15 Geomorphological Processes and Landscape Evolution of the Lagoon of Venice

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Abstract

The Lagoon of Venice, extending along the northern Adriatic coast in northeastern Italy, is the most important Italian lagoon. The delta systems of the Po, Adige and Brenta rivers delineate the lagoon from the south, whilst the Sile and Piave rivers border the lagoon in the north. The lagoon is closed by the barrier islands of Lido and Pellestrina and the spit of Cavallino. Inside the lagoon, several landforms typical of this peculiar environment are present: islands, salt marshes, tidal flats, fluvial deltas, tidal channels, sand dunes, ancient coastlines and man-made forms such as landfills, fish farms, coastal defences and artificial channels. Due to protracted human interference with natural processes, the Lagoon of Venice may be considered today as an artificial environment.

Keywords

Lagoon • Salt marshes • Venice • Adriatic Sea

15.1 Introduction

The Lagoon of Venice is the largest Italian lagoon and the most important heritage of the system of estuarine lagoons that for thousands of years and until the last century extended along the coast of the Adriatic Sea between Trieste and Ravenna, in northeastern Italy. The term "lagoon" is derived from the Italian *laguna*, which refers specifically to the Lagoon of Venice.

The lagoons are subjected to highly dynamic coastal processes, responsible for a fragile balance between terrestrial and marine processes, where, very often, an important role is played by humans. In fact, despite the history of significant environmental changes that occurred during the middle and late Holocene, the current setting of the Lagoon of Venice is mainly the result of a series of human interventions, especially those implemented in the last five centuries.

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15.2 Geographical Setting

The Lagoon of Venice is located in the Gulf of Venice (northern Adriatic Sea), along the coastal fringe of the Venetian–Friulian Plain. The lagoon basin forms an arc about 55 km long and 8–13 km wide. It is separated from the open sea by a narrow coastal strip consisting of a series of barrier islands (Fig. 15.1). From the ENE, the spit of Cavallino is the largest one, which in the past was nourished by the mouth of the Piave River. It is followed by the two barrier islands of Lido and Pellestrina, while further south the lagoon is separated from the sea by the left wing of the fluvial delta of the Brenta River (Fig. 15.1).

The inner boundary that separates the lagoon from the mainland is in most cases marked by artificial hydraulic works. Figure 15.2 shows the lagoon boundary, the so-called *Conterminazione lagunare*, which is more an administrative border than a geographical one. It was fixed with 99 stones in 1791 by the Venetian Republic and was updated by the Magistrato alle Acque (Water Authority) at the end of the 1990s.

On both sides of the lagoon, a system of river mouths debouch into the Adriatic Sea. To the south, the large Po

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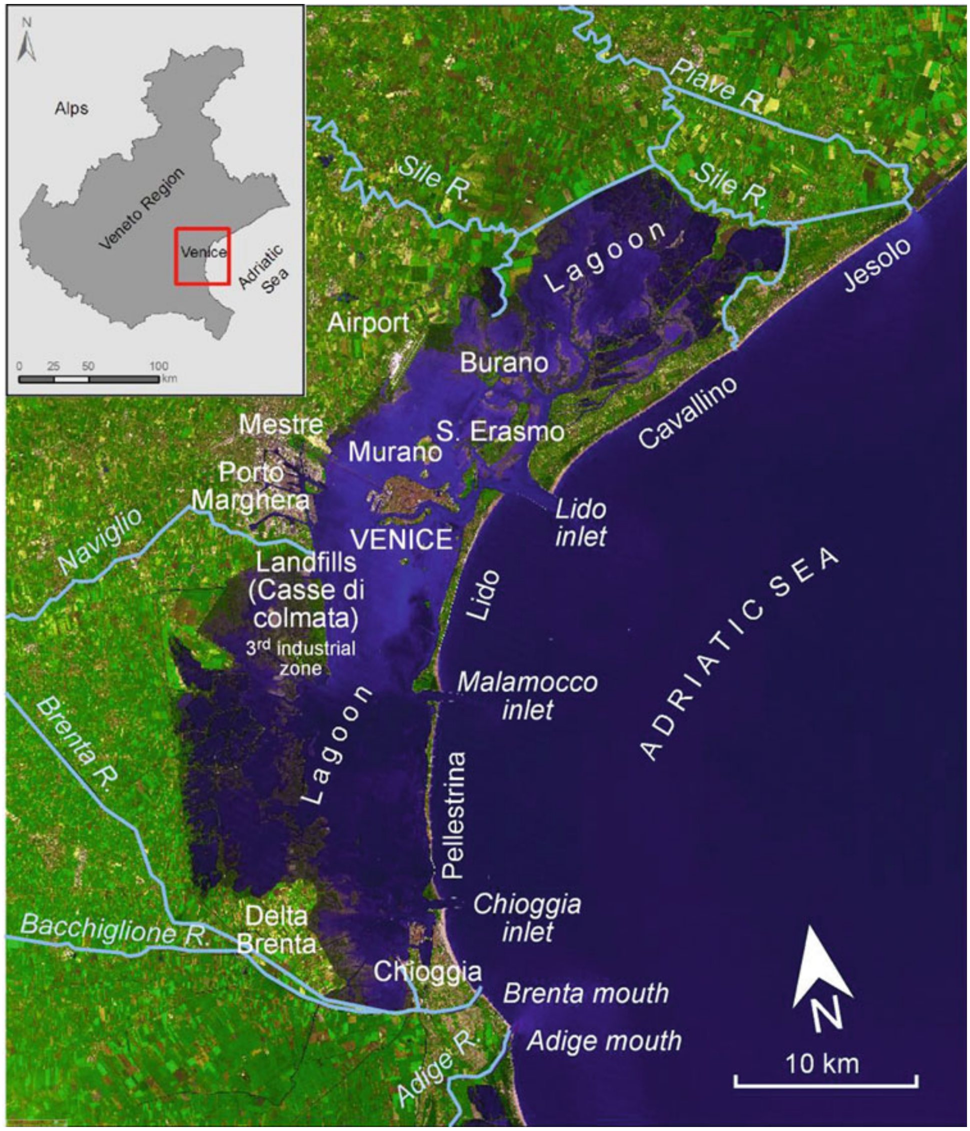

Fig. 15.1 Location map. Satellite image of the Lagoon of Venice and its mainland (Aster Image, 9 December 2001)

delta juts out into the sea; between the delta and the lagoon, the Adige and Brenta rivers (which also receive the waters of the Bacchiglione River) bring sediments to the southern part of the lagoon. To the north, the Sile, which occupied an old riverbed of the Piave in 1683, and the Piave rivers are delineating the lagoon, the latter with clearly identified fluvial ridges and deltas. Even in historical times, the Brenta and Sile poured their waters into the lagoon, but they have gradually been diverted outside it over the last five centuries.

Inside the lagoon basin, in addition to Venice and Chioggia, which are the two major groups of islands, there are other inhabited islands of appreciable size, such as Murano, Burano, Torcello and Sant'Erasmo. The others are smaller and almost all uninhabited.

The periodic ebb and flow of the sea water in connection with the cycle of the tides occurs via three tidal inlets at Chioggia, Malamocco and Lido.

15.3 Geomorphological Evolution

The Lagoon of Venice is part of the Venetian–Friulian plain formed by deposition by large river systems alternating with marine transgression. This sequence was mainly driven by the glacial and interglacial phases related to global climate cycles that occurred during the late Pleistocene and Holocene.

The central stretch of the Veneto plain consists of three alluvial megafans. The westernmost megafan was built by the Brenta River and stretches roughly in the NW–SE direction from the Brenta valley to the Venetian mainland. To the east, it borders the megafan of the Piave of Montebelluna, formed when the river was entering the plain west of Montello hill. Montello is located at the eastern end of the apex of the current Piave alluvial fan (megafan of the Piave of Nervesa).

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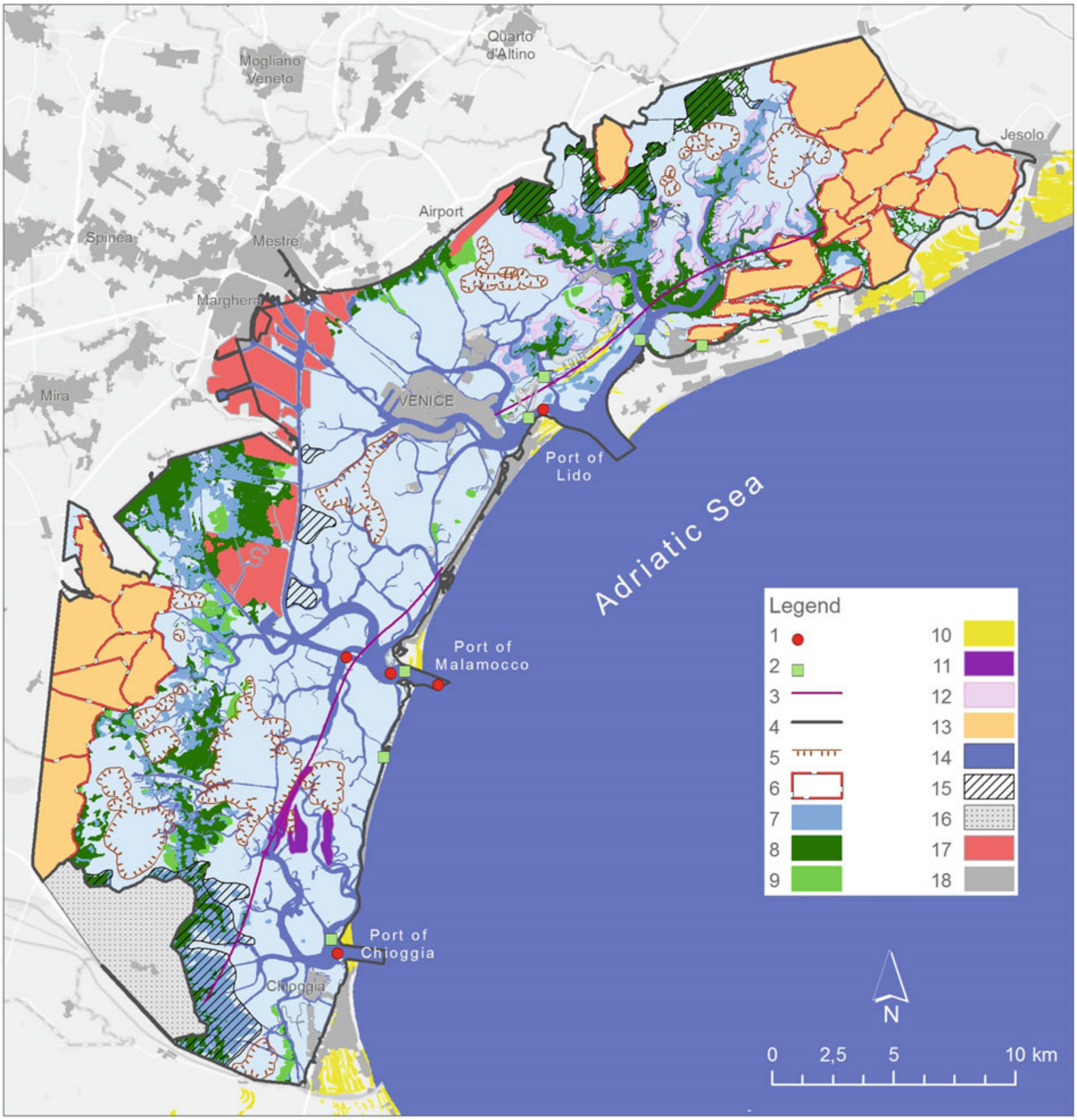

Fig. 15.2 Geomorphological sketch map of the Lagoon of Venice. Legend: *1* lagoonal inlet pool; *2* ancient lagoon inlet; *3* ancient coastline (5 ka BP); *4* ancient administrative lagoon boundary (*Conterminazione lagunare*); *5* depression in lagoon floor; *6* embankments; *7* tidal flat; *8* salt marsh; *9* artificial salt marsh; *10* sand dune; *11* relict of ancient barrier island; *12* lagoon tidal delta; *13* fish farm; *14* lagoon channel; *15* fluvial delta inside the lagoon; *16* reclaimed lagoon surface (Delta Brenta, 1840–1896); *17* landfill; *18* urbanized area

The plain to the west of the central and southern part of the Lagoon of Venice represents the terminus of the Holocene depositional system of the Brenta. This system is bordered to the north by the late Pleistocene deposits of the Brenta and to the south by the Holocene deposit of the Adige, with smaller contribution from the Po. The morphogenetic activity of the Bacchiglione is forced inside the large hollow formed by the juxtaposition of the Brenta system with the Adige system (Fontana et al. 2008, 2010; Carton et al. 2009).

The top of the Pleistocene deposits is marked by a paleosol—locally known as *caranto*—that contains carbonate concretions that are centimetres thick. This separates the Last Glacial Maximum (LGM) alluvial deposits from the overlying back barrier ones. Its top is an unconformity surface marking the Holocene–Pleistocene boundary between 4 and 7 m below mean sea level within the Lagoon of Venice (Donnici et al. 2011).

The formation of the lagoon took place after the marine transgression started at the end of the last glacial period,

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which reached its maximum in the Upper Atlantic (5–6 ka BP). In the Lagoon of Venice, the coastal wedge is quite thin and short, while most of the post-LGM deposits are lagoonal. Radiocarbon dating has shown that the paralic sediments along the margins of the lagoon are 1–2 thousands of years older than in Venice itself, where a structural high is present and lagoonal deposits range in age from 5.5 to 4.7 ka BP (Ammerman et al. 1995; Serandrei-Barbero et al. 2001, 2002). Alluvial and swamp deposits were buried by the marine ingression around 6.8 ka BP in the northern basin (Canali et al. 2007) and around 6 ka BP in the southern one (Favero and Serandrei-Barbero 1980).

After the maximum marine transgression, which went beyond the present coastline (Fig. 15.3, line A), a regression phase began, probably helped by the contribution of sediments from the Brenta in the southern sector of the lagoon and more to the south by the Adige and the Po. In the areas behind the line of maximum ingression, swamps and bogs formed as an effect of flooding and stagnation of fresh water (5–6 ka BP). In a relatively short period, the coastline moved forwards about 5 ka BP, towards the alignment of Motte Cucco–Peta de Bo–Val Grande (Fig. 15.3, line B). Upstream of this ancient shoreline, the first lagoons formed; from about 5 ka BP to mediaeval times we saw gradual development of the lagoon basins, fostered mainly by the stability of the coastline and the fact that the areas behind the barrier islands were not directly affected by the clastic contributions of rivers.

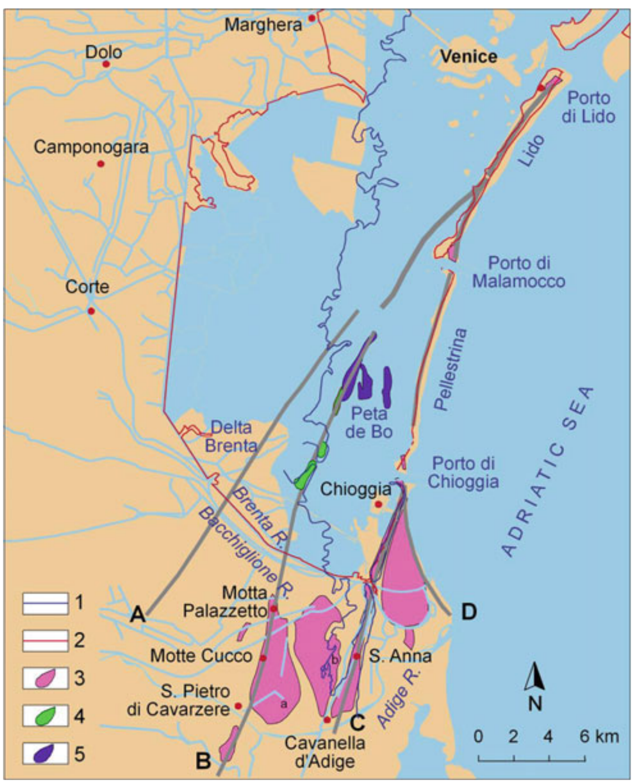

Fig. 15.3 The variations of the coastline in the southern part of the Lagoon of Venice. Legend: *Line A* limit of the maximum Holocenic ingression, after Favero and Serandrei-Barbero 1980; *line B* coastline of San Pietro di Cavarzere–Motte Cucco–Motta Palazzetto–Peta de Bo; *line C*: coastline Cavanella d'Adige–Sant'Anna–Chioggia; *line D*: present coastline; inner margin of the lagoon and coastline derived from historical cartography: *1* sixteenth century; *2* seventeenth century; *3* barrier island and complex of dunes, levelled or in elevation; ancient barrier island derived from: *4* historical cartography; *5* satellite images (modified after Bondesan and Meneghel 2004)

Between 2.8 and 2.5 ka BP the coastline rapidly moved forward along the Cavanella d'Adige–Sant'Anna–Chioggia line (Fig. 15.3, line C), where it remained until mediaeval times. Subsequent advancement of the coastline was probably caused by the Po River, but it was the Adige River which played a major role in sedimentation along the southern margin of the Lagoon. Also the Brenta River markedly contributed to coastal progradation, especially after an artificial fluvial diversion occurred at the end of the nineteenth century.

On the northern side of the lagoon, shoreline position was more stable and shoreline progradation started around 3 ka BP, induced by the action of the Piave River mouth (Amorosi et al. 2008). A marked advance was driven by the construction of the jetties at San Nicolò Port when, starting from 1872, a 2 km wide beach formed in about 80 years.

15.4 Landforms

The landforms inside the Lagoon of Venice can be classified according to the morphogenetic processes that have shaped them. Hence, alluvial, lagoonal and coastal features may be distinguished. These forms can be further classified according to bathymetry as subtidal zones located below the level of the average low tides; intertidal zones, alternately submerged and emerged; and supratidal zones (high tide platforms), submerged only by the highest tides (Fig. 15.2).

15.4.1 Alluvial Landforms

Within the Lagoon of Venice, alluvial and relict landforms inherited from continental environments are found. Among these, *fluvial ridges*, which are partially or completely submerged, form positive features inside the lagoon. These landforms are related to fluvial sedimentation due to repeated overbanking during floods. They can be relict forms determined by a natural or artificial withdrawal of the lagoon rim (which led to a partial submergence of the ridge) or they may have been generated by the advance of continental fluvial ridges in the lagoon environment. They are present in parts of the coastal plain invaded by the waters that now form the lagoon bottom, where there has been no subsequent sedimentation.

The *fluvial deltas inside the lagoon* are built of deltaic deposits formed along the lagoon's inner margin. The rivers, which at various times have poured their waters into the lagoon, created inner deltas with their sediments, consequently reducing the water surface area. The sediments are poorly reworked and deposits are generally thin, in a fan shape along the delta channels.

Some of the *islands* closest to the inner lagoonal margin arose on the fluvial deposits of rivers entering the lagoon.

15.4.2 Lagoon Landforms

Lagoonal landforms are widespread, and some have local names that have sometimes been proposed as scientific terms in Italian scientific literature.

The salt marshes (It.: *barene*) are among the most characteristic morphological elements of the lagoon. They are loamy, sandy flats situated a few centimetres above the sea level, dominated by dense stands of salt-tolerant plants such as herbs, grasses or low shrubs that contribute to their conservation. Currently, the lower limit of survival of halophilic vegetation coincides with the average sea level. They match, though not always perfectly, the forms defined by the international terms of *haute slikke* or *schorre*. They are characterized by a somewhat varying size and shape, but often in the vicinity of the channels they have a raised edge and a more depressed central part, similar to a "bowl" morphology. In other contexts, their form is tabular, with depressed edges or edges inclined towards the ponds where they link up with the intertidal flat. Various types of salt marshes were distinguished by Favero and Serandrei-Barbero (1983), depending on their continental (morphological relicts of the alluvial paleoplain inundated by marine transgression and subsequently emerged) or lagoonal origin (deposits that have developed as a result of natural lagoonal processes) and on the evolutionary behaviour that characterizes them.

Salt marshes of lagoon channel (It.: *barene di canale*) are very peculiar and largely present in the northern basin of the Lagoon of Venice. They are part of the natural levées located on the edge of the lagoon channels whose morphology is characterized by the presence of a raised edge at the feeder and a surface that slopes towards the side away from the channel (Fig. 15.4). The term "*gengiva"* (*gum*) has been proposed for submerged channel levées.

The mud flats (It.: *velme*) are barren silty intertidal flats located just below the sea level and extending from the lowest portion of the intertidal zone to the marsh areas. They usually show a low slope inclination. They are indicated in the international scientific literature by the terms tidal flats,

Fig. 15.4 Salt marshes, tidal flats and tidal creeks during low tide (*photo* A. Bondesan)

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marsh flats or *slikke*. These flat plains are limited by the network of lagoon channels that starts from the inlets and branch off into smaller courses.

For the subtidal forms, the term “swamp” (It.: *palude*) is locally used to indicate the portions of the lagoon bottom that are located below the average low tide level. Based on the morphology of the lagoon, other forms have also been identified, including depressions in the lagoon floor (generally less than 1–1.5 m) on which there is little deposition of lagoon sediments.

Water interchange occurs through three tidal inlets (It.: *bocca di porto* or *porto*), which identify three lagoon basins separated by underwater watershed lines, each of which has a dendritic network of lagoon channels that converges to each inlet. In former times, there were up to eight ancient tidal inlets, but these are now silted up.

The widest basin is that of the Port of Lido, which includes about 50% of the surface of the lagoon. The Malamocco basin includes about 30% of the lagoon and the Chioggia basin includes about 20%. At the inlets, also as a result of the construction of jetties, the ebb and flow creates strong currents that have dug lagoonal inlet pools. These are the deepest areas of the lagoon (approximately 50 m deep at Malamocco, 38 m deep at Chioggia, and 30 m deep at Lido).

The entire lagoon, including the subtidal zone, is crossed by a dense network of tidal channels representing the circulatory system of water coming into the lagoon from the tidal inlets and reducing their section inwards. The natural hydrographic network is defined by at least three orders of channels: (1) main channels that convey the fluvial or lagoonal water to the sea; (2) secondary channels that flow from the main channels draining or dispersing water within the lagoon basin; and (3) tertiary channels that depart from the main channels or, more frequently, from the secondary ones and meander between mud flats and salt marshes. The latter (*tidal creeks*) are usually delimited by smooth levées, often no more than 20 cm high. The *tidal creeks* are locally known as *ghebi*. They often feed small ponds of brackish water, indicated by the local term “*chiari”*.

The main channels have locally been recognized to be the legacy of an ancient river hydrographic system that existed before the marine transgression. In places, they are still linked with the tributaries of the lagoon.

The natural levées of lagoon channels are formed by sedimentary bodies on the sides of a channel, generated by the ebb and flow of tidal currents according to a genetic process similar to the formation of fluvial ridges in a continental environment. The contribution of sediments derived mainly from the tidal inlets form large salt marshes and tidal flats (Fig. 15.5).

The dendritic pattern of tidal channels that branch off from the inlets to the interior of the lagoon shapes a tidal lagoon delta *(“flood delta”)*, formed by the complex of islands, salt marshes, mud flats and natural levées of the lagoon channel. In this sense, the city of Venice and the large islands on the northern side of the lagoon are considered to be part of the great tidal lagoon delta of the Port of Lido inlet.

15.4.3 Coastal Landforms

Some islands and old barrier islands, now incorporated within the lagoon, have marine origin. A typical example is the island of Sant’Erasmo, a stretch of ancient coastline

Fig. 15.5 Salt marshes next to the lagoon channel along the Cenesa Canal in the northern Lagoon of Venice (*photo* A. Bondesan)

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isolated inside the lagoon that subsequently formed in a more advanced seawards position, the Cavallino coast (a large spit protruding from the northeastern coastal plain) and the barrier island of Lido. Other ancient beach ridges have been identified on the lagoon floor using remote sensing, historical maps and underwater surveys.

Seawards, the Lagoon of Venice is bordered by barrier islands and spits, characterized by variable widths from a few dozen metres to a few kilometres; these are Pellestrina, Lido di Venezia and Cavallino. Sottomarina constitutes the left wing of a protruding fluvial delta of the Brenta River.

Sand dunes have formed along the beaches, especially close to the inlets and along the river mouths where the sedimentary load was particularly high. Starting from the beginning of the nineteenth century, all the beaches have been subjected to drastic erosion, partially countered by the construction of dams, jetties, coastal defences and artificial nourishments.

15.5 An Artificial Landscape: Human-Induced Transformations

Human intervention in the lagoon environment commenced with the first human occupation, starting from Roman times along the lagoonal rim and from the fifth century AD in the town of Venice (Fig. 15.6), when the islands started to give refuge to Romanised people fleeing the Hun invasions.

The lagoon extent was regulated by the presence of river deltas and lagoon inlets, being controlled in their evolution by river sediment loads and tidal dynamics. After the twelfth century, the lagoon inlets were menaced by the progressive shallowing of water due to sand deposition caused by sedimentary drift converging in front of the lagoon from the side fluvial deltas (mostly the Piave and Adige rivers) and by silting up of the lagoon basin, mostly due to internal sedimentation of the Brenta and Sile rivers. For that reason, the Republic of Venice undertook an epic struggle against the rivers, diverting them outside the lagoon or turning them far aside. The projects were only partially carried out, mostly during the sixteenth and seventeenth centuries, changing not only the morphology of the surrounding alluvial plain and the coastal margin but also altering water dynamics and the pace of erosional processes. In order to prevent the lagoon from turning into a marshland, Venetian hydraulic projects reversed the natural evolution of the lagoon, in time causing progressive erosion of the main landforms, the coasts and the lagoon bottom (Bondesan and Furlanetto 2012).

Anthropogenic forms in the Lagoon of Venice have important, quite invasive, presence. Most of the islands of the lagoon are in fact associated with human intervention, which contributed to their elevation and conservation though defensive works (Fig. 15.7).

In the last two centuries, many transformations have been induced by humans. Peculiar features of the lagoon include the following. Fish farms (It.: *valli da pesca*) occupy an area

Fig. 15.6 Aerial view of Venice. San Marco Square on the *right* (*photo* A. Bondesan)

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equal to 16% of the water surface. They represent large lagoonal areas surrounded by embankments used for traditional fish farming, where water exchange is artificially regulated and natural processes are slowed down or halted (Fig. 15.8). Hydraulic reclamation for agriculture changed large parts of the inner margin, especially on the southern side of the lagoon where the Brenta River used to enter into the lagoon before its final deviation at the end of nineteenth century. Landfills are largely present in most of the islands and the industrial site of Porto Marghera. In the twentieth century, the Marco Polo International Airport was constructed inside the lagoon, occupying large tidal flats.

Among the lagoon islands, the large reclaimed areas known as *casse di colmata* have to be mentioned for their impact on the lagoon environment. Their construction took place from the 1920s to the 1960s, to accommodate the expansion of the industrial port and the vast complex of factories of Porto Marghera facing the lagoon. The industrial port is today connected to the Malamocco inlet by the Malamocco-Marghera Canal. This canal has an average depth of 15 m. Some of the most serious causes of degradation of the lagoon are due to its existence. In fact, it has increased the volume and speed of tidal inflows and outflows, resulting in the intense and rapid dismantling of the lagoon bottom.

Materials resulting from the excavation of the channel were used in the 1960s to create reclaimed areas for the Third Industrial Zone (never completed). In addition to the strong impact that the reclaimed areas had and still have on the lagoon, the fundamental problem is that these extended "artificial islands" have affected the quantity and quality of water exchange. In 1986, the first measures were approved for the hydro-morphological recovery of the site to restore some of the previously existing channels.

The gradual increase in sea level and the reduced longshore drift caused the pronounced erosion of the Venetian beaches, which the Republic of Venice has tried to protect since 1300 AD. The efforts to defend the littoral against the aggressive action of the sea culminated in the eighteenth century with the construction of the *murazzi* (large stone walls).

The barrier island of Pellestrina is the most slender island between Malamocco and Chioggia (Fig. 15.7c). In the early 1990s, it was reduced in some places to a width of a few tens of metres, making the Lagoon of Venice extremely fragile (it was bypassed by the waves in the surge that occurred in 1966).

In 1994, enormous artificial nourishment consisting of about 4.6 million cubic metres of sand was accomplished along approximately 9 km of coastline for an initial width of

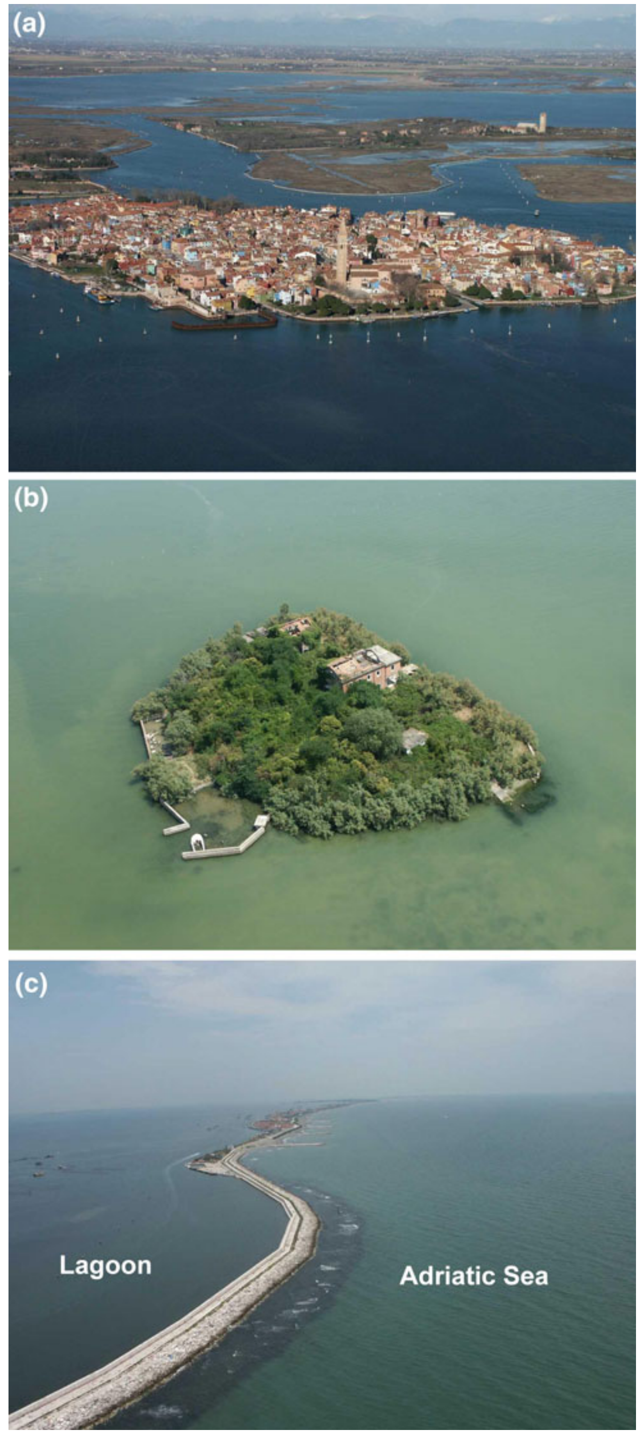

Fig. 15.7 Islands of the Lagoon of Venice. **a** Burano Island. The lagoon border is in the background, and the Alps are in the distance. **b** A typical small lagoon island (abandoned by people). They are usually artificially elevated with sediment accumulation and protected from erosion by concrete or stone walls. **c** The barrier island of Pellestrina is extremely narrow along its southern stretch (*photos* A. Bondesan)

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Fig. 15.8 Fish farms in the southern basin of the lagoon (Valle Averto). In the foreground is the system of pools for fish recovery, and in the background is the network of embankments (*photo* A. Bondesan)

Fig. 15.9 Exceptional tide peaks are causing increasingly frequent flooding of Venice (*photo* DeepGreen/www.shutterstock.com)

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about 100 m. This work, unprecedented in Europe, was completed in March 1999. The sand came from a submarine quarry located about 20 km off Malamocco in deep water from 20 to 24 m. This sand consisted of sediments belonging to transgressive coastal deposits. The intervention was supported by maritime works, such as jetties connected to a submerged berm, in order to form an organized structure in cells that can more effectively slow down erosion of sand.

Situated in the enclosed Gulf of Venice, the lagoon is subject to high variations in water levels due to extreme tides and low atmospheric pressure. These tides regularly flood much of Venice (Fig. 15.9). In the last decade, a huge effort was made to safeguard the Lagoon of Venice through the MOSE system (*MOdulo Sperimentale Elettromeccanico*, Experimental Electromechanical Module), which is an integrated system consisting of rows of movable gates installed at the Lido, Malamocco and Chioggia inlets that can temporarily isolate the Lagoon of Venice from the Adriatic Sea during high tides. MOSE is designed to protect Venice and the lagoon from tides of up to 3 m and from sea storms. The works to realize MOSE changed morphology at the tidal inlets and the jetties. Other defensive measures include construction of complex coastal defences, raising of quaysides and restoration through artificial re-nourishment of salt marshes and mudflats, subject to pronounced erosion during the last century, using the sediments excavated from canals.

15.6 Land Subsidence of Venice

Venice has suffered from both natural subsidence, ranging between 0.5 (Kent et al. 2002) and 1.3 mm/year (Carbognin et al. 2010) during the Quaternary period, and anthropogenic subsidence, particularly as an effect of over-exploitation of artesian aquifers for industrial water supply beginning in the 1930s and reaching its maximum from the 1950s to 1970s, when it doubled. The closure of the artesian wells in the 1970s resulted in a slight rebound (2 cm) and slowing down of anthropogenic subsidence. The subsidence recorded at the end of the last century was 1–3 mm/year along the coastline and 2–4 mm/year at the furthermost northern and southern boundaries (Carbognin et al. 2010). The elevation loss since 1897 is about 26 cm; 3 cm is the result of natural subsidence, 9 cm is the result of anthropogenic land subsidence and 14 cm is the result of an increase in the eustatic sea level. The subsidence caused an increase in the frequency and amount of flooding as well as erosion of the lagoon intertidal areas and the littoral (Brambati et al. 2003).

15.7 Conclusions

The Lagoon of Venice is characterized by complex morphology, with very different environments from the mainland and the sea, and contains constantly evolving landforms. Largely protected from silting by the Venetians in past centuries, it is now threatened by erosion caused by breaking waves and tidal forces. Man's interventions have been a decisive factor in a process that allowed preservation of the lagoon over the centuries. In this sense, the Lagoon of Venice is today a sort of open laboratory where human action drives or counters natural processes that challenge its survival.

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