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CASE STUDY

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Evolution of wetlands in the northern part of the Po Delta: The experience of unmanaged realignments

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Abstract

It is increasingly recognised that nature-based solutions in coastal ecosystems provide significant services compared to hard engineering measures. Several restoration projects are now being conducted worldwide to protect coastlines against flood risk and improve the ecosystems' quality. In the case of river deltas, managed realignment through levee breaching is becoming a recognised strategy for coastal wetland restoration. This study focusses on the formation of new wetlands in the Po River Delta after several natural dyke failures that occurred during the last century, when a large part of the land was abandoned and became wetlands. An historical review was performed to quantify the variation of the marsh extent in time developed after natural levee breaching in the easternmost lagoons of the delta and to understand the processes that determined their evolution. The analyses were based on orthophotos from the 1950s to the present-day integrated with tidal records, water and sediment discharge records, and GPS survey for vegetation distribution. The review indicated that, between the 1950s and 1980s, anthropisation and natural processes caused a strong decline in marsh extent, thus leading to the recent shape of the lagoons. Several breaches and inlets were developed because of a combination of human intervention and erosive processes, and new tidal systems were born. Three main depositional areas connecting the main river branches were identified in three separated lagoons of the delta. These lagoons presented a 'crevasse splay' type of deposition which allowed the development of new tidal flats and, in certain cases, of large freshwater marsh systems within less than 8 years after the breach. The newly formed wetland systems (>100 ha) demonstrate the ability of the Po River Delta to build new wetlands, also during periods of human-induced sediment starvation and high rates of subsidence, suggesting that further levee breaching should be exploited to favour marsh recovery.

KEYWORDS
intertidal marsh restoration, managed realignment, Po River delta, salt marsh, tidal flat

1 | INTRODUCTION

1.1 | Building-with-nature approach in wetlands

During the last decades, the conception of coastal defences has profoundly changed and, consequently, our approach to the coastal environment has also been adapted to find a new balance between natural and anthropic components. The previous approach, based on short-term exploitation of natural sediment resources (Capobianco & Stive, 2000) where sea and land were considered as two different systems, is now deemed obsolete (Slobbe et al., 2013), and new key concepts of coastal resilience and building-with-nature have been defined (Masselink & Lazarus, 2019). Although dykes, sea walls and other hard engineering measures and infrastructures are commonly perceived as the best solution for coastal protection, conventional coastal engineering is proving unsuitable because of high maintenance costs and undesired ecological impacts (Temmerman & Kirwan, 2015; Temmerman et al., 2013). Several studies have shown how these structures cause unavoidable long-term effects, such as increasing potential risk of casualties and damages when the defences fail (Smits et al., 2006; Van Koningsveld et al., 2008); ecological drawbacks, for instance, erosion of tidal environments and toxic algal bloom (Verspagen et al., 2006); variation of sediment transport and deposition along the coastlines (Armaroli et al., 2012); and change in the hydrodynamics, therefore, in the morphological evolution of the landscapes both before (Carniello et al., 2009; Finotello et al., 2023) and after the interventions (e.g. Tognin et al., 2022). Instead, it is well known that coastal ecosystems such as marshes, mangroves, dunes, coral reefs and shellfish reefs are fundamental in coastal protection thanks to their ability to reduce storm waves (Barbier et al., 2008; Bouma et al., 2014; Gedan et al., 2011; Shepard et al., 2011) and storm surges (Boutwell & Westra, 2015; Leonardi et al., 2018; Stark et al., 2015; Temmerman et al., 2012; Zhang et al., 2012), and to keep pace with sea level rise (Fagherazzi et al., 2012; Kirwan et al., 2010).

Several restoration projects are now being conducted worldwide. The purpose of these projects can be achieved through several strategies, such as river diversion, tidal flooding, sedimentation structures and vegetation planting (Cox et al., 2022), depending on the environmental context. In the case of river deltas, especially the river-dominated ones, river diversion is one of the most common approaches; it is based on breaching the river levees in order to activate sedimentation and water circulation in new areas of the deltaic system, thus allowing the ecosystem to reach a new equilibrium without human intervention (e.g. Allison & Meselhe, 2010). This process is nowadays becoming more and more popular, and dyke breaching can be considered an approach to land restoration. There are few examples of restoration in river-dominated deltas, such as in the Mississippi Delta (Boyer et al., 1997). Day et al. (2016) showed that large episodic river diversions allow a quick development of land, creating morphological structures called crevasse splay and, consequently, leading to the restoration of the wetland system; moreover, these diversions do not require large management expenditure and will create new self-designing subdeltas. The levee breaching is a strategy used in managed realignments as well (e.g. Garbutt et al., 2006; Spencer et al., 2008), where reclaimed areas are restructured (e.g. artificial channels, the surface is lowered) to aid inundation and speed up the natural developing of the coastal wetland. In the context of the Po Delta, this type of crevasse splay restoration occurred naturally, because of natural levee breaching, leading to an 'unmanaged realignment', which means that a portion of the delta developed following an evolution similar to a managed realignment although it was not caused by human intervention.

In the case of coastal wetland environments, one of the aims of a restoration project is to allow the development of a marsh, depending on the environmental context and human necessities. A coastal marsh develops on the upper portion of the intertidal area, typically composed of herbaceous halophytes that have adapted to tolerate regular saltwater inundation (Pratolongo et al., 2019) generally in low-energy and temperate coastlines (Adam, 2011; Allen & Pye, 1992). The development of a coastal marsh is strictly tied to bed topographic elevation relative to the local m.s.l. (mean sea level) and the tidal range. If its surface is located below a certain elevation, vegetation will not be able to grow, although a perfect level does not exist (Suchrow & Jensen, 2010). In this case, it would be considered a tidal flat, which is a non-vegetated intertidal (and subtidal) habitat mainly composed of sand or mud (Dyer et al., 2000). Coastal marshes formation depends on how fast sediment deposition occurs with respect to sea level rise (Orson et al., 1985; Redfield, 1972; Schuerch et al., 2012).

Deposition in coastal wetlands can be controlled by tidal or, in certain cases, river floods, as can be observed in the case of the Po River Delta. This deltaic system located on the north-eastern coast of Italy formed during the last 400 years because of human intervention (Bondesan, 1985), and it is characterised by several lagoons that host extended salt and freshwater marshes. During the last century, the shape of the delta and its component systems underwent important changes caused by a combination of several factors (i.e. subsidence, river floods and coastal storms), leading to a high coastline retreat that continued until the 1980s (Bezzi et al., 2021) when a partial recovery took place. Several natural dyke failures occurred and a large part of the land, once abandoned, turned into wetlands.

1.2 | Aims and objectives

The Po River floods of the 1950s–1960s and the subsequent evolution of the eastern lagoons of the delta provide an interesting opportunity to study the effects of an 'unmanaged realignment' for future building-with-nature management and/or restoration projects. The current study focusses on the temporal variation of the marsh extension of the eastern lagoons of the delta and the processes that controlled their evolution; in particular, it examines three main areas of interest formed because of levee breaching located within three lagoon systems: the Barbamarco Lagoon, the Burcio Lagoon, and the Basson–Canarin Lagoon. It is important to state that these levees breached naturally. The study was carried out through orthophoto interpretation and spatial analysis of vegetation from 1949 until 2018 integrated with tidal records, water and sediment discharge records, and GPS surveys of vegetation distribution. The results were contextualised with information derived from the literature, regarding mainly sediment deposition, subsidence rates, submerged areas and coastline changes.

The principal aims are: (i) to define and quantify the marsh extension variation of these lagoons during the last century and the main changes of this portion of the delta; (ii) to discuss the processes that influenced the formation of intertidal flats and marshes after multiple natural levee-breaching events, considering the size and location of the breaches, morphology, floods and discharge in time; (iii) to discuss local factors (e.g. position of the levee breaching and local strong deposition) versus regional factors (e.g. subsidence and sea level rise) and if future managed realignments can be feasible and efficient in the Po Delta context.

2 | STUDY SITE

2.1 | Geomorphological setting

The recent location of the Po River Delta was defined in 1604 when the Venetian Republic concluded the 'Porto Viro' bypass that diverted

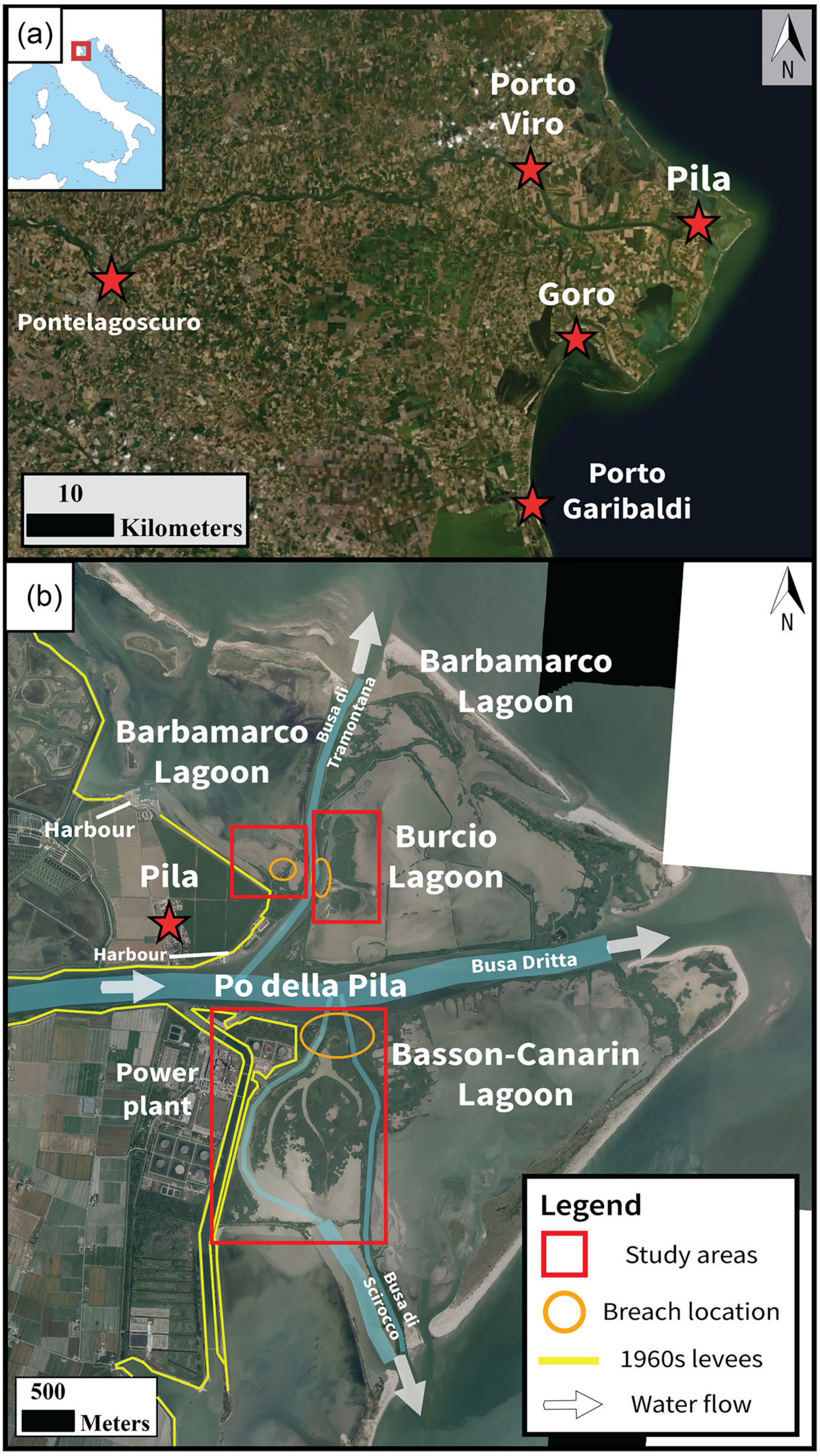

FIGURE 1 (a) Location of the Po Delta and the village of Pila, in the municipality of Porto Tolle. (b) Orthophoto provided by the Veneto region (Agea 2015) showing the three principal lagoons of the tip of the delta and the three main study areas that experienced an 'unmanaged realignment' (inside the red rectangles): the Barbamarco Lagoon, on the northern side of the Po della Pila; the Burcio Lagoon, located on the eastern side of the Busa di Tramontana; the Basson–Canarin Lagoon, to the south of the Po della Pila. It is shown the location of the breaches (orange circles), which occurred on the old vegetated embankments, and the position of the recent artificial levees improved in the 1960s (yellow lines).

the Po River course (Bondesan, 1985; Bondesan, 1990; Cencini, 1998; Simeoni & Corbau, 2009; Stefani & Vincenzi, 2005). During the last 400 years, the river divided into five distributary channels crossing the delta; these are, from north to south, the Po di Maistra, Pila, Tolle, Donzella or Gnocca, and Goro. Po di Maistra was the most important branch (Ciabatti, 1967) until 1872, when the Po della Pila became the main branch (Figure 1a, b). A generalised progradation occurred between 1800 and 1945 (Visentini, 1940), whereas human interventions became increasingly influential on the evolution of the delta. The most important landscape modifications were started in 1870 to improve living conditions in the area, in particular, to improve the economy and counteract malaria (Cencini, 1998). In fact, reclamation works were financed by the national government and several embankments were built to reinforce the natural dykes (Verza & Catozzo, 2015); human influence on the system greatly decreased after 1960s. The levees of the tip of the delta are mainly artificial. The most recent ones were mainly built inland, generally around reclaimed areas, and were made of rocks and cement (yellow lines in Figure 1b). Especially from 1950 to 1965, the structures were reinforced and their height increased between 1.5

and 3.5 m to counteract the impact of subsidence (Bondesan et al., 1995; Colombo & Tosini, 2011). The other levees have been colonised by vegetation and separate the main branch and the other channels from the lagoons.

During the last century the shape of the delta was highly impacted by a combination of strong floods (Piccoli, 1976), coastal storms (Perini et al., 2011), which hit the system multiple times between the 1960s and the 1970s, and high subsidence (Caputo et al., 1970; Fabris, 2019); moreover, dam construction and river dredging greatly reduced the sediment input (Billi & Fazzini, 2017; Bondesan & Simeoni, 1983; Dal Cin, 1983; Dal Cin & Simeoni, 1984). All these events caused breaches of the levees, the opening of new channels, and the submergence of several agricultural fields, thus the formation of new lagoons. The most severe changes took place between the 1950s and the 1970s. In 1951, an extreme river flood characterised by a water discharge exceeding 10 000 m^3/s occurred (Piccoli, 1976). Several heavy storms, characterised by wind speed between 10 and 18 m/s and a total marine water level up to 1.2 m above the mean sea level, caused strong erosion and enormous damage to human structures as well. In 1966 in particular, an extreme storm demolished the dykes and 150 ha of Porto Tolle territory was submerged (Garnier et al., 2018; Perini et al., 2011). More extreme floods occurred in the following years, concurrently with the highest subsidence rates ever recorded in the delta; the highest values were found between 1951 and 1957 with 25 cm/year, mainly caused by water pumping and methane extraction (Caputo et al., 1970). The gradual reduction in exploitation of groundwater resources progressively decreased the subsidence rates from 18 cm/year between 1957 and 1962 to 3.3 cm/year between 1962 and 1967. A slight increase of 3.8 cm/year is recorded between 1967 and 1974 (Caputo et al., 1970; Fabris, 2019). The trend of the whole delta system (i.e. shoreline, marsh extension, submerged and emerged areas) between 1950 and 1977 was highly negative because of coastline regression, marsh loss, and land submersion; most of the littoral suffered strong erosion with a mean shoreline shift of more than −200 m (Bezzi et al., 2021). In the following years, the subsidence rates decreased gradually from 1.8 cm/year between 1983 and 1991 to 1 cm/year between 1991 and 1999 (Fabris et al., 2014), reaching 0.6 cm/year between 1999 and 2013 (Fabris et al., 2014); these rates are similar to the natural subsidence values (i.e. 0.2–0.3 cm/year) and have remained stable until today (Bondesan & Simeoni, 1983; Cenni et al., 2021), although the subtidal and intertidal areas increased, probably due to hydraulic works carried out to improve the internal circulation of sea water and to promote fish farming (Fabris, 2019). After 1990, a number of storms occurred (Perini et al., 2011) but, unlike the previous periods, none of them significantly changed the landscape. Overall, during the last century, strong marsh loss occurred in all the lagoons of the delta, reaching values of about 48% compared to their maximum extension (Corbau et al., 2022; Verza & Catozzo, 2015). This erosional trend was greatly reduced between the 1980s and the 2000s when a process of stabilisation took place after the interruption of resource exploitation (e.g. water and gas extraction and dredging of river material). The first signs of a slow recovery occurred after 2002 and, starting in 2010, the delta progressively showed aggradation of new mouth bars at the main distributary mouth, indicating that an evident ongoing constructive process had begun (Ninfo et al., 2018).

With an area of 700 km^2 and a coastline of 90 km, the Po Delta is one of the major anthropogenically affected deltas of the world (Maselli & Trincardi, 2013). Its structure depends on the Po River, which flows for 650 km in northern Italy in WE direction with an average discharge of 1500 m^3/s (Ludwig et al., 2009) and has a catchment area of over 70 000 km^2 (Bondesan, 1990); it finally flows into the Adriatic Sea. Because of the strong dependency on the river, the delta was originally considered *river dominated*, but it probably shifted to *wave dominated* after the high anthropic influence of the 1950s (e.g. dam construction, river dredging and land reclamation) (Bondesan & Simeoni, 1983; Correggiari et al., 2005; Dal Cin, 1983; Nelson, 1970; Trincardi et al., 2003). The delta is characterised by an average microtidal range of about 0.5 m (spring-tidal range about 1 m); the tidal regime is mixed and semi-diurnal. The Po della Pila is the easternmost branch of the tip of the delta, and it is characterised by the highest water and sediment discharge (38–56% of the total water discharge [Maicu et al., 2018] and 71% of the total sediment discharge [Nelson, 1970]). It divides into three smaller branches: the Busa di Tramontana northward (10–15% of the total water discharge of the Po River), the Busa Dritta in the centre (35–25), and the Busa di Scirocco southward (6–3%) (Maicu et al., 2018) (Figure 1b). However, each river branch is associated with a particular delta plain and delta front depositional systems that are dominated by different combinations of fluvial and marine processes (Correggiari et al., 2005; Syvitski et al., 2005; Trincardi et al., 2003). The suspended load represents the principal component of the sediment transport (around 80%), whereas the bedload is about 12–20% (Canali & Allodi, 1963; Dal Cin, 1983; Idroser, 1994; Nelson, 1970; Visentini, 1940). Because of the importance of the Po della Pila at the present time, the tip of the delta is the portion of the delta that can be considered as river dominated (Correggiari et al., 2005; Trincardi et al., 2003). Seasonal flood differences occur between summer and winter: June is commonly characterised by melting snow and November is predominantly a month of rain (Marchi et al., 1995; Palinkas et al., 2005); floods between January and August are usually lower than winter floods, with a discharge of about ~4000–6000 m^3/s (Tesi et al., 2011). Large floods occur between October and December (>6000 m^3/s) causing significant deposition in the prodelta (Tesi et al., 2011). The coastline of the delta consists predominantly of sandy components (Dal Cin, 1983; Simeoni et al., 2000) whereas the internal part of the lagoons is characterised by finer sediment, mostly clay and silt.

2.2 | The tip of the Po Delta

The study area of this paper concerns the three main eastern lagoons of the Po Delta: the Barbamarco Lagoon, the Burcio Lagoon and the northern portion of the Basson–Canarin Lagoon system (Figure 1b).

i. The Barbamarco Lagoon is located between the mouth of the Po di Maistra and Po della Pila on the northern side of the tip of the delta; it stretches for 7 km to the northwest and can reach 3 km at its widest point (Figure 1b). The Po River flows inside the lagoon through the two small channels of the Busa di Tramontana, and the water reaches the Adriatic Sea via two inlets called Bocca Nord and Bocca Sud. Wave action is limited by the sand bar that separates the lagoon from the sea and, here, the most important processes that influence sediment transport are the river and tides.

ii. The Burcio Lagoon is located between the Busa di Tramontana and the Po della Pila; protected by 3.5 km of sand barriers and extending for a maximum of 3 km, it represents the most north-eastern extension of the delta (Figure 1b). Marshes cover the borders of the lagoon as well as old dykes that have persisted from previous agricultural fields, made in the 1950s during land reclamation. A few human structures, probably farms and houses now underwater, are all that remain in the southern part.

iii. The Basson–Canarin Lagoon extends for about 5 km in south-western direction between the Po della Pila and the Busa di Scirocco, which is a small channel that develops southward. As can be seen in Figure 1b, this lagoon system is divided into two portions by a central vegetated levee. Next to the Basson–Canarin Lagoon stands a, now inactive, thermoelectric power plant (built by Enel Productions S.p.A., the largest Italian power company).

The eastern lagoons of the tip of the delta reached their present-day configuration because of the combination of several processes (i.e. subsidence, river floods and coastal storms) that occurred during the last century; nowadays, hundreds of hectares of agricultural fields, houses and other anthropic structures are underwater. Strong changes occurred to the eco-geomorphology of this part of the delta as well. Land reclamation and high subsidence have caused vegetation loss in wetlands. Although material exportation from the riverbed was reduced and some attempts of natural restoration were carried out, the marsh of this part of the delta did not fully recover, compared to its pre-1950s extension (Gaglio et al., 2017). The set of complex forces exerting influence on the delta causes the marsh vegetation to be characterised by several plant communities; it is composed principally by the associations of *Spartinetum maritimae*, *Puccinellietum palustris*, *Salicornietum radicantis*, *Salicornietum fruticosae*, *Agropyro-Inuletum crithmoidis*, *Halimionetum portulacoidis* (Ferrari et al., 1985). Although most of the levees that define the structure of the delta are man made (Cencini, 1998; Colombo & Tosini, 2011), the lagoons under investigation are mainly delimited by artificial embankments covered by reeds (*Phragmites australis*) (Verza & Catozzo, 2015). The dyke failure that regards this study occurred on this type of levee.

3 | METHODOLOGY

3.1 | Orthophotos analysis

Eighteen orthophotos taken between 1949 and 2018 were available from the IGM (Istituto Geografico Militare Italiano) and the Veneto Region archives (Table 1). The oldest orthophotos (1949–2011) were georeferenced based on unchanged ground control points, mainly represented by permanent artificial structures, identified on the georeferenced and rectified images of the AGEA (Agenzia per le Erogazioni in Agricoltura) flights provided by the Veneto Region archives (2003–2018). The RMSE (root mean square error) derived from the georeferencing procedure was calculated for each orthophoto, and it ranged from a minimum of 0.4 m to a maximum of 2.69 m (see Table 1 for more details). The number of ground control points (GCPs) and the transformations used were chosen based on the RMSE obtained, which should generally be less than one half the

TABLE 1 Dates and characteristics of the orthophotos; since old images were acquired in analogic format, the resolution was not always provided in the metadata of the images.

Date	Scale	Altitude	Archives	Resolution	RMSE
10/07/1949	18 000	3600	IGM	/	0.88 m
14/10/1955	33 000	5000	IGM	/	2.69 m
11/07/1962	33 000	3600	IGM	/	1.27 m
17/07/1969	35 000	5400	IGM	/	1.47 m
10/08/1977	29 000	4500	IGM	/	0.4 m
04/06/1983	/	2600	Veneto Region	/	0.66 m
06/07/1989 (IRFC[a])	35 000	5400	IGM	/	0.5 m
03–07/1990	/	3000	Veneto Region	90 cm	1.2 m
01/07/1991	36 000	5500	IGM	/	0.16 m
03/09/1992	35 000	5940	IGM	/	0.49 m
14/09/1996	38 000	5800	IGM	/	1.04 m
05/10/1999	/	2500	Veneto Region	70 cm	0.83 m
2003	/	/	Veneto Region	50 cm	Previously georeferenced by AGEA
2006	/	/	Veneto Region	50 cm	Previously georeferenced by AGEA
06/2006–09/2007	10 000	/	Veneto Region	50 cm	Previously georeferenced by AGEA
21–22/08/2008	/	1250/2500	Veneto Region	70 cm	0.62 m
17/09/2012	/	/	Veneto Region	20 cm	Previously georeferenced by AGEA
2015	/	/	Veneto Region	20 cm	Previously georeferenced by AGEA
14/04/2018	/	/	Veneto Region	20 cm	Previously georeferenced by AGEA

Note: Dates are in day/month/year format.
[a]Infrared false colour.

pixel size of the image (Vanderstraete et al., 2003) according to the US National Map Accuracy Standards (Stathopoulou & Cartalis, 2009). The ideal number of GCPs chosen for these images is 12 GCPs per photo, but not all images allowed this standard to be maintained, mainly because of varying coverage and, in certain cases, unclear positions of the reference points. All orthophotos were georeferenced in the WGS84/UTM zone 33°N (EPSG:32633) coordinate system.

Three main points of interest were identified in the lagoons of Barbamarco, Basson-Canarin and Burcio (red squares in Figure 1b) where high deposition occurred after natural levee breaching and new intertidal flats formed; in the case of the Basson–Canarin and Burcio Lagoons, a considerable marsh development occurred. These areas had been occupied by rice fields that were permanently submerged during the 1950s and 1980s and, consequently, abandoned; however, in subsequent years, marsh vegetation started encroaching back on these portions of the lagoons. The marshes considered in these study sites are mainly composed of *P. australis*, which is the predominant species covering the levees and the internal portion of the investigated lagoons. This reed is considered a freshwater marsh species (e.g. Silliman & Bertness, 2004; Smith, 2013) and, most importantly, is a common and endemic species of the Po Delta (Verza & Catozzo, 2015). A second marsh plant found only in the Barbamarco Lagoon is the pioneer species *Spartina* sp. Its presence was identified in the recent orthophotos (i.e. after 2012) thanks to previous surveys that were carried out with drone images and field observations (see Brunetta et al., 2021); the presence of this plant was important to give context to marsh evolution in the Barbamarco Lagoon, as compared to the other lagoons (see Sections 3.3 and 5.2). The marsh coverage was identified by the authors based on texture, colour variation and comparisons with recent high-quality photos. The distinction between rice fields, intertidal flats and marsh vegetation can be observed because of their variations in morphology and their individual tones seen in the aerial imagery. The pixels representing the Phragmites and other plant species were characterised by homogeneous dark tones that were highly distinguishable compared to the water/intertidal flat pixels, which were characterised by brighter tones. The land cover was classified as it follows: (i) fully vegetated (i.e. area characterised by vegetation only), (ii) partially vegetated (i.e. vegetation patches alternated with water/intertidal flats) and (iii) water and tidal flat only. The marshes considered here are those that developed after levee breaching and the consequent intertidal flat formation; the marsh that was present before the dyke failure was used as a reference to document the initial conditions. Once identified, the area of the marshes (hectare) in each orthophoto was computed based on the digitisation of vegetated areas carried out in GIS environment, and the variations in hectare and in percentage were calculated based on the previous condition (e.g. marsh extension in 1977 − marsh extension in 1989 = marsh extension variation; hence, marsh extension in 1977/marsh variation [1977–1989]*100 = variation in percentage); the rates of changes (ha/years) were calculated as well. The accuracy of the area calculation was evaluated for each orthophoto through a GIS buffer that was applied based on the RMSE derived from the georeferencing. An accuracy assessment to evaluate the manual classification was carried out digitising 10 times the boundaries of a marsh block (~2.5 ha) sufficiently comparable with others of the study area. The analysis was performed by the same user to avoid differences in the digitisation. The coefficient of variation obtained is 0.45%, allowing to estimate the manual error per each marsh extension. The tidal conditions of the orthophotos were not considered in the interpretation because of the microtidal range. The difference in pixel size between aerial orthophotos and satellite images was negligible for the interpretation and manual tracing, because the two typologies presented very similar resolutions (i.e. between 0.2 and 0.9 m for aerial orthophotos and between 0.35 and 0.52 m for satellite images).

TABLE 2 Satellite images from Google Earth Pro 7.3.4.8248 (64 bit) (SIO, NOAA, U.S. Navy, NGA, GEBCO, Maxar Technologies 2020) captured between 2009 and 2020.

Date	RMSE	Coordinates (WGS84)
13/04/2009	0.28 m	44°58′26.52″N 12°30′12.95″E
06/03/2011	0.5 m	
16/08/2013	0.31 m	
22/06/2017	0.34 m	
03/04/2020	0.38 m	

Note: The coordinates (WGS84), chosen by the authors as representative of each site, refer to the location of the Burcio lagoon. Dates are in day/month/year format.

The variations of the marsh coverage of the Basson–Canarin Lagoon have been evaluated for the period from 1969 to 2015, which means starting from the levee-breaching and subsequent permanent or partial submersion of the rice fields to the most recent orthophoto that includes this portion of the Basson–Canarin Lagoon. The same type of analysis was carried out for the Burcio Lagoon between 2009 and 2020, therefore before the system started its most recent development until nowadays, using satellite images (Table 2) from Google Earth Pro 7.3.4.8248 (64 bit).

3.2 | Tidal records and flow discharge analysis

Complementary hydrodynamic information, such as flow discharge and tidal variations, are needed for a correct interpretation of the delta's dynamics and its evolution. The Annual Water Volume (km^3) is provided by Correggiari et al. (2005) between 1918 and 1987, whereas the full historical record of daily discharge from 1925 to 2020 is obtained from AIPO (Agenzia Interregionale del fiume Po); the dataset was measured at the gauging station of Pontelagoscuro, which is located about 70 km upstream from the study area (see Figure 1a). Because sediment transport measurements ceased in 1984, the dataset chosen is the one provided by Ninfo et al. (2018), where they calculated the Sediment Transport Capability Discharge (Q_k, here called STCD) based on the same record of AIPO, which is represented by Equation (1):

$$Q_k = Q_{max} * Q_{10d} / (Q_{max} - Q_{10d}) \tag{1}$$

where Q_{10d} is the average of the highest discharges that occurred 10 days a year and Q_{max} is the highest discharge of the year.

This STCD calculation has been chosen keeping in mind the absence of tributaries between the gauge station of Pontelagoscuro and the mouth, which causes the sediment to undergo continuous variations in deposition and transport conditions without external inputs. However, a certain time lag should be expected in the delta response to the variability of sediment yield. This calculation considers that the most impacting floods of the Po River cause high sedimentation and modify the delta. However, floods that occur during longer periods have a strong influence on the bed material transport to the mouth as well. Because periods characterised by large and frequent floods may have a higher morphological impact than individual exceptional floods (Ninfo et al., 2018), the analyses were integrated with the dataset of AIPO. It is important to state that this dataset was used qualitatively to determine the periods characterised by possible high sediment flux transported by the floods; it does not represent the real sediment transport. In this study, although the influence of waves and tidal currents on sediment transport is highly relevant on the littoral morphology, inside the lagoons it is considered negligible compared to the influence of the riverine processes (Maicu et al., 2018).

For tidal measurement, the gauging station of Porto Garibaldi, which is located ~40 km southward of the delta was taken into account. The tide gauge of the Po della Pila was not chosen for this analysis because the influence of the river would not allow a correct calculation of the variation of the local mean high tide (MHT) and mean sea level. The time range chosen for the data collected by the Porto Garibaldi tide gauge was from 2009 to 2019. For the tide gauge analysis, the local mean sea level, calculated over the whole 10-year time series, was chosen as the vertical reference datum, because the Italian vertical reference (Genova 1942) is located about 12.3 cm below the current mean sea level, in the case of Porto Garibaldi.

3.3 | The intertidal flat of the Barbamarco Lagoon and marsh distribution

This study is combined with the results of Brunetta et al. (2021), which concerns the evolution of the intertidal flat in the southernmost part of the Barbamarco Lagoon. In the cited paper, morphology and rates of vertical changes of the intertidal flat were obtained based on drone surveys, producing DEM (digital elevation models) of difference (DoDs) through geomorphic change detection analyses (Wheaton et al., 2010). These analyses and dataset will assist and support the discussion of this study. The reader is redirected to the original paper for further details.

In addition, a small dataset of *Spartina* sp. distribution was collected on 29 October 2020 in order to measure the elevation and location of the plant on the tidal flat surface. The position of each point was measured using an RTK-GPS Trimble R8 and referring to the WGS84/UTM 33°N coordinate system and the vertical datum ETRF 2000, corrected to the local mean sea level in order to compare the points with the tide gauge dataset.

4 | RESULTS

4.1 | The first time interval (1949–1955): land reclamation

The oldest orthophoto available for this study was captured in 1949 (Figure 2a). At this moment in time, the Po della Pila and the other lagoons were separated. Although the original photo is deteriorated in some parts, agricultural fields are clearly visible. Rice fields covered 220 ha out of the total 500 ha of the Burcio Lagoon (see the red polygons in Figure 2a), and the other man-made structures used to cover most of the territory. A well-developed marsh covers both the Burcio (270 ha) and the Basson–Canarin Lagoons (>380 ha) (see the green polygon in Figure 2a, b). The southern section of what will become the Barbamarco Lagoon presented several parallel artificial channels that develop in a northern–western direction (see the yellow lines in Figure 2a). In the central-northern section, a large natural tidal channel extended from the sand barrier in land (see light blue lines in Figure 2a). The thermoelectric power plant located southward to the Po della Pila branch had not been built yet. Some of the features described previously are more clearly visible in the better-quality orthophoto of 1955 (Figure 2b). The photo shows that the natural levees of the tidal creeks were covered by vegetation, suggesting that marsh species were also present in this central part of the forming lagoon (see the green polygon on the northern side of the Barbamarco Lagoon in Figure 2b). The presence of complex tidal creek systems has also been seen in other lagoons of the Po Delta during the 1940s–1950s (Corbau et al., 2022). New rice fields are visible in the southern portion of the orthophoto (>75 ha was reclaimed from the marsh; see the red polygons in Figure 2b).

4.2 | The second time interval (1955–1977): extreme events

The most severe changes took place during the following decade. In 1960, the Po River had a peak STCD higher than 67 000 m^3/s and an annual water volume of about 80 km^3. These floods occurred concurrently with several heavy storms (Garnier et al., 2018; Perini et al., 2011) and the highest subsidence rates ever recorded in the delta (Caputo et al., 1970).

The consequences of these combined events are visible in the orthophotos of 1962 (Figure 2c), when the whole Barbamarco Lagoon was completely and permanently submerged; these events originated the recent configuration of the lagoon. The agricultural fields of the Burcio Lagoon and the Basson–Canarin Lagoon were also covered by water and consequently abandoned (see the blue polygons in Figure 2c). It is important to state that in this phase (1955–1962), no levee breaching occurred; the rice fields and the marshes were flooded by water coming directly from the sea inlets. The Po della Pila was connected to the Barbamarco Lagoon via a new channel, probably man made to allow boats to navigate between the harbour of the village of Pila and the one located in the western side of the Barbamarco Lagoon, seen here under construction (Figure 3).

The first main natural breach occurred in the Basson–Canarin Lagoon, as visible in the orthophoto of 1969 (Figure 4a). Between 1962 and 1969, the dyke that separated the Po della Pila branch and the rice fields next to the power plant failed, and the new natural opening allowed the freshwater to flood the lagoon (Figure 4b). In its first appearance in 1969, this breach was about 140 m, although a vegetated island of about 40 m of width was present in the middle of the creek (Figure 4b). A marsh developed during the following years (Figure 4c) reaching its maximum extension in 1989, with a rate of growth between 5 and 7 ha/year (a total of about 130 ha in about 20 years, Figure 4d). More than 100 ha was covered by *P. australis*

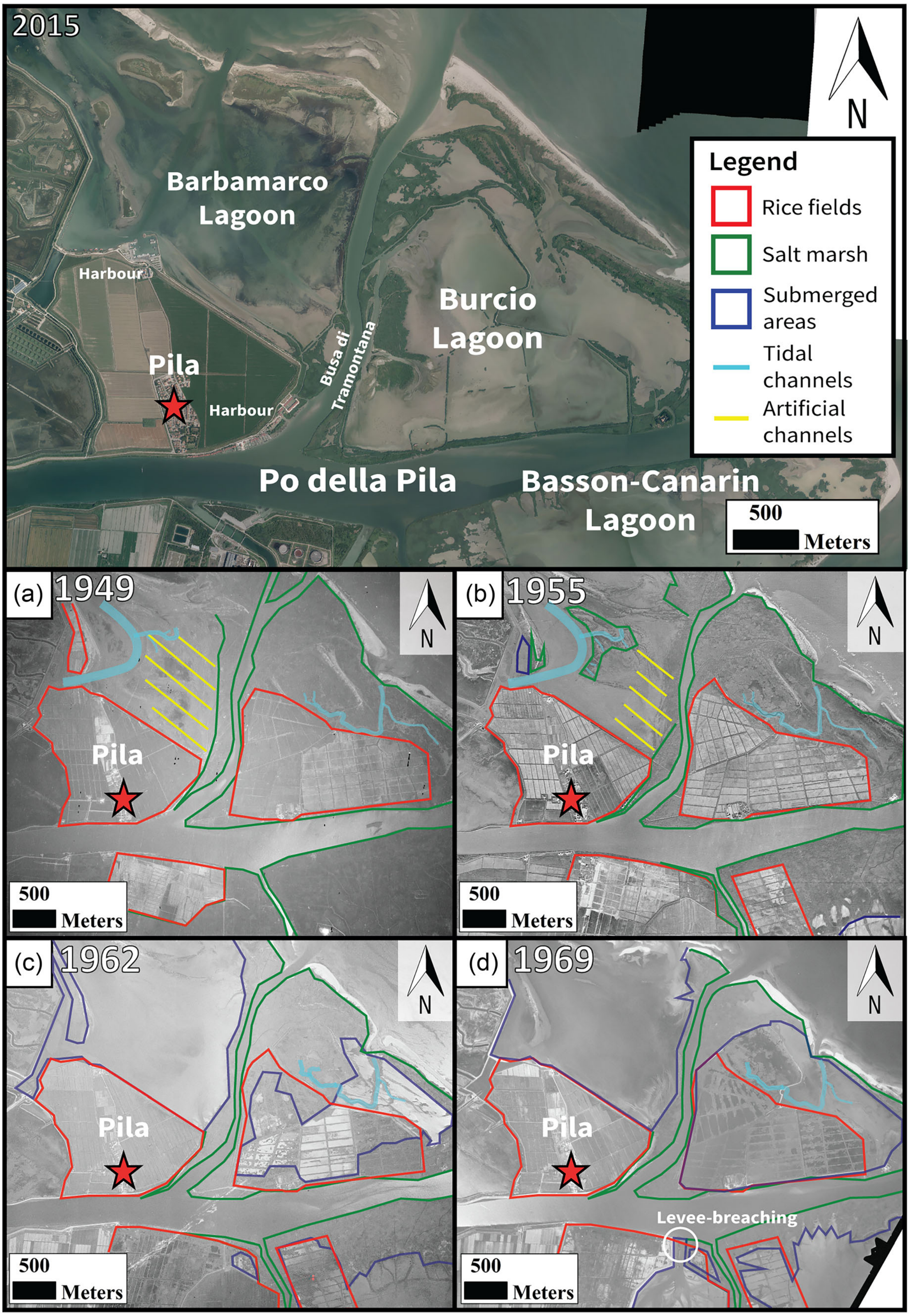

FIGURE 2 The inundation of the Po Delta between 1949 and 1969. In 1949 (a) the Barbamarco Lagoon was only partially a lagoon and land reclamation continued until 1955 (b). N 1962 (c) and 1969 (d) subsidence, river floods and coastal storms submerged most of the rice fields, giving rise to the recent configuration of the lagoons. The red polygons represent the rice fields, the yellow lines represent small channels, the green polygons represent the marsh, the light blue lines represent the tidal creeks, and the blue polygons represent the areas that were submerged (permanently and partially).

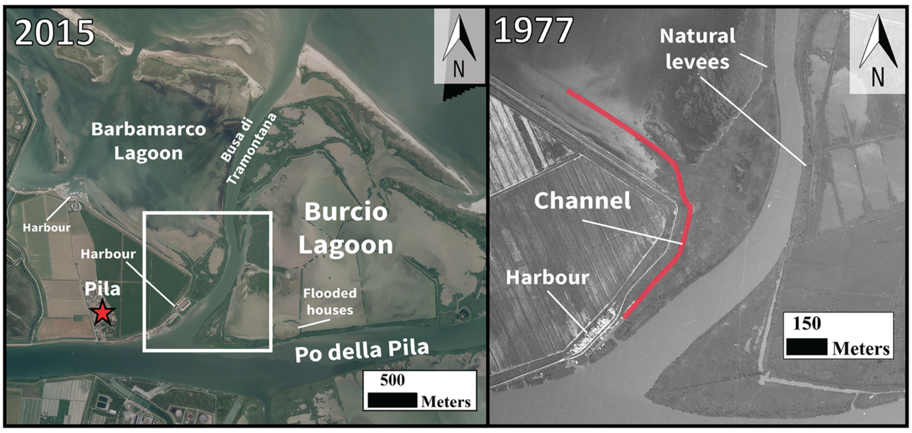

FIGURE 3 The channel that connects the Po della Pila with the Barbamarco Lagoon (red line) was first seen in 1962 but only stabilised its shape after 1977.

and a tidal network was defined by four channels that extended southward. Then, the marsh experienced vegetation loss until 2007, reaching about 90 ha (Figure 4e), but a small recovery is visible in the following years (∼100 ha, Figure 4f). The breach changed position in time and shifted about 250 m eastward after 1977, before stabilising its width at 90 m in 1989 (Figure 4c, d). The extension, variation in time and rates of extension of the marsh are summarised in Table 3.

The year 1977 was characterised by several large floods (43 000 m^3/s of STCD; 80 km^3 of annual water volume). The tip of the delta experienced the most important marsh loss, which peaked in 1989, where the plant coverage of the Burcio Lagoon was diminished to about 170 ha, and the coverage of the Basson–Canarin Lagoon contracted to about 150 ha (excluding the marsh that developed after the breach).

4.3 | The third time interval (1977–1999): Small recovery

From 1977 to 1996, natural processes and human activities resulted in the opening of several new connections between the lagoons. In 1983, a small channel developed on the west side of the Busa di Tramontana inside the Barbamarco Lagoon (Figure 5a) and a new mouth connecting this lagoon to the sea opened (Bocca Sud) (Figure 5a, b). Engineering works in both harbours were progressing and a new artificial mouth controlled by a flood gate (Porte Vinciane) was opened next to the southern part of the west side of the Busa di Tramontana (Figure 5b). These gates were built to control fresh and sea water mixing (i.e. salinity) of the lagoon (Colombo & Tosini, 2011). However, this small mouth was closed in 1996, and a smaller dam was built 70 m southward (Figure 5d). During 1990 and 1996, a progressive reduction of marsh vegetation is visible on the channel connecting Po della Pila to the Barbamarco Lagoon, with regression of about 80 m that persisted during the following years (see southern portion of Figure 5c, d). Two sandy islands were artificially built during the early 1990s (Verza & Catozzo, 2015) in order to recreate new marshes (Colombo & Tosini, 2011) (Figure 5c).

It should be noted that after 1983 the marshes separating the lagoons (i.e. Barbamarco and Burcio Lagoons) from the Busa di Tramontana were gradually decreasing in width (especially next to the Porte Vinciane, from ∼30 in 1983 to ∼8 m in 1996, see Figure 5c). In 1996, on the opposite side of the Porte Vinciane (east of the Busa di Tramontana), the second breach of about 70 m connecting the river branch with the Burcio Lagoon (Figure 5d) occurred. The decrease in width of the marsh that separated the lagoon may have contributed to the levee breaching. After 1989, the lagoons of the delta reached a state similar to the current one.

4.4 | The fourth time interval (1999–2020): tidal flat and marsh formation

In the early 2000s, the third natural breach occurred allowing the deposition of a large amount of sediment inside the Barbamarco Lagoon. The orthophoto of 2003 (Figure 6b) shows a new channel that was artificially dug in the southernmost part of the Barbamarco Lagoon, perpendicularly to the small channel made in 1977: it was probably dug to connect the harbours of Porto Tolle and the Barbamarco Lagoon (that achieved its maximum extension in 2003) to enable boats to reach the Bocca Sud inlet. This event is important because this channel allowed sediment transported by river floods to reach the inner southern part of the lagoon which had previously been inaccessible (Brunetta et al., 2021). As shown in Figure 6c, d, this channel did not have stabilised levees in 2008, and several breaches gradually developed as the levees were covered by reeds in 2012. The intertidal flat developed from several crevasse splays fed by river floods (Brunetta et al., 2021) and extended along the channel that connected the harbours of the Barbamarco Lagoon. Sediment deposition in the southern part of the Barbamarco lagoon is visible in the orthophotos of 2015 and 2018 (Figure 7a, b). It is important to note that in 2012 (and in the orthophotos of Brunetta et al., 2021), several patches of vegetation (*Spartina*) are visible for the first time in the young intertidal flat and in the back-barrier areas, although they disappeared by 2015 (see Section 5.2 for more details). *Spartina* sp. grows in small patches around the intertidal flat, but its location is not stable; it grows during spring–summer and dies during autumn–winter, without maintaining the same location. The GPS survey showed the location of the plant lies between −0.09 and 0.13 m above m.s.l., with an average elevation of 0 m above m.s.l.. In the southern part of the Barbamarco Lagoon, *P. australis* distribution did not change from the early 2000s to today and it did not colonise the intertidal flat.

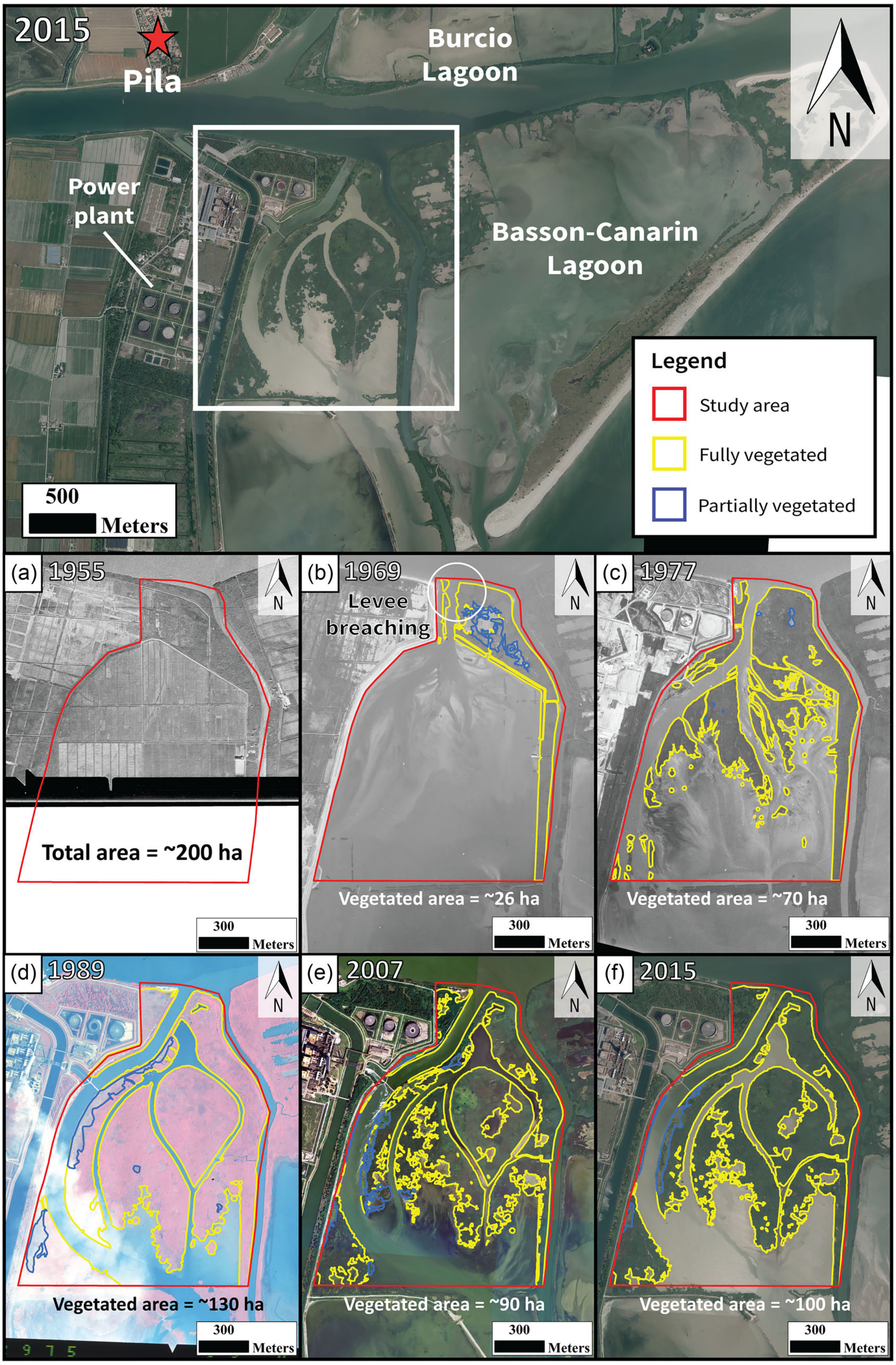

FIGURE 4 A portion of the Basson–Canarin Lagoon experienced an 'unmanaged realignment' dynamic. The dyke protecting the rice fields failed, and the area was submerged between (a) 1955 and (b) 1969. The new breach allowed fresh and salt water to flood the lagoon, and a marsh started its development in the following years, as shown in (c) 1977, reaching its maximum extension in (d) 1989; marsh loss occurred until (e) 2007, and a small recovery was present until (f) 2015.

On the other side of the Busa di Tramontana, the breach of the Burcio Lagoon that formed in 1996 underwent an important enlargement, reaching its maximum width of about 250 m in 2003 (Figure 6b). After 2010, a STCD of around 20 000 m^3/s occurred and strong sedimentation is visible next to the breach of the Burcio Lagoon as shown in the orthophotos of 2009 and 2011 (Figure 8a, b);

TABLE 3 Marsh extension, variation in time and rates of extension after the levee breaching in the Basson–Canarin Lagoon.

Basson–Canarin marsh						
Year	Total marsh extension (ha)	Fully vegetated (ha)	Partially vegetated (ha)	Variation	%	ha/year
1969[a]	25.67 ± 2.88	22.67	3.00	/	/	/
1977	69.88 ± 2.16	69.55	0.33	44.47 ± 7.55	173.24	5.50
1989	130.62 ± 2.1	123.73	6.89	60.48 ± 6.57	86.23	7.47
2007[b]	92.08	87.27	4.80	−38.54	−29.51	−4.76
2015[b]	103.44	99.65	3.79	11.37	12.35	1.41

[a]Marsh extension after the breach (initial conditions).
[b]The orthophotos were previously georeferenced by AGEA (Regione Veneto) and used as references.

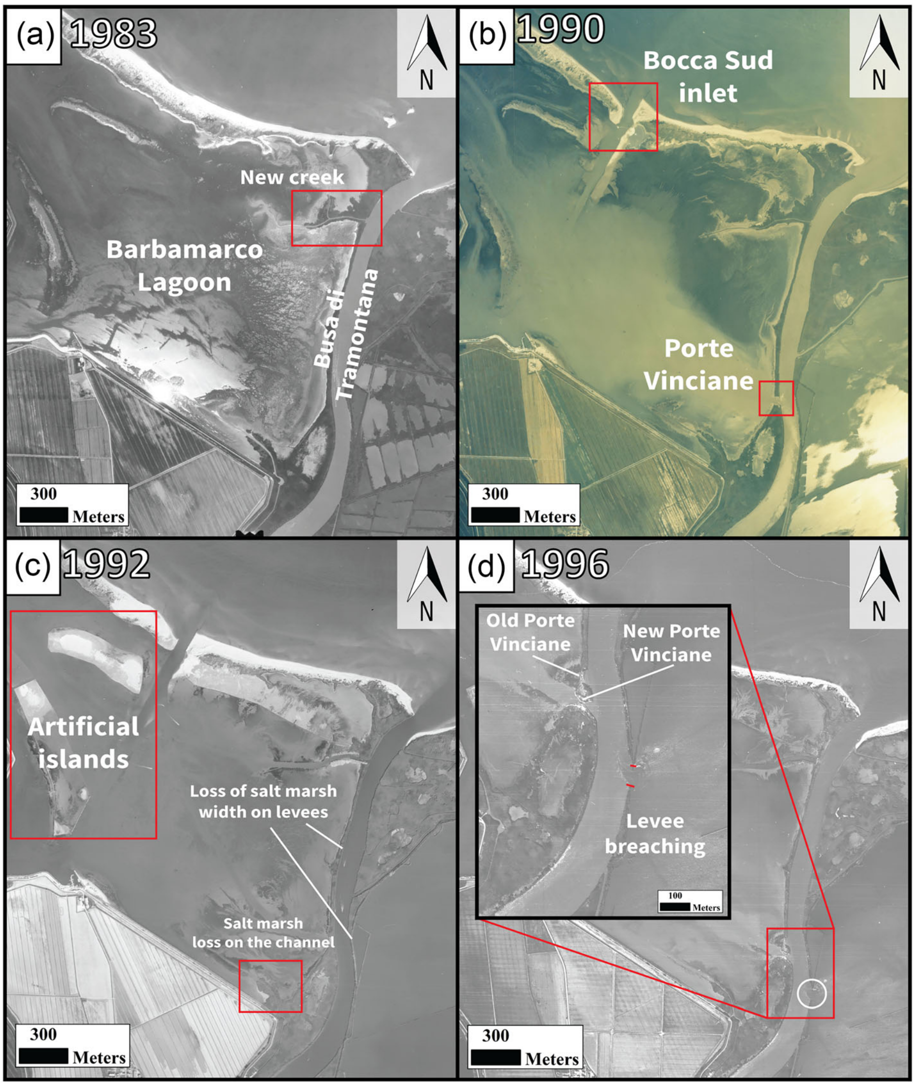

FIGURE 5 Between (a) 1983 and (b) 1990, the Bocca Sud mouth and the artificial mouth (Porte Vinciane) were opened. Two artificial islands were built in (c) 1992 to recreate new marshes. In (d) 1996, the levees that separated the Busa di Tramontana and the Burcio Lagoon failed, as visible in the south-eastern portion of the orthophoto.

an intertidal flat of about 18 ha emerged (Figure 8b). Between 2011 and 2013, this intertidal flat was rapidly covered by reeds, allowing the formation of a marsh of about 15 ha (Figure 8c). This growth continued the following years reaching 28 ha in 2020 (Figure 8d–f), although the rates of extension variation decreased substantially compared to its first years of development (from 6 ha/year in 2011–2013 to 0.3 ha/year in 2017–2020). Four main channels characterised by different widths (between 15 and 50 m) developed after the marsh formation. More details can be found in Table 4.

According to the tidal records of Porto Garibaldi, from 2009 to 2019, the local mean sea level underwent a wide range of variations on a yearly basis, from −0.07 to 0.06 m (Figure 9). In particular, from 2011 to 2012, the m.s.l. was between −0.7 and −0.09 m, corresponding to the lowest value of the dataset; after this period, the m.s.l. ranged between 0.05 (2014) and −0.06 m (2017). These variations affected the MHT level as well, which decreased to 0.17 and 0.15 m between 2011 and 2012, respectively, while in the other years ranged between 0.3 and 0.18 m.

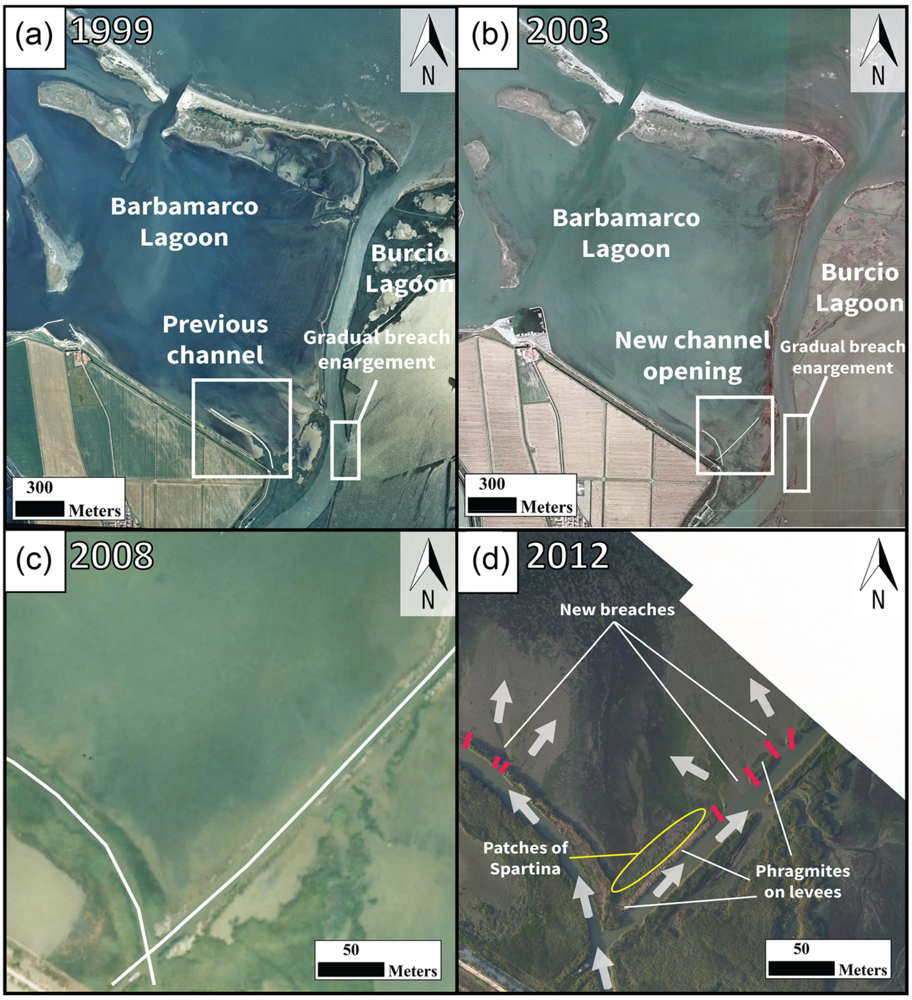

FIGURE 6 Between (a) 1999 and (b) 2003, a new channel was dug (NE direction) in the southern section of the Barbamarco Lagoon, whereas the breach of the Burcio Lagoon was widening. Strong sediment injection occurred after (c) 2008, and the levees were reinforced by wild reeds, which are visible in the orthophoto of (d) 2012. This orthophoto shows several small breaches (red segments) that developed in this period (2008–2012) and the patches of *Spartina* (yellow circle). The arrows indicate the paths followed by the floods inside the channels and then out of the breaches on the crevasse splays.

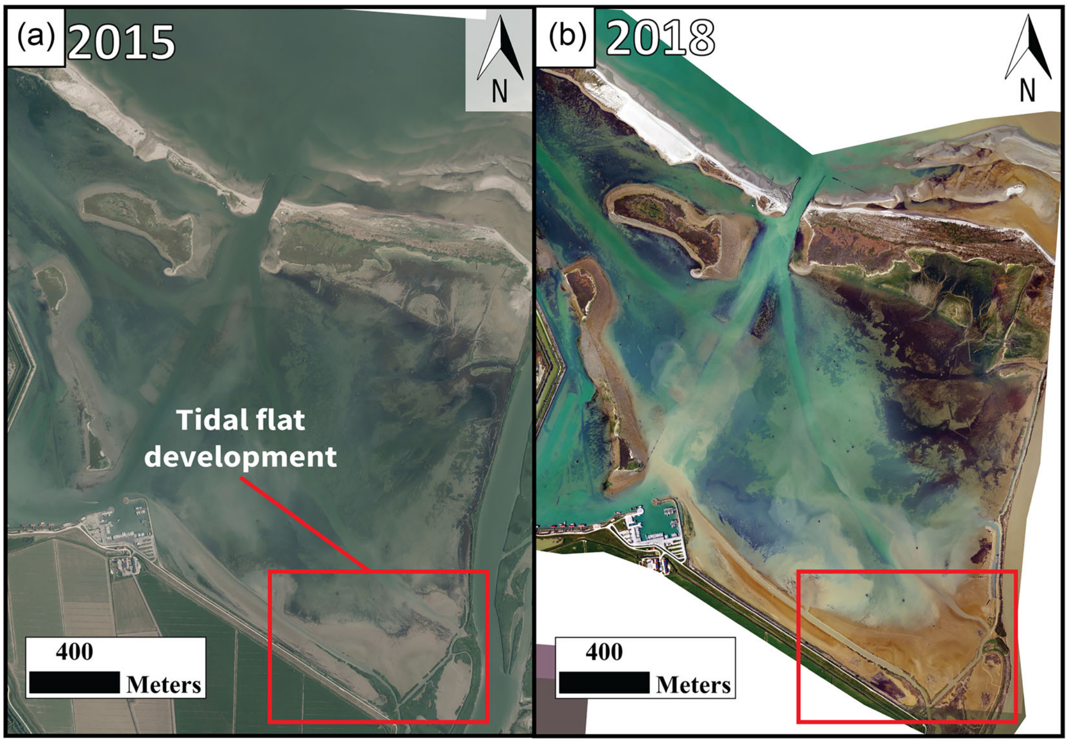

FIGURE 7 The new intertidal flat located in the southern part of the Barbamarco Lagoon is visible in both the orthophotos of (a) 2015 and (b) 2018. It is important to note that, until nowadays, marsh vegetation grew only beside the levees and not on the intertidal flat.

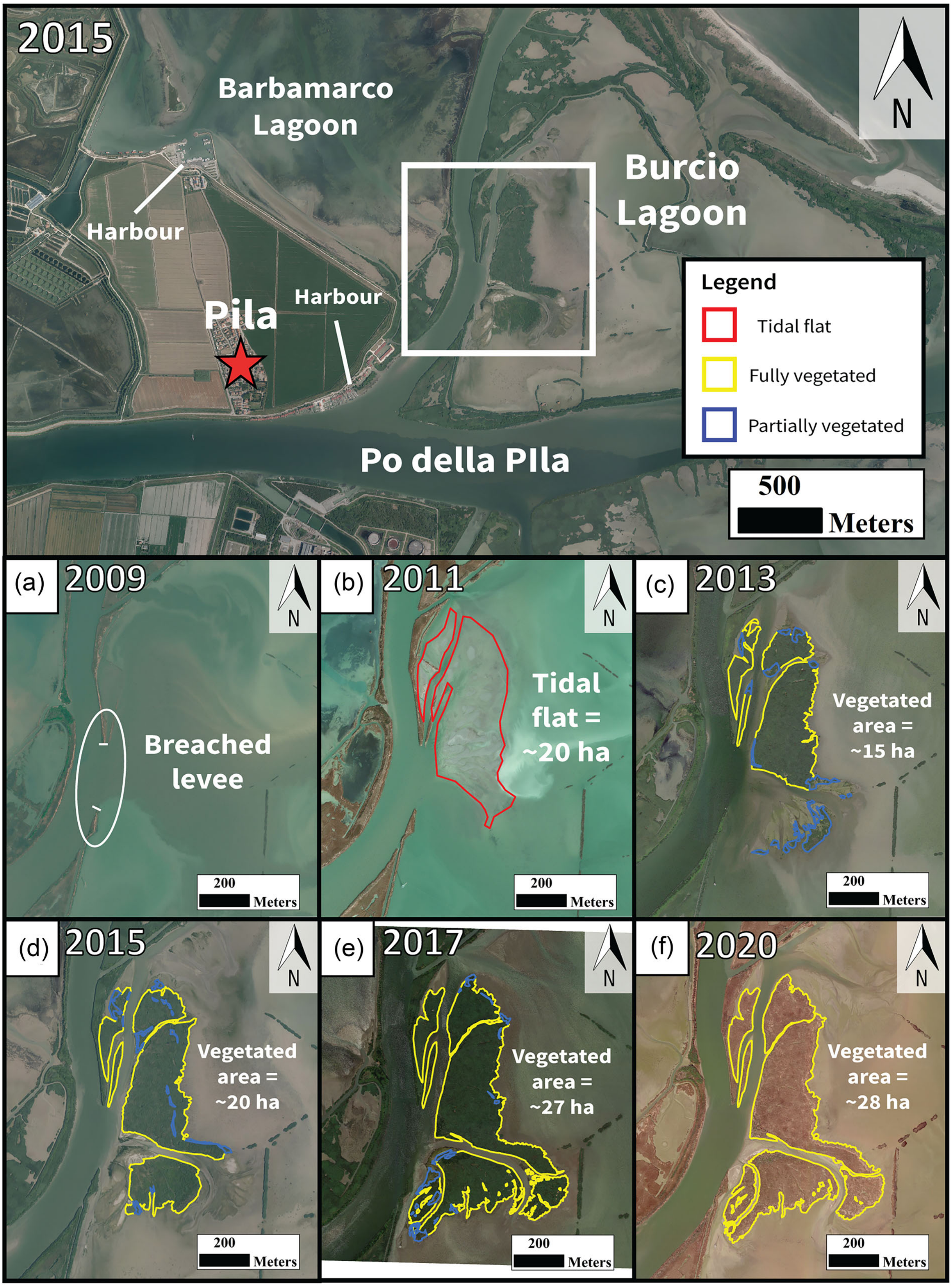

FIGURE 8 The Burcio Lagoon underwent an 'unmanaged realignment' dynamic similar to the Basson–Canarin Lagoon. After (a) 2009, the wide breach that formed in the previous years allowed high sedimentation in the Burcio Lagoon and an intertidal flat formed in (b) 2011. In (c) 2013, wild reeds covered the area and established a new system between (d) 2015, (e) 2017 and (f) 2020.

TABLE 4 Marsh extension, variation in time and rates of extension after levee breaching in the Burcio Lagoon.

Burcio marsh						
Year	Total marsh extension (ha)	Fully vegetated (ha)	Partially vegetated (ha)	Variation	%	ha/year
2011[a]	18.89 ± 0.19	/	/	/	/	/
2013	15.35 ± 0.51	13.06	2.30	15.35	/	6.29
2015	21.06	20.19	0.87	5.71	37.18	3.55
2017	27.35 ± 0.7	26.41	0.94	6.29	29.84	2.79
2020	28.17 ± 0.64	28.17	/	0.82	3.01	0.30

[a]The orthophotos were previously georeferenced and used as references.

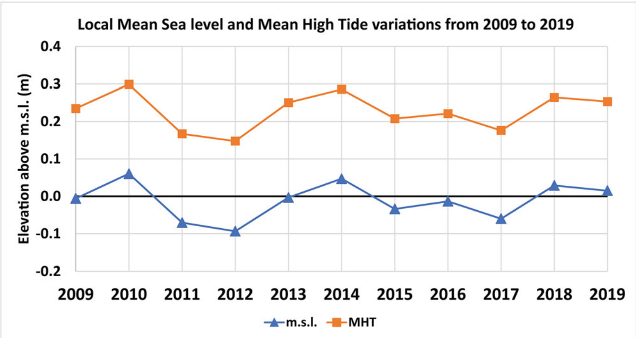

FIGURE 9 Local mean sea level and mean high tide (MHT) variations between 2009 and 2019 obtained from the tide gauge in Porto Garibaldi.

5 | DISCUSSION

5.1 | Evolution of the new marsh systems of the Burcio and Basson–Canarin Lagoons

The results showed that the Burcio and the Basson–Canarin Lagoons were subjected to a progressive increase in marsh coverage after natural levee breaching of the Po della Pila branch. It is interesting to note that the marsh that grew inside the Basson–Canarin Lagoon (1969–1977) developed during the period characterised by the highest subsidence rate (Figure 10). Based on Caputo et al. (1970) and Fabris (2019), the rates of subsidence from 1951 to 1977 were highly impactful on the morphology of the delta. In this phase, this process was the main cause for the overall marsh loss and the lagoon formation. However, between 1976 and 1977, there were frequent floods with water discharge higher than 6000 m^3/s, which are the ones that cause the most significant deposition (Tesi et al., 2011), with important STCDs, and the highest annual sediment load after 1960 (about 15 $\times$ 10^6 tons, Correggiari et al., 2005). Furthermore, the levee breaching occurred next to the main branch of the Po River, meaning that a large amount of sediment could move inside this portion of the Basson–Canarin Lagoon in contrast to other portions that are separated from the Po della Pila.

Although the delta was undergoing strong transgression, land submergence, and general marsh loss, an intertidal flat and, subsequently, a marsh developed where the breach occurred; thus, a large number of flood events characterised by a high sediment content allowed the formation of a marsh able to keep up with subsidence. The gradual decrease of the rates of subsidence in the following years may have improved the conditions allowing for marsh vegetation to further colonise the lagoon.

A reduction in marsh coverage is visible in 2007 (from 130 to 90 ha, see Figure 4e and Table 3). Since strong floods and high STCD occurred between 1989 and 2007, while the rates of subsidence were diminishing (from 1.8 to 0.6 cm/year, Fabris et al., 2014), this behaviour is at odds with the previously described condition; this discrepancy might be caused by a low frequency of floods, although the values of the STCD are high (see Section 5.3.2. for a detailed discussion). Moreover, Fabris (2019) showed that between 1999 and 2008, an increase in permanently submerged areas occurred, and it was ascribed to a combination of significant human interventions, which aimed at improving fish and mollusc farming and river navigation, combined with an increase in storm frequency (Carbognin et al., 2010; Ericson et al., 2006; Perini et al., 2011). Hence, it might be possible that the growth of the marsh continued until 1999 and then the most important loss occurred between 1999 and 2008. After 2007, the marsh system started to recover, although expanding at a lower rate (i.e. 2.2 ha/year).

The evolution of the marsh system derived from the levee breaching occurring in the Basson–Canarin Lagoon followed a different development compared to other marsh systems of the tip of the delta and may appear contradictory; however, the results highlight how the marsh evolution rather depends on a single (or very few) component (e.g. subsidence, water and sediment discharge) that prevails over the others in a certain time interval (see Section 5.4.2. for more details).

Although the marsh that developed in the Basson–Canarin system is older than the Burcio one (i.e. ∼50 vs ∼10 years), they were both characterised by similar rates of (positive) marsh expansion (i.e. around 5 ha/year) during their first years of development. Compared to the Basson–Canarin marsh, the location of the levee breaching of the Burcio Lagoon, which is in the Busa di Tramontana branch and not directly in the Po della Pila branch, might have influenced sediment deposition, reducing the amount of sediment able to reach this location and progressively decreasing the rates of expansion of the newborn marsh of the Burcio Lagoon, compared to the Basson–Canarin marsh (see Section 5.3.4 for more details). Although no relevant increase in marsh vegetation was found after the important flood that occurred in November 2019, which caused high deposition in several portions of the delta (Brunetta et al., 2021), it is plausible that the vegetation did not have sufficient time to develop before the last orthophoto was taken in April 2020.

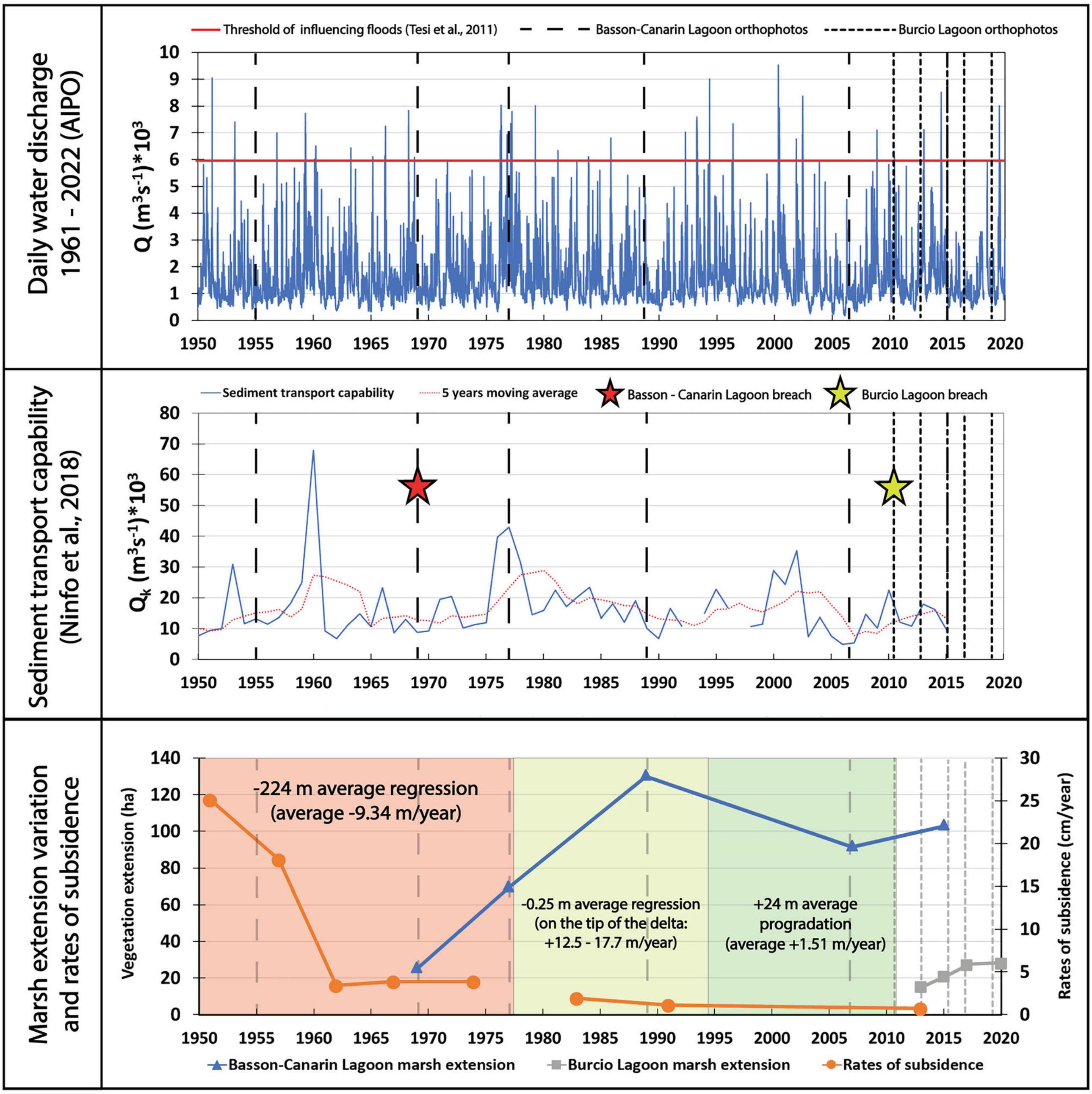

FIGURE 10 Timeline of the processes that shaped the Po River delta from 1950 to 2020. The figure includes the daily water discharge (obtained from AIPO), the sediment transport capability (Ninfo et al., 2018), the rates of subsidence (Caputo et al., 1970; Fabris et al., 2014), the coastline changes (Bezzi et al., 2021) and the variation of marsh extension in the lagoons of Basson–Canarin and Burcio. The red line in the daily water discharge graph represents the threshold for most influencing floods (higher than 6000 m^3/s, based on Tesi et al., 2011).

5.2 | The intertidal flat of the Barbamarco Lagoon

A different evolution was observed in the Barbamarco Lagoon, compared to the other two under investigation. The tidal system visible in 1955 disappeared completely, and no intertidal flats were seen before 2010. The only restoration project that was carried out inside the Barbamarco Lagoon consisted of the construction of two sandy islands artificially built in the 1990s (Verza & Catozzo, 2015). However, the increase in river sediment supply (Bezzi et al., 2021; Ninfo et al., 2018) and the opening of new connections between the lagoon and the branches next to the Busa di Tramontana generated a new intertidal flat that is following a positive trend of accretion with an average rate of vertical changes of about 1.3 cm/year (value calculated through DoDs between DSM products obtained from several seasonal drone surveys between 2018 and 2020; the area refers to the intertidal flat of about 8 ha; see Brunetta et al., 2021 for more details). The river floods likely control sediment deposition, and several crevasse splays cover the intertidal flat. Brunetta et al. (2021) pointed out that accretion is higher at the northern-western border of the mudflat, suggesting that the intertidal flat is increasing in area as well as in elevation; this behaviour is visible in the recent orthophotos (2015–2018) as well. Furthermore, to counteract the high sediment deposition that prevents fishing vessels from travelling across the mouth, several dredgings have been made at the southern mouth of the Barbamarco Lagoon (i.e. Bocca Sud) during the last decades. If the river sediment input is constant in time, the intertidal flat could slowly cover the lagoon, possibly leading to a similar configuration to the one present before 1950.

However, after 20 years, a marsh has still not developed in this section of the lagoon, and only two species are present (i.e. *Spartina* sp. and *P. australis*). There are several possible reasons to explain why the marsh did not develop in the southern part of the Barbamarco Lagoon:

i. The MHT could be too high compared to the elevation of the intertidal flat surface; in fact, marshes usually develop when tidal flats reach MHT, from a mere morphological point of view (Bakker, 2014; De Vlas et al., 2013). The MHT of 2019 is about 0.25 m above m.s.l. and the highest values of the surface range between 0.1 and 0.2 m. Low elevation indicates longer submersion periods, which reduces the window of opportunity for seedlings to establish and grow sufficiently to overcome disturbances (van Belzen et al., 2022). Strong colonisation of *Spartina* on the most elevated portion of the tidal flat occurred between 2011 and 2013 only (visible in the orthophoto of 2012, Figure 6d); this event could be related to the lower levels of MHT and m.s.l. that characterised these years (0.17 and 0.15 m between 2011 and 2012, respectively). It is important to note that *P. australis* has not been able to increase its extension on the intertidal flat during the last 20 years as well.
ii. The salinity fluctuation in the Barbamarco Lagoon is high and may influence the spread of both species. Although no salinity measurements were carried out during this study, it is well known that wild reeds need freshwater to develop and they mostly grow next to the levees, which are next to the river channels (Verza & Catozzo, 2015). Instead, *Spartina* is able to survive under high ranges of salinity (Adams & Bate, 1995), suggesting that for this species salinity may not be the only factor influencing the plant growth (Hu et al., 2015; Ning et al., 2020). A detailed discussion about the influence of salinity can be found in Section 5.3.1.
iii. Excavations and boat crossings. The channel that connects the Po della Pila with the Barbamarco Lagoon is commonly used by fishermen to move between the two harbours. The waves generated by the boats are a possible cause of erosion in the southern-western part of the tidal flat (Brunetta et al., 2021), as observed at other sites around the world (e.g. Ciavola, 2005; Everett et al., 2022; Houser, 2010; Rapaglia et al., 2012; Rapaglia et al., 2015), as well as marsh loss on the levees; furthermore, this channel is regularly dredged to prevent boats from running aground.
iv. Other biochemical factors may influence marsh vegetation growth, for example, insufficient drainage at low tide; in fact, low drainage can interfere with seedling establishment, especially in muddy systems (Cao et al., 2021). The presence or the absence of nutrients, such as nitrogen or phosphorus, can alter biomass accumulation and marsh evolution as well (Alldred et al., 2017; Turner, 2011; Turner et al., 2009).

Overall, the two species are limited and struggle to expand on the intertidal flat. The most probable influencing factor for *Phragmites* expansion would be salinity, because the species is found mainly alongside river channels. In the case of *Spartina*, which is continuously developing but never establishing, it is possible that the window of opportunity remains insufficient, although temporary favourable conditions seem to occur during the seasons.

5.3 | From intertidal flat to marsh: differences in marsh system evolution

Levee-breaching and sediment injections influenced the evolution of the marshes of the Basson–Canarin Lagoon in the 1970s and 1980s, as well as in the Burcio Lagoon and the Barbamarco Lagoon in more recent years (i.e. after 2010), although the evolution of the latter study area is at odds with the other two marshes. The essential factors for consideration are: (i) the salinity fluctuations inside the lagoons, (ii) the sediment discharge, (iii) the morphology of the lagoons and (iv) the sizes and location of the breaches with respect to the Po della Pila branch.

5.3.1 | Influence of salinity distribution

As discussed in Section 5.2, the establishment of wild reeds is strictly connected to the channel location, because they need both freshwater flux and a sufficient elevation above the mean sea level. The colonised areas of the Burcio and the Basson–Canarin Lagoons are the closest to the Po della Pila branch and have the largest breaches, which means that they have direct and better access to freshwater, and they are protected from the sea water by the lagoon itself. Based on the hydrodynamic and salinity model developed by Maicu et al. (2018), the Burcio and the Basson–Canarin Lagoons are characterised by freshwater (with stable practical salinity units [psu] values lower than 10 ± 2, where 35 psu are equivalent to 35 g/L of salt and ±2 is the salinity range of surficial daily variation). *Phragmites* is commonly found with salinity values between 0 and 13 psu (Packett & Chambers, 2006), suggesting that the local salt concentration is favourable for the species. In fact, the colonised areas are located next to the principal river branch. A different condition is found in the Barbamarco Lagoon. Freshwater floods only flow through the small channel that connects the Busa di Tramontana with the lagoon, whereas seawater moves inside the lagoon from the Bocca Sud inlet. This low hydrodynamic mixing generates sharp gradients where freshwater is confined in the southern part of the Barbamarco Lagoon with variable psu values between 10 and 15 ± 10, and higher salinity is found in the northern section, with variable psu values from 17 to 25 ± 10 (Maicu et al., 2018). Because *Phragmites* has specific salinity requirements in order to establish and *Spartina* conditions are not yet ideal because of long submersion period, variable salinity and/or not enough nutrients, marsh distribution could be limited; it is possible that the condition of the Barbamarco Lagoon is allowing both plants to grow but not to colonise and extend their domain. Instead, the Burcio and the Basson–Canarin Lagoons present better conditions for the wild reeds to grow. Overall, the historical review showed that marsh zones without a direct connection to the river and, as a consequence, low deposition rates, tend to retreat; by contrast, new channels that connected the lagoons to the Po della Pila branch increased vegetation cover.

5.3.2 | Floods and sediment discharge in time

Sediment transport is one of the fundamental processes that allows coastal wetlands formation, which here is mainly driven by the river floods. Combining the studies of Ninfo et al. (2018), Bezzi et al. (2021), Brunetta et al. (2021) and the results of this paper, there is evidence that frequent strong floods are one of the most important factors for the formation of, firstly, intertidal flats and, later, marshes, in deltas where sediment supply is controlled by the river; however, they are not clearly correlated with the increase of vegetation in a marsh. For example, the correspondence between the marsh growth of the Burcio Lagoon between 2011 and 2013 and the high STCD of about 22 500 m^3/s that occurred in 2010 is visible in the orthophotos (Figure 8a–c). The case of the Basson–Canarin Lagoon is highly related as well; since between 1976 and 1977, a strong STCD of 40 000–43 000 m^3/s allowed the development of the marsh system and compensated high subsidence rates, as shown in the orthophoto of 1977 (Figure 4b, c). However, in the same marsh, vegetation loss occurred between 1989 and 2007 although several important floods of about 29 000 and 35 000 m^3/s of STCD occurred in 2000 and 2002 (Figure 4d, e). This discrepancy might be related to the distribution of the discharges in time during the year. In fact, the STCD represents the whole year; hence, it is not possible to distinguish the seasonality of the discharges from this sole value. The water discharge data collected by AIPO between 2000 and 2002 show that the higher values occurred mainly in October–November 2000, May 2002 and November 2002, so high discharges coincided with the typical periods expected. The water discharge in November 2000 reached the highest value since 1961, despite the infrequency of the floods of these years (2000–2002); only a few periods were characterised by high discharges. Because the STCD calculation is based on water discharge levels, it proves more reliable when there are frequent floods rather than one single, stronger flood. It could be that the real sediment transport for the period of 2000–2002 was, overall, lower than expected. Despite the vegetation loss that occurred between 1989 and 2007, this study shows that, in the presence of favourable conditions, marshes can potentially grow and cover wide areas in less than 2 years. In the Barbamarco Lagoon, too, the limits of vegetation extension are clearly visible; after 20 years of sediment accretion, several new crevasse splays, and the infilling of the Bocca Sud mouth, the marsh has not developed further. Probably, in this particular case, strong floods characterised by high sediment discharge are fundamental but not always sufficient, because other factors, such as subsidence or salinity, might also interfere with marsh establishment.

5.3.3 | Influence of the morphology of the lagoons

It is also important to consider both the lagoons' shape and sediment distribution. The Barbamarco Lagoon is much larger than the Burcio Lagoon and the restored section of the Basson-Canarin Lagoon. Because of this morphology and the limited connection to the river via a small channel, it is plausible that the intertidal flat of the Barbamarco Lagoon is slowly extending north-westwards without marsh establishment. Furthermore, this lagoon is highly influenced by boats crossing (i.e. wave-induced erosion) and the presence of harbours. On the other side, the Burcio Lagoon is basically an empty enclosed shallow basin, unexploited by man, that is directly connected to the river. This condition is highly convenient for any future marsh restoration.

5.3.4 | Influence of the breaches on marsh development

The most important aspect to note is that most of the factors discussed here (especially salinity and sediment deposition) are strongly dependent on the distance of the lagoon from the main branch and the breaches' sizes and forms. Hence, efficient river connection to the lagoons has a high impact on deposition and vegetation establishment. This interpretation is supported by the fact that the only areas that have developed marshes are connected directly to the river while all the other marsh areas mainly experienced loss. Pontee (2015), who investigated the Steart coastal management project (Bridgwater Bay, UK), noticed that the size of the breaches does not particularly influence the infilling process of the intertidal flat, whereas the location (and the number) of the breaches have a higher impact. However, the study of Pontee (2015) does not discuss how the breach location influences the sediment supply inside the system. It is important to consider that in the Po Delta the main sediment supplier is the river; thus, the sediment transport does not follow the same pattern that characterises tidally dominated systems (i.e. impulsive events of deposition because of floods, crevasse splay formation versus constant deposition in time owing to tidal inundation). Despite these statements, the breach location in river-dominated deltas may be even more influential, compared to tidally dominated deltas, because of the non-proportional distribution of water and sediment discharge between the river branches. The Po della Pila splits into three smaller branches (see Figure 1b); the central branch (Busa Dritta) is characterised by a total water discharge between 25% and 35%, whereas the Busa di Tramontana between 10 and 15% (Maicu et al., 2018). The sediment transport in the Busa di Tramontana may be lower compared to the Po della Pila branch, giving a possible explanation for the evidence of strong deposition and the high rates of marsh development in the Basson–Canarin Lagoon with respect to the other study areas.

5.4 | Local and global perspectives

5.4.1 | Sediment deposition versus subsidence and SLR

The process of marsh formation is complex and depends on the combination of a large number of factors, which include the SLR, the subsidence and the sediment accretion of the delta. The SLR is difficult to consider, because its rates are highly dependent on the considered interval of the historical record. Long time series of tidal records (1875–2017 from Trieste tide gauge) show that the SLR rate is about 0.13 cm/year, whereas the short time series (1992–2017) have higher rates of 0.38 cm/year (Da Lio & Tosi, 2019). The average rates of subsidence in the delta greatly decreased in time during the last century and are now around 0.6 cm/year (Cenni et al., 2021; Fabris et al., 2014). However, the areas around the tip of the delta can reach higher rates (e.g. around 1 cm/year in the area next to the power plant [Fiaschi et al., 2018]). The average rate of vertical changes of the Barbamarco Lagoon is about 1.3 cm/year. Because its tidal flat is not well connected compared to the other two lagoons and these values are quite high for a microtidal flat (e.g. Andersen et al., 2006; Hatton et al., 1983; Jankowski et al., 2017), it is presumable that the other marshes may experience similar rates of vertical changes, if not higher. The possible future evolution of the tidal flats depends on the rates that are observed.

Assuming that in the next 50 years the river will maintain the same sediment supply, taking into account the recent rates of subsidence around 1 cm/year and the short time series of SLR of about 0.38 cm/year constant in time (i.e. a total of 1.38 cm/year of RSLR), in the worst case scenario the system may decrease in elevation by 69 cm, but 65 cm may deposit in the same period; hence, the marshes would be located about 4 cm below in elevation compared to the present-day situation. Considering the best case scenario, hence rates of subsidence of about 0.6 cm/year and the long-time series of SLR of about 0.13 cm/year (i.e. total of 0.73 cm/year of RSLR), the system may decrease in elevation by 36.5 cm, which means that sediment deposition may allow an increase of the surface of 28.5 cm. Based on these two scenarios, it is more probable that the intertidal flats will not be submerged by the sea water (below m.s.l.), especially if efficient connections between the river and the lagoons will increase sediment deposition and marsh formation; however, it is important to take into account that these three factors will change in time; hence, a comparison between short-term and long-term rates of sedimentation is needed.

5.4.2 | Marsh recovery: global versus local

It is widely demonstrated that during this last century the Po River Delta experienced a period of strong erosion until the 1970s and 1980s. However, our study shows that not only destructive processes were ongoing during these years. Although subsidence was extremely high before 1977 (i.e. from 25 to 3.8 cm/year) and strong marsh erosion occurred in most portions of the delta (overall loss >200 ha), strong sediment deposition because of river floods allowed extended marshes to develop inside previously reclaimed areas (overall > 100 ha). This process highlights how local-scale factors, such as the position of levee breaching and local strong deposition, have a high influence on the evolution of salt marshes. These types of factors are usually not considered in global-scale predictions, which suggest that marshes cannot keep pace with SLR (Crosby et al., 2016; Nardin & Edmonds, 2014; Spencer et al., 2016). Instead, local-scale evaluations give opposite outcomes (Kirwan et al., 2016); in fact, it was demonstrated that high rates of subsidence can be outpaced by high sediment loads (Schuerch et al., 2018). For example, the marsh development on a crevasse splay was described in the river-dominated delta of the Mississippi River (Louisiana, USA), where freshwater floods enhanced the stability of floating marshes (i.e. developed on a crevasse splay) by reducing overall salt stress (Paola et al., 2011; Sasser et al., 2007) and allowing the marsh to compensate subsidence (Cahoon et al., 2011). The importance of the local context is also shown in this study, because certain portions of the lagoons within the same delta system evolved differently, reaching opposite outcomes (i.e. marsh loss or growth) depending on the morphology of the depositional areas inside the lagoons, their distance from the main branch, the size of the breach and the channel connecting them to the river, the salinity fluctuations, and the sediment discharge.

Both cases of the Burcio and the Basson–Canarin Lagoons demonstrate how marsh species can quickly colonise large intertidal flats (i.e. about 40–50 ha in less than 10 years after the breach for Basson–Canarin and ∼20 ha in less than 2–3 years for Burcio). Other study cases experienced marsh growth during similar time horizons, such as in the managed realignment in Tollesbury and the Orplands (Blackwater Estuary, UK), where ∼20 ha was covered by pioneer plants in 6 years (Garbutt et al., 2006), and ∼45 ha was colonised in 8 years (Spencer et al., 2008), respectively. However, in other studies, the marsh growth was slower or did not occur at all. In the restoration project of Perkpolder (Scheldt Estuary, The Netherlands), none of the 75 ha were colonised by pioneer plants even several years after the breach (i.e. from 2015 to nowadays); this outcome might be related to low elevation lying well below the MHT and poorly consolidated mud conditions (see Brunetta et al., 2019; Cao et al., 2021). In certain cases, crevasse splay formation and marsh development can reach even higher rates of growth, such as for the Brant Pass Splay in the Mississippi Delta, where hundreds of hectares (>500 ha) were covered by marsh plants in less than 10 years (Cahoon et al., 2011). Overall, we believe that if the conditions are favourable, marsh plants can rapidly cover extended portions of intertidal flats.

5.4.3 | Managed and unmanaged realignment

Overall, although managed realignment is a measure determined by human choices, a natural restoration can take place without human intervention. The orthophotos show how the different phases of tidal flat and marsh evolution in the Po Delta are highly similar to the steps followed by recent restoration projects, typically dykes breaching, submersion of the land and vegetation establishment. The lesson is twofold: (i) from one side, it suggests that, based on the environmental context and human necessities, a natural breach might be exploited for restoration rather than trying to 'repair' the damage; therefore, following a real 'unmanaged realignment'; (ii) the second lesson is that in specific cases, such as in river-dominated deltas, a breach may allow the restoration of a wetland ecosystem. Therefore, a minimum intervention (i.e. breach only) can be highly efficient for restoration purposes, although it is not always a sufficient condition, as demonstrated in the previous paragraphs. An example of 'unmanaged realignment' that was not exploited can be considered the case of Halfway River in Nova Scotia (CA) (Bowron et al., 2018). This river flows inside the Minas Basin of the Bay of Fundy, an ultratidal environment with a tidal range of about >10 m. The tidal effects were mitigated by a levee that limited the salt water to affect the river system. However, in 2017, the embankment failed and the connection with the basin resulted in the re-establishment of a natural hydrological regime, without any constraint on the water flows. The connection led to the development of a salt marsh and a tidal wetland habitat throughout the now tidally influenced segment of the river. However, the levee was soon re-built in the following years, and the restoration of the previous constrained hydrology caused the marsh dye off.

Levee breaching and the development of a transitional ecosystem were perceived by the locals as a defacement of the previous environment; therefore, the embankment was fixed. This example shows how human perception of environmental changes can limit the natural evolution of certain ecosystems.

5.4.4 | Managed realignment for the Po River Delta

The process of embankment failure and the formation of new intertidal areas were experienced by other deltas as well. For example, in 2009, the Ganges–Brahmaputra delta was hit by Cyclone Aila that caused the failure of several embankments (Auerbach et al., 2015). The new tidally inundated areas experienced high deposition before the dykes were repaired. Thus, Auerbach et al. (2015) agreed on the fact that controlled embankment breaches can support elevation recovery. This managed realignment through crevasse splay should be exploited in the Po Delta to recover and restore portions of lagoons that were abandoned by man and have no economic value, such as the Burcio Lagoon. New breaches that connect the Po della Pila directly to other sections of the lagoon will lead to strong sedimentation and marsh establishment. It is important to consider where new intertidal flats can turn into marsh as well; in fact, if other factors interfere with vegetation (i.e. salinity, nutrients, etc.), the transition may not occur, such as for the case of the Barbamarco Lagoon. As previously mentioned, human necessities alter the perception of the processes as well; in fact, it is interesting to note how the conception of the lagoon has changed over the course of the century. Boats could not move freely before the area became a lagoon, but now the waters are highly exploited by fishermen and local people (i.e. mussel farming); in fact, the strong sediment deposition of the Barbamarco Lagoon is considered a problem because the infilling of the channels and the mouth do not allow boats to navigate across the lagoon. Furthermore, new breaches can change water circulation, which means variations in salinity and sediment transport as well. They will change the sediment budget distribution between the lagoons and areas outside the delta system, which could mean higher sediment deposition inside the lagoon and lower sediment export. Therefore, these aspects need to be investigated through appropriate tools (e.g. numerical models validated with on-field monitoring) to build up realistic scenarios of marsh evolution that will support the design of the proposed realignment to maximise ecological co-benefits and cost-effectiveness of these possible projects.

It is interesting to note that in the case of the Po Delta, a standard managed realignment procedure based on the creation of an artificial tidal flat through field expropriation and excavation of channels might not be a suitable option for this environment because of the main processes that control the deltaic system (e.g. high riverine sediment supply and low tidal influence). Therefore, it is difficult to compare the Po Delta with the northern European restoration projects (e.g. Brunetta et al., 2019; Friess et al., 2012; Garbutt et al., 2006; Vandenbruwaene et al., 2012); in these sites, the morphology and the sediment deposition are mainly controlled by tidal influence. In the case of the Po Delta, the river is the main sediment supplier and vegetation presence depends on the salinity distribution; thus, a new intertidal area cannot be located far from the river branches; otherwise, sediment deposition will be highly reduced and the water quality may not be suitable for the marsh to establish. Furthermore, most of the land has been submerged and is following a natural evolution; the recent configuration does not allow the construction of artificial structures to enhance sedimentation, which are unnecessary if the crevasse splay method is followed as a means of sediment input to the flat. It is important to consider also that artificial structures may cause unnatural behaviours during the first years of development, such as in the case of the Kleine Noordwaard (van der Deijl et al., 2018; Verschelling et al., 2017) or the Perkpolder restoration projects (Brunetta et al., 2019), where inlets experienced erosion and sedimentation was concentrated inside or next to the channels in order to find a morphological equilibrium. In any case, these types of projects are mostly used for tidal-dominated environments; hence, a different approach must be taken for microtidal deltas such as the one of the Po River. By contrast, the current study is highly similar to the case of the Brant Pass Splay (Mississippi, USA). Cahoon et al. (2011) showed that marsh growth on a crevasse splay is rapid (i.e. around a decade) but tends to slow down in time, because the rates of accretion reduce as elevation increases, and also depends on the size of the crevasse and the distance from the breach. It is worth noticing that as the crevasse expands, the mid to the outer reach of the splay will experience lower rates of accretion, which can be outpaced by subsidence. Hence, the growth of the ecosystem crevasse-marsh, as it becomes larger and larger, will depend on the health and the stability of the marsh that developed on it (Cahoon et al., 2011).

Overall, this study shows how the crevasse splay approach can be extremely efficient in river-dominated deltas but, at the same time, not always sufficient. In fact, several other factors (i.e. salinity and sediment transport) alter the vegetation establishment; hence, high attention must be given to the opening of new connections, in particular in river-dominated deltas rather than in tidal-dominated deltas.

6 | CONCLUSIONS

This paper focusses on the marsh evolution of the northern-eastern lagoons of the Po River Delta (Italy) that developed after an unmanaged levee breaching between the 1950s and the present day. The combination of flood events, coastal storms, high subsidence and low sediment supply from the river caused the submersion of most of the agricultural fields, the loss of extended marsh areas between the 1950s and 1970s (overall >200 ha), and a strong coastal retreat. A historical review highlighted that the natural levee breaching that occurred in Basson–Canarin Lagoon (1955–1969) and the Burcio Lagoon (1992–1996) allowed the formation of extended marsh systems (>100 ha), composed of *P. australis*. The breach inside the Barbamarco Lagoon (2003–2008) formed an intertidal flat that is building-up without being colonised by marsh vegetation.

Based on the results of this study, an unmanaged realignment can take place without human intervention, although managed realignment is usually a measure determined by human choices. Depending on the environmental context and human necessities, a natural breach can be exploited for restoration rather than fixing the levee; therefore, following a real 'unmanaged realignment'. The crevasse splay approach can be extremely efficient in river-dominated deltas but, at the same time, not always sufficient. In fact, local-scale factors (i.e. position of the levee breaching, local strong deposition and the size of the breaches) may lead to different outcomes (i.e. intertidal flat only or marsh growth) within the same system. These factors are highly influential on marsh development, although they are usually not considered in global-scale predictions, which recently suggest that marshes cannot keep pace with SLR. Furthermore, the breach location in river-dominated deltas may play an even more important role, compared to tidal-dominated deltas, because of the non-proportioned distribution of water and sediment discharge between the river branches.

Although subsidence was extremely high and marsh loss occurred in most portions of the delta, the unmanaged breach and the strong sediment deposition because of river floods allowed extended marshes to develop inside previously reclaimed areas, highlighting that high rates of subsidence can be outpaced by high sediment loads, at least locally. Furthermore, marsh growth can be achieved rapidly (i.e. few years) if the conditions are conducive but can take longer if the conditions do not meet plant requirements. The study also shows how aerial photography is the key for identifying the evolution of the Po Delta marshes during the last century, highlighting how managed flooding can be exploited to restore abandoned portions of the delta lagoons and marsh dynamics.

Future studies should investigate the recently vegetated tidal flats (e.g. Burcio Lagoon) from a morphological and biological point of view to verify the feasibility of a restoration project to recover the unused section of the Po Delta and increase low marsh cover. It is important to emphasise that such an analysis should take into consideration the possibility of opening new breaches, or closing channels, because these actions can influence sediment transport inside and outside the delta.

AUTHOR CONTRIBUTIONS

Riccardo Brunetta: Conceptualisation, Data curation, Formal analysis, Investigation, Methodology, Writing. **Paolo Ciavola**: Funding acquisition, Supervision, Writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors declare that no financial interests or personal relationships influenced the research reported in this paper.

DATA AVAILABILITY STATEMENT

The orthophotos related to this paper can be requested to the IGM (Istituto Geografico Militare), the Veneto region, and Google Earth Pro. The information regarding the rates of accretion and the morphology of tidal flat of the Barbamarco Lagoon are published at DOI:10.3390/rs13122322. The datasets regarding the river sediment discharge can be found at DOI: 10.1038/s41598-018-21928-3, and the water discharge at DOI: 10.1016/j.margeo.2005.06.039. The other datasets can be requested directly to the authors.

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