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Chapter 14

Status and Sustainability of Mediterranean Deltas: The Case of the Ebro, Rhône, and Po Deltas and Venice Lagoon

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1 INTRODUCTION

The Mediterranean Sea is a semi-enclosed high salinity regional sea whose only outlet to the Atlantic is the Strait of Gibraltar. The drainage basin of the Mediterranean stretches from the slopes of the Alps in temperate east central France to tropical rainforest south of the equator in the Nile drainage. The northern coast of the Mediterranean is the southern shore of Europe. This is an area of high population density, a first world standard of living, and relatively high freshwater input including three of the largest rivers in southern Europe: the Ebro, Rhône, and Po. There are also important coastal lagoons including the Venice Lagoon. By contrast, the southern coast of the Mediterranean is semiarid to arid with one of the largest deserts of the world—the Sahara. With the exception of the Nile, there is almost no riverine input. With a few exceptions such as in the Nile delta, population density is low and the living standards are much lower than Europe.

Continental runoff to the Mediterranean Sea is low in general terms, except in the Adriatic Sea and the Gulf of Lion (mostly due to the Po and Rhône Rivers, respectively). Originally, the highest discharge was from the Nile River, but nowadays it has been greatly reduced due to human intervention. The Mediterranean River mouth estuaries are highly stratified (salt-wedge) due to the low tidal range, and their hydrology is controlled by river discharge (Ibáñez et al., 1997). With only a few exceptions, in the Mediterranean basin all estuaries are part of deltaic systems.

The conspicuous presence of deltas in the Mediterranean is due to low tidal energy and high sediment river discharge due to heavy rains and abrupt relief inland. The Mediterranean Sea is characterized by very weak astronomical tides (20–30 cm) in most of the areas. However, the area near the Gibraltar Strait has higher tides due to the proximity of the Atlantic Ocean. The northern Adriatic Sea also has higher tides (up to 1 m) due to its geomorphic features. Meteorological (barometric) tides can be much higher than astronomical tides, so they play an important role in the ecology of coastal Mediterranean marshes. For instance, the monthly maximum surge height due to meteorological tides is about 1 m in the Ebro delta. Minimum sea level is usually recorded in winter due to atmospheric high pressures.

There is a very large cultural diversity and several of the oldest civilizations began in the Mediterranean basin. Because of this, humans have had significant and wide ranging environmental impacts. Climate change is projected to significantly impact the area in terms of warming and drying, which will be exacerbated by human development (see Day and Rybczyk, 2018, this volume). There has been massive change in the basin especially as related to water management in terms of dams, water diversions, and channelization. The Mediterranean climate is strongly seasonal with wet winters and dry summers and extreme rainfall events are relatively common. There are well-known climate events such as the Mistral in France and the Sirocco in the Adriatic, but no super storms such as tropical cyclones and extratropical storms such as those which occur in the Atlantic and Pacific.

The Mediterranean wetlands have been largely reduced and changed by human activity for centuries, but especially during the last 50 years. Between 1942 and 1984, more than 30,000 ha (about 40%) of wetlands were lost in the Rhône delta, France. Over the last century, Tunisia lost 28% of coastal wetlands, more than 60% in Spain and Greece, and more than 70% in Italy (Ibáñez et al., 2002). The largest wetland areas remaining in the Mediterranean are associated with the
main deltaic areas: the Ebro (Spain), Rhône (France), Po (Italy), and Nile (Egypt). There are also important marsh areas surrounding coastal-barrier lagoons, such as those existing in the coast of Languedoc (southwest France) and the lagoon of Venice (Italy).

Large portions of the Mediterranean coastal marshes are occasionally or seasonally flooded by seawater, most of the time due to marine storms, but they are little or not directly influenced by tides. This fact plus the low rainfall leads to salt marshes dominated by succulent halophytes. In the Mediterranean, a considerable portion of salt marshes has been transformed into brackish marshes due to freshwater runoff caused by human activities, especially in those marshes surrounding coastal lagoons, but there are also natural brackish marshes, most of them dominated by reed beds. There are some cases where freshwater marshes are affected by sea-level changes, but there are virtually no tidal freshwater marshes in the Mediterranean [see Ibáñez et al., 2002 for a detailed characterization of the Mediterranean coastal marshes].

In this chapter, in addition to describing the general features of the Mediterranean deltas and their wetlands, we focus on three extensively studied characteristic coastal systems—the Ebro delta in Spain, the Rhône delta in France, and the Po delta and adjacent Venice Lagoon in Italy (Fig. 1). Our objective is to describe the environmental conditions in these four riverine-influenced systems and consider how global change in the 21st century will impact these coastal wetland areas.

The systems discussed in the paper comprise a broad range of coastal wetland habitats in the northwestern Mediterranean (Fig. 1). These include freshwater and low-salinity tidal reed-bed marshes at the mouths of the three large rivers and the

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**FIG. 1** The three deltas (including the Venice Lagoon) are discussed in this paper. (From Day JW, Ibáñez C, Scarton F, Pont D, Hensel P, Day JN, Lane R: Sustainability of Mediterranean deltaic and lagoon wetlands with sea-level rise: the importance of river input. Estuar. Coasts 34: 483-493. DOI: https://doi.org/10.1007/s12237-011-9390-x, 2011, used by permission.)
Dese River that drains into the Venice Lagoon; there are marine sites with low freshwater influence, estuarine tidal marshes, and impounded freshwater and saltwater marshes. Detailed descriptions of the marshes are provided elsewhere (Rhone—Hensel et al., 1998, 1999; Pont et al., 2002a, 2017; Ebro—Ibáñez et al., 1997, 2010; Cercós et al., 2002; Benito et al., 2014; Po and Venice Lagoon—Scarton et al., 1998, 2002; Day et al., 1999; Solidoro et al., 2010).

2 THE EBRO DELTA

The Ebro delta is the most important delta in Spain. About 65% of the area of the delta is rice fields, while natural areas, including coastal lagoons and wetlands, cover about 80 km$^2$ (Fig. 2). The river length is 910 km and the drainage basin is about 85,000 km$^2$. The Ebro delta has a surface area of about 330 km$^2$ and contains some of the most important wetland areas in the western Mediterranean. These marshes include a combination of fresh, brackish, and saline wetlands that serve as habitat for waterfowl and fisheries. These natural areas support important economic activities associated with tourism, hunting, fishing, and aquaculture. For more information on the Ebro delta features see Ibáñez and Caiola (2016).

Impacts on the Ebro delta have occurred due to changes at two scales: the delta plain and at the level of the Ebro River basin. Human activities in the drainage basin have had a very notable and large impact, especially in recent decades. Sediment discharge has been reduced by about 99% due to the construction of dams (Sánchez-Arcilla et al., 1996; Ibáñez et al., 1996a, 1997; Rovira et al., 2015). This has led to coastal retreat because of wave erosion and elevation loss in the delta due to a lack of sediment input to the delta plain, thus subsidence and sea-level rise (SLR) are no longer offset by new sediments coming from the Ebro River. To prevent excessive waterlogging of wetlands, vertical accretion needs to keep pace with the local combined effects of eustacy and subsidence. The sediment deficit in the delta created by the dams, coupled with land subsidence, accelerated SLR, and the low elevation of the delta plain, puts the delta and its wetlands at major risk for submergence, salt-water intrusion, and coastal erosion (Ibáñez and Prat, 2003; Genua-Olmedo et al., 2016). From the perspective of the drainage basin, the most important management action for the sustainable management of the delta

![FIG. 2 Map of the Ebro delta showing the distribution of land uses and habitat types in the Ebro delta. (From Benito X, Trobajo R, Ibáñez C.: Modelling habitat distribution of Mediterranean coastal wetlands: the Ebro Delta as case study. Wetlands, 34(4), 775–785, 2014.)](image-url)
is the restoration of the sediment flux in the river, by the remobilization of sediments trapped in reservoirs and increasing freshwater discharge to the delta via controlled floods (Ibáñez et al., 1997; Rovira and Ibáñez, 2007).

Prior to the construction of large dams on the lower Ebro in the 1960s, very large floods with high sediment concentrations occurred about every few decades. The last very large flood occurred in 1937; it produced the last major change in the position of the river mouth, leading to the creation of the Garxal lagoon. The largest direct impact on the delta was the conversion of over 65% of the wetland area to rice fields, mostly from 1860 to 1960. While this was a very large ecological impact, the extensive irrigation system prior to the construction of the Ribarroja-Mequinenza dams led to high accretion rates in the rice fields that was sufficient to offset SLR and subsidence. Since the construction of the large dams, high sediment delivery no longer occurs via the irrigation network and the fringes of the delta are falling below sea level (Ibáñez et al., 1997). Estimates of relative sea-level rise (RSLR) rates indicate mean rates ranging from 2.08 mm yr\(^{-1}\) over 132 years (1965–1833) to 6.26 mm yr\(^{-1}\) over 31 years (1965–1934) (Ibáñez et al., 1996b). Recent measures by satellite (unpublished data) confirm this range of subsidence, with maximum values of 5–6 mm yr\(^{-1}\) close to the river mouth.

There are significant areas of marshes remaining in the delta. Salt marshes occur along the backshore of the outer coast, especially around the main Ebro River mouth (Garxal) and the secondary mouth (Migjorn), and around some coastal lagoons (Fig. 2). Salt marsh communities are dominated by Arthrocnemum macrostachyum, which have low cover (10%–20%) and lower vegetation height, and Sarcocornia fruticosa with nearly 100% cover and greater height. The Sarcocornia salt marshes are at the lowest elevation. Brackish marshes occur in areas strongly influenced by the Ebro River or by drainage water of the rice fields, and receive periodic influx of fresh water, nutrients, and sediments. They are mostly located around the fresher coastal lagoons and dominated by Phragmites australis. Freshwater marshes have almost disappeared and are located close to the inner border of the delta and are dominated by Cladium mariscus.

The rate of accretion in the brackish marshes, which are impacted by river input, is higher than in salt marshes (Ibáñez et al., 2010). Because of variations in sediment input, subsidence, and organic soil formation, some of the marshes have the potential to accommodate SLR while others do not (Fig. 3). The factor leading to high elevation gain in the brackish marshes is organic soil formation because of the very low levels of sediments in the river due to dams.

Restoration of wetlands in the Ebro delta has used several different methodological approaches aimed not only at restoration of wetlands and shallow lagoons with submerged aquatic vegetation but also water quality improvement. Renaturalizing hydrology is central to restoration in deltas. Wetland restoration is essentially taking place in abandoned rice

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**FIG. 3** Comparison of mean elevation change, vertical accretion, and shallow subsidence for the different marsh sites. The dashed line is the IPCC 2007 projection for global sea-level rise (SLR) rates, and the shaded area represents relative sea-level rise (RSLR) rate projections estimated by Ibáñez et al. (1996b) for the Ebro delta. (From Ibáñez C, James P, Day JW, Day JN, Prat N. Vertical accretion and relative sea level rise in the Ebro delta wetlands (Catalonia, Spain). Wetlands 30: 979–988, 2010.)
fields to recover wetland habitat (marshes and lagoons), reduce nutrient levels in water draining from rice fields, and to improve habitat for protected bird species (Forés, 1992; Comín et al., 2001; Forés et al., 2002). Typical vegetation in these restored wetlands includes *P. australis*, *Scirpus maritimus*, *Typha latifolia*, and *Scirpus lacustris*. The restored wetlands and shallow water bodies provide habitat for endangered species such as the fish the Spanish toothcarp (*Aphanius iberus*) (Prado et al., 2017). Artificial islands have been constructed for a number of endangered bird species to breed, including slender-billed gull (*Croicocephalus genei*), Audouin’s gull (*Larus audouinii*), little tern (*Sterna albifrons*), and gull-billed tern (*Gelochelidon nilotica*).

### 3 THE RHÔNE DELTA

The Rhône is one of the most important rivers in Europe with a drainage basin of 96,000 km² and a mean annual flow of about 1700 m³ (Welcomme, 1985, Fig. 4). The Rhône discharge is characterized by low water levels at the end of the summer and high discharge typically from October through February. There is high interannual variability of mean monthly discharge because it is strongly influenced by the geological and climatic heterogeneity of the catchment, from a continental-oceanic climate in the northern Saone plain to an Alpine climate in the Jura and Alps mountains and a Mediterranean climate in the south (Vivian, 1989).

Major human influences have affected both the Rhône River and its tributaries since the Middle Ages including: (a) channelization to improve navigation, (b) dike construction to protect against floods during the 19th century, and (c)

![FIG. 4 Map of the Rhône delta. The area between the Grand Rhône and the Petit Rhône is the Camargue. The shaded areas in the northern Camargue show the areas flooded during the floods of October 1993 and January 1994, and the open circles are the locations of levee breaks during the October and January floods, respectively. Large circles are major breaks and small circles are minor breaks. CR is the Canal du Rousty where water flowed from the upper Camargue to the Vaccarès Lagoon. ES is a pumping station where water was pumped to the Mediterranean. SL is the connection between the south lagoons and the sea (Pertuis de la Fourcade). The inset is la Palissade where flooding led to up to 10 cm of sediment deposition. (From Pont D, Day J, Ibanez C. The impact of two large floods (1993–1994) on sediment deposition in the Rhone delta: implications for sustainable management. Sci. Total Environ. 609: 251–262, 2017, used by permission.)](image-url)
hydroelectric development during the second half of the 20th. Nevertheless, the suspended solid discharge of the Rhône River remains significant (Pont et al., 2002b) with a mean annual value of 7.4 million tons ranging annually from 1.2 to 19.7 million tons.

The Rhône discharges to the Mediterranean through two tributaries that are still active today—the Grand Rhône and Petit Rhône that carry about 90% and 10% of the mean annual discharge, respectively. The delta has a total area of 1450 km² and the zone between the two branches is called the Isle de Camargue (850 km², Fig. 4). The main evolutionary stages since 7000 BP have been described by several authors who have indicated the combined effects of SLR (L’Homer et al., 1981) and climatic changes on the Rhône River discharge and delta development (Probst, 1989). As the main distributaries (i.e., branches of the river that do not return to the main stream after leaving it) have often shifted in the past, the delta has a Mediterranean shoreline of about 50 km along the Golfe du Lyon.

The northern Camargue consists mainly of old inactive river distributary channels (elevation up to 2–3 m) in association with low-salinity marshes (soil elevation from 0 to 0.5 m) where water depth is usually approximately 0.5 m. The southern part of the Camargue consists mainly of a complex pattern of former coastal barrier ridges, abandoned distributary ridges (elevation less than 2 m), and brackish lagoons (soil elevation from −0.8 to 0.1 m), of which the Vaccarès lagoon is the largest with a mean area of 64 km². It receives most of the runoff from rainfall (pluvial inputs) and a part of agricultural drainage waters (mainly due to rice cultivation) entering in the Camargue.

After the large floods of 1840 (9640 m³/s) and 1856 (11,640 m³/s), the existing dikes were increased in size to protect the Camargue against flooding and to allow agricultural development. The dikes are 96 km long and have an elevation higher than the 100-year flood level (9.7–2.2 m high from North to South). During the same period, a dike (the Digue a la Mer) was also built along the seashore to reduce seawater intrusion during storms. From 1869 to the present, Rhône freshwater enters most of the Camargue only by pumping stations and is distributed by a network of channels for irrigated agriculture, mainly rice. The total volume of irrigation input is of the same order of magnitude as the mean annual rainfall input (509 × 10⁶ m³ per year). Most of the drainage water is returned to the river or the sea by pumping.

Only a small area located near the mouth of the Grand Rhône (La Palissade, about 800 ha) remains open to natural overflow from the river. The vegetation in shallow impoundments semi-isolated from the Rhône influence is dominated by halophytic vegetation (Arthrocnemum and Juncus spp.) reflecting highly saline soil conditions. The vegetation in areas connected to the Rhône (S. maritimus and Phragmites communis) shows the importance of regular inputs of the river in mitigating soil salinity levels.

In recent decades, a number of studies have shown that wetland productivity as well as accretion is higher in areas receiving the Rhône River water. Hensel et al. (1998) measured short-term sedimentation rates over periods of a few weeks in different areas of the Rhône delta. The highest sedimentation rates occurred at La Palissade, the natural area near the mouth of the river with a high river water input. Marine and impounded sites without river influence had significantly lower rates of short-term sedimentation. Similarly, vertical accretion and vertical elevation gain in wetlands were more than 10 times higher in areas of the Rhône delta impacted by regular floods of the Rhône compared to marine and impounded sites (Hensel et al., 1999, Fig. 5). The net primary production of wetlands, especially Salicornia-type marshes, was much higher in areas affected by the Rhône discharge (Ibañez et al., 1999). Arthrocnemum and Typha marshes affected by the Rhône water had a much higher productivity than grazed marshes in the same area and productivity was low in impounded marshes without any connection to the Mediterranean Sea. Pont et al. (2002b) concluded that the Rhône delta wetlands with riverine influence were most likely to survive predicted SLR while marshes isolated from the river would not survive. The wetlands in the lower part of the Rhône delta are currently falling below sea level and Pont et al. (2002a) concluded they will disappear if accretion is not enhanced.

The results of this study and others in the Rhône delta indicate that riverine input can enhance accretion. River water will also reduce salinity stress and improve wetland productivity. Day et al. (2016b) concluded that deltas with areas below sea level will not be sustainable due to rising sea levels and resource constraints (see also Tessler et al., 2015).

Pont et al. (2017) reported the effects of two large floods that occurred in October 1993 and January 1994, with peak discharges of 9800 and 10,980 m³/s and total suspended solid transport of 10.7 × 10⁶ and 9.7 × 10⁶ tons, respectively (Fig. 4). Both floods led to multiple levee breaches in the Northern part of the delta resulting in the introduction of large volumes of water and sediments which led to the formation of crevasse splays (the fluvial deposits formed after the breach) near the river channel and thus to two extensive depositional fans that covered over 10,000 ha in the northern part of the Camargue. In the Northern inundated area, accretion ranged from 70 mm near the breaches to 4 mm 6–8 km away. In the Palissade, the total deposition from both floods was as high as 10 cm. The Rhône delta is facing an uncertain future with projected SLR. The results of this study show that large introductions of river water can help to sustain the delta in the face of accelerated SLR. Controlled introductions of river water using riverside closable structures, as is being done in other deltas (e.g., Day et al., 2007), and in particular in the Mississippi delta (Day et al., 2016a, b; Peyronnin et al., 2017, Rutherford et al., 2018),
could be done in a way that delivers water and sediments to the places where it is needed most and at the same time used to protect important infrastructure.

In summary, the dike breaks led to the formation of crevasse splays near the river channel and to two extensive depositional fans that covered over 10,000 ha in the northern part of the Camargue. The results of such large floods carried out in a controlled manner could lead to sedimentation over large areas of the delta and help to sustain the delta in the face of accelerated SLR. Diversions of river water are currently taking place in the Mississippi delta and could serve as an example for the Rhône delta (Day et al., 2016a, b; Peyronnin et al., 2017; Rutherford et al., 2018).

4 THE PO DELTA AND VENICE LAGOON

The Po is one of the most important rivers discharging to the Mediterranean with a length of 650 km and a mean discharge of about 1500 m³ s⁻¹ (ranging from 275 to 10,000 m³ s⁻¹) m⁻¹ and a basin area of about 72,000 km² (Zanchettin et al., 2008). The Po delta covers about 61,000 ha (Fig. 1) and discharges to the Adriatic through at least five distributaries. The delta has been created over the past several thousand years as the river successively occupied a number of different river channels (Sestini, 1992). Formerly, most of the deltaic plain was covered by extensive freshwater wetlands, but these were largely claimed for agriculture. Much of the deltaic plain is now 1–4 m below sea level due to subsidence caused primarily by extraction of shallow deposits of natural gas with a high-water content (Sestini, 1992). The fringes of the delta are

![Elevation change plots for different years](image-url)
characterized by beaches and dunes, shallow lagoons, and salt marshes. There are extensive reed swamps (approximately 2500 ha) dominated by *P. australis* bordering the lower ends of the main river channels. The background rate of geological subsidence in the Po delta is 1–3 mm yr\(^{-1}\) (Sestini, 1992; Bondesan et al., 1995; Tosi et al., 2016) but human-induced subsidence has been as high as 5–20 mm yr\(^{-1}\) and in a small area in the western Po delta, subsidence was 100 cm between 1958 and 1962 (Bondesan et al., 1995).

During the development of the Po delta, the river migrated widely over the deltaic plain and at times discharged considerably far north of the present main channel, for example, the Po della Pila (Sestini, 1992). During these times, there was a large discharge into the southern part of the Venice Lagoon. The Brenta River also discharged directly into the Venice Lagoon, but it was diverted to the south by the Venetians in 1507 to prevent sedimentation in the lagoon. The Brenta was diverted back into the southern lagoon from 1840 to 1896 to relieve flooding in the agricultural land along the artificial diversion canal. During this period, about 2300 ha of coastal marshes formed in a large fluvial delta (Favero et al., 1988). Thus, the southern part of the Venice Lagoon is considered a deltaic lagoon and has a higher geologic subsidence (1.2 mm yr\(^{-1}\)) than in the central lagoon where subsidence is less than 0.5 mm yr\(^{-1}\) (Tosi et al., 2016).

Scarton et al. (2002) reported that above (ABG) and belowground (BLG) production of *P. australis* along a distributary channel strong was higher than that of *S. fruticosa* in the southern Venice Lagoon that had a low freshwater input from the Brenta River. Marsh productivity in the Venice Lagoon was higher near sites of freshwater input and at higher elevations (Day et al., 1999; Scarton et al., 1998, 1999).

The Venice Lagoon, the largest Italian lagoon and one of the largest of the Mediterranean, has an area of about 550 km\(^2\) (Fig. 6) and connections to the Adriatic Sea through three large inlets. Over the past five centuries, sediment dynamics of the lagoon have been extensively changed (Gatto and Carbognin, 1981; Sarretta et al., 2010). The Brenta, Sile, and Piave Rivers, which originally discharged into the lagoon, were diverted from the lagoon to the sea beginning in the 16th century. Presently, only a few small rivers (total discharge about 32 m\(^3\) s\(^{-1}\)) discharge into the lagoon (Zuliani et al., 2005).

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The import of coarse marine sediments into the lagoon has been greatly reduced because of the construction of long jetties at the inlets at the end of the 19th century. There is a net export of about 0.8 M m$^3$ of sediments from the lagoon (Sarretta et al., 2010).

Most of the lagoon is occupied by a large central waterbody (about 370 km$^2$) and extensive intertidal salt marshes (about 35 km$^2$). The mean depth of the lagoon is 1.1 m and the tide range is 0.6–1 m, and extensive tidal flats (about 50 km$^2$) are exposed at low tide. The subtidal areas are partially vegetated by macroalgae and seagrasses (such as Zostera marina, Zostera noltei, and Cymodocea nodosa). The dominant salt marsh species include Limonium serotinum, Puccinellia palustris, S. fruticosa, and Spartina maritima (see Scarton, 2005). The salt marsh area in the lagoon, has decreased from about 12,000 ha at the beginning of the century to about 3500 ha at present due to reclamation (land-claim), erosion, pollution, and natural and human-induced subsidence (Sarretta et al., 2010). An extensive program of saltmarsh creation using sediments dredged from lagoon channels began at the end of the 1980s; these 1300 ha of dredge islands now make a suitable place for breeding waterbirds, with about 4000 pairs counted in recent years (Scarton, 2017).

There have been a number of studies of wetland ecology, accretionary dynamics, and erosion in the Po delta and Venice Lagoon. Short-term sedimentation in the Venice Lagoon averaged 3–7 g dry m$^2$ day$^{-1}$ per site with a maximum of 76 g m$^2$ day$^{-1}$ (Fig. 7). The highest values were measured during strong pulsing events, such as storms and river floods that mobilized and transported suspended sediments. Accretion ranged from 2 to 23 mm yr m$^2$ d$^{-1}$ and the change in soil elevation ranged from 32 to 13-8 mm yr$^{-1}$. The sites with highest accretion were near a river mouth and in an area where strong wave energy resuspended bottom sediments that were deposited on the marsh surface (Day et al., 1999). The community composition and productivity of marshes in the lagoon are strongly correlated with elevation with respect to mean water level. Species composition varies with elevation and Pignatti (1966) described four plant associations correlated with elevation and other factors: a Puccinellia-Arthrocnemum association from 25 to 40 cm msl (mean sea level), a Limonium-Puccinellia association from 15 to 30 cm msl, a Limonium-Spartina association from 5 to 20 cm msl, and a Salicornia spp. association from 5 to 10 cm msl. High-precision elevation measurements for eight saltmarsh species, together with the allochthonous and invasive Spartina townsendii, are presented by Scarton et al. (2003). ABG and BLG production at the highest marsh elevations described by Pignatti (1966) were 666 and 1378 g m$^{-2}$ yr$^{-1}$, respectively. As marsh elevation is reduced, productivity decreases. For the Salicornia community, ABG and BLG productivity are 307 and 100 m$^{-2}$ yr$^{-1}$, respectively (Day et al., 1999).

The potential of coastal marshes to cope with SLR depends on their ability to increase in elevation sufficiently rapidly to keep pace with the water level rise. This depends on a combination of mineral sediment deposition and in situ organic soil formation (sensu Cahoon et al., 1995). Climate change combined with water level management is likely to make lagoon marshes less sustainable. Since BLG productivity is strongly correlated with marsh elevation, organic soil formation
decreases as water levels rise relative to marsh elevation. As noted above, almost all riverine input of sediments to the Lagoon has been eliminated and there is a strong net export of sediments to the Adriatic. The highest mineral sediment input to the lagoon marshes occurs during southerly Sirocco winds that elevate water levels and resuspend sediment from open water sediments. The strong waves also lead to elevated erosion rates of exposed marsh shorelines (Day et al., 1998).

The MOSE gates are designed and currently under construction (due for completion in 2022) to prevent flooding of the city of Venice during elevated water levels. This is extremely important for protection of the city. The gates will be closed only when the tide is higher than 1.1 m above sea level. Currently, this happens 3–7 times a year; for the future, 10, 12, and 15 days are estimated with SLR of 10, 30, and 50 cm (Ferrarin et al., 2013). Closing the gates prevents the elevated water levels that lead to flooding of the marshes and high rates of mineral sediment deposition on the marsh surface (Day et al., 1998). As marsh elevation decreases relative to lagoon water levels, BLG productivity will decrease as indicated above. Thus, both processes that lead to high rates of marsh surface elevation gain, mineral sediment input, and organic soil formation, will diminish. This can be offset by the reintroduction of riverine input to the lagoon and by maintenance dredging to maintain marsh elevation.

5 DISCUSSION

The information presented for these Mediterranean systems show that wetlands strongly influenced by river input have the highest productivity and the highest rates of accretion. Day et al. (2011) summarized data on accretionary dynamics for these systems over a 10-year period (Fig. 8). Riverine input led to high average vertical accretion (10.7 mm yr\(^{-1}\)) and marsh surface elevation gain (7.3 mm yr\(^{-1}\)). By comparison, for non-riverine sites, both accretion (3.7 mm yr\(^{-1}\)) and surface elevation change (3.3 mm yr\(^{-1}\)) were significantly lower. Impounded habitats in the Rhône Delta had a very low average accretion (0.8 mm yr\(^{-1}\)) and elevation change (1.9 mm yr\(^{-1}\)).

Accretionary dynamics in deltas are strongly impacted by episodic events such as storm events and river floods (Day et al., 1995, 2007) and human activities have greatly reduced the impact of these events (Day et al., 2007, 2016b; Syvitski et al., 2009; Pont et al., 2002b, 2017; Giosan et al., 2014; Ibáñez et al., 2014; Tessler et al., 2015). The development, functioning, and sustainability of deltas result from external and internal inputs of energy and materials that occur as pulses in a hierarchical manner producing benefits over different spatial and temporal scales (Odum et al., 1995; Day et al., 1997, 2016a, b). Inputs range from daily tides to switching of distributary channels, which occur in the order of hundreds to over a thousand years, and include frontal passages, river floods of varying magnitude, strong storms and associated storm surges, and formation of crevasses. Infrequent events, such as channel switching, crevasse formation, and great river floods control the location and rate of sediment delivery to the delta and thus impact the geomorphology. Pulsed events are especially

![FIG. 8](https://example.com/fig8.png)  
**FIG. 8** Wetland vertical accretion vs surface elevation change for the coastal Mediterranean riverine (black circle), marine (white circle), and impounded (black star) sites. Mean surface elevation changes for the marsh types were compared to water level rise due to 20th century eustatic sea-level rise (ESLR); RSLR for the different sites, and RSLR plus the 21st century predicted ESLR from the IPCC (2007) (RSLR + IPCC). To accommodate rising sea level, coastal wetlands must grow at a rate \( \geq \) water level increase, implying that only sites with high sediment input will survive the predicted SLR. (From Day JW, Ibanez C, Scarton F, Pont D, Hensel P, Day JN, Lane R. Sustainability of Mediterranean deltaic and lagoon wetlands with sea-level rise: the importance of river input. Estuar. Coasts 34: 483-493. https://doi.org/10.1007/s12237-011-9390-x, 2011 used by permission.)
important considering projections of SLR (e.g., FitzGerald et al., 2008; Deconto and Pollard, 2016). The two last floods in the Rhône delta fit within this framework of pulsing events, specifically lead to crevasse formation during large floods (Pont et al., 2017). In general, however, episodic events have been reduced for all levels in these Mediterranean systems. In order to adapt to climate change and increase the resilience of the Mediterranean Deltas, an integrated management of the river basin and the delta must be implemented through the development and deployment of nature-based solutions based on ecological engineering techniques.

6 SUMMARY AND CONCLUSIONS

The Mediterranean deltaic systems considered in this paper have been strongly modified by a variety of human impacts that affect their sustainability. However, each system has a unique combination of impacts that informs management and restoration approaches although each example has lessons that apply to other deltas both in the Mediterranean and worldwide.

Ebro. There has been a massive reduction of freshwater and sediment delivery to the Ebro delta. Within the delta, over 65% of wetlands have been converted to rice fields. Prior to the construction of large dams, accretion in the delta was maintained by the irrigation network that delivered sediments to the rice fields. There was also high deposition in river mouth areas during large floods. Sustainable management of the delta must include a pulsing regime of freshwater flow and mobilization of sediment from reservoirs to direct these into the delta plain. Thus, the major problem for the Ebro is the reduction of input from the basin. Without increased and better managed sediment and freshwater input to the delta, the delta will deteriorate despite ongoing wetland restoration in the delta plain. The ongoing conflict between the Spanish government and Catalonia demonstrates how political issues can compromise sustainable management and ecological restoration.

Rhône delta. The Rhône River has not had a significant decrease in discharge or suspended sediment concentration. The main problem in the Rhône delta is that almost all river input to the delta plain has been eliminated by dikes. The major freshwater input to the delta is via pumping, mainly for rice. Thus, there is a large amount of river control, but very large floods with high concentrations of sediments still occur regularly. The only area that regularly receives river input is at the mouth of the Grand Rhône. Wetland areas of the lower Camargue are falling below sea level and without more sediment input, this will continue. The two large floods demonstrated how river water and sediment can be delivered to extensive areas of the delta and lead to high rates of accretion. This suggests that managed diversions from the river can be used to sustain the delta. The two functioning distributaries, the Grand Rhône and the Petit Rhône, could be used to deliver water to the entire delta plain.

The Po delta and Venice lagoon: Svyitski and Kettner (2007) suggest that the Po River experienced a strong decrease in its sediment load (17.2–6.4 Mt yr$^{-1}$) from 1933 to 1987, in contrast to a small increase in water discharge. Other estimates give a sediment discharge of about 15 Mm$^3$ yr$^{-1}$ (Bever et al., 2009). Furthermore, the river has at least five functioning distributaries that discharge to the Adriatic Sea that leads to river water being distributed widely on the deltaic wetland fringe fronting the sea. A major impact in the Po delta was the formation of the polders that are up to 5 m below sea level. It is likely that these cannot be maintained and will permanently flood in this coming century. Overtime sediment from the Po River could be used to fill in some of these whereas others could be converted to shallow lagoons. Wetlands at the river mouths can be maintained with river sediments (as is true for the other two deltas). However, one questions how much sediment transport for the Po has decreased, given the paucity of data concerning bed and suspended transport. For the Venice Lagoon, there is a need for sediment input to marshes if they are to survive SLR. This would suggest the need for diversion of river water into the lagoon from the Po as well as other small rivers. An ongoing project, financed with EU funds, will study the ecological effects of diverting about 1 m$^3$ s$^{-1}$ from the Sile River into the northern lagoon. Operation of the MOSE flood protection scheme will partly decrease resuspended sediment input to marshes. This can be offset by the reintroduction of river input to the lagoon and maintenance dredging to maintain marsh elevation.

REFERENCES


