UNIVERSITÀ DEGLI STUDI DI PADOVA

Second Cycle Degree in Environmental Engineering
ICEA Department

Master Thesis

Alberto Frascari

QUALITATIVE MAPPING AND CHARACTERIZATION OF SALTWATER INTRUSION IN CHANNELS AND RIVERS OF THE VENICE LAGOON, SOUTHERN BASIN

Supervisor
Prof. Paolo Salandin

Academic Year 2013-2014

INDEX

Introduction

The Venice lagoon is the largest lagoon in Italy, and the most important survivor of the system of lagoons, which in Roman times characterized the upper Adriatic coast from Ravenna to Trieste. Bounded by the Sile River to the North and the Brenta River to the South, the Venice Lagoon is oblong and arched in shape.

The coastland surrounding the southern Venice Lagoon is a precarious environment, which is subject to both natural changes and anthropogenic pressure. In historical times, human intervention, going from the diversion of tributaries to more recent rash groundwater exploitation, has reversed the natural evolutionary trend, favoring the deepening of the lagoon and seriously modifying the morphological setting of the environment. Most of these territories, which were completely reclaimed at the beginning of the last century, are mechanically drained by pumping stations to make agricultural activity possible.

A number of critical problems affecting the coastal plain, lying almost completely below the mean sea level (4 m b.s.l), are analyzed in this study, i.e. sea-level rise, land subsidence, coastal erosion, flooding, encroachment of salty water from the mouth of the river network and salinization of groundwater and soils.

The combined effect of sea level rise, land subsidence and overexploitation of groundwater has enhanced the saltwater contamination of water resources and soils with serious environmental and socio-economic impacts, (i.e. farmland productivity).

After an accurate description of the hydrological, geomorphological and bathymetric characteristics of the investigated area, the study presents in details the EC instrumentation setting and the monitoring strategies, pointing out the salinity distribution on the territory.

Afterward, the collected data are presented and discussed: some possible relations between the observed values and results from other researches and monitoring networks (Carbognin and Tosi, 2003; De Franco et al., 2009; Mulligan et al., 2007; Teatini et al., 2011; Villatoro et al., 2010a) are investigated.

This report was therefore performed with the aim to study saltwater intrusion processes and dynamics in the Venetian region, in order to improve the knowledge of this complex hydraulic basin and underline the importance of the monitoring issues.

CHAPTER 1

Cartographic analysis of the studied area

1.1) Origin and evolution of the Venice lagoon

The Lagoon of Venice is the largest lagoon in the Mediterranean and is located in the northern Adriatic Sea (45°N, 12°E). It extends for about 50 km along the coast and has an average width of 15 km. It was originated nearly 6000–7000 years ago during the Flandrian transgression, when the rising sea flooded the upper Adriatic Würmian paleo-plain and outlined the coast in approximately the present position (Gatto and Carbognin, 1981).

The ancient lagoon was smaller respect to the present one and the exchange of its waters with the sea occurred through eight inlets, against the three that it has now. Originally, two main factors affecting the lagoon basin: i) the continuous sediment supply from the tributaries: Adige, Bacchiglione, Brenta, Sile and Piave rivers flowing into the lagoon, so that the filling was greater than the natural subsidence and the eustatic sea level rising; ii) the noticeable coastal nourishment, also coming from the Po river to the South, that led to a gradual silting-up of the tidal inlets (Branbati et al., 2003).

These two processes would inevitably lead to the disappearing of the lagoon basin. Venetians, considering the lagoon as a source of security against enemies and strategic power with its channels and port, began to carry out several hydraulic works to preserve it. They worked out in order to avoid the lagoon being a marshland, the first major intervention was the diversion of its major fluvial tributaries towards the sea to avoid sediment input into, this manmade operation also induced an important reversal trend in the natural evolution of the entire lagoon modifying the setting of the drainage basin.

In the southern Venice watershed, these processes were triggered in the 1540 by the diversion of the lower course of the Brenta and Bacchiglione rivers system into the Adriatic Sea in the south of the lagoon (Figure 1) (Tosi et al., 2009).

These works, in addition to reducing silting , had three main consequences on the lagoon: a) the salinity progressively increased, as a result of the reduced freshwater load ; in fact at present, most of the lagoon has salinity values of the same order of magnitude as those measured in the Adriatic Sea (30-33‰) except in the area near the inner coast; b) the nutrient loads, and particularly that of phosphorus, decreased as a consequence of the reduced input from the terra firma and c) the reduced silting no longer compensated for the subsidence rate, so that the mean depth of the lagoon and the erosion increased and the lagoon bottom became more flattened (Ravera 2000).

The Lagoon of Venice, like most lagoons, is liable to major and sudden variations and, consequently, its equilibrium is permanently unstable. This is the cause of its great changes, evolving either into a marine bay or, by a natural succession, through a salt-marsh environment, to dry land.

As a consequence, on the geological scale, the life of a lagoon is always rather short. Indeed, the load of solid material discharged into the lagoon from its tributaries would bury it or, if the violence of the sea exceeded the solid load from the watershed, the sandbars protecting the lagoon would be demolished and the lagoon transformed into a marine bay. This would be the fate of the Lagoon of Venice without the uninterrupted work undertaken by the Serenissima Republic of Venice to arrest the processes of the natural succession. Thanks to this work, the lagoon has maintained its identity through the centuries (Ravera 2000).

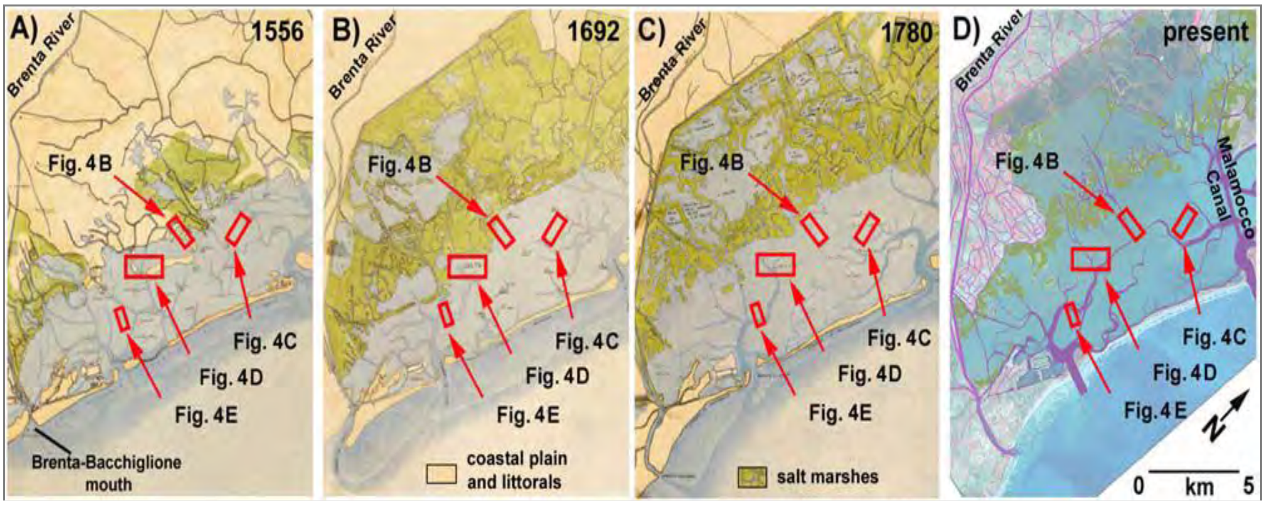

Figure 1: (A–D) Schematic evolution of the southern lagoon basin from 1556 to the present, (Tosi et al., 2009).

An important study (Tosi et al., 2009) reconstructed the stratigraphic framework of the lagoon using a Very High Resolution Seismic (VHRS) system, as is shown in the (Figure 2).

The seismic profile underline a complex Holocene sequence due to changes in the sediment supply rates from rivers mouths and in relative sea level rise (Figure 2a). In Figure 2b, seismic reflectors indicate the presence of two Pleistocene fluvial channels down to about 15 m depth. Complex channelized sequences including vertical and lateral changes in seismic faces occur both in the late Pleistocene and Holocene successions, and are signs of continual high hydrodynamics.

An example of buried channel-levee systems (Unit H2) is shown in Figure 2c and it evidence the presence, at least two thousand years ago, of the Brenta river that were active during the Roman Empire and until the Late Middle Ages. Other signs of the presence of Brenta river courses in the lagoon and the formation of deltaic systems are given in Figure 2d, where a buried, and superficial Holocene channel-levee is recognizable within Unit H2.

Finally, in the Figure 2e, is represented the detailed architecture and evolution of the tidal channels that is composed of two distinct phases. The first, characterized by a vertical sequence of channel-fill deposits, is representative of aggradation, whereas the second, more recent one (Unit H3) demonstrates the lateral migration of the channel.

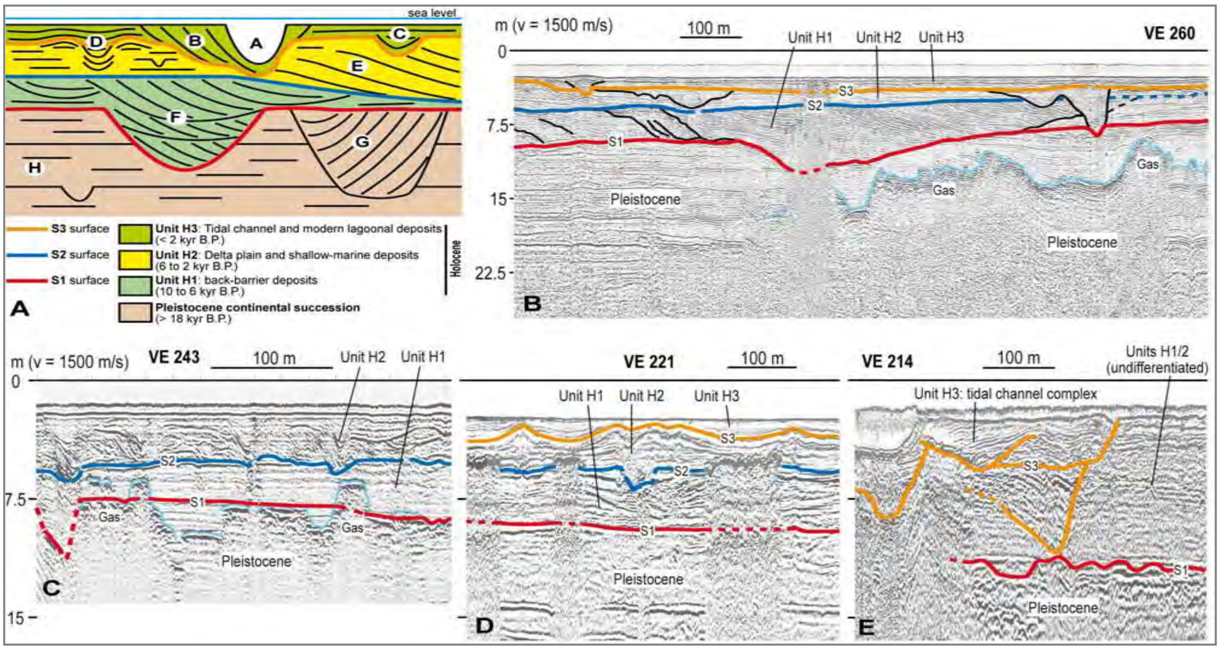

Figure 2: (a) Simplified architectural scheme of the Holocene deposits in the southern Venice Lagoon. Unit H1 represents the transgressive sequence, whereas Unit H2 is the regressive sequence. Unit H3 consists of sediments deposited during the recent human-induced transgression that followed delta abandonment. A-Active tidal channel; B-Lateral accretion; C-Buried tidal channel; D-Channel-levee system; E-Clinoforms; F-Early Holocene estuarine and fluvial channels; G-Pleistocene river; H-Pleistocene alluvial plain. (b) Late Pleistocene and Holocene complex channelized sequences. (c) Holocene inactive tidal channel fill system. (d) Holocene inactive channel-levee system. (e) Migration of a Holocene tidal channel complex system.

The lagoon development, as demonstrated before, has been subjected to a complex combination of natural processes and human interventions, such as land subsidence, eustacy, salt water intrusion, sea floor erosion, river diversions, and inlet and channel dredging (Tosi et al., 2009). These changes were decisive to enhance the lagoon hydrodynamics, accelerating erosion and modifying the flora and fauna habitat.

In the present lagoon, since the Brenta river flows into the Adriatic sea, subsidence and erosion prevail over deposition; as a result, a tidal flat persists and the channel network is more developed and necessarily than in the past.

So the final environment is mainly composed by salt marshes, shallows (0.5–1 m deep), and few deeper channels connecting the inner lagoon to the Adriatic Sea through the Chioggia inlet.

The lagoon bottom is usually characterized by a 1–2 m thick unconsolidated silty–sandy layer, sometime rich in organic matter, below which the clay and sand alternation is correlated with the regional faces.

From the lagoon bottom down to 30–40 m depth semi-impervious lenses confine only locally the groundwater flow.

1.2) Geological and morphological setting

From the geological point of view the sedimentary sequence down to 100 m deep is related to the Late Pleistocene (110000– 100000 years BP) and Holocene depositional events representing the uppermost part of the Venice mainland. These deposits are generally composed of inter-bedded sandy and silty layers with abundant shells and are characterized by various faces related to both depositional, environment and climatic changes (Figure 3) (de Franco et al., 2009).

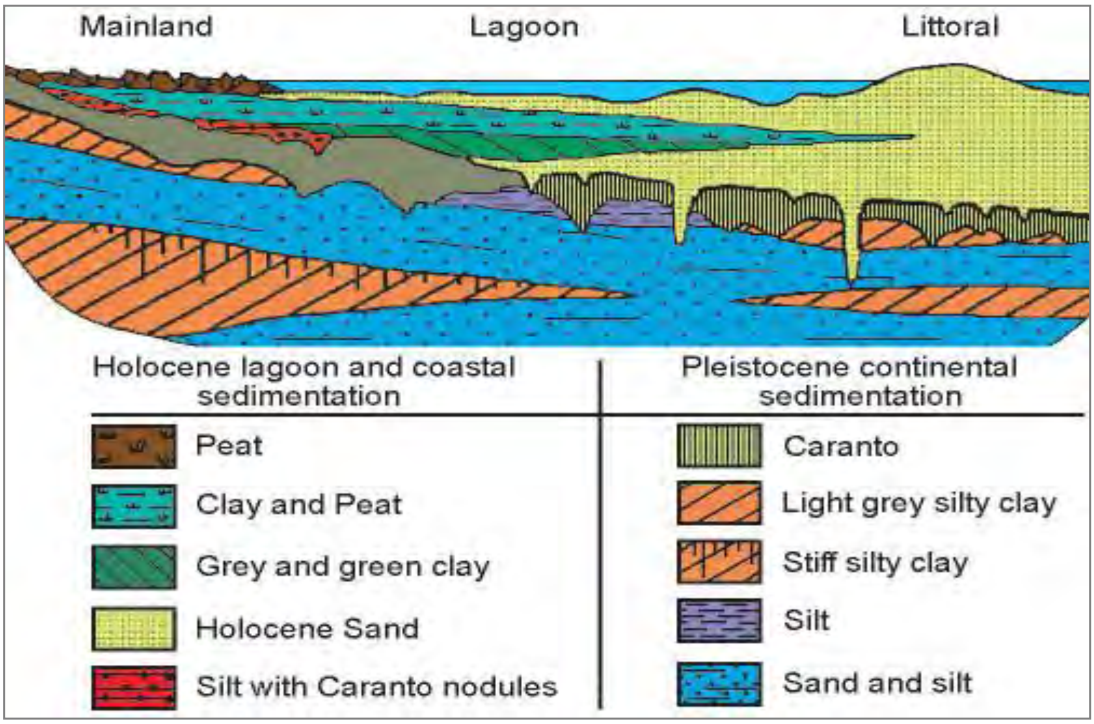

Figure 3: Holocene-Pleistocene stratigraphical sequence across the central Lagoon of Venice (Brambati et al., 2003).

Referring to the whole Venetian Plain, the geological setting down to about 5000 m consists of Prepliocene, Pliocene and Quaternary deposits as is shown in Figure 4 (Brambati et al., 2003).

The pre-Quaternary substratum is characterized by fold and faulted over-folds, which are parallel to the main tectonic trend of the Apennines and include several gas-bearing traps at depths on the order of 2000 m.

Quaternary sediments range between 3000 m (southern zone) and hundreds of meters (northern zone). They mostly consist of sandy and silty-clayey layers of alluvial and marine origin. The bottom follows the structure of the substratum showing a little tectonic disturbance only in the northern sector where the lagoon of Venice is found. The thickness of the Neozoic formations and, consequently, the subsidence rate exhibits a non-uniform space distribution (Brambati et al., 2003).

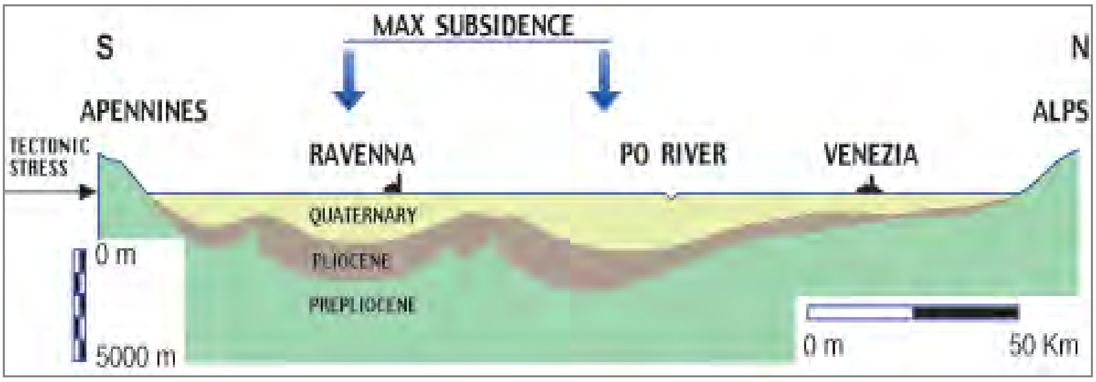

Figure 4: Schematic geological section across the eastern Po Plain (Brambati et al., 2003).

Considering the distinguish in time and space the geological subsidence, the most important morphological problem release to the Venice area, firstly took place throughout the Quaternary. Long-term subsidence, occurring millennia before the origin of the Lagoon, especially due to the tectonic processes, while natural consolidation of sediments played a fundamental function in successive periods (late Pleistocene and Holocene), mostly after the Lagoon had begun to form (Molinaroli et al., 2007).

During the last century, the relative lowering of Venice has totaled 23 cm, consisting of about 12 cm of land subsidence, both natural (3 cm) and anthropogenic (9 cm), and 11 cm of sea-level rise (Gatto and Carbognin, 1981).

The principal anthropogenic activities that is responsible for the land subsidence is the uncontrolled groundwater withdrawal that became very intensive during the industrial boon after the 2nd World War.

The relative land subsidence of the area is also strictly correlated with sea level rise increasing in the last century. The relative sea-level rise of 23 cm has created great concern regarding the fate of the Venice coastlands because it has contributed to increases in (a) flooding, both in frequency and degree; (b) internal hydrodynamics leading to erosion of the lagoon bed, silting-up of channels and changes in the habitat of flora and fauna; and (c) fragility of littoral strips which provide tenuous protection in defending the entire Lagoon against destructive sea storms (Molinaroli et al., 2007).

The rivers and channels comprised in the Venice coastland played an important role for the developing of geological characteristics, in fact the Brenta river system was the major factor influencing in the Late Pleistocene-Holocene the evolution of the central and southern Venice Lagoon.
At present, the distal margin of the Late Pleistocene Brenta river alluvial fan is exposed in the watershed NW of Venice (Tosi et al., 2009).
The Venice coastland is a kindly sloping sandy beach with a system of dune ridges which have the same direction as the present coastline. These features are the result of the coastal advance that occurred during the last 2500 years, while the present littoral shape is mainly due to human intervention, such as the diversion of the Brenta river mouth from the lagoon to the Adriatic Sea at the end of the 19th century, and the construction of the jetties at the Chioggia inlet between 1911 and 1930, which have strongly modified the coastal hydrodynamic and sediment transport regime (Rizzetto et al., 2003).
The entire area is characterized by a high hydrogeological risk, due to the critical land elevation of the territory and to the water level of rivers and channels, which may be up to 5 m above the surrounding ground surface.
Sedimentological investigations show that the high conductivity deposits correspond well to the Holocene sedimentation and are bounded by the Holocene–Pleistocene. This unit is marked by an erosional unconformity with the uppermost part of the Pleistocene series generally made by an over-consolidated stiff clayey layer, well known by Venetians as ‘‘caranto’’, and used as the base on which to build the foundations of the historical palaces of the city due to its good geotechnical properties (Teatini et al., 2011).
Subsequent evolution of the basin has occurred through different phases. Initially, during the high-stand sea level, a significant role was played by the alluvial yield, which was not counterbalanced by both sea level rise and subsidence causing the filling in of the basin and propagation of the river mouths.
In historical times, human intervention, going from the diversion of tributaries to more recent rash groundwater exploitation, has reversed the natural evolutionary trend, favoring the deepening of the lagoon and seriously modified the morphological setting of the environment (Brambati et al., 2003).

1.3) The role of Paleo-channels in the Venice lagoon

From a geomorphologic point of view, the area can be divided into two units: (1) the eastern littoral zone near Chioggia city, constituted of sandy dunes from ancient beach ridges and eolian deposits, (2) the central and occidental parts, where the channels of interest are situated, characterized by fluvial ridges deposits, paleo-channels and peat layer inherited from the degradation of reeds (Phragmite Australis) which covered the area before the intense work of reclamation during the 1930s, when the zone was occupied by swamps and freshwater marshes (Gattacceca et al., 2009).

Paleo-channels, ubiquitous in coastal areas, are commonly infilled with sediments that are more permeable than the surrounding matrix and so may act as preferred pathways for flow and transport.

Extensive numerical modeling of groundwater flow and salt transport was conducted to determine the role of paleo-channels in freshwater/seawater exchange within a typical coastal plain layered aquifer system.

A paleo-channel was represented as a high permeability geologic unit that breaches a confining unit offshore. The paleo-channel clearly enhances fluid exchange across the seafloor. Both fluid outflow from the confined aquifer to the ocean and fluid inflow from the ocean to the inland are larger through the paleo-channel than through adjacent sediments.

In all of the simulations, fluid outflow through the paleo-channel occurred at least in part through the channel flanks, resulting in fresher pore water salinity along the flanks than within the channel axis (Mulligan et al., 2007).

The area is crossed by some well preserved paleo-channels generally characterized by coarse texture, visible from satellite images as shown in Fig. 5, that could potentially connect the study site to the Lagoon.

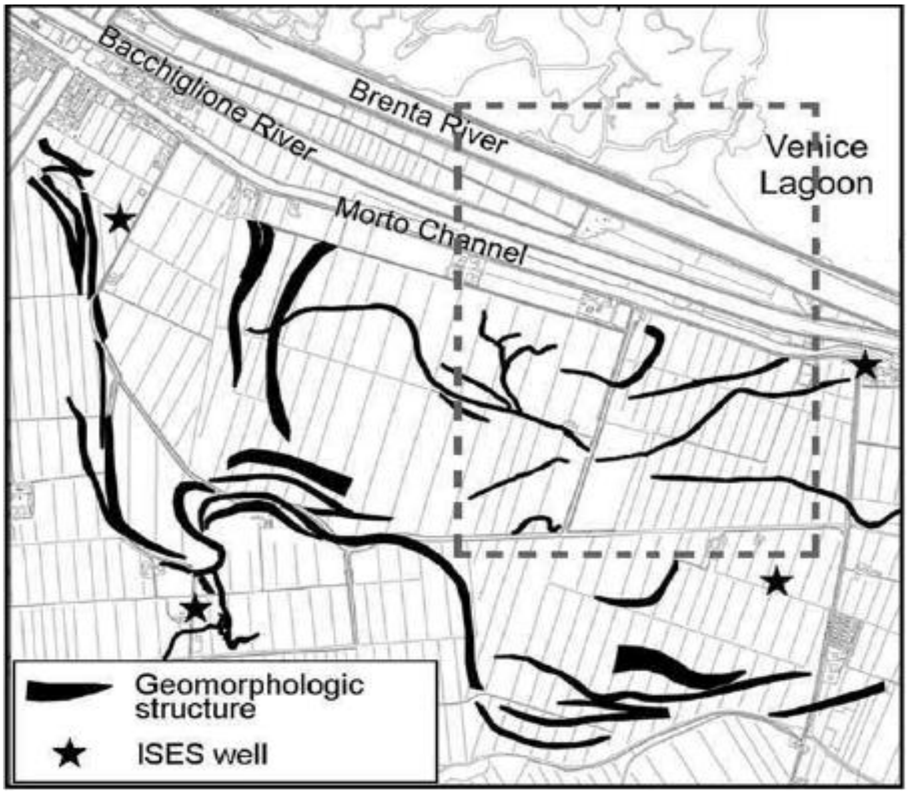

Figure 5: Mapping of the paleo-channels diffusion structures (De Franco et al., 2009).

As mentioned before, such paleo-channels can provide a hydraulic connection between freshwater aquifers and the sea, facilitating saltwater intrusion landward or freshwater discharge offshore.

Simulations carried out by (Mulligan et al., 2007) also reveal that the freshwater/saltwater transition zone is closer to land below paleo-channels than in locations with a continuous confining unit. This indicates that such channels are likely to be significant modes of saltwater intrusion into confined aquifers when excess freshwater extraction occurs on land.

Therefore, coastal water resource managers should consider offshore geologic features, like the role of paleo-channels, when considering modes of intrusion and water-resource vulnerability to saltwater contamination (Mulligan et al., 2007).

Many traces of ancient fluvial, lagoon channels and drainage canals, such as the old course of the Canale Vecchio dei Cuori or the Brenta river, have been found by means of geomorphic investigations.

Concerning the saltwater contamination, the freshwater infiltration through the Cuori canal embankment into the basin and the presence of an aquitard, characterized by thick silt-clayey layers from 5 to 10 m below the ground surface, preclude the salty pollution in the southern area, whereas a paleo-river system favors the saltwater propagation from the lagoon in the northern part (Rizzetto et al., 2003).

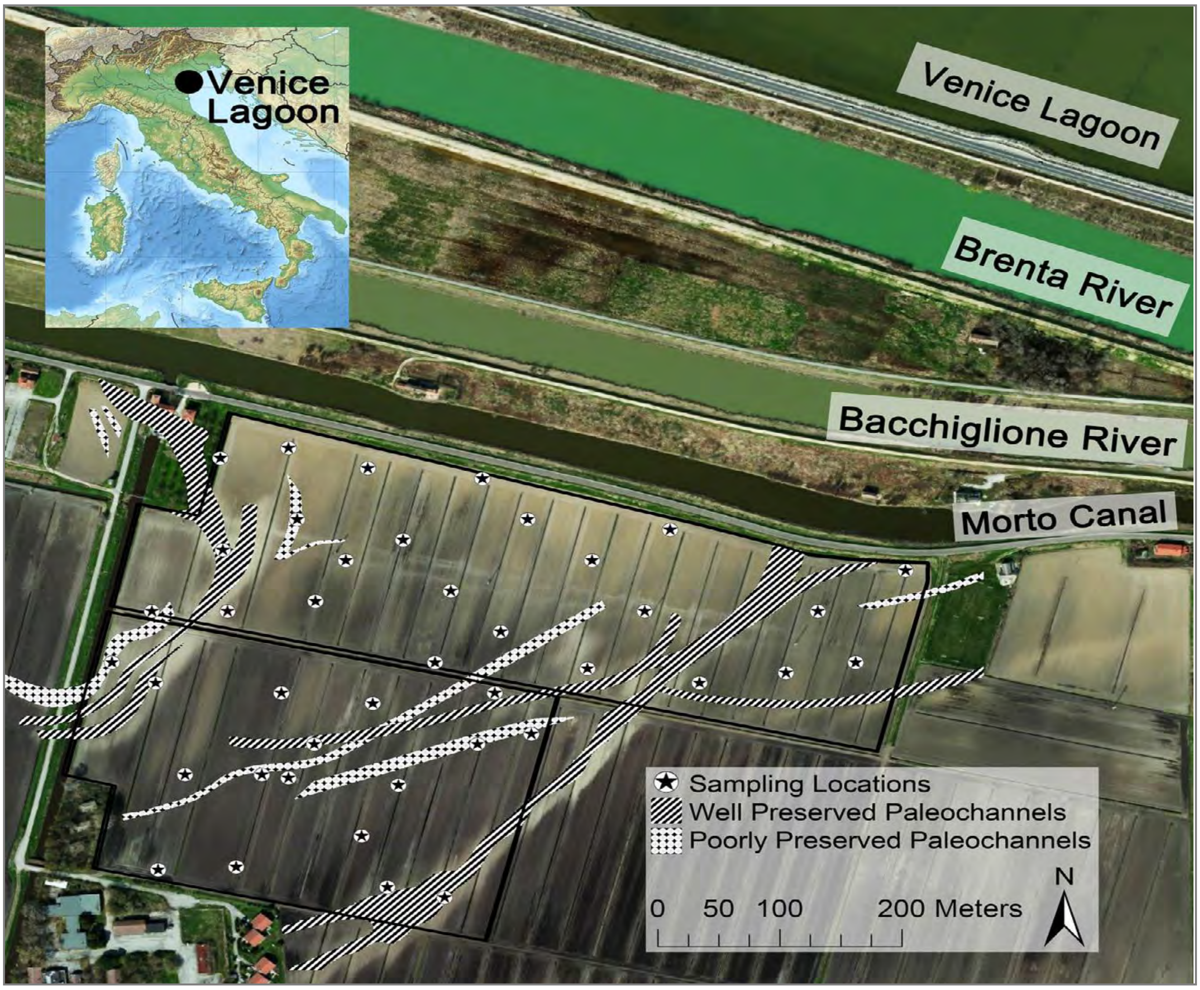

Figure 6: Map of the study area with highlights on local poorly and well preserved paleochannels and soil sampling locations, (Scudiero et al., 2013).

The two characteristics analyzed before, the freshwater flow and infiltration through a river or a channel and the presence of a silty-clayey aquitard, reprensents an important hydrogeologic units able to close down the saltwater diffusion.

On average, soil samples in the study area (Figure 6) were characterized by medium to high salinity. The lowest salinity values (<0.4 dS/m) were recorded in the coarser portions of the paleo-channels, and the highest values (>1.5 dS/m) in the northern part of the study area, outside the paleo-channels but near the Morto channel and the Bacchiglione river (Scudiero et al., 2013).

Paleo-channels are characterized by coarse sediments and thus by higher hydraulic conductivity. The relatively high hydraulic conductivity of these units, and the critical altimetry make the entire area prone to salt water intrusion. Water electrical conductivity distribution reveals the presence of saline water, as well as the existence of fresh water dispersion, near river courses and paleo-channels (Di Sipio et al., 2006).

Saltwater contamination as explained in all the studies is due to marine and lagoon water intrusion, river encroachment of tide and its dispersion, and the rise of freshwater/saltwater interface due to maintaining the fresh water table at low levels in reclaimed areas by pumping stations. Paleo-river beds, ancient dunes and littoral ridges, combined with climate changes, contribute to the worsening of this process.

From a water supply perspective, paleo-channels should be considered sites of increased vulnerability to saltwater intrusion.

1.4) Sediment transport studies

Knowledge of the spatial and temporal distribution of sedimentation, including processes of deposition, transport, and erosion, is fundamental for making sound decisions on a wide variety of management issues in estuaries and transitional basins. Sedimentation and erosion changes bathymetry and therefore habitat extent and distribution. Predicting natural and anthropogenic changes to ecosystems and designing successful restoration projects require knowledge of deposition and erosion patterns (Molinaroli et al., 2009).

Habitat mapping, as sea-riverbed classification and characterization, is an important tool for coastal studies and management, particularly for the investigation of sediment transport and the impact of human activities on the sea-riverbed. Mapping the benthic community of sands and gravel at different spatial and temporal scales, requires studying both the morphology and the composition of the sea-riverbed, which often involves sea-canalbed sampling or coring, as well as acoustic surveying (Villatoro et al., 2010a).

Interpretation of the morphological features and their changes its fundamental in order to theorize about the hydrodynamics and sediment dynamics, from which transport pathways and magnitudes can be estimated (Villatoro et al., 2010a).

The study carried out by (Molinaroli et al., 2009) focus on bathymetry and textural properties of subtidal flat sediments in the Venice Lagoon as revealed in sampling campaigns performed in 1970 and 2000. The difference between data from the two campaigns delineates morphological variations in the shallow lagoon beds over the thirty-year time scale and related changes in grain size distribution resulting from both natural and anthropogenic causes.

Bathymetric data were provided by the "Servizio Informativo del Magistrato alle Acque di Venezia" (Venice Water Authority Information System = MAV). The data were drawn from two survey campaigns, one conducted in the 1970s and the other in the 2000s.

One-hundred and fifty sediment samples (~10 cm depth) were collected by PVC pipe from beds at depths of between 0.1 and 2.4 m (Molinaroli et al., 2009).

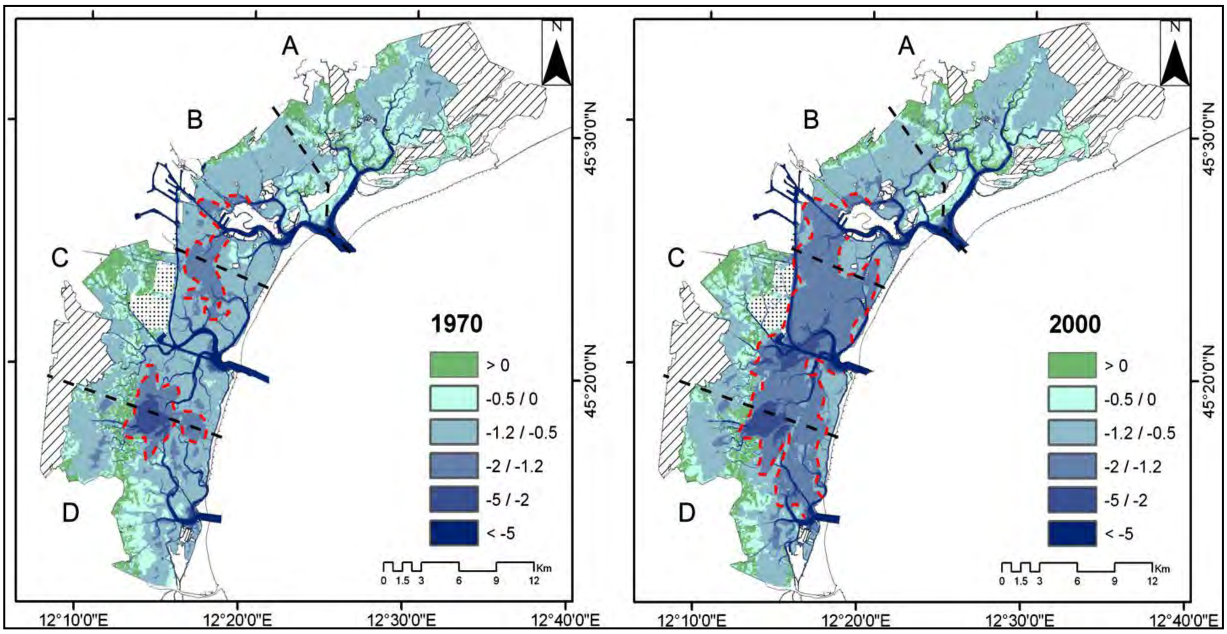

Figure 7: Color-shaded bathymetric maps of Venice lagoon (left: 1970; right: 2000). Overall increase in depth shown by progressively darker blue colors and migration of −1.2 m contour (dotted red line), (Molinaroli et al., 2009).

The results confirm a previous study (Molinaroli et al., 2007) in which Venice lagoon sediments sampled in the period 1997–98 were found to be more similar to back-barrier tidal flats (Danish Wadden Sea) and bays (Minas Basin, Bay of Fundy, Canada) than lagoon sediments (Mugu Lagoon, California).

The changes in grain size distribution in the study area from 1970 to 2000 reflect both natural and anthropogenic changes. The bulk of the fine silt and clay fractions (≤22 μm) may represent sediment carried by fluvial system. With the reduction of sediment supply by rivers, due to the mechanical drainage system (pumping plants and sluice systems) that govern the inland regime, only fine sediment was added to the lagoon during these 3 decades.

The southernmost basin (Chioggia, D), as is shown in (Figure 7) is of the "exploited-subsiding lagoon" type. It is still in a quasi-natural condition, but exploitation for aquaculture and fishing and high subsidence has influenced its morphology: 1 km² of salt-marshes out of 13 km² was lost between 1970 and 2000. Its sediments were depleted in both silt and clay (−10%) and consequently enriched in sand. Forty percent was moderately eroded, but there was also some deposition (25%) due to disintegration of salt-marshes, and more than 30% of the area is still stable. Nevertheless, erosion prevails over deposition (E/D~2), and the grain-size patterns in eroded and stable/depositional areas are similar.

It is thus possible that the coarser sand fraction (≥105 μm) is subject to internal re-sedimentation in this sub-basin, whereas in sub-basin C it is probably lost to the sea (Molinaroli et al., 2009).

Bathymetric maps, as is demonstrated from the study analyzed before, provide details of the seabed surface and allow to identify morphological features, as well as studying their evolution, thus providing insight into general coastal dynamics, particularly sediment transport and saltwater intrusion.

Another important studies that utilize the bathymetric maps as a tool for underlying the morphological features of the southern basin of the Venice lagoon is the one carried out by (Villatoro et al., 2010a).

A series of color-coded bathymetric maps of southern Venice Lagoon have been produced for 1927, 1970 and 2002 (Fig. 8). In these, it can be seen that the mean depth of the Southern Basin, calculated from the interpolated bathymetries, has increased from -0.8 m in 1927, to -0.9 m in 1970, to -1.2 m in 2002. Likewise, the modal depths (the most frequent) have increased from -0.3 m in 1927, to -0.65 m in 1970, to -1 m in 2002 (Villatoro et al., 2010a).

Bathymetric comparison analysis confirms that the Southern Basin suffered widespread erosion between 1927 and 2002. The surfaces resulting from the comparison between the 1927 and 1970 bathymetry and between the 1970 and 2002 bathymetry reveal that, during the first period studied there was significant loss of sediment around the major channels, as well as in tidal flats and salt marshes (Villatoro et al., 2010a).

The bathymetric data was used in conjunction with the sediment character to better describe the sea-riverbed morphology.

The chemical quality of the sediments that are exposed today at the bottom of the lagoon (intertidal areas, shallows, canals) is the result of complex interactions between a number of factors and processes including present and past pollution sources; hydrodynamics and sediment transport; erosional and depositional processes; fishing activities; boat traffic; dredging; and early diagenetic processes.

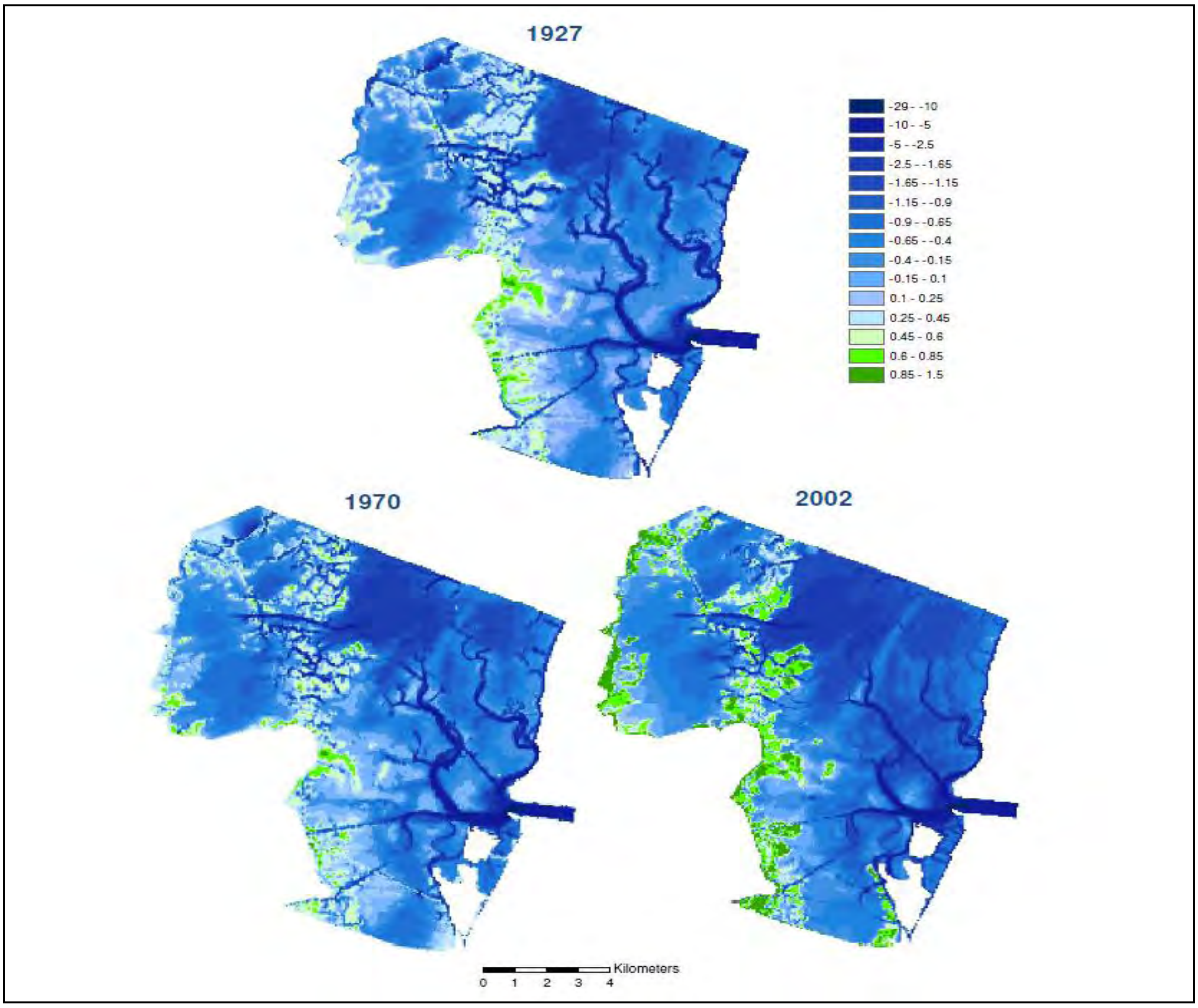

Figure 8: Color-coded bathymetric maps of Venice Lagoon south sub-basin for 1927, 1970 and 2002 (Villatoro et al., 2010).

The most simple and traditional way of characterizing the seabed is through the collection of samples and their subsequent analysis, which often includes granulometry and mineralogy studies. Mineralogical studies provide information about the source of the sediment, whilst the identification of the sediment characteristics, such as grain size and shape, is important for the interpretation of the hydrodynamic environment, transport history and depositional conditions (Villatoro et al., 2010a).

In general, larger grains will have a higher threshold for motion and require stronger flows to transport them, whilst finer sediment will be set in motion and transported more easily.

The average rates of erosion in the South Basin were 0.3 cm/y between 1927 and 1970 and 1.25 cm/y, between 1970 and 2002 (a total of 14 and 40 cm, respectively), adding up to an overall mean of 0.72 cm/y (Villatoro et al., 2010a).

Median sediment diameters within Chioggia Inlet and the adjacent beaches range from 100 to 400 μm, very fine to medium sand. Fine and medium sand is found inside the inlet and in the delta area, whilst medium sand dominates the littoral. Very fine sand is only found along the outer parts of the coast, surrounding the delta who described a mud-belt located along the Venetian littoral at depths greater than 8 m (Villatoro et al., 2010a).

Also the coring samples, made by McClennen et al., 1997, taken from the lagoonal marshes, sub-tidal flats and barrier islands shows the same overall stratigraphy.

The deeper deposits consist of thinly and distinctly laminated silt and very fine sand with a few freshwater peat layers, indicating fluvial and associated flood plain-lacustrine deposits.

The top section of all lagoon cores is composed mostly of medium to dark grey silt displaying some subtle layering and containing variable abundances of organic matter, small marine shells and partially-decayed plant fibers (McClennen et al., 1997).

Another survey, (Berto et al., 2007), analyze the sediment characteristics and their possible diffusion in the studied area. The results shows that sandy silt and silt were prevalent in the southern lagoon. Clay (<2 μm) was present in reduced amounts (<7%) in all sediment samples. Grain size progressively decreased from the tidal inlet towards the inner areas of the lagoon and in the lower energy zones. Very fine to medium sands were found only in the marine area and in some sites near Chioggia town.

It appears, from these literature information, that long-term morphological changes in southern Venice Lagoon are driven by erosion of the tidal flats and river-canals banks, together with the export of sediment through the Chioggia Inlet. It is evident that, even though some of the material eroded from the tidal flats is deposited into the tidal and navigation channels, the inlets play a major role in the lagoon's sedimentary budget, in exporting both sand and fines.

Anthropogenic influence has had a determinant role in the long-term volumetric balance of the Southern Basin, with: human-induced subsidence, increasing the depth of the lagoon; the activity of the pumping stations that favor the suspension and transport of the sediments; illegal clam fishing and ships resuspending sediment; and dredging for navigation purposes and salt-marsh reconstruction, etc. (Villatoro et al., 2010a).

CHAPTER 2

The Southern Drainage Basin: Venice Lagoon

2.1) The hydraulic characteristics of the Southern basin

The Venice Lagoon and its drainage basin form a vast system, where historical and recent cities, large and medium–small industrial districts and intensive agricultural activities coexist within a peculiar environment. The drainage basin is constituted of an ensemble of tributary sub-basins with contrasting characteristics and freshwater fluxes; the hydraulic pathways are generally complex and not univocally established (Zonta et al., 2005).

The Lagoon has a drainage basin of 1850 km^2, which provides a mean yearly freshwater input of 35.5 m^3/s, constituted of an aggregate of tributary sub-basins having different morphological characteristics and extension, from a few to hundreds square kilometers (Figure 9).

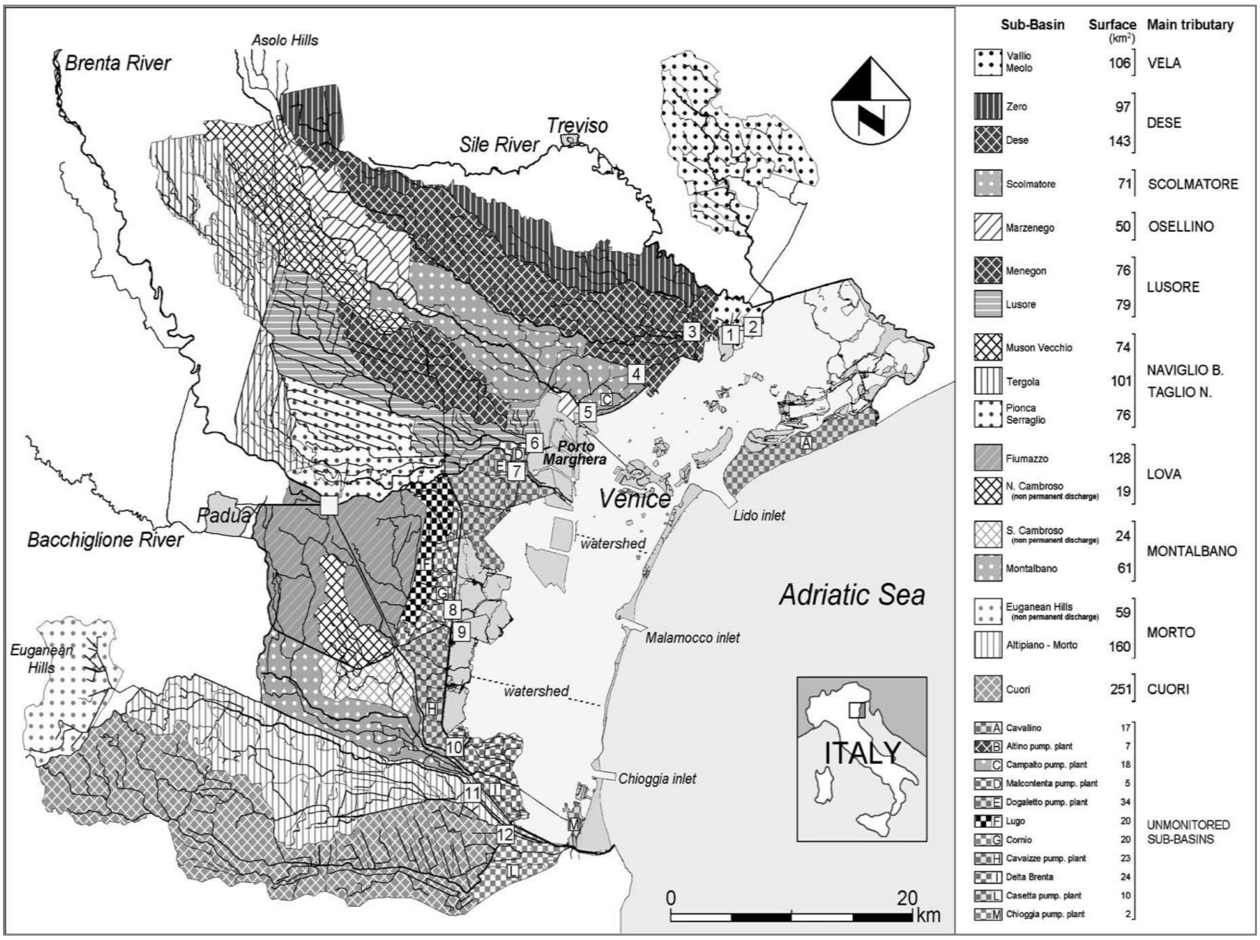

Figure 9: Maps of the Venice lagoon and its drainage basin; the different sub-basins are evidenced (Zonta et al., 2005).

Even if about 30 stream outfalls are countable, 12 main tributaries account for about 90% of the whole drainage basin surface. These streams have different hydraulic regimes (natural, mechanical, alternate mechanical) and can be regulated and diverted (Zonta et al., 2005).

The hydraulic network of the drainage basin of the lagoon is the result of the merging of the natural hydrography with the intricate pattern of artificial canals that were dug in different periods, for irrigation or land reclamation.

As required by strategies for the management of the water resources, the drainage density of the system is generally high. In fact, every single parcel of the territory must be reached by drainage collectors or their lateral derivations, in order to maximize the efficiency of water transport into the cultivated lands or, alternatively, to ensure the rapid discharge of the excess rainfall.

The basin morphology combines with the variety of aspects related to the hydraulic management of the different sub-basins that constitute the system include continuous inputs from rivers (Sile and Brenta), draining external territories, interconnections between neighbouring tributaries that are activated both for the regulation of the flow and during emergencies, the possibility to divert a considerable fraction of the peak runoff from certain sub-basins to rivers outside the drainage basin and flood-related inputs from external territories. These features render the morphology a dynamic factor, adding further complexity in the definition of the pattern of freshwater flow from the tributaries (Zuliani et al., 2005).

The drainage basin that comprise the area of interest, enclosed between the Morto channel and the Gorzone channel, lies below the sea level in the order of 2-4 m.

The regime of the drainage channels and of the tributaries, that are small streams with low individual discharge, situated in this region is mainly conditioned by artificial regulations through a complex network of pumping stations and sluice systems for the diversion of the flow in flood conditions and for agricultural purpose.

The tributaries under analysis are characterized by partial (Morto Channel) and completely (Cuori channel) mechanical drainage and consequently artificial regime, the flow is mainly discontinuous and, besides the rainfall regime, it depends on several factors, basically correlated to the different strategies adopted for the water management, including the possibility of release outside the basin a portion of the excess rainfall.

The drainage basin comprising the two tributaries and their channels system is called South Basin and includes the area monitored by the Adige-Euganeo reclamation Authority.

This basin can be subdivided into two hydrographic sub-basins, the Morto sub-basin and the Cuori sub-basin, which both flows into the lagoon at the Trezze location (Figure 10).

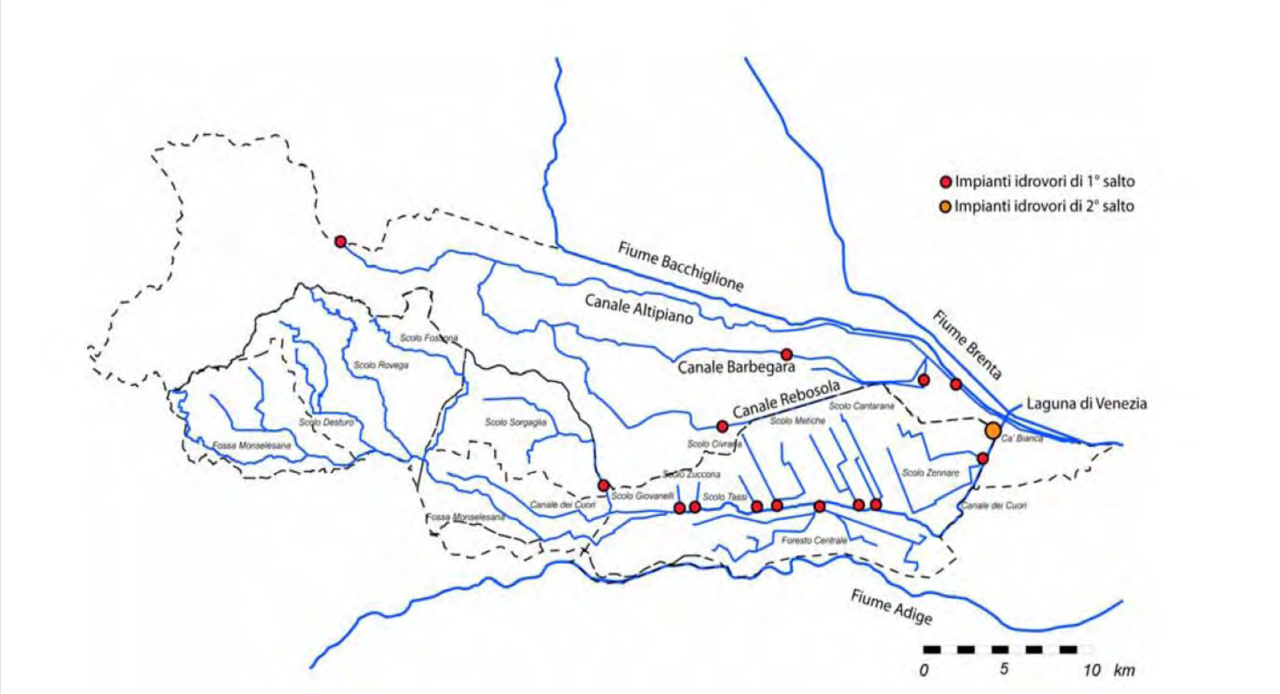

Figure 10: The hydraulic system of the Venetian South Basin (Uccelli et al., 2006).

The Morto sub-basin (219 km^2) is mainly governed by numerous pumping plants (e.g., Cà Bianca, Priula and San Silvestro) and by the Trezze and Priula sluice systems.

The flow discharged is mostly regulated by the Trezze sluice system, composed of 5 gates, and its sent to a system of 5 sag pipes, ("botti a sifone"), that lets the water flow goes below the Bacchiglione and Brenta river and finally flows into the southern part of the lagoon.

The flow can also be controlled, for a couples of week in a year, by a self-regulating sluice system: mitre gates, ("porte vinciane"), situated where the channel flow into the Bacchiglione river, this occurs in presence of two concomitant factors: high tide and low hydrometric level of the Bacchiglione river compared to the Morto channel. In this situation the hydraulic charge of the outer water, Morto canal, (higher than the inner one, Bacchiglione river) pulls on the doors, opening them.

In flood conditions, the discharge of a 59 km^2 territory (part of the Euganean Hills) is directly diverted to the Bacchiglione river through the Trezze pumping plants and consequently to the Adriatic Sea via the Bacchiglione and Brenta River.
The second hydrographic sub-basin is the Cuori sub-basin which collects the water of an extended lowland, locally lying 4 m below the mean sea level. It drains a large area of territory collecting, through pumping plants, the contribution of eleven sub-basins whose role is especially release to agricultural use.
The drainage system regarding the Cuori channel, comprising an area of 251 km^2, is completely mechanical and regulated by the pumping plant of Ca' Bianca, which is one of the largest in Europe with an instantaneous flow of 42 m^3/s. The flow coming from the Cuori canal is controlled by the Cà Bianca pumping plant and sent to the Morto channel at the Trezze's location; then the water-flux finally goes to the lagoon or to the Adriatic sea in the same way explained before.
The drainage characteristics of the two basins are collected and summarized in the following table, Table 1.

Table 1: Characteristics of the measurement sections and extent of the relative sub-basins, in both normal and flood conditions during the year 1999 (Zuliani et al., 2005).

Tributary	Width (m)	Mean depth (m)	Flow type	tide influence	Sub-basin surface (Km^2)		Rainfall (10^6 m^3)	Runoff (10^6 m^3)
					Normal flow	Flood	(annual)	(annual)
Morto	22	2,4	partially regulated	yes	219	160	161,1	34,7
Cuori	44	2,2	totally regulated	no	251	251	185,9	39,3

2.2) Hydrogeological setting and saltwater intrusion

Understanding the hydrogeological processes is critical and fundamental for the management of water resources in coastal areas. Wetlands, lagoons, and estuaries have a unique flora and fauna depending on the ground-surface water processes.

The mainland under study is characterized by low-lying countryside, considerably below the mean sea level (3–4 m) and keep drained by a system of pumping stations controlled by the Adige-Euganeo reclamation authority.

The composition of the soil is often rich in organic matter even if some sandy exposed and buried features occurs, like the presence of several sandy paleo-channels crossing the farmland with a main direction from inland to the lagoon boundary.

The investigated subsoil is the upper 140 m depth of the regional multi-aquifer system underlying the overall Venice plain. The upper 50 m of the system that take place under the overall Venice flatland are composed of a 15 m thick phreatic aquifer and locally confined aquifers between 20 and 40 m depth characterized by a complex architecture due to the presence of lateral heteropies and vertical transitions, and of confined aquifers developed at the regional scale below 50 m depth, (Figure 11) (Viezzoli et al., 2010).

In Figure 11 is also shown the quantification of the subsoil thickness affected by salt water and, consequently, the evaluation of the depth below the lagoon bottom at which the fresh water occurs.

The permeability registered in this particular area shows a significant lateral and vertical variability due to the high textural heterogeneity of the deposits, with values that vary from $10-2$ to $10-5$ cm/s and from $10-5$ to $10-9$ cm/s for the aquifers and aquitards, respectively (Carbognin and Tosi, 2003).

Salty water seriously affects this unit, and also the one represented by the surface rivers and drainage channels, along most of the Venice coastland. This topic is fully analyzed in this study because the salt contamination of land and water is seriously impacting the farmland productivity of this region.

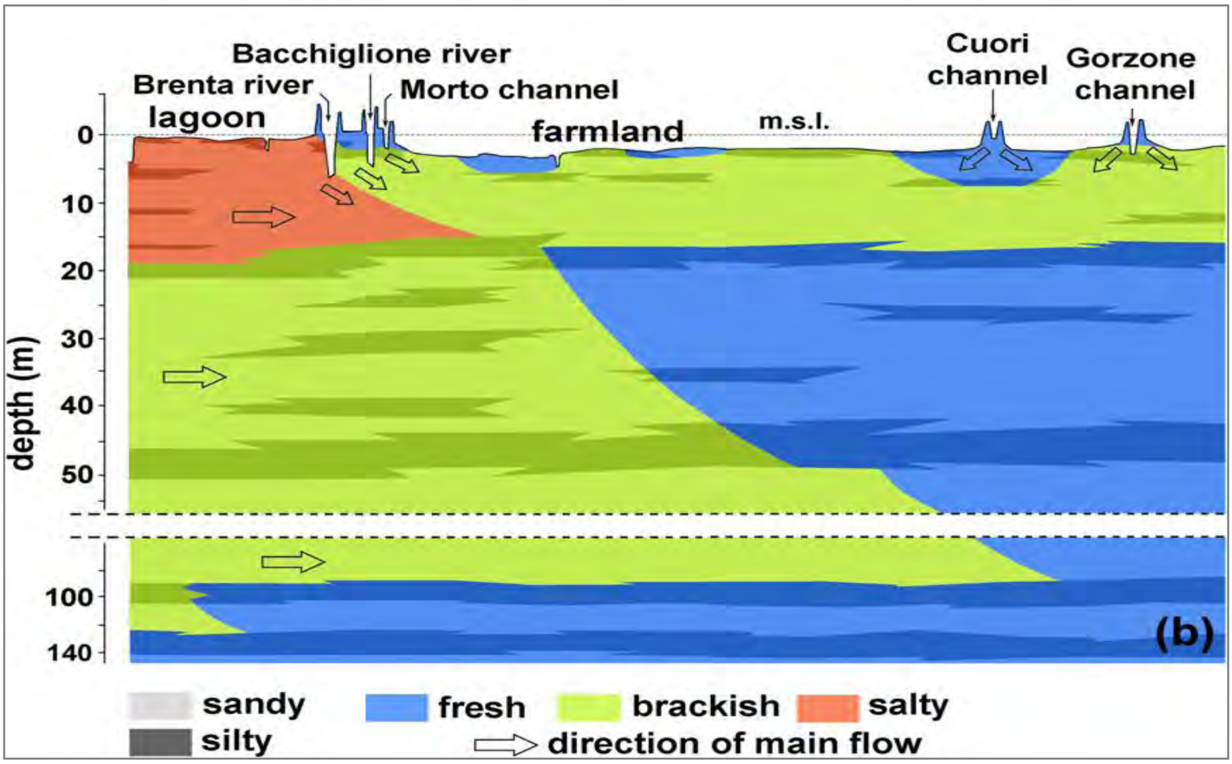

Figure 11: A conceptualization of the hydrogeologic setting of the Venice Lagoon subsurface in the (b) southern portions obtained by integrating the results of the AEM survey with previous available information (Teatini et al., 2011).

The salt plume intrudes irregularly inland from the nearby sea and lagoon up to 10–15 km in the northern and southern farmlands bounding the coastal water body through the groundwater flow and by the final sections of rivers beds and channels (Teatini et al., 2011).

The seawater intrusion is enhanced by various factors: (i) the land elevation well below the mean sea level, due to the subsidence that is also increased in the last decades, (ii) the presence of several buried paleo-channels crossing the lagoon margin and acting as preferred pathways for groundwater flow and solute transport, (iii) the seawater intrusion along the rivers mouths due to the simultaneously verifying of the high tide and low hydrometric level in the river, (iv) a general decrease in the freshwater river (e.g., Brenta, Bacchiglione, Adige and Gorzone) discharge, (v) the water levels in the drainage channels kept low by pumping stations and, (vi) the over exploitation of the groundwater through a systems of wells (Rizzetto et al., 2003; de Franco et al., 2009).

The salinization dynamics affecting this complicated environment is especially sensitive to the variations in the freshwater river (Brenta, Bacchiglione, Adige, and Gorzone) discharge, to the hydrometric levels in the drainage channels maintained by the pumping stations, and climatic conditions. Other important factors controlling the saltwater intrusion are the freshwater releases for irrigation purposes that is a very current topic regarding all the organizations acting on the territory.

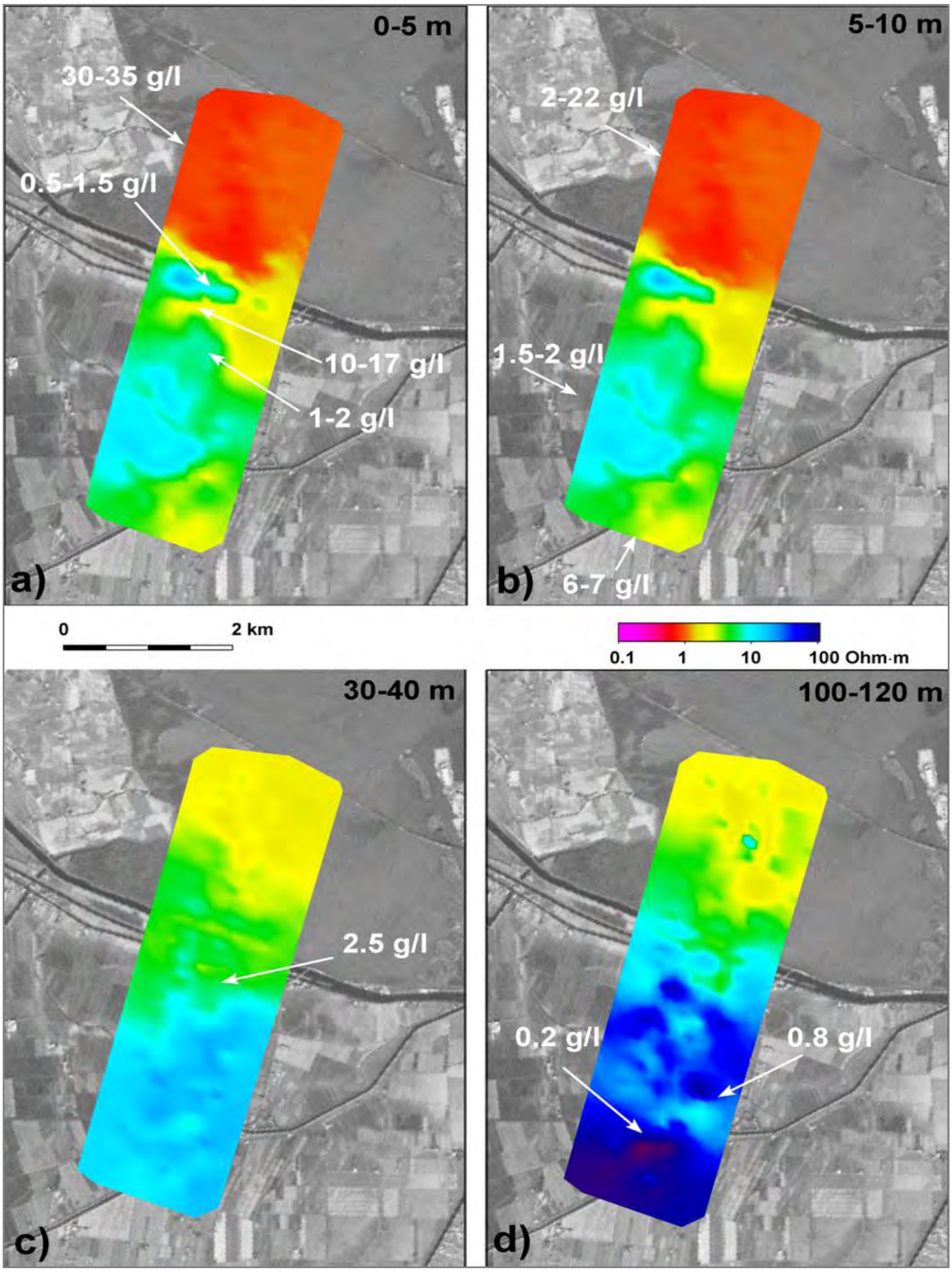

Figure 12: Average resistivity maps for the 0–5 (a), 5–10 (b), 30–40 (c), and 100–120 (d) m depth intervals obtained by the SkyTEM system in the southern lagoon sector. The salinity values measured in some boreholes scattered in the study area are shown according to the well depth (Teatini et al., 2011).

Two important studies, (de Franco et al., 2009) and (Teatini et al., 2011), analyzed the diffusion of the saltwater intrusion through the groundwater flow in this area using electrical resistivity tomography (ERT), airborne electromagnetic (Sky TEM system) and water conductivity in a few boreholes and also with level measurements and monitoring points in the watercourses.

Their results show that seawater intrusion seriously affects the upper 15 m depth and is characterized by a certain seasonal fluctuation whose dynamics is very sensitive to the extent of the seawater encroachment along the river mouths, and hence the riverbed seepage (Figure 12).

Their results also show that the hydrological regime and consequently the saltwater contamination are expected to be controlled by several natural and anthropogenic factors such as rainfall events, tidal regime, and reclamation activities.

The water quality in the shallower subsoil, only the upper 3-5 depth of the phreatic aquifer, is significantly improved by local rainfalls that rapidly supply freshwater. The higher mean sea level generally occurring in fall–winter season is expected to increase the saltwater contamination in the shallow subsoil and with respect to the tidal regime a significant negative correlation coefficient exists at monthly to seasonal time scale for depths below 15 m.

Since the farmland is kept drained by a network of 1-2 m deep channels whose levels are artificially controlled, the main impact of the pumping station activities are expected to occur on the upper formations. A decrease of the reclamation water level produces an increase of the salinity concentration in the groundwater, because when the canals and rivers, in turn, are not recharging the aquifers they lead to the rising up of the salty water.

The upstream runoff is an important factor influencing the salinity intrusion. The larger the fresh water amount coming from upstream is, the shorter the distance of the salinity intrusion will be and the less the effect of the salinity intrusion will be.

It affects every water-use activity in the estuary, e.g. domestic, agricultural, industrial and other uses; therefore it may damage the interests of people of very large areas in the estuary. Thus, prediction of salinity intrusion in estuaries has received a lot of attention by researchers.

The problem release to the water salinity, as underlined before, seriously affects the agricultural activities compromising the soil properties and characteristics. With reference to the tolerance limits for crops in the study area and to the characteristics of sands, rich in silt components, three classes of the water quality were identified in previous researches (Carbognin and Tosi, 2003): salty if the water electrical conductivity (EC) exceeds 5 mS/cm (i.e., less than 2 ohm m), brackish if EC ranges between 2 and 5 mS/cm (5 and 2 ohm m) with salt concentration higher than 1 gr/l and water unsuitable for irrigation purposes, and fresh if EC is less than 2 mS/cm (>5 ohm m).

The California Clean Water Team (CWT, 2004) reports values of 0.03–1.5 mS/cm for potable water in U.S. and 0.1–2.0 mS/cm for freshwater streams.

Understanding the complex interactions between vegetation growth, root water uptake, atmospheric and soil dynamics under stressed conditions is therefore necessary to optimize land productivity while preserving water resources.

2.3 Sediment Threshold for transport

The study of flow and sediment characterization and dynamics is an important tool for coastal management because through it, one can understand and describe phenomena such as nearshore morphological changes (erosion or accretion), scour around structures and many other topics associated with the transport of sediments by tidal currents (uni-directional flow) or coastal currents (littoral drift).

The general principle is that sediment is moved by the friction exerted by the flow over the bed.

The characteristics of the flow in unidirectional currents vary according to the velocity. At low velocities, the flow is laminar, which is when the layers of the flow slide smoothly over each other without mixing of fluid particles.

The grain Reynolds number, $Re = \bar{u}d_{50}/\nu$, is a measure of turbulence within the flow and is often used to define the type of flow. $\bar{u}$ is the average flow velocity; d_{50} is the median grain diameters and ν is the kinematic viscosity of the fluid ($\nu = 10^{-6}$ m^2/s at 20°C).

The logarithmic velocity profile is thus, expressed as (Bruun, 1978): $u=(u^*/k)\ln(z/z_0)$ where k is the Von Karman constant (k = 0.4), z_0 is the elevation corresponding to zero velocity (roughness length), and u* is the friction velocity, which is the rate of turbulent shear, defined by the gradient of the logarithmic velocity profile. Thus, the friction velocity can be expressed in terms of the bed-shear stress (τ_0) through the relationship: $u^*=(\tau_0/\rho)^{-½}$.

The fluid exerts both a drag and a lift force over the bed (Fig. 13). The total drag force, which consists of friction drag and form drag, is written as:

$$F_D=½\rho C_D A n u^2$$

where C_D is a drag coefficient, An is the area of the body normal to the flow, ρ is the fluid density, and u is the average velocity. The lift force (F_L) is written in the same way as the drag force.

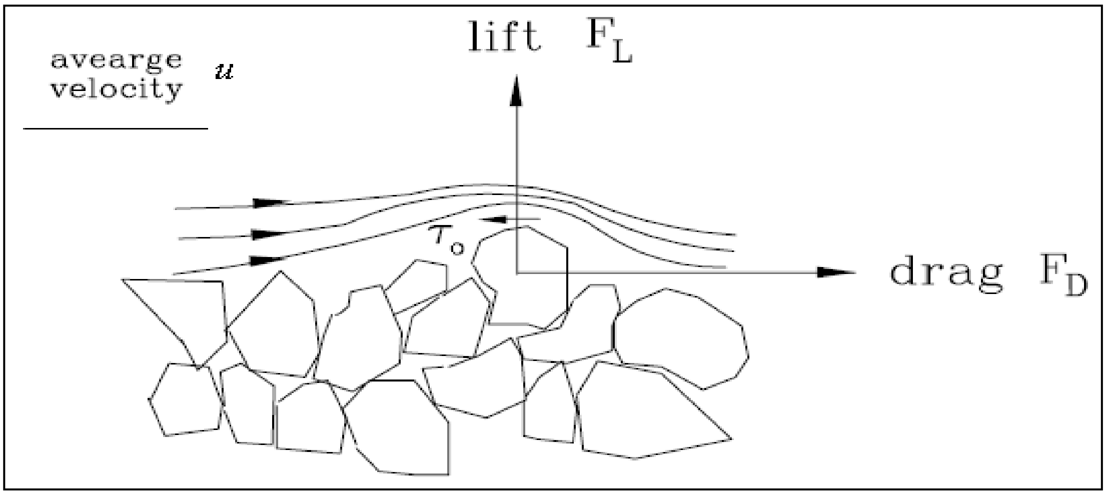

Figure 13: Fluid forces acting on a grain resting on the bed (modified from Liu, 2001)

The grain also exerts a resistant force F_D on the flow (Fig. 14), so that if A' is the area of the grain, the bed-shear stress is:

$$T_0 = F_D/A' = \frac{1}{2}\rho C_D u^2$$

which is known as the quadratic stress law.

Knowing the settling velocity of a grain (Ws) is important in the study of the balance forces that keep a particle in suspension (Bagnold, 1966). Ws is the constant velocity of a grain as it falls in still water, when the upward fluid drag force (F_D) on the grain is equal to the downward submerged weight of the grain (Liu, 2001; Soulsby, 1997).

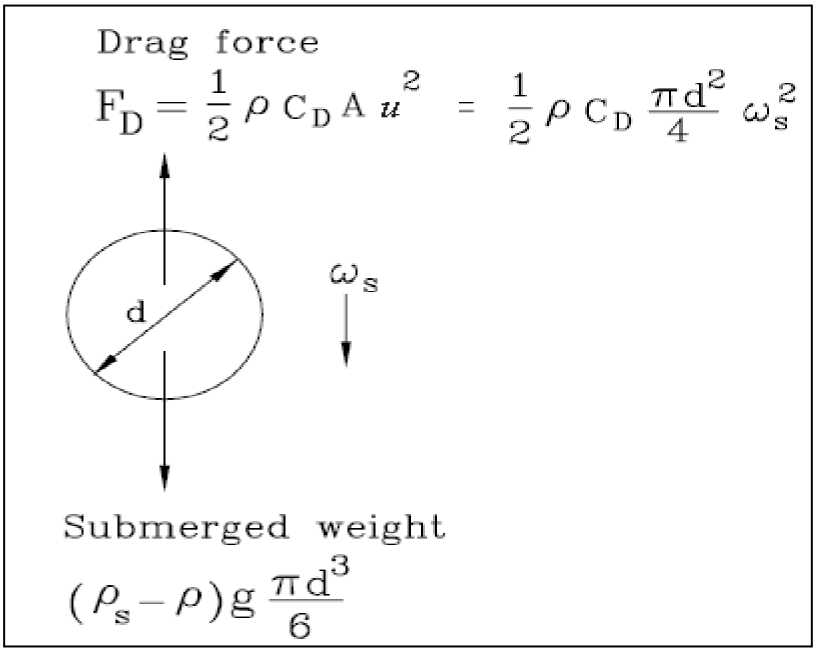

Figure 14: Balance of forces acting on a settling grain (modified from Liu, 2001).

Soulsby's settling formula (Soulsby, 1997) is based on the dimensionless grain diameter D*:

$$D^* = d_{50}(g(\rho s-\rho)/\rho\upsilon^{2})^{-1/3}$$

Where υ is the kinematic viscosity of seawater (0.7×10^{-6} m^2/s at 30°C).
Soulsby's formula is:

$$Ws = \upsilon/d_{50}[(10.36^2 + 1.049(D^*)^3)^{1/2} - 10.36]$$

For the grain transport to occur, the forces of F_L and F_D must be sufficient to overcome the gravitational forces (submerged weight, see Fig. 14).
Shields (1936) was the first to formulate the threshold condition for incipient motion by equating the drag force F_D to the friction force acting on the grain, through the Shields parameter:

$$\Theta c = Tc/d_{50}g(\rho s-\rho)$$

where $Tc = \rho u^*_{crit}{}^2$ is the critical shear stress at the point of incipient motion, ρ is density of water and sediment, g is gravity (9.81 m/s^2) and d_{50} is the grain median diameter, which can be expressed in terms of the grain Reynolds number (Re), as in the original Shields diagram (Fig. 15) (Villatoro et al., 2010a).

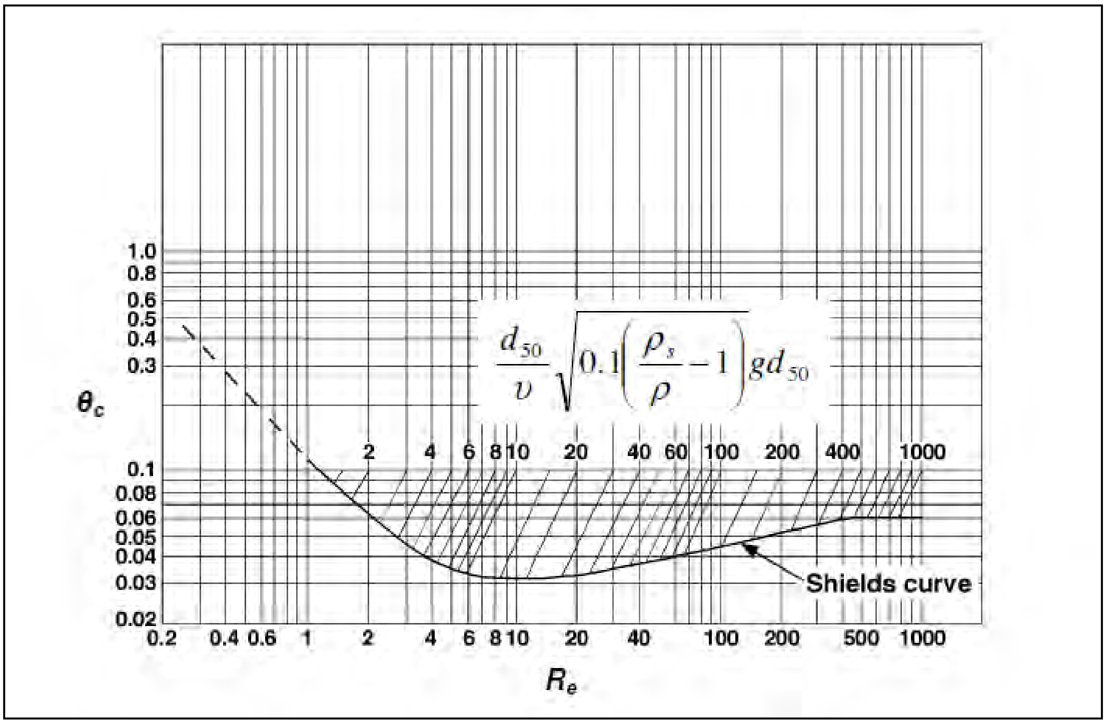

Figure 15: Original Shields diagram (modified from Shields, 1936).

The critical traction threshold (Θc), as described by Shields (1936), need to be obtained for each sample and plotted against the grain Reynolds number (Re). These values were compared to threshold curves, in order to assess the presence and the modes of the transport (Fig. 15).
The results are then plotted in the Shields diagram in order to see if they are above or below the Shield's traction threshold. All the samples ranging above the curve are in the suspension region.

2.4) Anthropic factors influencing the sediment transport

An important aspect that should be analyzed to complete the dissertation on sediment transport and water management, is related to the natural or human reasons that create the incipient motion of sediments.

In the study area there are some hydrologic infrastructures causing the erosion and the transport of sediments. These events happen only during some periods and for some particular reasons explained below.

The interaction of the infrastructures with the respective canals is consecutively analyzed for each case: Cà Bianca Pumping Plant, Trezze Sluice system, Priula Pumping Plant and Sluice system and finally San Silvestro Pumping Plant (Figure 16).

Figure 16: Map of the study area with the location of the hydraulic infrastructures.

Considering the Cà Bianca Pumping Plant, situated at the end of the Cuori canal, the flow discharged can vary from 18000 m^3/y registered in 2007 to 59000 m^3/y registered in 2013 (Figure 17).

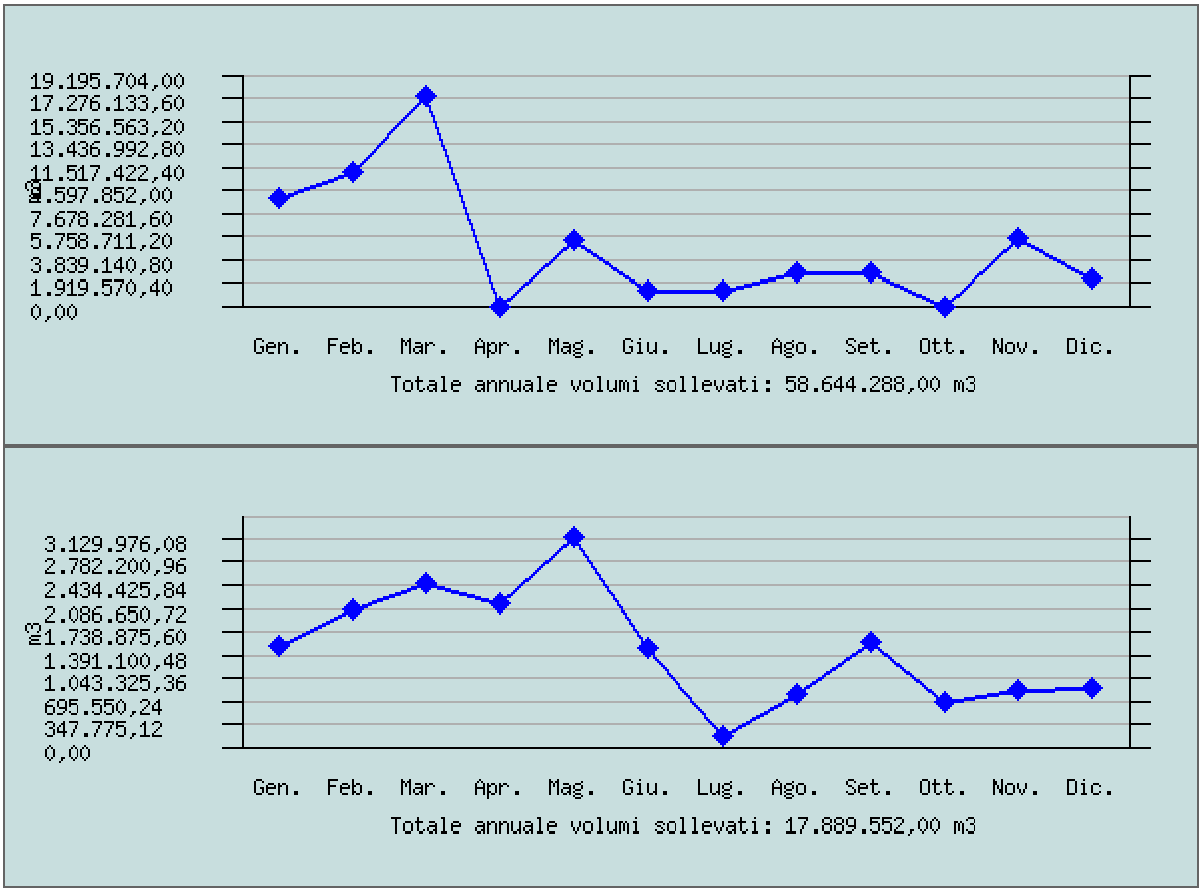

Figure 17: Annual trend of Cà Bianca Pumping Plant raised volumes respectively of the year 2013 and 2007 (Adige-Euganeo Reclamation Authority database).

These volumes represented in the graphs, considering the order of magnitude, are evaluated significant values if compared with the other Pumping stations. As a consequence, the Pumping Plant of Cà Bianca, working with these huge volumes, can cause transport of sediments and localized erosion in the neighborhood of the recharging/discharging zone; it can also interact with the flow-rate regime of the drainage basin.

The second aspect underlined from the graphs, regards the seasonality within the Pumping Plant is working. During the periods of spring and fall season the Pumping Plant is subjected to an intensive work because it has to drain the entire Cuori basin, favoring the flow discharge into the lagoon/sea and saving in this way the territory from flooding.

Analyzing the site of Trezze, it is possible to note the importance of the Sluice system that regulate the flow discharged into the lagoon through the sag pipes.

The water flow is sufficiently maintained stable during all the year, as is shown in the following graph (Figure 18).

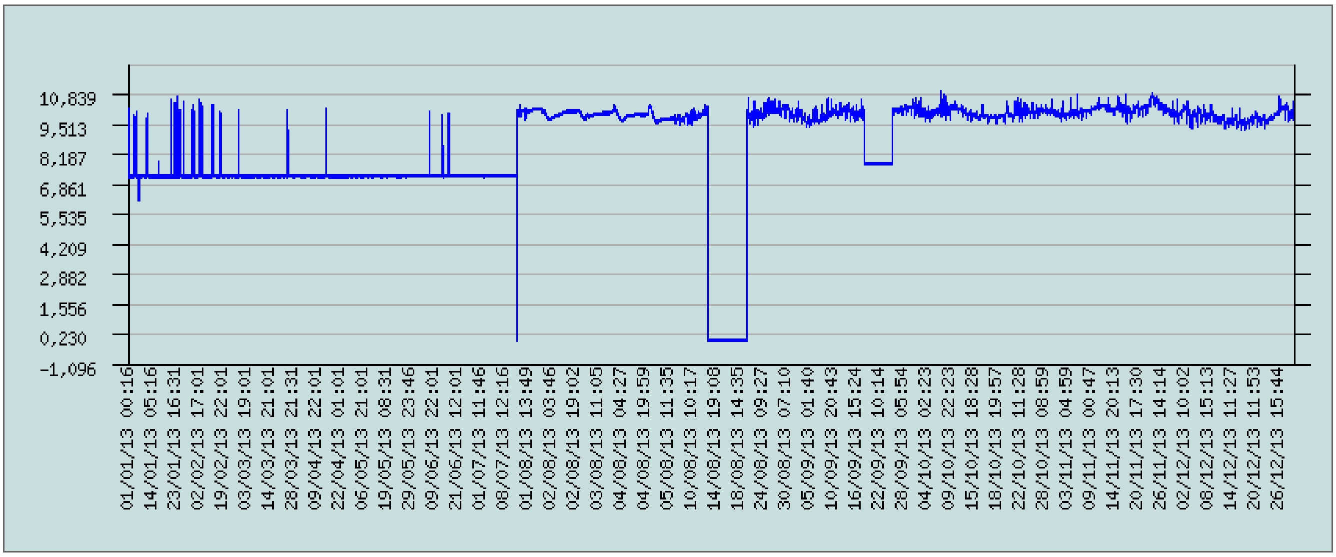

Figure 18: Upstream water level at the Trezze Sluice system during the year 2013 (Adige-Euganeo Reclamation Authority database).

The steady water flow guarantees that, during most of the year, the action of the Sluice system can difficulty cause changes in the morphological dynamics of the canal. The peaks drawn in the graph represent the occurrence of exceptional events as an intense precipitation.

The problem regarding sediment transport occurring at Trezze location is mostly correlated to the use of the Pumping Plant. The activity of the Pumping Plant, governed by the Adige-Euganeo Reclamation Authority, is connected to extreme precipitations, in fact during these events it favors the flow discharge into the sea, saving the landscape from flooding; this explains the two peaks in Figure 19.

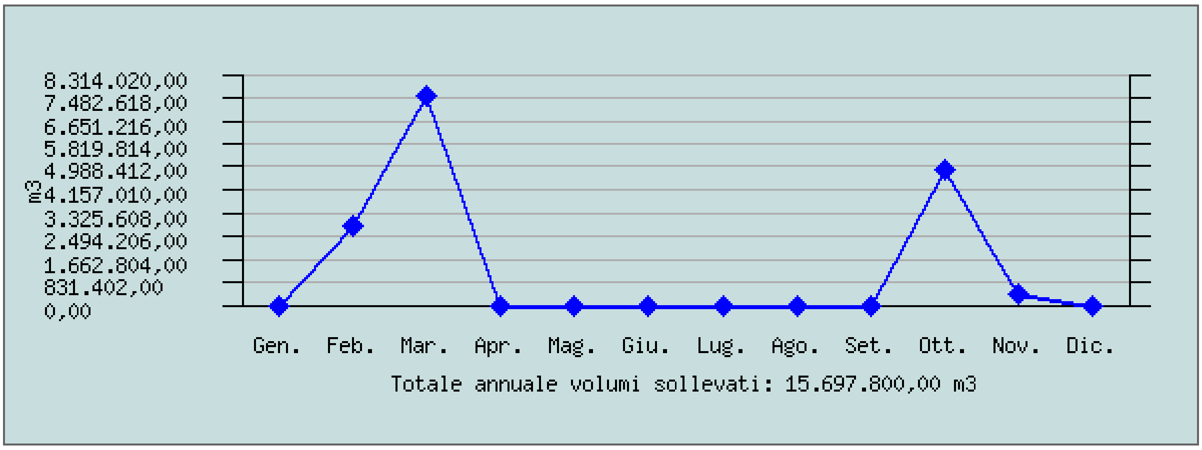

Figure 19: Annual trend of Trezze Pumping Plant raised volumes of the year 2013 (Adige-Euganeo Reclamation Authority database).

At the Priula location, the Pumping Plant, fishing from the Priula canal, is recharging the Morto canal upstream of the Sluice system. In this case, the unavoidable interaction of the hydraulic infrastructure with the canal dynamic occurs when it is necessary to discharge into the sea/lagoon the water accumulated in the Priula sub-basin. During these events the flow is firstly pumped from the Priula canal through the Pumping Plant into the Morto canal (the flow is sent upstream of the Sluice system), then the Sluice system regulates the flow sending it to the Trezze location and consequently to the sea/lagoon as explained before.

This mechanism of interaction between the Pumping Plant and the Sluice system is quite constant during all the year (Figure 20 and 21). This fact guarantees that the transport/erosion of sediment is uniform and localized upstream of the Sluice system.

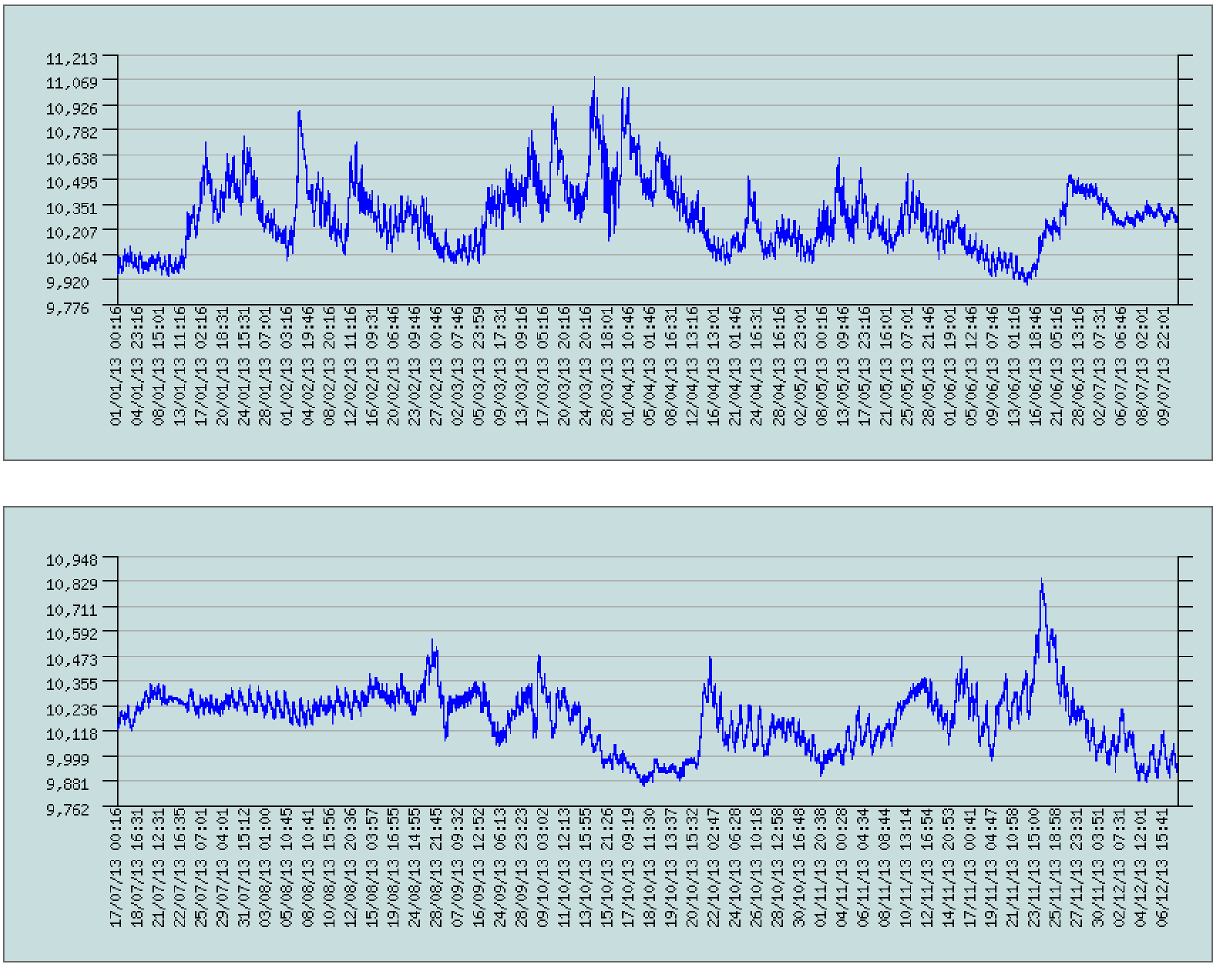

Figure 20 : Up stream water level at the Priula Sluice system during the first and the second semester of the year 2013(Adige-Euganeo Reclamation Authority database).

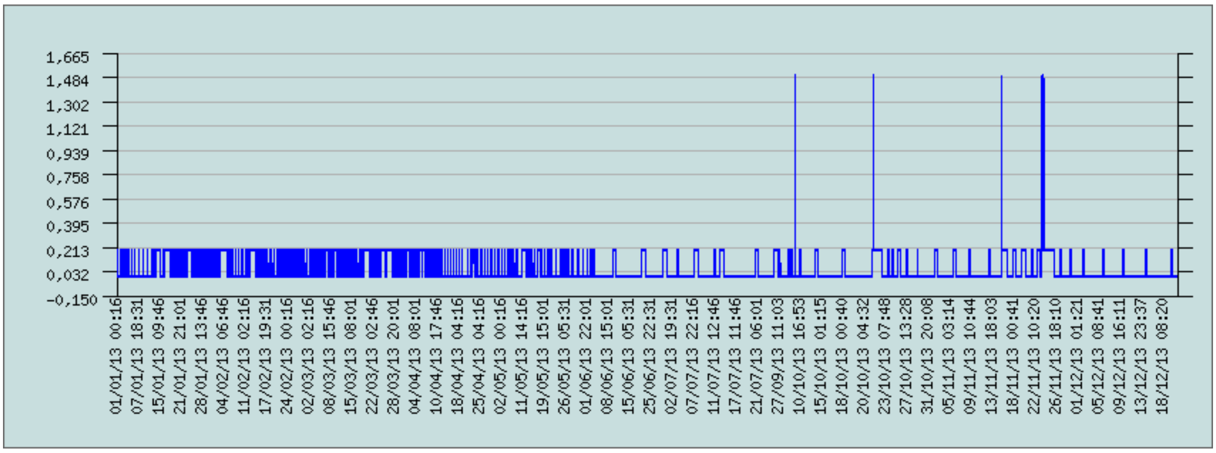

Figure 21: The instantaneous flow-rate of the Priula Pumping Plant during the year of 2013 (Adige-Euganeo Reclamation Authority database).

The last hydrologic infrastructure analyzed in this study is the San Silvestro Pumping Plant that drain the water flow collected in the San Silvestro canal into the Morto canal. This Pumping Plant is working annually with a uniform and non-intense water flow in a similar way as the Priula Pumping Plant (Figure 22).

This analysis is useful for understanding the spatial and temporal distribution of the sedimentation/erosion process which is an important tool for the correct hydrologic infrastructure management acting on the territory.

Another human action interacting with the morphological dynamics of the canals and their bathymetry is the banks cleaning and the canal-bed purging.

Analyzing the frequency and the procedure within these two actions are applied on the canals by the in charged Reclamation Authority, is possible to better understand the sedimentation process intensity and diffusion.

The banks cleaning occurs in the same way and at the same time for the Cuori and Morto canal.

The mower of the banks is made with a motor raw situated on small boats. The frequency applied to this techniques is once a year, it occurs during fall season because is necessary to respect the growing season of the plants living in the canals banks and acting as natural filter for the organic nutrients load degradation.

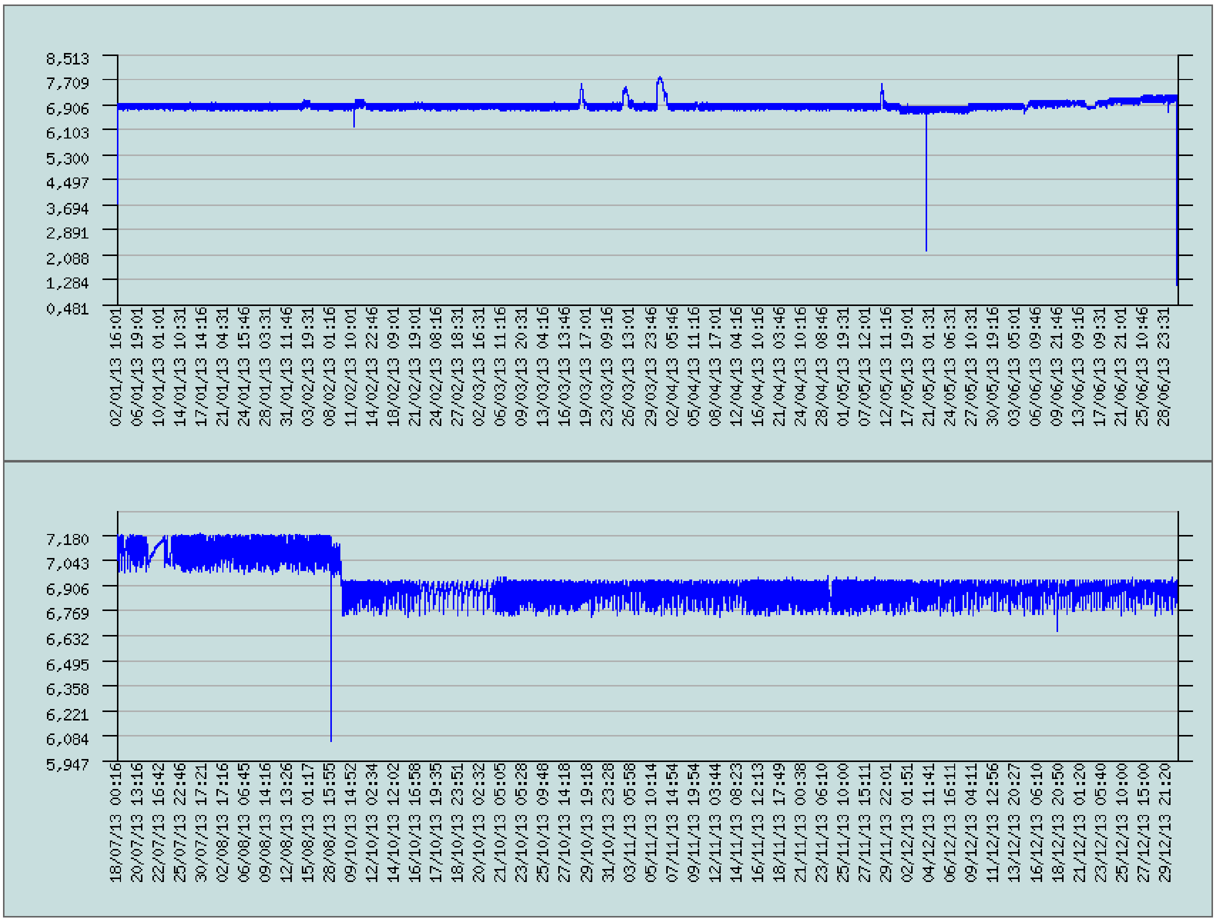

Figure 22: Trend of the water level in the inlet basin of the San Silvestro Pumping Plant during the first and second semester of the year 2013 (Adige-Euganeo Reclamation Authority database).

The canal-bed purging is very different and more complicated respect to the previous technique. The return time can varies for each site depending on the soil composition and on the flow-rate regime acting on the canal. The last time that the two canals bed were excavated was in 1998 for the Morto canal and in 2001 for the Cuori canal.

These two human actions are fundamental aspects that have to be analyzed and taken into consideration in order to better understand the complex dynamics acting on the hydrogeological features.

CHAPTER 3

Study on water salinity distribution

3.1) Methods of sampling

The salt water contamination process in the Venice watershed between the southern edge of the lagoon and the Brenta River was investigated through hydrological surveys and a monitoring network of surface water campaign.
In this agricultural region, where the surface hydrologic network is entirely artificially controlled by irrigation/drainage canals and pumping stations, salinization problems have long been encountered in soils, canals and groundwaters.
This study goes in the direction to improve our understanding of the origin of salinization and mineralization of the hydrological features and soils.
In order to focus on these aspects, Temperature (°C), EC (electrical conductivity, µS/cm) and Salinity (psu) values of the surface waters along the Morto and Cuori canals were analyzed on the field through a portable conductivity meter (Figure 23) during the period between February and March 2014.

Figure 23: Image of the portable conductivity meter.

The samples and analysis were conducted at four sites in the southern lagoon: one of them is situated upstream of the Cà Bianca pumping station in the Cuori canal, the others are located along the Morto canal (San Silvestro, Priula and Trezze) as is shown in (Figure 24).
For each site the measures were taken at three points: in the center of the canal and also along the two banks, and for each point were collected two measures: one on the canal-bed (considering the different bathymetry of each site), and the other on the surface-water. It was decided to behave in this way to give a more appropriate and representative description of salinity concentration in the canals, in fact, the salinity

concentration on the canal-bed should be higher if compared with surface-water, due to the higher density of the saltwater respect to freshwater.

All of these measures were realized from a small boat kindly granted from the Adige-Euganeo Reclamation Authority, placing a conductivity probe in the water and measuring the flow of electricity between the Electrodes.

The electrical conductivity is a parameter that indicates the content of dissolved salts in the water: salts are charged ions and as such allows the passage of current in the water itself.

Conductivity measurements are affected by temperature so the water temperature was measured at the same time as conductivity. The temperature increase improves the mobility of the charged species and thus increase the conductivity

Figure 24: Map of the study area with the location of the sampling points.

The suitability of a saline water for irrigation is so dependent upon the conditions of use, including crop, climate, soil, irrigation method and management practices, for these reasons, water quality classifications are not always advised for assessing water suitability for irrigation. However, it is useful to give a classification scheme (Table 2) for the purpose of identifying the levels of water salinities.

Table 2: Water salinity ratings (Rhoades et al., 1992).

water type	EC (dS/m)	salinity rating
fresh	<0,7	low
slightly saline	0,7 to 2	moderate
moderately saline	2 to 10	high
Highly saline	10 to 45	very high
marine water	45 to 60	extremely high

After the water salinity ratings, three classes of water quality have been established and used for the report analysis on the basis of acceptable limits for the main horticultural and agricultural uses of soils in the study area (Carbognin and Tosi., 2003).

It was therefore decided to classify the waters as follows:

- *Salty*, those with conductivity values, measured in canals, above 5000 µS/cm (3000 mg/l) and electrical resistivity of the soil below 4.5 ohm*m;
- *Brackish*, those with conductivity values including between 5000 and 2000 µS/cm (3000 – 1200 mg/l), and electrical resistivity of the soil between 4.5 and 7 ohm*m;
- *Fresh water*, those with electrical conductivity values below 2000 µS/cm (1200 mg/l) and electrical resistivity of the soil above 7-10 ohm*m.

The natural conductivity of fresh water varies from very low values (30 µS/cm) to very high values (2000 µS/cm) which is unsuitable for irrigation.

The measures that are included in the critical range explained above (in the neighborhood of 2000 µS/cm) need to be taken accurately into consideration because are the values that better represents the beginning of a possible salt contamination.

3.2) Analysis and results

It is evident that EC measures provides valuable information about possible salinization of surface water, and, from this, relevant considerations could be carried out about its interaction with tidal regime, fresh waters discharge and groundwaters, contributing significantly to the overall understanding of the hydrogeology in these delicate areas.

The results from the dataset sampled on February shows how the values measured on the field vary within the critical range between 1400 µS/cm and 1900 µS/cm, which is the threshold limit for the beginning of the saltwater intrusion process.

The results carried out on the field are reported in Table 3 and 4, and are also represented on a aerial photograph, (Figure 23), which is reproduced with the conductivity classes registered on the field.

Table 3: Values of Temperature, Electrical Conductivity (EC) and Salinity, performed on the field, concerning the samplings points of Priula and Cà Bianca.

PRIULA (25.02.14)				
	T (°C)	EC (µS/cm)	SAL. (psu)	
centro canale	10,5	1468	0,7	In superficie
	9,8	1653	0,8	profondo (3m)
sponda Dx	10,3	1472	0,7	In superficie
	10,1	1404	0,6	profondo (3m)
sponda Sx	10,3	1476	0,7	In superficie
	10,2	1480	0,7	profondo (3m)

CA' BIANCA (25.02.14)				
	T (°C)	EC (µS/cm)	SAL. (psu)	
centro canale	11,3	1884	0,9	In superficie
	10,5	1882	0,8	profondo (2m)
sponda Dx	11,4	1846	0,9	In superficie
	11,2	1848	0,9	profondo (2m)
sponda Sx	10,7	1862	0,9	In superficie
	10,6	1860	0,9	profondo (2m)

Table 4: Values of Temperature, Electrical Conductivity (EC) and Salinity, performed on the field, concerning the samplings points of Priula and Cà Bianca.

TREZZE (25.02.14)				
	T (°C)	EC (µS/cm)	SAL. (psu)	
centro canale	10,2	1485	0,7	In superficie
	10	1530	0,8	profondo (3m)
sponda Dx	10,2	1486	0,7	In superficie
	10,1	1446	0,7	profondo (3m)
sponda Sx	10,2	1491	0,7	In superficie
	10,2	1491	0,7	profondo (3m)

SAN SILVESTRO (25.02.14)				
	T (°C)	EC (µS/cm)	SAL. (psu)	
centro canale	10	1584	0,8	In superficie
	9,2	1630	0,7	profondo (1,2m)
sponda Dx	9,7	1600	0,7	In superficie
	9,5	1616	0,8	profondo (1,2m)
sponda Sx	9,8	1590	0,7	In superficie
	9,3	1595	0,7	profondo (1,2m)

In the Figure 25 are shown the maximum values of electrical conductivity recorded in the measurement campaign, whose values are represented for classes of conductivity.

Considering only the Morto canal, containing the measuring points of Trezze, Priula and San Silvestro, are represented the maximum values of EC which follow a uniform trend with a slightly increase that goes from the nearest station to the lagoon, Trezze, to the farthest station, San Silvestro.

This trend, even if is not very explanatory, goes in the opposite direction respect to the literature studies, (de Franco et al., 2009) and (Teatini et al., 2011), analyzing the process of seawater encroachment along rivers/canals mouths in others coastal areas.

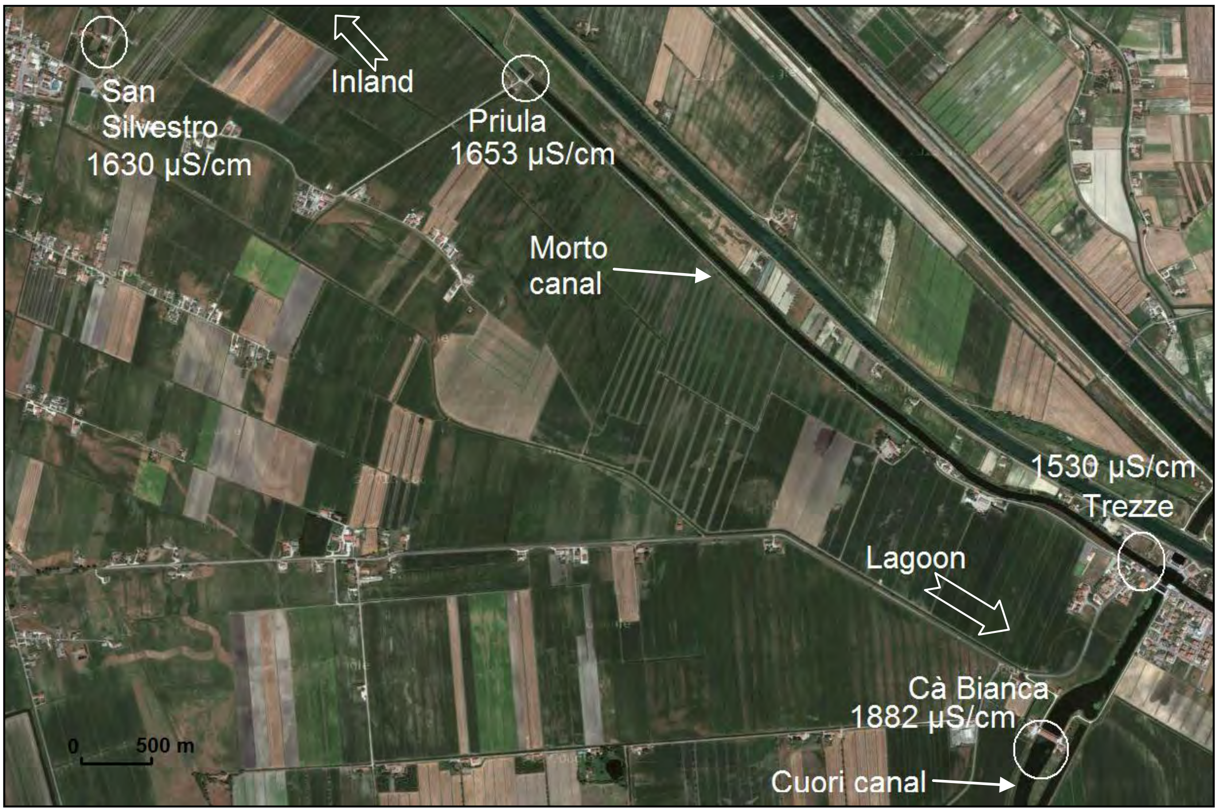

Figure 25: Map of the Electrical Conductivity distribution.

Some considerations could be drawn regarding this aspect:

First of all, during the sampling date the Morto canal was discharging into the lagoon and all the Sluice systems were operating; for this reason the values measured on the field need to be integrated with others measures and factors such as seawater encroachment along rivers/canals mouths could not be one of the determinants causes of saline contamination; on the other hand two important factors should be taken into account because of their possible influence in the field:

the canal water level kept too low by pumping plants controlled by the regarding Authorities for the hydrological safety of the area which favors the rising up of the salty water along the aquifers which unfortunately are already subject to the process of saline contamination, as explained in Chapter 2.2 and demonstrated from the studies (Rizzetto et al., 2003) and (De Franco et al., 2009). The second factor is the presence of sandy Paleochannels in the study area and their connection with the canals-bed, in fact, acting as preferential path flows, they could favor the intrusion of salty water, (Mulligan et al., 2007) and (Rizzetto et al., 2003).

The further assessment considers the EC measurements of the Cà Bianca station, located in the Cuori canal, during the month of February and for the period ranging between 2001 and 2014 in order to evaluate the time trend of the saline concentration.

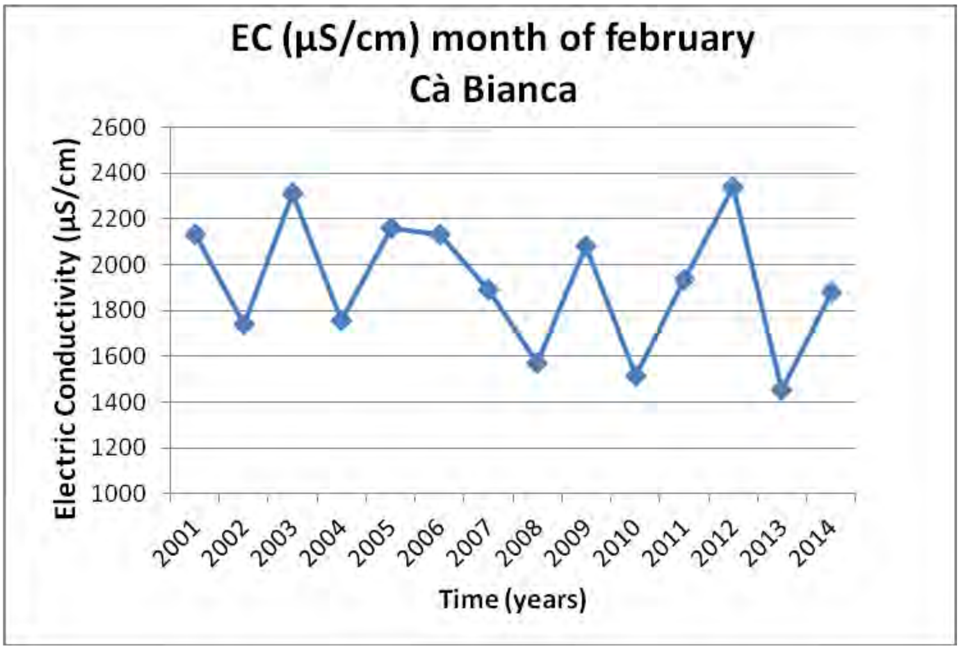

Figure 26: Electrical conductivity trend for the Cà Bianca station considering only the month of February during the period from 2001 to 2014.

As is drawn in the graph above, (Figure 26), all the data are included in the critical range explained in chapter 3.1 which consist of Brackish and Fresh water.

This graph underline the importance to take some actions in order to face the problems of salinity diffusion and persistence, because the EC trend remain constant within values that are not considered optimum for the proper management of the resource and territory.

From the following graph, (Figure 27), is possible to notice that seawater intrusion seriously affects the hydrological features of the study area and the problem is characterized by a certain seasonal fluctuation, especially high during winter season.

Simultaneously at the realization of Electrical Conductivity graph has been drawn the graph with the Temperature trend affecting the Cuori canal upstream the Cà Bianca pumping plant (Figure 28).

The graph regards only the Cuori basin, where the flow is mechanically and totally regulated by the Cà Bianca pumping station and for this reason there is a reduced tidal influence, and is drawn considering the period that goes from 2001 until 2014 which is realized thanks to the consistent monitoring network that was made during this period by all the projects and Authority that have collaborated in this difficult area.

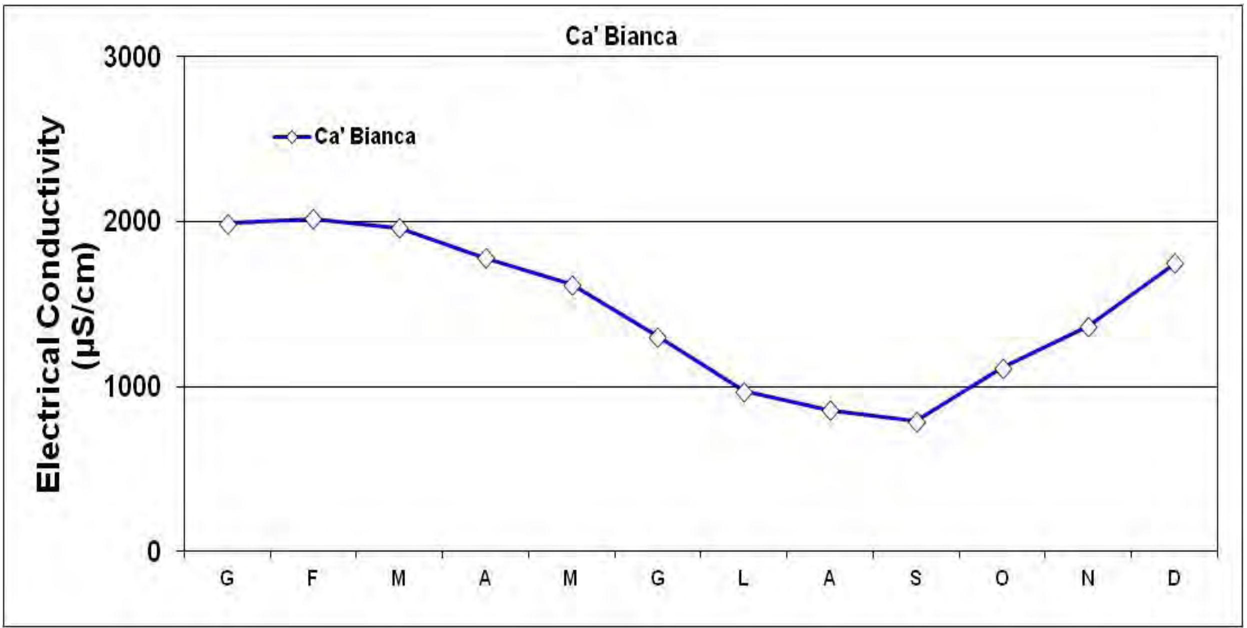

Figure 27: Electrical Conductivity trend for the Cà Bianca station in relation with the months of the year for the period between 2001 and 2014.

Concluding this dissertation, some important factors that influence spatiotemporal evolution of salt contamination could be pointed out:

- The collecting/releases of freshwater, in fact the reduced freshwater discharges that occur in the Cuori and Morto canals during some periods, and corresponding at the same time to events like high tides, allow the seawater to flow up from the river mouths for several kilometers.
- The operation of Cà Bianca pumping station is one of the most significant factors due to maintaining the fresh water table at low levels in reclaimed areas during fall and spring seasons in order to prevent flood event, favoring in this way the saltwater intrusion thought the aquifers. Because in fall and spring season the freshwater/saltwater interface of the aquifers discreetly increase and can reach the canal bed allowing the interaction between the salty aquifers and the canals.
- Paleoriver beds, ancient dunes and littoral ridges, combined with climate changes, contribute to the worsening of this process.
- The climatic conditions like tidal regime which play, in the case of the Cuori canal, a negligible role in the dynamics of the encroachment process, became

fundamental for the Morto basin which is constantly or temporarily in hydraulic communication with the water of the lagoon or the sea (Carbognin et al., 2003).

- Also the location of the area well above the surrounding farmland as the Morto and Cuori canals are fundamental water-bodies impacting on the groundwater quality, as well as the opposite is true. If the two canals contain seawater, they are a potential source of severe contamination for the aquifers in the surrounding farmland. Conversely they are likely to play a fundamental role in controlling the contamination level in the shallow aquifer when they contain freshwater.

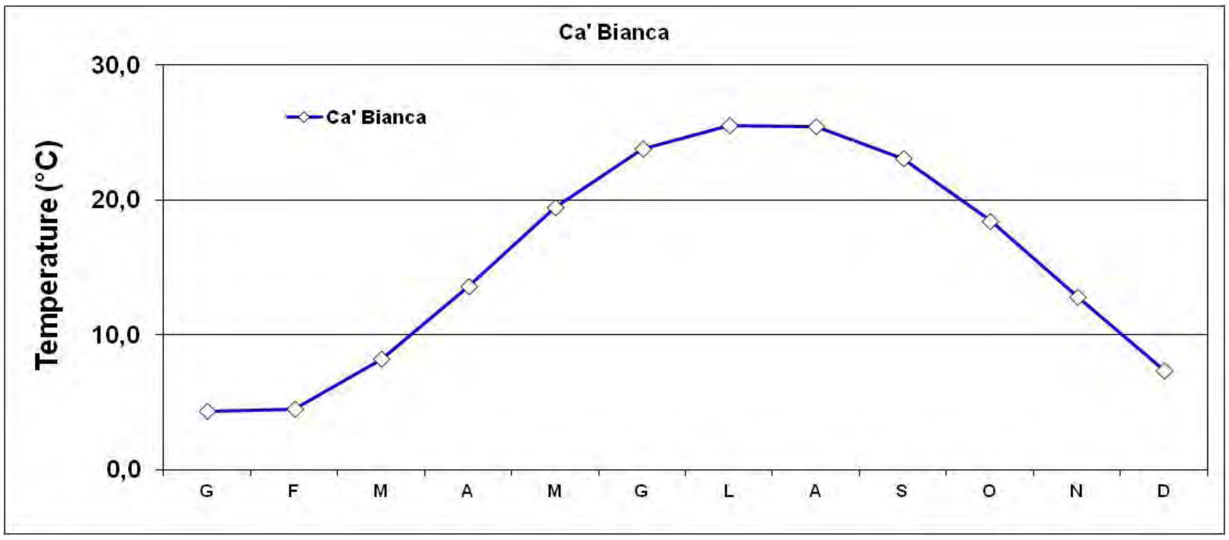

Figure 28: Temperature trend for the Cà Bianca station in relation with the months of the year for the period between 2001 and 2014.

Finally in this chapter is underlined that the dynamics of the seasonal fluctuation for the Electrical conductivity at the Cà Bianca stations is very sensitive at all the factors explained above and only an analysis that takes equally into account all the aspects can be considered effective to address with the salinity problem that afflict this area.

The analysis of water electrical conductivity network allows therefore to identify the presence of saline contamination that goes back along the canals and rivers mouth, following the direction from the lagoon to the inland and whether significant variations have taken place over time.

The creation of this monitoring network wants to provide that precise knowledge of the phenomenon characteristics and its variation over time is essential for the implementation of future management interventions.

Conclusions

The dynamics of saltwater intrusion along the Morto and Cuori canals profile have been studied by Electrical Conductivity analysis and monitoring network, managed by the Adige-Euganeo Reclamation Authority, in order to control the interaction between surfacewater and groundwaters, and define the encroachment of the salty water through the river mouth.

The results of this study allow the determination of the superficial extension and diffusion of the salt water contamination in the direction of the mainland, the factors influencing this process and, finally, the relationship between hydrological features, infrastructure and conductivity values.

The accurate processing and interpretation of the entire data-set allow also to point out the evolution of the saltwater contamination process at different time and spatial scales.

The outcome of the investigation underlines therefore that EC measurements provide valuable information of ground characteristics and surface water salinity. Moreover, they give the possibility to focus on their interaction, contributing significantly to the overall understanding of the hydrogeology in these delicate areas.

The hydrogeological characteristics of each basin, analyzed in detail in this report, are essential not only for specific and local purposes, but also to increase our general understanding. This broader perspective focuses on how sedimentological and chemical characteristics affect the responses of transitional environments to forcing factors, and thus provide essential data for environmental decision making and future management of the Venice Lagoon.

Because of the dynamic behavior of seawater intrusion, monitoring is needed to assess the contaminant evolution, especially in reclamation areas such as the Venice coastland, where very complex geomorphological and hydrogeological features significantly affect the drainage basin.

Conclusively, monitoring issues and techniques, performed in order to understand the natural and anthropogenic causes and mechanisms of salinization, is a fundamental step towards the sustainable management of this intensively cultivated area.

References

Amos, C.L., Villatoro, M., Helsby, R., Thompson, C.E.L., Zaggia, L., Umgiesser, G., Venturini, V., Are, D., Sutherland, T.F., Mazzoldi, A. and Rizzetto, F., 2010. The measurement of sand transport in two inlets of Venice lagoon, Italy. Estuarine, Coastal and Shelf Science, 87(2): 225-236.

Bagnold, R.A., 1966. An approach to the Sediment Transport Problem from General Physics, U.S. Geological Survey Professional Paper 422-I, Washington.

Berto D, Giani M, Boscolo R, Covelli S, Giovanardi O, Massironi M, Grassia L., 2007. Organotins (TBT and DBT) in water, sediments, and gastropods of the southern Venice lagoon (Italy). Marine Pollution Bulletin 55:425–435.

Brambati, A., Carbognin, L., Quaia, T., Teatini, P., Tosi, L., 2003. The Lagoon of Venice: geological setting, evolution and land subsidence, Episodes, 26(3), 264-268.

Carbognin, L., Tosi, L., 2003. Il Progetto ISES per l’analisi dei processi di intrusione salina e subsidenza nei territori meridionali delle Province di Padova e Venezia. Grafiche Erredici Padova (Italy), p. 95.

Carbognin, L., Rizzetto, F., Tosi, L., Teatini, P., Gasparetto-Stori, G., 2005. L’intrusione salina nel comprensorio lagunare veneziano. Il bacino meridionale. Giornale di geologia Applicata, **2**: 119-124.

De Franco, R., Biella, G., Tosi, L., Teatini, P., Lozej, A., Chiozzotto, B., Giada, M., Rizzetto, F., Claude, C., Mayer, A., Bassan, V., Gasparetto-Stori, G., 2009. Monitoring the saltwater intrusion by time lapse electrical resistivity tomography: the Chioggia test site (Venice Lagoon, Italy). J. Appl. Geophys. 69, 117–130.

Di Sipio, E., A. Galgaro, and G. M. Zuppi (2006), New geophysical knowledge of groundwater systems in Venice estuarine environment, Estuarine Costal Shelf Sci., 66, 6 – 12, doi:10.1016/j.ecss.2005.07.015.

Engelund, F., 1965. A criterion for the occurrence of suspended load. La Houille Blanche, 8: 7.

Gattacceca J. C., Vallet-Coulomb C., Mayer A., Claude C., Radakovitch O., Conchetto E., Hamelin B., 2009. Isotopic and geochemical characterization of salinization in the shallow aquifers of a reclaimed subsiding zone: The southern Venice Lagoon coastland. Journal of Hydrology 378 (1-2), pp 46-61.

Gatto, P. and Carbognin, L., 1981, The Lagoon of Venice: Natural environmental trend and man-induced modification. Hydrological Sciences Bulletin, 26/4/12, pp. 379-391.

Ghezzo, M., Sarretta, A., Sigovini, M., Guerzoni, S., Tagliapietra, D., Umgiesser, G., 2011. Modeling the inter-annual variability of salinity in the lagoon of Venice in relation to the water framework directive typologies. Ocean & Coastal Management 54, 706e719.

Liu, Z., 2001. Sediment transport. Aalborg University, Aalborg, Denmark.

Manoli, G., Bonetti, S., Scudiero, E., Teatini, P., Binning, P.J., Morari, F., Putti, M., Marani, M., 2013. Monitoring and modeling farmland productivity along the Venice coastland, Italy, Procedia Environ. Sci., 19, 361-368.

McClennen, C.E., Ammerman, A. J., Schock, S.G., 1997. Framework stratigraphy for the Lagoon of Venice, Italy: Revealed in new seismic-reflection profiles and cores. J. Coastal Res., 133, 745–759.

Molinaroli, E., Guerzoni, S., Sarretta, A., Cucco, A., Umgiesser, G., 2007. Links between hydrology and sedimentology in the lagoon of Venice, italy. Journal of Marine Systems 68 (3e4), 303e317.

Molinaroli, E., Guerzoni, S., Sarretta, A., Masiol, M., Pistolato, M., 2009. Thirty-year changes (1970–2000) in bathymetry and sediment texture recorded in the lagoon of Venice sub-basins, Italy. Marine Geology 258, 115–125.
Mulligan, A.E., Evans, R.L., Lizarralde, D., 2007. The role of paleochannels in groundwater/seawater exchange. J. Hydrol. 335, 313–329.

Rhoades, J. D., Kandiah, A., Mashali, A. M., 1992. The use of saline water for crop production. FAO. Irrig. & Drain. Div., No.48, Rome, Italy.

Rizzetto, F., Tosi, L., Carbognin, L., Bonardi, M., Teatini, P., 2003. Geomorphological Setting and Related Hydrogeological Implications of the Coastal Plain South of the Venice Lagoon (Italy). In: Servat, E. et al. (Eds.), Hydrology of the Mediterranean and Semiarid Regions. IAHS Publ. n. 278, Wallingford, UK, pp. 463–470.

Roe, S., 2007. A laboratory study of the deviation of the suspension threshold of fine and very fine sand. MSc dissertation, University of Southampton, Southampton, UK.

Scudiero, E., Deiana, R., Teatini, P., Cassiani, G., Morari, F., 2011. Constrained optimization of spatial sampling in salt contaminated coastal farmland using EMI and continuous simulated annealing, Procedia Environ. Sci., 7, 234-239.

Scudiero, E., Teatini, P., Corwin, D.L., Berti, A., Morari, F., 2013. Delineation of site-specific management units in a saline region at the Venice Lagoon margin, Italy, using soil reflectance and apparent electrical conductivity, Computers and Electronics in Agriculture, 99, 54-64.

Shields, A., 1936. Application of similarity principles and turbulence research to bed-load movement. Report 167,26 pp.

Soulsby, R.L., 1997. Dynamics of marine sands: A manual for Practical Applications. Thomas Telfod Publications, London, 249 pp.

Teatini, P., Tosi, L., Viezzoli, A., de Franco, R., Biella, G., Tang, C., 2010. Driving the modeling of saltwater intrusion at the Venice coastland (Italy) by ground-based, water-, and air-borne geophysical investigations. In: World Environmental and Water Resources Congress 2010: Challenges of Change., R.N. Palmer ed., ASCE., 1146-1155.

Teatini, P., Tosi, L., Viezzoli, A., Baradello, L., Zecchin, M., Silvestri, S., 2011. Understanding the hydrogeology of the Venice Lagoon
subsurface with airborne electromagnetics. J. Hydrol. 411, 342-354.

Tosi, L., Rizzetto, F., Zecchin, M., Brancolini, G., Baradello, L., 2009. Morphostratigraphic framework of the Venice Lagoon (Italy) by very shallow water VHRS surveys: evidence of radical changes triggered by human-induced river diversion. Geophys. Res. Lett. 36, L09406. doi:10.1029/2008GL037136.

Uccelli, A., Nicòtina, L., Casara, T., Beraldin, F., Cecconi, G., Settin, T., Rinaldo, A., Marani, M., 2006. Acque dolci che si versano nella laguna di Venezia: schema geomorfologico continuo. Xxx° Convegno di Idraulica e Costruzioni Idrauliche (IDRA 2006).

Van Rijn, L.C., 1993. Principles of sediment transport in rivers, estuaries, and coastal seas. Acqua Publications, Amsterdam, The Netherlands.

Viezzoli, A., Tosi, L., Teatini, P., Silvestri, S., 2010. Surface water–groundwater exchange in transitional coastal environments by airborne electromagnetics: the Venice Lagoon example. Geophys. Res. Lett. 37, L01402. doi:10.1029/2009GL041572.

Villatoro, M.M., Amos, C.L., Nicholls, R.J., Weaver, P., 2010a. Sand transport in Chioggia Inlet, Venice Lagoon and resulting morphodynamic evolution. University of Southampton, Faculty of Natural and Environmental Sciences, School of Ocean and Earth Sciences, PhD Thesis.

Villatoro, M.M., Amos, C.L., Umgiesser, G., Ferrarin, C., Zaggia, L., Thompson, C.E.L. and Are, D., 2010b. Sand transport measurements in Chioggia inlet, Venice lagoon: Theory versus observations. Continental Shelf Research, 30(8): 1000-1018.

Zonta, R., Costa, F., Collavini, F., Zaggia, L., 2005. Objectives and structure of the DRAIN project: an extensive study of the delivery from the drainage basin of the Venice Lagoon (Italy). Environment International 31 (7 SPEC. ISS.), 923e928.

Zuliani, A., Zaggia, L., Collavini, F., Zonta, R., 2005. Freshwater discharge from the drainage basin to the Venice Lagoon (Italy). Environment International 31 (7 SPEC. ISS.), 929e938.

Acknowledgments

Un primo doveroso ringraziamento và al Prof. Salandin, il quale mi ha permesso di lavorare all'interno di un ambiente pratico e creativo permettendomi così di ampliare la mia formazione sul campo. All'Ing. Gasparetto e al Consorzio di Bonifica Adige-Euganeo per la collaborazione e la disponibilità fornitami durante il mio percorso di tesi.

Il grazie più sentito và alla mia famiglia: a mamma, papà e Andi, senza i quali non sarei mai riuscito a raggiungere questo obbiettivo ma soprattutto per il loro amore che non è mai mancato e che mi ha permesso di diventare la persona che sono; alla nonna, alle zie, agli zii e ai cugini per la fiducia e il sostegno datomi in questi anni e per far parte di questa bellissima famiglia che tanto mi ha insegnato.
Un grazie immenso alle "famiglie acquisite": quella vicentina, quella padovana e quella bolognese per tutte le avventure passate insieme, per tutti i momenti condivisi e per il nostro crescere assieme; un grazie a tutti gli amici sparsi per il mondo e infine un grazie speciale alla Pata per la sua allegria (up and down) e la contagiosa voglia di amare.

BOMBO DI CLAT!!!!