the cell, which is the one located furthest north.

Figure 93 Left: Tagliamento River mouth. Right: Bocca of Porto Baseleghe. (Source: P. Ruol et al.)

Cell VE1 is located in between the Tagliamento River mouth (Figure 93, left) and Baseleghe harbor (Figure 93, right). The coastline extends for a length of about 10 km (Figure 94) and belongs to the municipal territory of San Michele al Tagliamento, Bibione in the province of Venice.

Cell VE1	2012 - 2015	2015 - 2018
Deposit area	211587 m^2	40408 m^2
Erosion area	8600 m^2	142078 m^2

Table 4 Areal variations of cell VE1.

The study for each cell is divided into the two time intervals 2012-2015 and 2015-2018.

5.1.1 Cell VE1: time interval 2012-2015

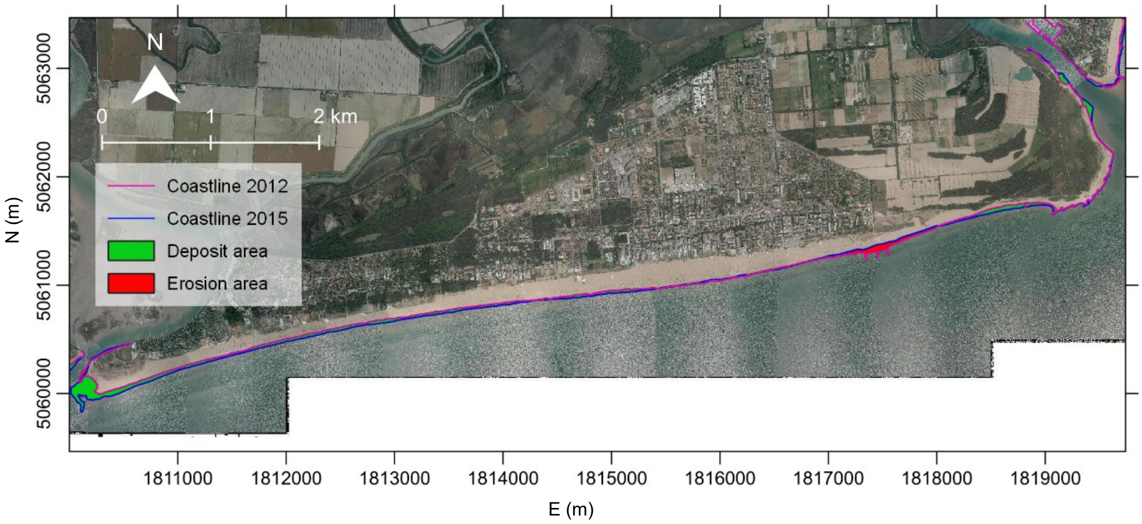

Figure 94 Cell VE1, 2015 orthophoto.

As reported in the previous chapter, the first section of the coastline of cell VE1 (mouth of the Tagliamento River) has experienced significant sand accumulation. West of the barriers, on the other hand, there has been a retreat of the emerged beach (Figure 95).

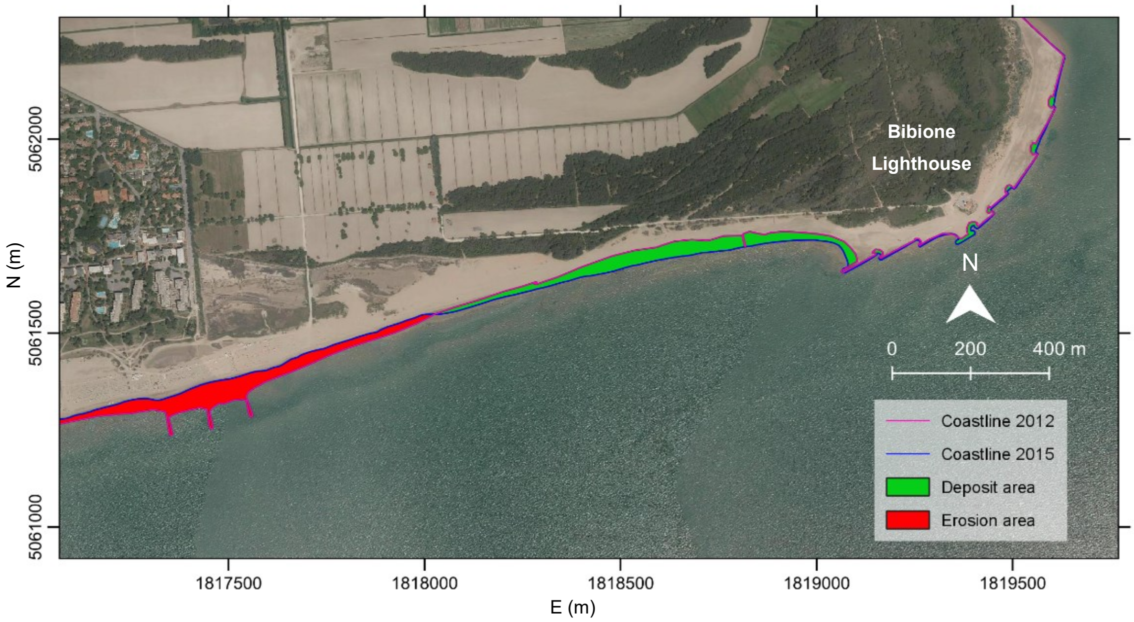

Figure 95 Bibione lighthouse, 2015 orthophoto.

This phenomenon is certainly to be related to the combined effect of littoral solid transport parallel to shore induced by wave action directed from east to west and insufficient supply of sandy material from the mouth of the Tagliamento [7]. It is also evident from the study of the bathymetry of the area that deposits of material delivered to the sea by the

Tagliamento River are no longer flowing close to the coast but bypassing the areas most in crisis, partly feeding submerged bars relatively far from shore, and partly being lost offshore (thus no longer available for littoral solid transport). It is possible that the presence of the barriers in the right at the mouth of the Tagliamento River and the periodic dredging of the navigable wedge may have contributed to the removal of riverine sediments from the shore. The combination of these phenomena is probably responsible for the erosion found in downstream of the barriers.

The central section of this littoral cell (Figure 96), in front of Bibione town center, is a touristic area. Observing the trend of the shoreline, it can be seen that the first part still shows a slight tendency to erosion, while continuing westward an advancement of the shoreline is observed.

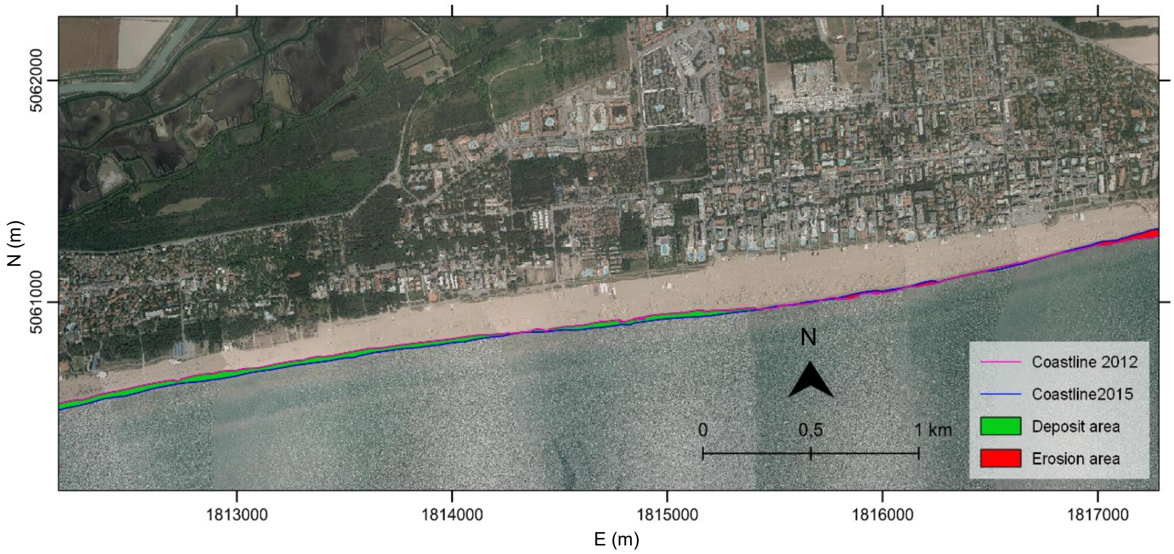

Figure 96 Bibione, 2015 orthophoto.

In fact, in that area, sediments from the Tagliamento estuary come sufficiently close to the shoreline, leading to such advancement. It is conceivable that the erosive phenomena manifested initially in the area of the Lighthouse, and now extended as far as Piazzale Zenith, are destined to progress toward the sub-bank, affecting, however, areas currently characterized by wide sandy shores.

In this central area the prevailing trend is accretion, with a medium rate of deposit of +6.3 m/yr. The orientation of the coast between Bibione and Porto Baseleghe, gradually less inclined from west to east, means that this section of coastline is more balanced, respect to mouth of Tagliamento river or Porto Baseleghe, since it is fed by the sands delivered to the sea by the Tagliamento River. The direction of solid transport is from NE toward SW.

Moving south , the recent evolution of the mouth of Porto Baseleghe shows a progressive advancement in a westerly direction, in the order of tens of meters per year, which certainly needs to be analyzed and monitored (Figure 97).

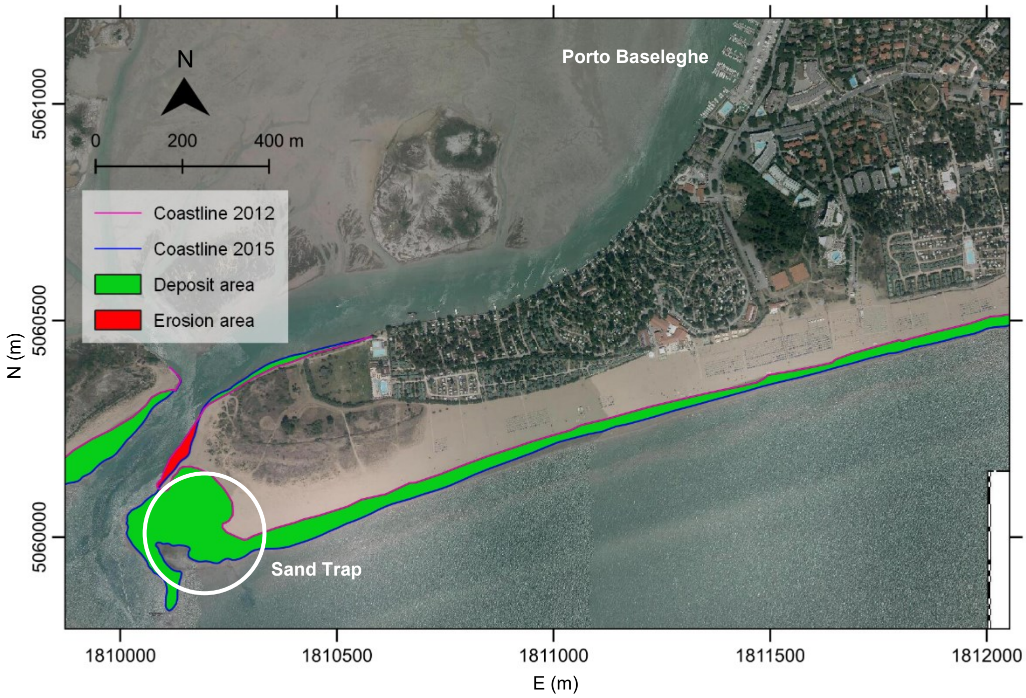

Figure 97 Porto Baseleghe, 2015 orthophoto.

Upstream of the Mouth of Porto Baseleghe there is a sand trap. The sand trap serves to remove sand and coarse particles from the water. When the water passes through the sand trap, the water will be slowed down and the heavier particles can fall to the bottom [19]. The sand trap was made in 2006 with the aim of intercepting the sands before they deposited in Porto Baseleghe.

5.1.2 Cell VE1: time interval 2015-2018

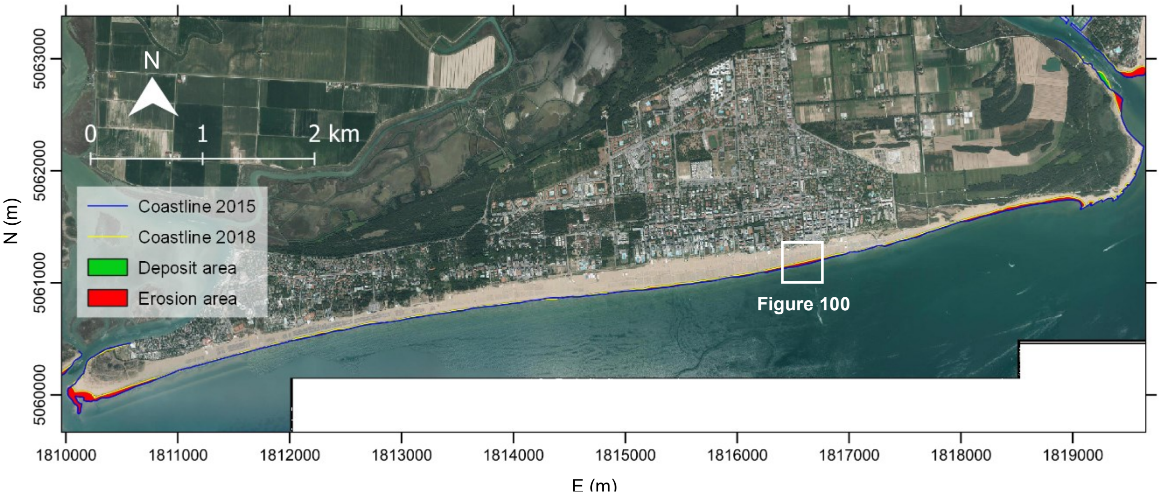

Figure 98 Cell VE1, 2018 orthophoto.

The trend changes completely respect to years 2012-2015 (Figure 98). Showing a prevailing tendency to erosion with a medium rate of -3.5 m/yr but also with picks of -20 m/yr. The value of erosion area of cell VE1 is the greatest among all cells in the time interval 2015-2018.

The first section of the coastline on the right at the Mouth of the Tagliamento River manifests a significant tendency to retreat, reflecting the fact that the fluvial solid input is insufficient to maintain the current configuration of the river delta (Figure 99).

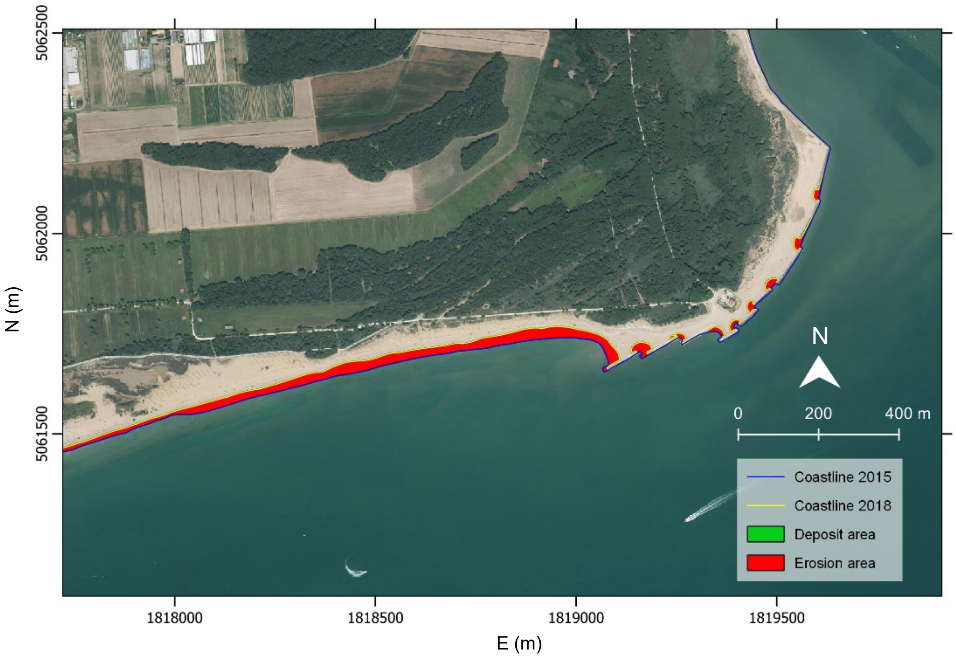

Figure 99 Bibione lighthouse, 2018 orthophoto.

Erosion prevails also going South toward Bibione and Porto Baseleghe. With a maximum retreating distance of -26.4 m (Figure 100). The distance medium value between 2018 and 2015 coastlines is -10.8 m.

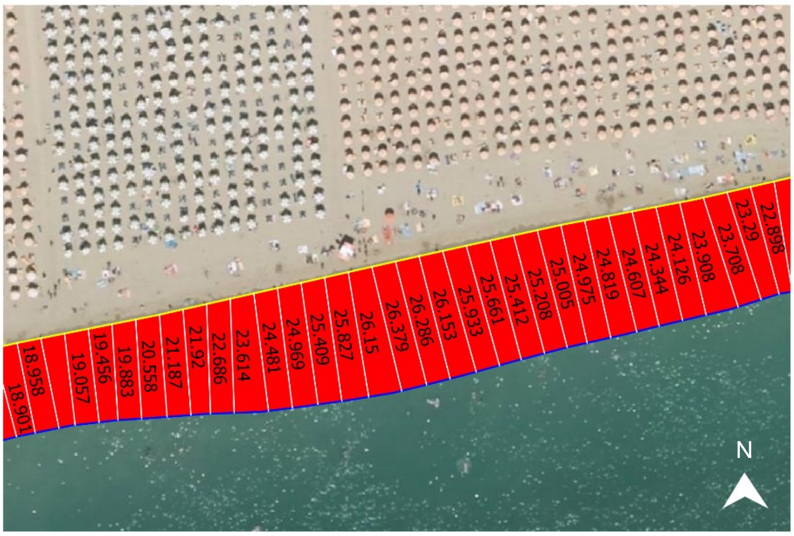

Figure 100 Bibione's coast with indication of perpendicular distances between coastlines of 2015 (blue) and 2018 (yellow), 2018 orthophoto.

The coast located on the mouth of Canale dei Lovi shows a completely different behavior respect to the previous years 2012-2015 (Figure 101). Periodic artificial beach nourishment is carried out in the area to counter beach erosion.

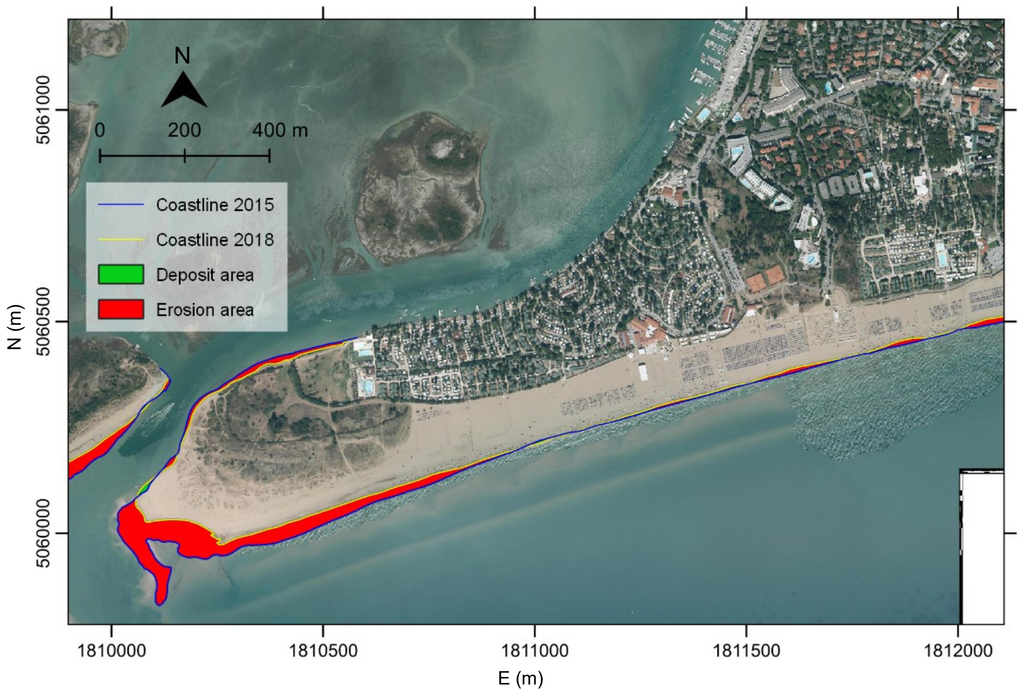

Figure 101 Porto Baseleghe, 2018 orthophoto.

The observed behavior is very different in 2015-2018 respect to 2012-2015. Considering what we have seen up to this point, it can be said that the coast of cell VE1 is not stable.

5.2 Cell RO7

The stretch of coastline between Busa di Scirocco and Busa Storiona extends for about 7 km. The shoreline of this cell is not continuous, being interrupted by Busa Canarin and the mouth of Busa Bastimento (Figure 103).

Figure 102 Bastimento beach. (Source: R. Ferraris)

This stretch of coast has a strong environmental and naturalistic value (Figure 102), in fact it is part of the Po Delta Regional Park.

Cell RO7	2012 - 2015	2015 - 2018
Deposit area	25311 m^2	20237 m^2
Erosion area	110674 m^2	95235 m^2

Table 5 Areal variation of cell RO7.

5.2.1 Cell RO7: time interval 2012-2015

Figure 103 Cell RO7, 2015 orthophoto.

In the vicinity of Busa Scirocco, before 2012, a reef was built (Figure 104, red line) in order to contrast the erosion phenomenon. The reef is completely buried in the inside and induces, on the sea side, the formation of an accumulation zone, which is better visible in the orthophoto of 2018, Figure 108. The erosion phenomenon is significant in the northern part of cell RO7, for this reason, a groin was built after 2012 (see the green line in Figure 104) in order to contribute to the future accumulation of sand.

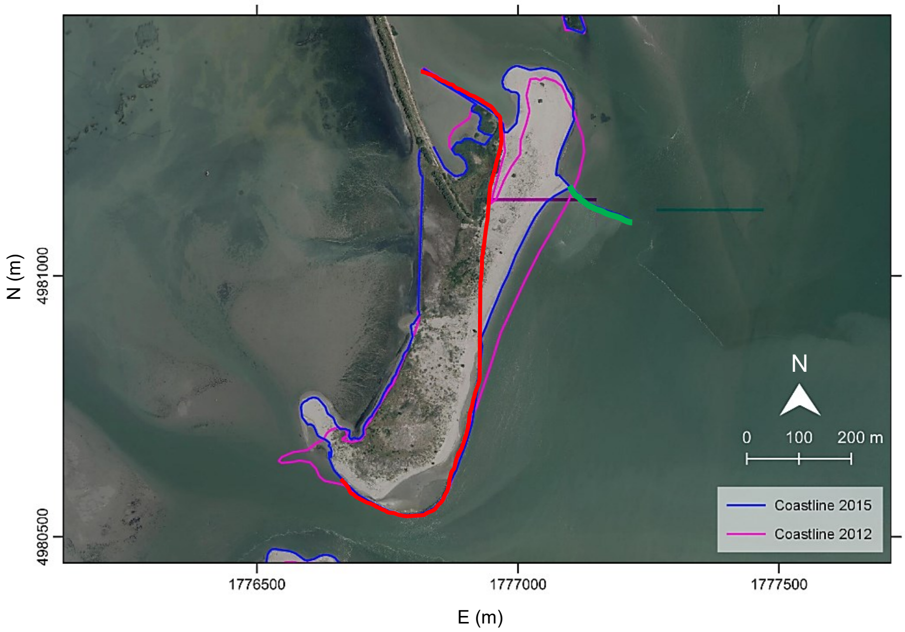

Figure 104 Coastal zone between Busa di Scirocco and Busa Canarin, 2015 orthophoto. The location of the stone reef is indicated with the red line.

About the part of the littoral cell between Busa Canarin and Busa Storiona, a retreat is found along all of it.

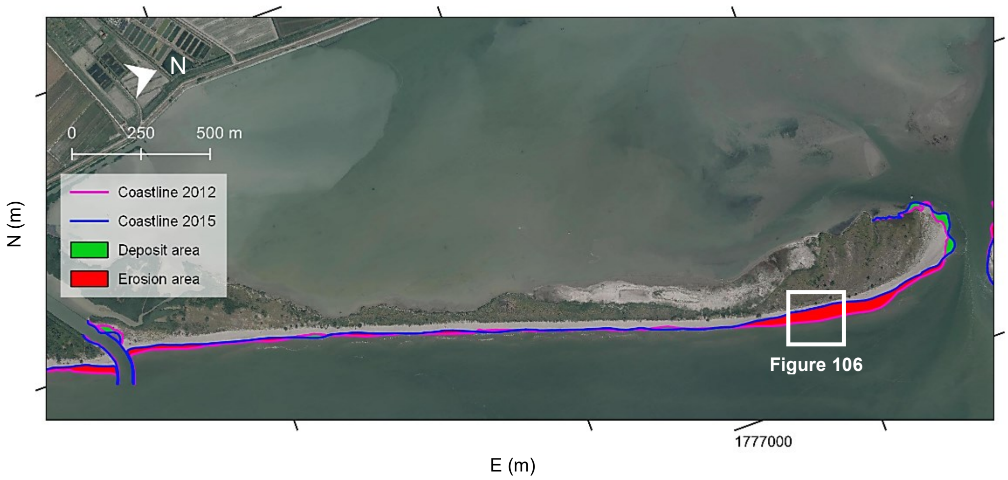

Figure 105 Coastal zone between Busa Canarin and Busa Bastimento, 2015 orthophoto.

In particular, between Busa Canarin and Busa Bastimento (Figure 105) the erosion area is about 37400 m^2 with a maximum retreating distance of -50 m in the northern end (Figure 106). This part shows a medium erosion rate of -3.8 m/yr.

Figure 106 Indication of perpendicular distances between coastlines of 2012 (pink) and 2015 (blue), 2015 orthophoto.

Moving south, we encounter the last island (Figure 107), which ends with Busa Storiona.

Docks made of stone have been built in order to protect the coast (Figure 108). Unfortunately this defensive work points out some issues, since erosion processes still take place.

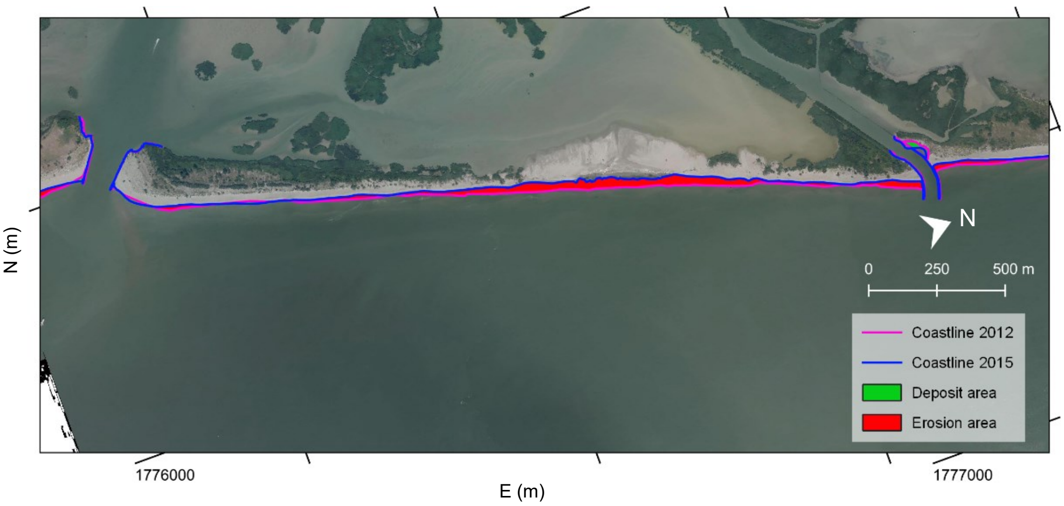

Figure 107 Coastal zone between Busa Bastimento and Busa Storiona, 2015 orthophoto.

In this last section of cell RO7 (Figure 107), the erosion area accounts for 49950 m^2, while the accretion area is only 1823 m^2.

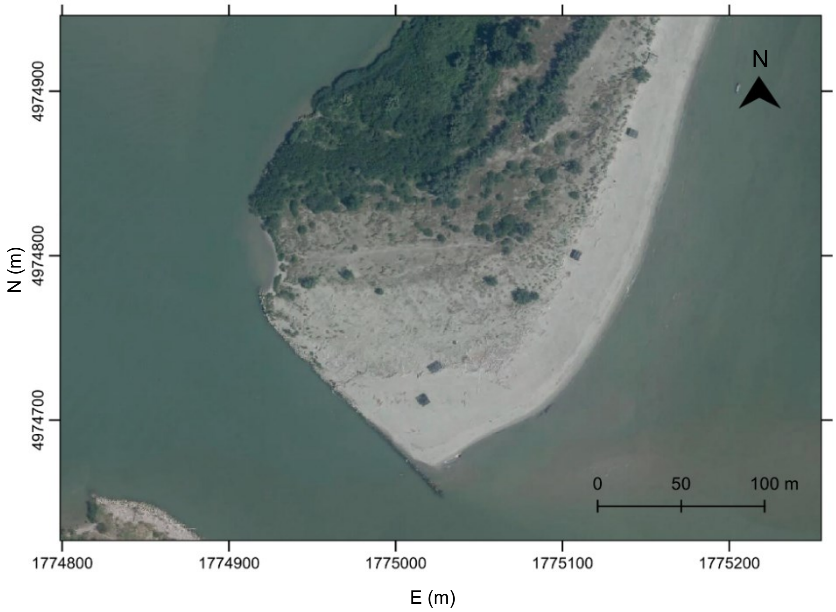

Figure 108 Southern end of cell RO7, 2015 orthophoto.

5.2.2 Cell RO7: time interval 2015-2018

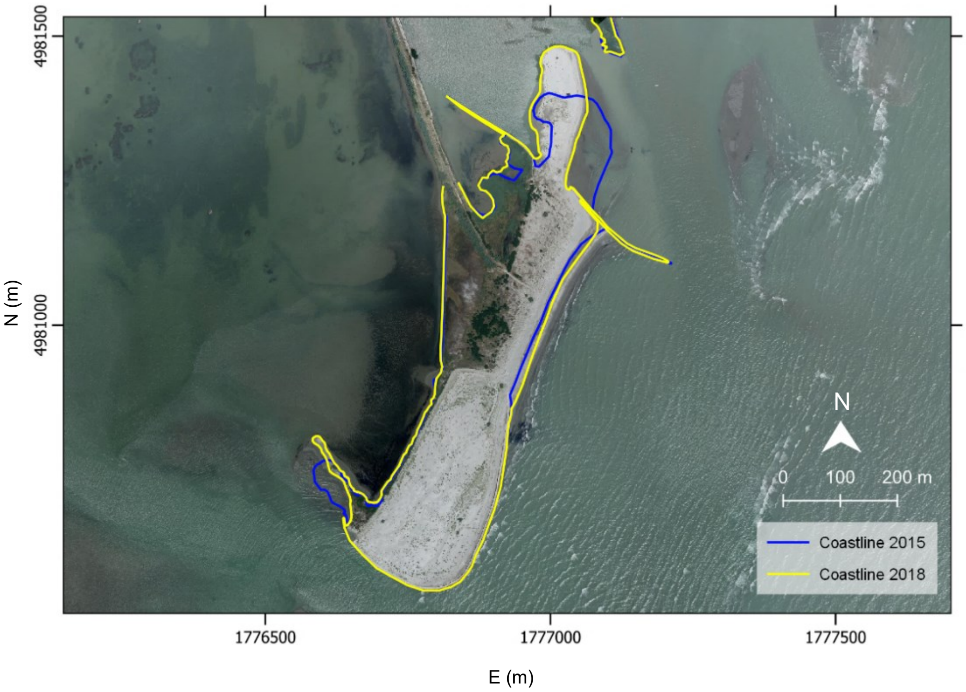

Figure 109 Coastal zone between Busa di Scirocco and Busa Canarin, 2018 orthophoto.

Considering the first section of cell RO7, from Busa di Scirocco to Busa Canarin, it is evident that the previously constructed stone reef (indicated with the red line in Figure 104) helped the accumulation of sands in the most recent years (Figure 109).

The behavior of the coast of cell RO7 hasn't changes, the erosion process is still the main phenomenon but slightly less strong than in the past three-year period.

As for the section between Busa Canarin and Busa Bastimento (Figure 110), the erosion area is 42156 m^2 with a maximum retreating distance of -32 m^2.

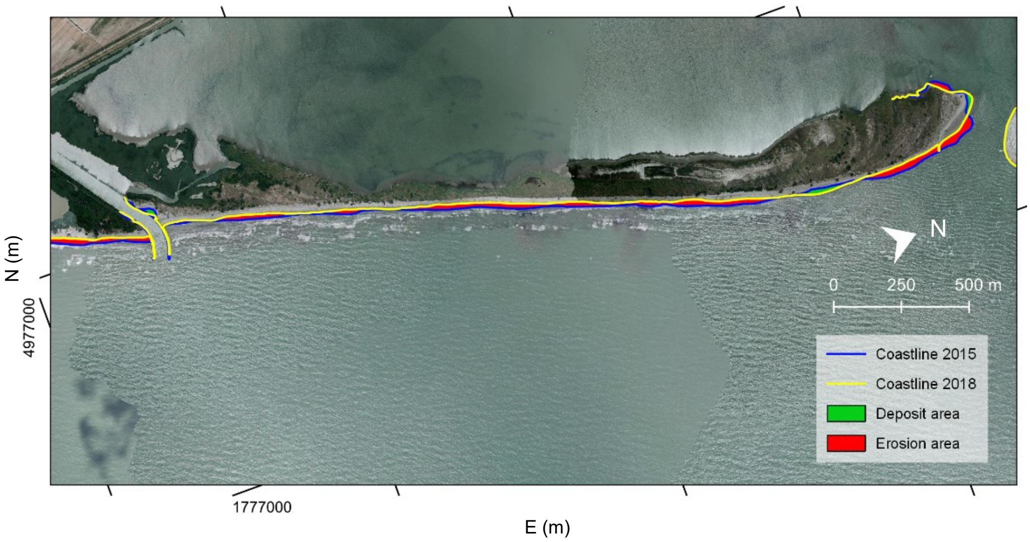

Figure 110 Coastal zone between Busa Canarin and Busa Bastimento, 2018 orthophoto.

Same considerations apply to the last section (Figure 111) of cell RO7. Here the erosion area is 40115 m^2.

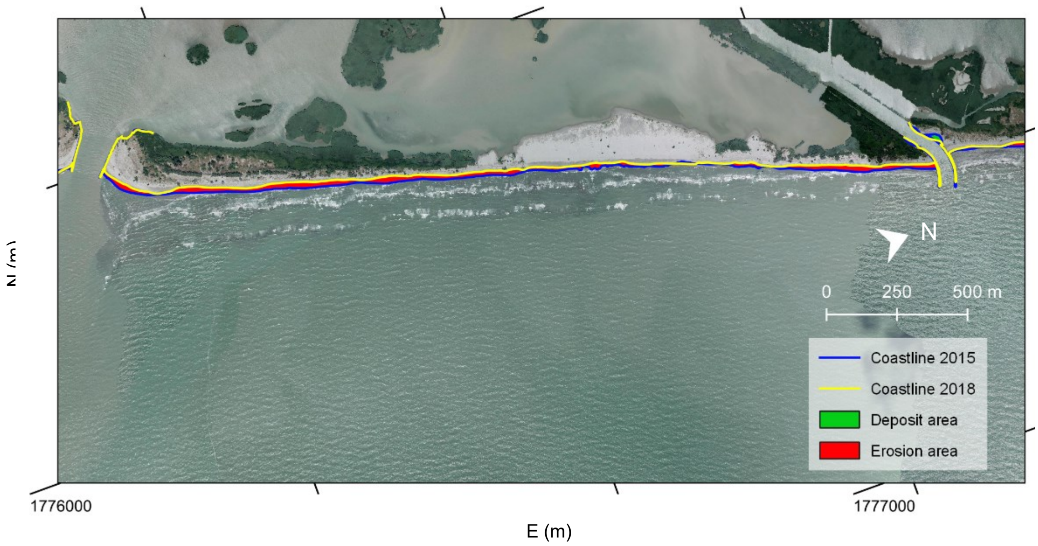

Figure 111 Coastal zone between Busa Bastimento and Busa Storiona, 2018 orthophoto.

5.3 Cell RO9

The stretch between Po di Tolle and Po di Gnocca bounds the Sacca di Scardovari from the sea. The lagoon behind it, which is of great environmental importance, is part of the Po Delta Regional Park.

Figure 112 Conchiglie beach. (Source: A. Bonelli)

This coastal cell is composed of three distinct stretches: the Conchiglie beach (Figure 112), the scanno to protect Sacca Scardovari and the area on the hydrographic left of the Po di Gnocca mouth.

Cell RO9	2012 - 2015	2015 - 2018
Deposit area	178074 m^2	158963 m^2
Erosion area	56433 m^2	78227 m^2

Table 6 Areal variation of cell RO9.

In this cell, it was recorded the highest deposit value in the three-year period 2015-2018.

5.3.1 Cell RO9: time interval 2012-2015

As mentioned in the previous paragraph, cell RO9 can be analyzed, dividing the area into three parts (Figure 113). Going north to south we first encounter the Conchiglie beach, then the Scanno that protects Sacca Scardovari and finally the area next to the Po di Gnocca mouth.

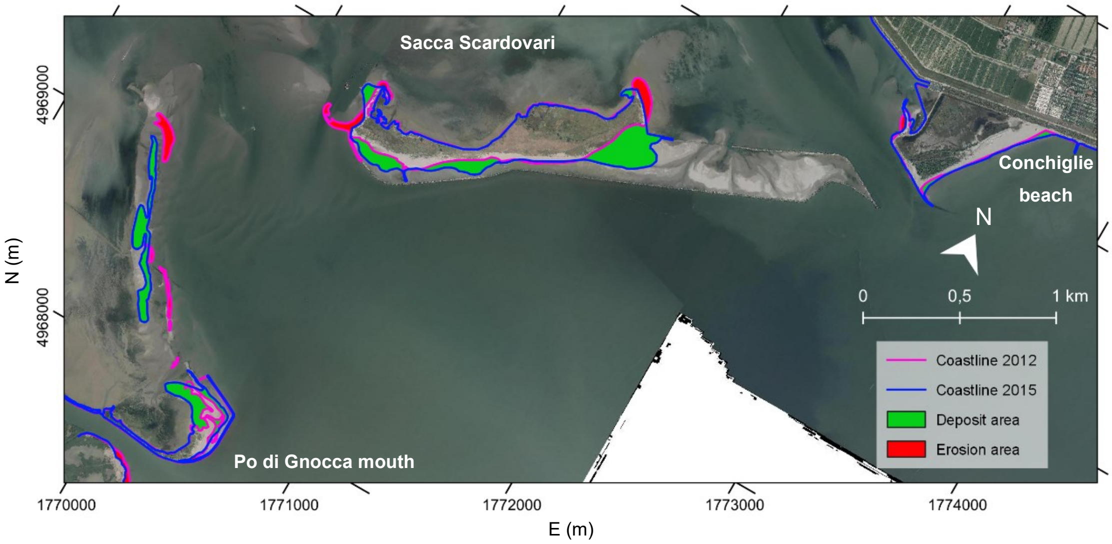

Figure 113 Cell RO9, 2015 orthophoto.

The first part includes the Conchiglie beach, a beach equipped for bathing use (Figure 114).

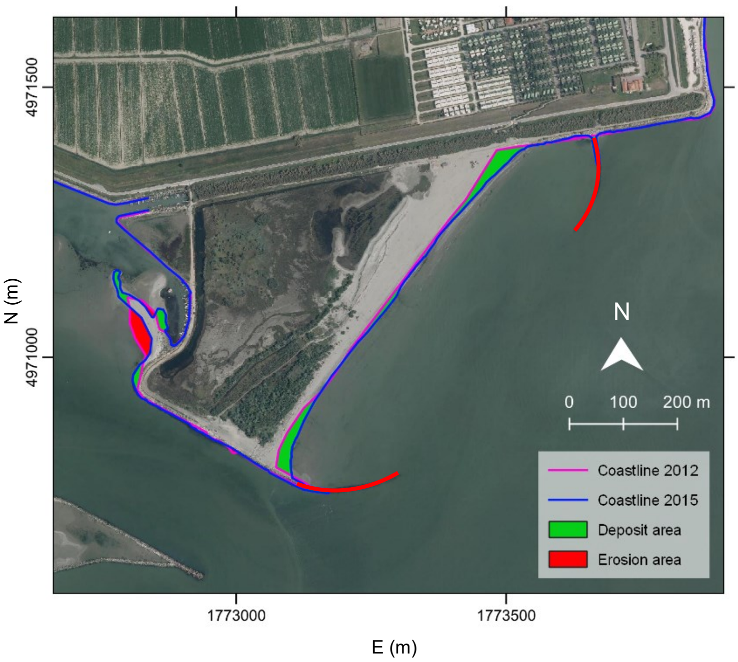

Figure 114 Conchiglie beach, the red lines represent the stone reefs, 2015 orthophoto.

Before 2012, a strong erosion trend was observed in this area. This phenomenon was probably due to the presence of the Po di Tolle reef. This stone reef moved away sediments transported offshore and did not favor deposition in this area.

Two submerged reefs at either end of this small stretch were completed in 2014 [7] (see red lines in Figure 114). It is possible to appreciate the change in trend that happened in the years 2012-2015, in fact erosion is not long happening in this part of cell RO9. The two stone reef worked efficiently. The deposit area accounts for 7270 m^2.

The second stretch is the scanno that protects Sacca Scardovari, a lagoon of considerable environmental and fishing interest, where there are numerous shellfish farms (Figure 115).

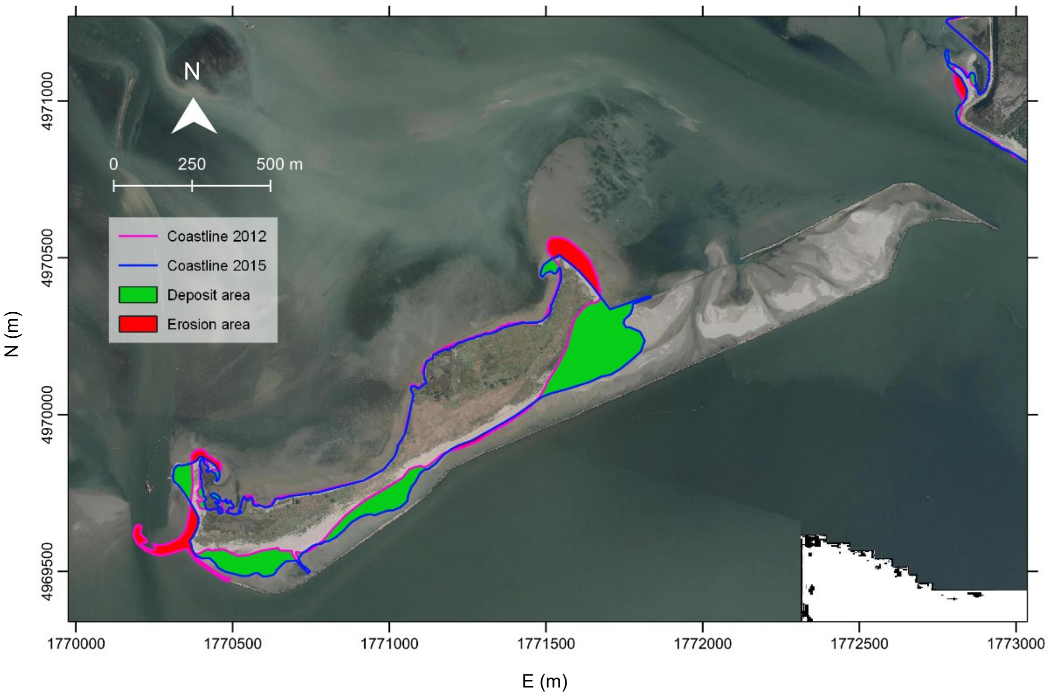

Figure 115 Scanno that protects Sacca Scardovari, 2015 orthophoto.

Observing the evolution that took place in the past, the fragility that characterizes this scanno is evident, it shows rapid morphological evolution. From the variation of the shoreline, it could be observed how the island migrated southwest over the different years taking on different conformations, also as a result of numerous anthropic interventions. In the late 1990s, two reefs were built and later an additional protective reef was built in front of the scanno, which stiffened its position [7].

The reef worked, in fact from 2012 to 2015 deposition was the main phenomenon with an accretion area of 98425 m^2.

Moving south, we encounter the Po di Gnocca mouth, and the area located on the hydrographic left is protected by a stone cliff built in 2008 (Figure 116).

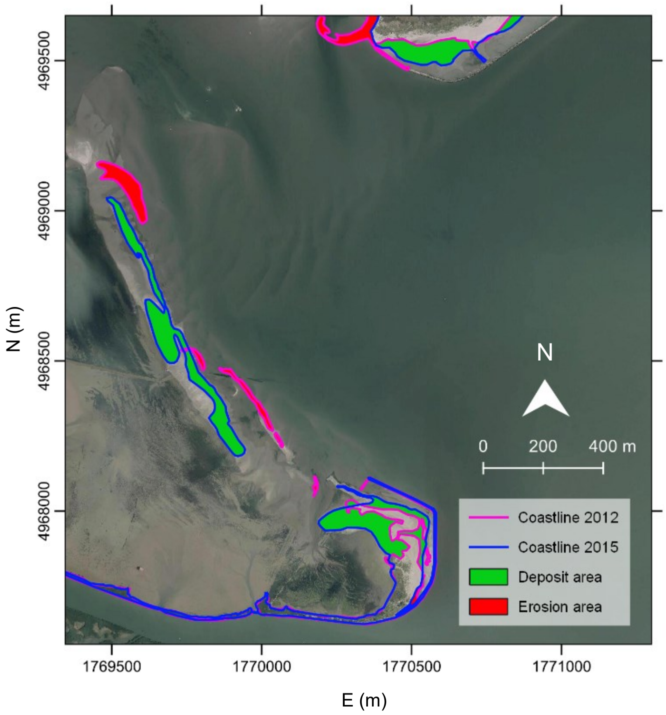

Figure 116 Po di Gnocca zone, 2015 orthophoto.

This last stretch of coast is very unstable and fragile, subjected to rapid morphological evolution.

5.3.2 Cell RO9: time interval 2015-2018

Cell RO9 presents the highest value of deposit area in this time interval (Figure 117).

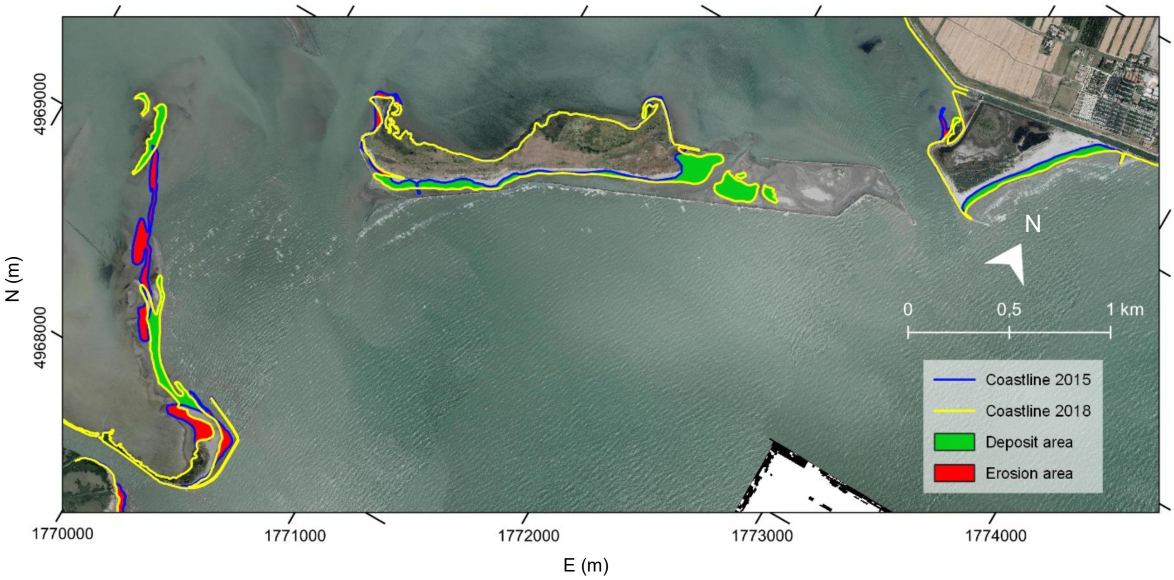

Figure 117 Cell RO9, 2018 orthophoto.

Observing both Conchiglie beach and the scanno in front of Sacca Scardovari it is easy to see how the stone reefs built in the past played a key role in protecting the coast and promoted also sedimentation.

About the Conchiglie beach (Figure 118), the deposit area measures 24774 m^2.

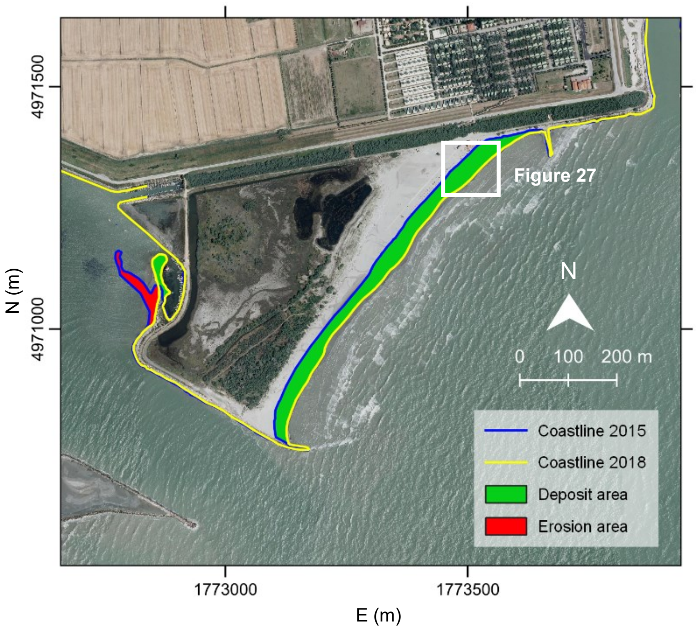

Figure 118 Conchiglie beach, 2018 orthophoto.

The medium rate of deposit in this first zone is +8.8 m/yr with picks of +13.3 m/yr. The maximum accretion distance measures +40 m (Figure 119).

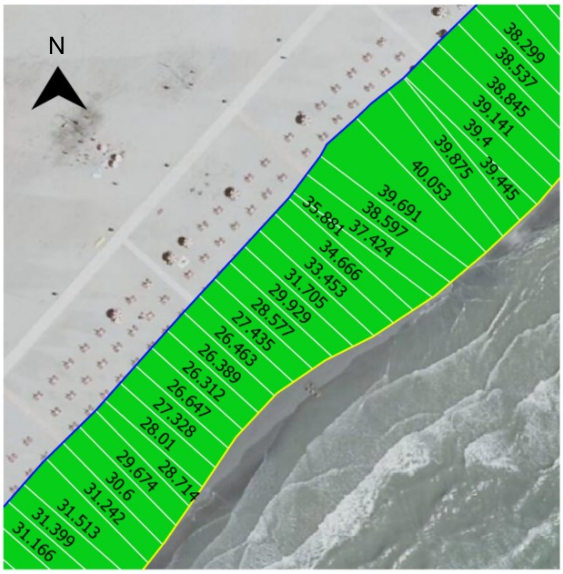

Figure 119 Indication of perpendicular distances between coastlines of 2015 (blue) and 2018 (yellow), 2018 orthophoto.

The trend looks stable, accretion is still the main phenomenon since 2012.

Going south (Figure 120), the scanno shows again a coastal advancement, demonstrating that the protective reef plays an important role. The deposit area is 83599 m^2.

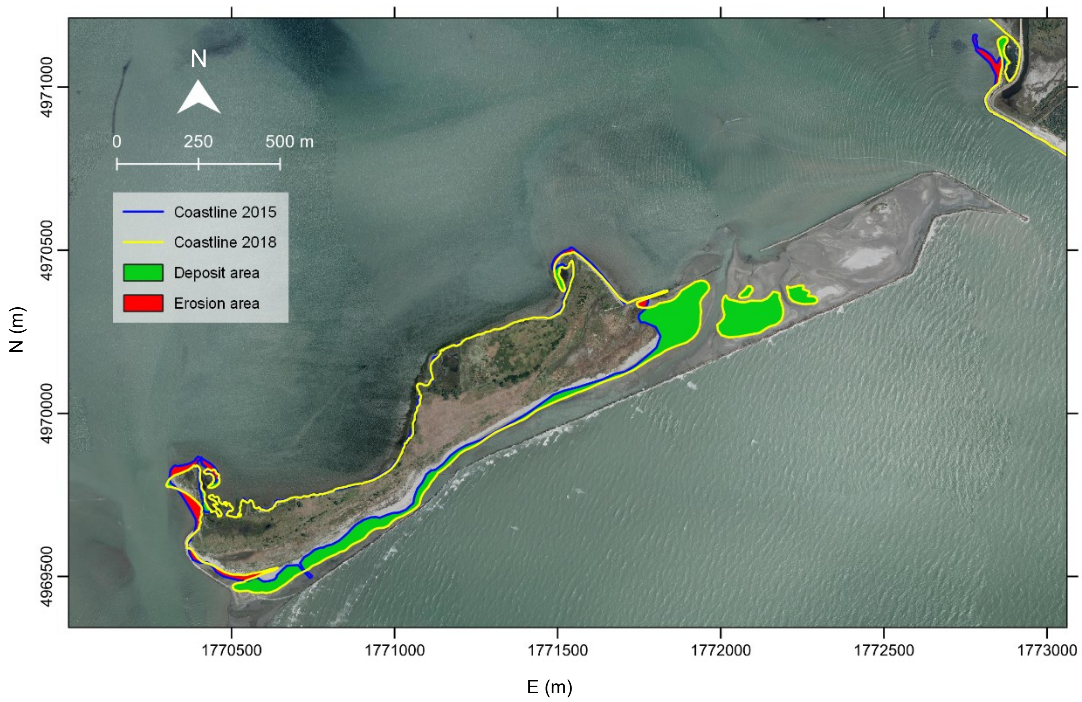

Figure 120 Scanno that protects Sacca Scardovari, 2018 orthophoto.

Finally, in the last part of cell RO9, there is the last stretch of coast which, as previously stated, is very unstable and fragile (Figure 121). The deposit area measures 49801 m^2, while the erosion area is 60864 m^2.

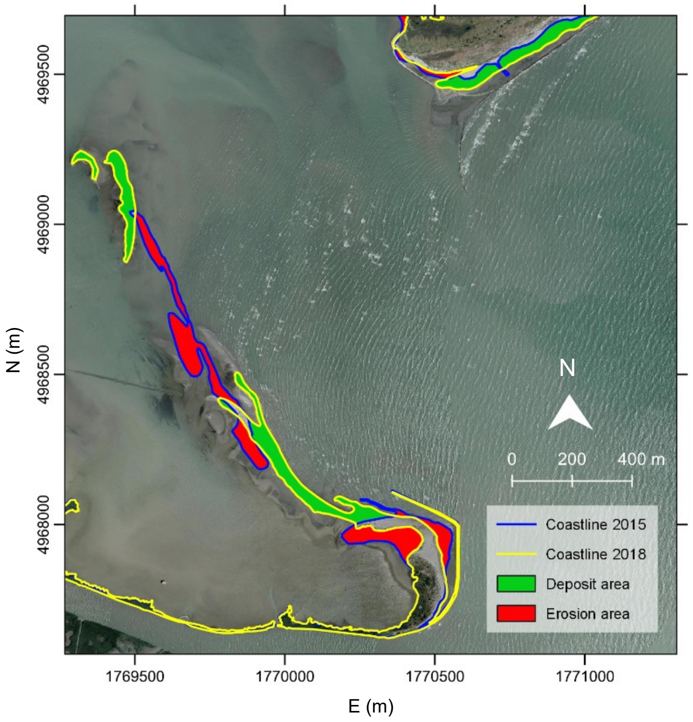

Figure 121 Po di Gnocca mouth, 2018 orthophoto.

6. Conclusions

Beach morphology and long-term shoreline changes derive from the sum of natural phenomena and anthropic activities. The coastal shoreline is the indicator traditionally used to define the trend of the sandy coasts, highlighting depositional or erosional phenomena [4].

In beaches subject to anthropic activities like those of the Northern Adriatic coast, this interpretation becomes challenging, because shorelines migrate landward or seaward depending not only on changing sea-level or sediments' transport, but also on nourishment carried out periodically for beach protection. In order to use beaches for tourism it is fundamental to preserve their width. Therefore, monitoring morphological beach changes and coastline evolution trends is necessary to plan efficient maintenance work as well as replenishment and constructing engineering structures to avoid coastal drift.

This study provides a general picture of the condition of the Veneto coast, based on the comparison of the shorelines of years 2012, 2015 and 2018.

In order to make this comparison, it was necessary to draw the ground-sea transition line from multi-temporal digital orthophotos using the QGIS software and perform calculation using the methodologies described in chapter 3. QGIS proved to be an excellent tool for line drawing and calculation of area variation between two coastlines, while it presented limitations in calculating perpendicular distances between lines, especially when coastlines are highly irregular.

In the key phase of this study, the 20 cells into which the Veneto coast was divided are considered, and for each of them, on the basis of the elaborations and measurements carried out and the information gathered in the documents provided by the Veneto Region, the recent evolutionary trends are highlighted.

Regarding the province of Venezia, it is observed that in the period 2012-2015 the predominant trend is accumulation with an area of 1107687 m^2, while in the period 2015-2018 a prevalence of erosion phenomenon is observed, with an area of 439226 m^2.

Considering the province of Rovigo, the values of erosional and depositional areas are much more close. In the period 2012-2015, the main phenomenon is accumulation with an area of 737859 m^2, while, between 2015 and 2018, erosion prevails with an area of 555930 m^2.

The study also focuses on those cells that showed the highest values of erosional and depositional areal variations. The cells with the greatest deformations of shoreline are VE1, RO7 and RO9.

Hereafter, some of the weaknesses of this study are mentioned. As previously stated, the study is based on the comparison of coastlines traced on orthophotos and it's important to consider the possible presence of these errors: the georeferencing of the orthophoto in the software, the accuracy of the orthophoto (pixel size), the sensibility of the user who drew the line and also the possible presence of high or low tide when the orthophoto was taken.

It is quite clear that the resulting coastlines traced on the orthophotos and the areal values obtained using QGIS software are not intended to, nor can they, take the place of punctual and specific surveys, which will have to be carried out at a much larger scale.

The shoreline is constantly changing therefore geomatic methodologies are fundamental because allow to acquire important geographic information that can be analyzed in laboratory. The methodologies and instruments used for this thesis have produced a good result for an initial overview of the coastal status and evolution. This first global analysis can then be integrated with detailed surveys that provide more precise results.

To study the coastline, it is necessary to understand, and to understand, it is necessary to manage and thus govern the future as much as possible in order to preserve the coastal zone [20].

7. References

[1] D. Bartlett and J. Smith, *GIS for Coastal Zone Management*. CRC Press, 2004.

[2] M. K. Ghosh, L. Kumar, and C. Roy, "Monitoring the coastline change of Hatiya Island in Bangladesh using remote sensing techniques," *ISPRS J. Photogramm. Remote Sens.*, vol. 101, pp. 137–144, 2015, doi: 10.1016/j.isprsjprs.2014.12.009.

[3] J. G. Gibb, "Rates of coastal erosion and accretion in New Zealand," *http://dx.doi.org/10.1080/00288330.1978.9515770*, vol. 12, no. 4, pp. 429–456, 2010, doi: 10.1080/00288330.1978.9515770.

[4] A. Zanutta, A. Lambertini, and L. Vittuari, "UAV photogrammetry and ground surveys as a mapping tool for quickly monitoring shoreline and beach changes," *J. Mar. Sci. Eng.*, vol. 8, no. 1, 2020, doi: 10.3390/JMSE8010052.

[5] M. Fabris, "Monitoring the coastal changes of the Po River Delta (Northern Italy) since 1911 using archival cartography, multi-temporal aerial photogrammetry and LiDAR data: Implications for coastline changes in 2100 A.D.," *Remote Sens.*, vol. 13, no. 3, 2021, doi: 10.3390/rs13030529.

[6] M. Fabris, "Coastline evolution of the Po River Delta (Italy) by archival multi-temporal digital photogrammetry," *Geomatics, Nat. Hazards Risk*, vol. 10, no. 1, pp. 1007–1027, 2019, doi: 10.1080/19475705.2018.1561528.

[7] P. Ruol, L. Martinelli, and C. Favaretto, "Studio e monitoraggio per la definizione degli interventi di difesa dei litorali dall'erosione nella Regione Veneto," 2016.

[8] M. Klein and M. Lichter, "Monitoring changes in shoreline position adjacent to the Hadera power station, Israel," *Appl. Geogr.*, vol. 26, no. 3–4, pp. 210–226, Oct. 2006, doi: 10.1016/J.APGEOG.2006.01.001.

[9] ISPRA Ambiente, "Mare e ambiente costiero," 2011.

[10] Arpav Veneto, "Acque marino costiere," 2021. https://www.arpa.veneto.it/temi-ambientali/acqua/acque-marino-costiere (accessed Oct. 12, 2022).

[11] G. Fontolan, A. Bezzi, D. Martinucci, S. Pillon, and C. Popesso, “GCV - Geodatabase gestionale delle coste venete,” 2014.

[12] U. Simeoni and C. Corbau, “A review of the Delta Po evolution (Italy) related to climatic changes and human impacts,” *Geomorphology*, vol. 107, no. 1–2, pp. 64–71, Jun. 2009, doi: 10.1016/J.GEOMORPH.2008.11.004.

[13] G. Fontolan, “Criteri di intervento e opere di difesa dei litorali.” Università degli Studi di Trieste, 2016.

[14] Map@Syst, “What is an orthophoto? – Geospatial Technology,” 2019. https://mapasyst.extension.org/what-is-an-orthophoto/ (accessed Oct. 19, 2022).

[15] M. Fabris, “Notes of the Course ‘Land Surveying and Graphical Information System GIS.’” 2020.

[16] Regione del Veneto, “Ortofoto digiltali a colori,” 2018. https://www.regione.veneto.it/web/ambiente-e-territorio/ortofoto (accessed Oct. 19, 2022).

[17] QGIS Official Website, “Discover QGIS,” 2022. https://www.qgis.org/en/site/about/index.html# (accessed Oct. 19, 2022).

[18] F. Pieri, “Tutorial QGIS 1: l’evoluzione dell’informazione geografica e il GIS open source – openoikos,” 2016. https://www.openoikos.com/blog/le-basi-di-qgis-levoluzione-dellinformazione-geografica-e-il-gis-open-source/ (accessed Oct. 19, 2022).

[19] Ministry of Environment of Denmark, “Sand traps,” *Climate Change Adaption*, 2014. https://en.klimatilpasning.dk/knowledge/technologies/normal-rainfall-and-cloudbursts/sand-traps/ (accessed Nov. 02, 2022).

[20] J. Camp, E. Flo, A. Rene, and N. Sampedro, “Studying the coastline. Understanding the border,” *Ocean we want*, pp. 154–155, 2022.