Secular diachronic analysis of coastal marshes and lagoons evolution: study case of the Po river delta (Italy)

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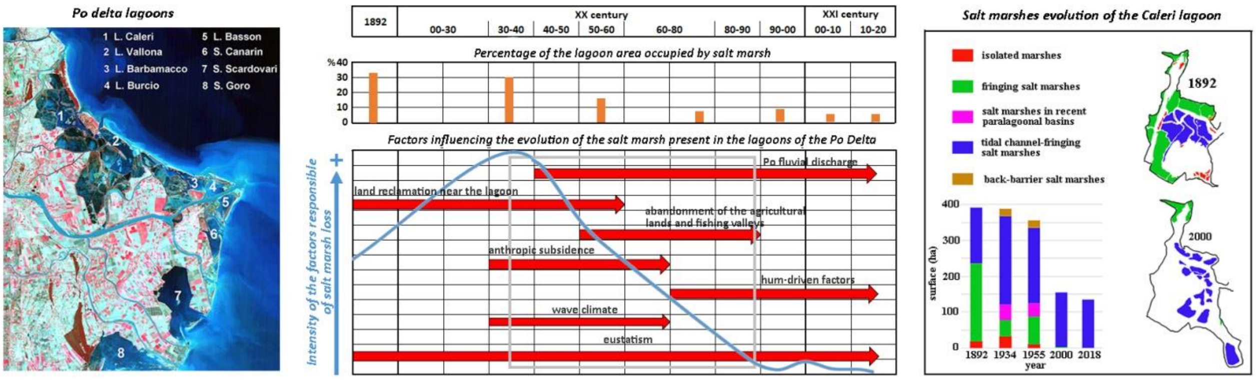
HIGHLIGHTS

Assessing historical salt marshes and lagoon morphological evolution.
Results point towards a net loss of salt marsh during 1892–2018.
Saltmarshes represent about 3% of the lagoon area in 2018
Relative sea level rise lead to salt marshes losses
Human interventions are essential factors in controlling salt marshes evolution.

GRAPHICAL ABSTRACT



ABSTRACT

Coastal lagoons and salt marshes are rapidly changing under the influence of sea level rise and human induced changes. Within this context, the proposed study describes the evolution of the lagoons of the Po Delta (Italy) and the historical transformations of the salt marshes using historical maps and aerial data from 1892 to 2018. The methodology applied provides a crucial quantification of coastal lagoon and salt marsh evolution.

Image analysis shows that most of the lagoons were formed between 1892 and 1934, while the most recent are developed between 1978 and 1988. Lagoons reached their actual shape and dimensions by 1955. Lagoons present different morphological characteristics with the lagoon of Caleri having a higher morphological diversity due to the presence of salt marshes and a complex hydraulic network. Since 1988, fringing salt marshes were the dominant morphology, then marsh morphology switched to a fringing, isolated and channelized morphology.

Over the last 120 years, the Po Delta lagoons have experienced a high rate of erosion and environmental degradation. Our analysis suggests that three main phases are present in coastal lagoon marsh evolution that explain the development. In the last years, those lagoons experienced a progressive reduction of fringing and isolated salt marshes. The first one (1892-1934), characterized by high fluvial sediment input and a fast seaward progression of the river mouths, corresponds to the maximum salt marsh development. The second phase (1934-1978), characterized by a negative sediment budget and human activity induced alterations (subsidence), presents a small increase of the lagoon extension associated with a reduction of the salt marsh. Finally, the third phase (after 1978), characterized by a low sedimentary budget and high human control, is characterized by a stabilization of the lagoon extension and a drastic reduction of the salt marshes.

KEYWORDS

Salt marshes, lagoon evolution, cartographic documents, aerial photography, coastal morphodynamics, natural and anthropic impacts.

I- INTRODUCTION

Coastal lagoons occupy 13% of the coastal areas and are characterized by a water surface area ranging from less than 1 ha up to 10,000 km^2 (Barnes, 1980; Kjerfve, 1994). These tidal systems are formed by channel networks, mudflats and marsh platforms. They are important ecosystems with essential eco-systemic services that provide natural and economical resources (Borja et al.,2015; Kirwan et al., 2016; Rendón, 2019) and tidal system evolution are affected by both natural and anthropogenic factors (Mee, 1978; Sikora and Kjefie, 1985, Rendón, 2019). Nicholls et al. (1999) suggested that the expected sea level rise could cause 22% loss of the world's wetlands in 2080, but may reach 40% for the period 1990-2080 if they are added to those related to human activities (Michener et al., 1997; Fagherazzi et al., 2020). According to different studies, Mediterranean present coastal lagoons will suffer the effects of climate changes, especially in the Italian regions risking to totally disappear in 2050 (Muscio, 2004; Cataudella et al., 2015).

Salt marshes are integrated features in lagoon systems, which are silt and clay sedimentary deposits stabilized by halophytic vegetation (Boorman, 1995). They achieve important hydrodynamic functions attenuating tidal currents, improving water quality and ecosystem services enhancing coastal habitat and fisheries. Furthermore, the networks of tidal channels, which develop close to the salt marshes, constitute preferential routes for the water transport during the flood and ebb phases and for the exchange of sediments and nutrients between the sea and the intertidal area (Fagherazzi et al., 2012; Hughes, 2012; Fleri et al., 2019).

Coastal lagoons develop between the low and high tide levels, in areas characterized by a sufficient sediment supply (Chapman, 1960; Kirwan et al., 2016) associated with low tidal currents or in areas protected from the wave action (Allen, 2000). Their evolution, which usually begins with a gradual salt marsh emergence (Pethick, 1984), is characterized by natural cycles of erosion and growth lasting tens to hundreds of years (Pethick, 1984; French and Stoddart, 1992; Fagherazzi and Furbish, 2001; D'Alpaos et al., 2006: Zhang et al., 2020).

Salt marshes evolution is influenced by natural (weather-marine climate, currents, sediment dynamic, sea-level change, tidal processes, storm frequency and displacement of the main channels) and anthropogenic factors (coastal squeeze, grazing, ship and boat wakes, dredging activities, pollution, eutrophication, refuse disposal and trampling) (Boorman, 2003). Salt marshes under the effects of natural or anthropogenic pressures may alter marsh spatial distribution (Best et al., 2007: Borchert et al., 2018). The fragmentation of salt marshes into patches due to wave’s energy and/or tidal currents can occur through various phases such as marsh platform perforation, dissection, fragmentation and attrition as described by Baily and Pearson (2007). However, the colonization of the salt marsh by the vegetation favours the sedimentation and counteracts erosion (Nardin et al., 2016; Nardin and Edmonds, 2014). Furthermore, the deposition of fine sediments allows the formation of “mudflats and shallow systems'' located below the mean sea level (Allen & Duffy, 1998).

Recently, it has been recognized that anthropogenic pressure and accelerated Sea Level Rise (SLR) could lead to a loss of 20-90% of all the present global wetlands by 2080 (Nicholls, 2004; French, 2006, Schuerch et al., 2018). Besides, since the development of salt marsh depends on the relationship between the capacity of the basin and sediment availability (Nichols, 1989) while considering that the deltaic sediment supply is decreasing worldwide (Syvitski et al., 2005), a progressive loss of salt marsh in deltaic lagoons is expected in the near future (Oertel and Woo, 1994). Here, we focus our investigation on the Po river delta lagoons system where salt marsh changes have been tracked through historical images. We explored a remote sensing methodology to assess natural and human-driven morphological changes from which coastal processes are conjectured . The goal of our study is to identify and quantify the impact of different features in deltaic lagoons which can lead to a different marsh system.

II- METHODS AND MATERIALS

II-1 STUDY AREA: THE LAGOON’S SYSTEM OF THE PO DELTA

The Po river delta, northern Adriatic Sea, hosts the largest Italian lagoon system and covers about 400 km^2 (Figure 1a). The Po delta has a triangular shape. It extends from the shoreline to 30 km offshore and is divided by a series of semi-enclosed water bodies. Most of the lagoons, separated from the sea by barrier islands parallel to the shore or sandy spits, are generally classified as “bar-built estuaries” (Pethick, 1984) with a salinity gradient near the inlet similar to the estuary. They are also considered as “typical lagoons” (Barnes, 1995) or, according to the Kjerfve (1986), as “restricted lagoons” because they have a well-defined tidal circulation and are usually oriented shore-parallel.

The configuration of the modern Po Delta is relatively recent and dates to the development of a new delta lobe from the 17th century until 1950s due to river hydraulic management (Bondesan and Simeoni, 1983; Simeoni and Corbau, 2009; Simeoni et al., 2007). According to Nelson (1970), the vast progradation of the Po Delta during the last 400 years was generated by the redistribution of the Po River discharge to a small area, transforming the Delta from a cuspate to a lobate, supply-dominated, morphology.

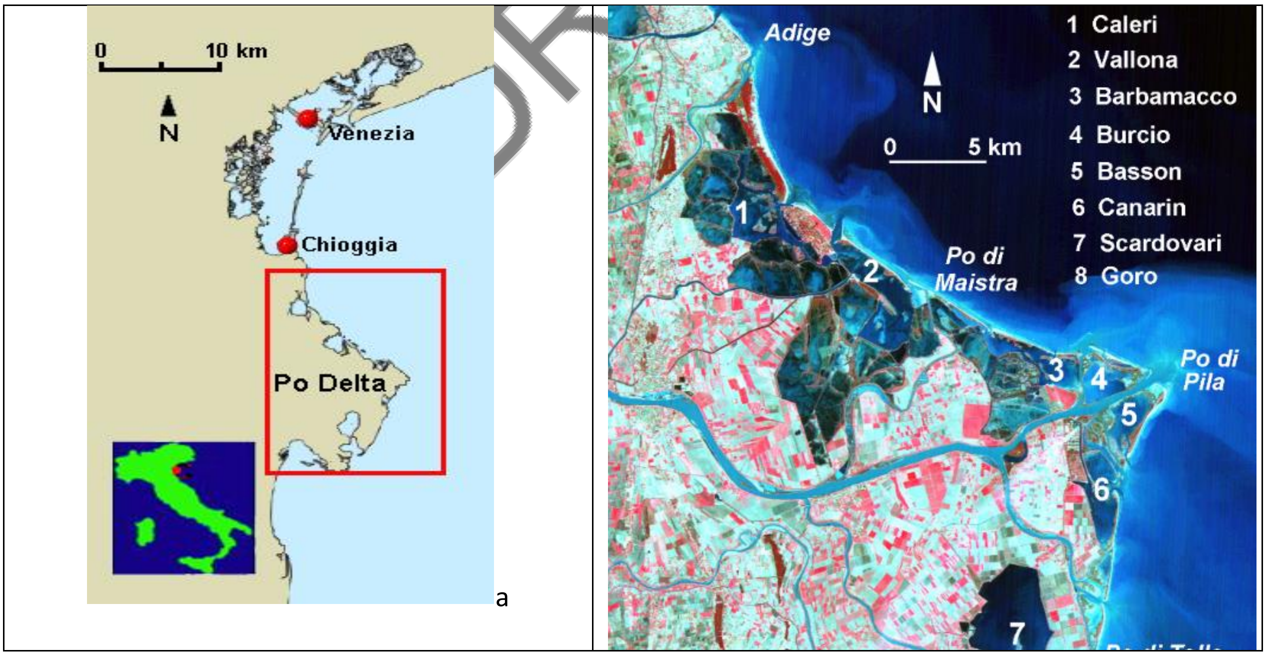
In the present delta configuration, the main watercourse of the Po river is divided into 5 delta branches (Po di Maistra, Po di Pila, Po di Tolle, Po di Gnocca and Po di Goro) (Figure 1). Artificial banks have been built along the landward edges of lagoons and wetlands to protect reclaimed lowlands from tidal flows and flooding. The Po delta area is characterized by about 20,000 ha of standing water, with 51% of lagoons and the remaining 49% consists of portions of lagoons for aquaculture (43%) and wetlands (6%). The main lagoons are eight (Figure 1): four of them are located in the northern part of the Delta (Lagoons of Caleri, Vallona, Barbamarco and Burcio) and four in the southern portion of the delta (Lagoons of Basson, Canarin, Scardovari and di Goro). The lagoons are generally very shallow with water depth ranging from 0.6 to 2 m, while the channels are deeper ranging to a minimum of 3 m in the lagoons of Barbamarco, Bason and Canarin to a maximum of 12 m in the lagoon of Caleri. It should be noted that dredging activities of the channels are performed regularly (40.000 m^2/yr to maintain an efficient inlet) to allow efficient ricreative and economical activities related to shellfish farming (Verza and Cattozzo, 2015).

The Caleri lagoon is situated in the northern part of the Po delta area and its evolution was determined by the derivation of the northern branches of the Po and by the abandonment of the Po di Tramontana (Ruol et al., 2016). Since the modern delta develops in its southern lobe (Ruol et al., 2016), the conformation of the Caleri lagoon is, therefore, older than the other lagoons. It receives freshwater mainly from a pumping station and secondarily from the Po di Levante (Maicu et al., 2018). The Vallona lagoon is situated southward to the Caleri lagoon and its evolution has been determined by the formation of a spit at the left side of the Po di Maistra river and its progressive lengthening northward. After the 1950s, a second inlet developed in the eastern part of the lagoon associated with the development of an island barrier. It receives freshwater from a pumping station and is connected to the Po di Maistra (Maicu et al., 2018).

The formations of the lagoons of Barbamarco, Burcio, Basson and Canarin are related to the seaward extension of the delta of about 800 m since the beginning of the 20th century. The Barbamarco lagoon has a triangular shape with two inlets. It is supplied by freshwater from the Po di Maistra and Busa di Tramontana (Maicu et al., 2018). Both the Burcio and the Basson lagoons are connected with river branches by small channels and with the sea through the inlet, with the inlet of Basson lagoon being protected by a jetty. The Canarin lagoon is connected to the sea with a shallow mouth and freshwater comes from the Po di Tolle (Maicu et al., 2018).

The lagoon of the Scardovari developed in the beginning of the 19th century due to the seaward progression of the Po di Tolle, Gnocca and Goro branches. The rapid development has allowed the formation of the second basin linked to the Scardovari lagoon at the beginning of the 20th century, and its actual configuration is related to the union of the two lagoons before the 1950s (Vatova and Faganelli, 1951). The inner part of the lagoon is characterized by a strong deepening due to subsidence (Mattichio, 2009), while a channel connecting the lagoon to the Po di Gnocca and two pumping stations provide freshwater into the lagoon.

The lagoon of Goro was created in the last 1800s with the formation and development of the Goro spit (Simeoni et al., 2007). It has approximately a triangular shape, with a maximum length of 11 km and a maximum width of 5 km. It is connected to the sea by two inlets. Freshwater inputs are mainly from the Po di Volano and Po di Goro, at least until 1994 when the Po di Goro discharge was considerably reduced due to human regulations (Bencivelli, 1998).



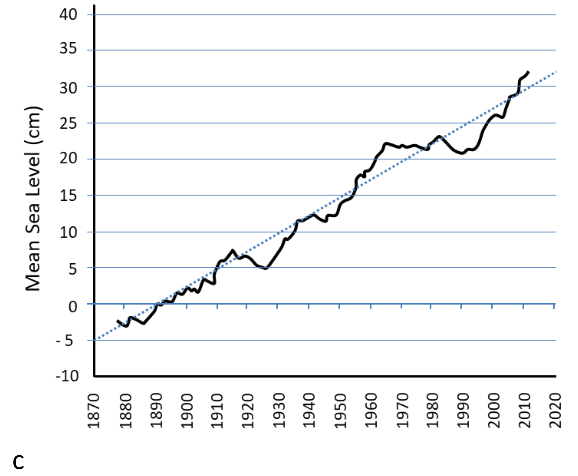


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Figure 1: Study area a) the Po delta with b) the lagoons and fluvial inlets, c) mean sea level rise at Venezia **(**Baldin and Crosato, 2017)

II-2 HYDRODYNAMIC CONDITIONS-COASTAL PROCESSES ALONG THE PO RIVER DELTA

The hydrodynamics of the Po delta area is influenced by currents, winds, tides and by river freshwater input. The tides are semi-diurnal. The tidal regime is microtidal with a range of 0.6 m on average and a maximum value of 1 m..

The climate conditions are characterized by moderate rain precipitation (inferior to 600 mm/y) and occasional snow precipitation. However, Maicu et al. (2018) observed that the average of the last 25 years is about 730 mm/year. The same authors, analyzing the wind conditions from 2009 to 2016, reported that in the northern part of the delta (Caleri, Vallon and Barbamarco lagoons), the prevailing winds were from NE and secondarily from W. In the southern part (Goro and Scardovari lagoons) the prevailing winds were from SE and secondarily from NE. In the central part of the Delta, the winds are principally from NE and from W and SE.

The Po Delta is characterized by one of the highest relative sea level increases (Kent et al., 2002; Lambeck et al., 2004; Antonioli et al., 2009). The eustatic trend of the Upper Adriatic from 1896 to 1993 was 1.13 mm/yr - (Co.Ri.La., 1999). The annual average values highlight a sea level rising trend (Figure 1c) over the last 145 years (Baldin and Crosato, 2017). The authors report that the sea level rise is not always constant and uniform over time. Indeed, there are 3 phases characterized by relative stability, or even countertrend (decrease of the sea level) around 1915 and 1925, 1935 and 1945, and 1965 and 1995. The authors suggest that these phases are mostly due particular meteorological cycles related to inter-decadal atmospheric variations, in particular the North Atlantic Oscillation and the Mediterranean Oscillation.

However, some phases are characterized by a high sea level rise due to subsidence phenomena, in particular between the 1930s and 1960s, also observed in the Po delta. Indeed, during the last century, the delta area was affected by high rates of subsidence due to both natural and anthropic factors. The long-term natural subsidence has been estimated to be 2.00 mm/yr (Carminati and Di Donato, 1999) while the anthropogenic subsidence reached 250mm/yr in the central sector of the delta from 1951 to 1957, and 180 mm/yr between 1958 and 1962 (Caputo et al., 1970; Borgia et al., 1982). Furthermore, the lagoons were affected by different subsidence rates as observed in Table 1: the lagoons of Burcio, Basson and Canarin presenting higher values of subsidence between 1950-1957 and 1957-1967, while from 1967 to 2017 the lagoon of Scardovari and secondly the Goro lagoon presented the highest values of subsidence. It seems that the subsidence moved from north to south from 1957 to 2015. Consequently, the loss of elevation, between 1900 and 2015 was impressive, with an average value of more than 1.5 m, and reaching more than 3 m in the inner part of the delta m (Corbau et al., 2019a). Today the subsidence, although reduced, is still ongoing (Baldi et al. 2009; Bock et al. 2012; Cenni et al. 2013; Fabris, Achilli, and Menin 2014), and most of the study area, lying below the sea level, is prone to fluvial floods.

The variation of the fluvial discharge of the Po river system is well documented (Ciabatti, 1967; Bondesan, 1990a; Simeoni *et al.*, 2000a, b, c; Coreggiani *et al.*, 2005; Simeoni *et al.*, 2007; Simeoni e Corbau, 2009). During the 20th century, the fluvial discharge has reduced from 12.8 Mt/year (1918-1943) to 4.7 Mt/yr (1986-1991) (Simeoni and Bondesan, 1997). The fluvial discharge for the different branches of the Po river is distributed between Goro (8% fluid and 8% solid flow), Gnocca (16%, 11%), Tolle (12%, 7%), Pila (61%, 74%), and Maistra (3%, 1%) (Nelson, 1970; Correggiani *et al*., 2005). It must also be noted that the sediment input to the coastal environments has almost completely stopped over the last 50 years, because of massive anthropogenic alteration of rivers, such as dam construction, soil protection and massive legal and illegal riverbed quarrying (Cencini, 1998; Simeoni and Bondesan, 1997).

Table 1: Values of the subsidence, expressed in mm/yr, for the different lagoons estimated from Corbau et al. (2019a)

	Years				
Lagoon	**1900-1950**	**1950-1957**	**1957-1967**	**1967-1974**	**2000-2015**
L. Caleri	-2,2 - -2,3	-20 - -40	-30 - -45	<16	-3 - -5
L. Vallona	-2,3 - -2,4	-40 - -60	-45 - -55	<16	-5 - -6
L. Barbamarco	-2,3 - -2,4	-40 - -100	-55 - -60	<16	-5 - -10
L. Burcio	-2,2 - -2,3	--100	-60 - -65	<16	-10 - -12
L. Basson	-2,2 - -2,3	-100	-60 – 65	<16	-10 - -12
L. Canarin	-2,3 - -2,4	-80 - -100	-60	-16 - -24	-10 - -12
L. Scardovari	-2,5	-60 - -20	65 - -40	-28 - -40	>-12
L. Goro	-2,5 - -2,6	-40 - -20	-50 – 40	-18 - -28	-12 - 14

Furthermore, the relation between the tidal prism and the area of mouth section (Figure 2) shows that the lagoon of Vallona has the major tidal prism with the better hydraulic efficiency, while the lagoon of Basson has the minor hydraulic efficiency.

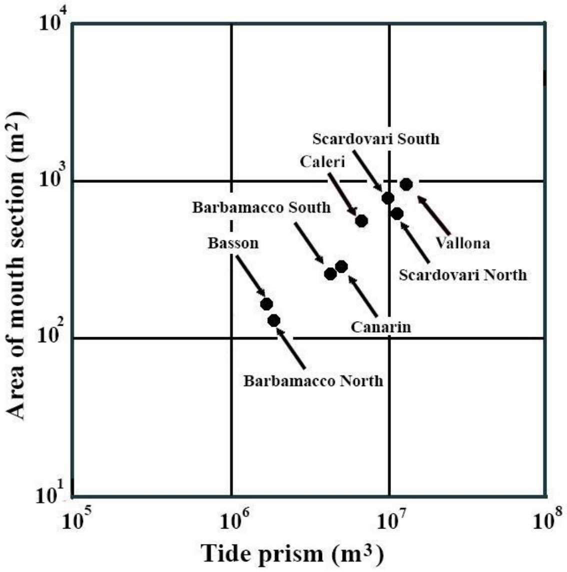


Figure 2: Relation between the tidal prism and the area of mouth section of the Delta Po lagoons; (modified from Ruol et al., 2016).

III - MATERIALS AND METHODS

The analysis performed in this study is based on historical maps, aerial and satellite images and lidar data, projected in the ERTF89-2000, UTM 33N reference system (Table 2). Historical maps have been georeferenced by converting the coordinates reported in the grid, while the aerial orthophotos were already georeferenced.
The analysis of the different images may be affected by intrinsic errors of georeferencing (Dolan et al., 1980); in particular, the accuracy of the 1892 and 1934 maps is smaller due to the survey method used in the pre-satellite age. Furthermore, it has not been possible to correct the tidal influence because the times of the photograph relative to the tide were unavailable.

Table 2: Characteristics of the image data set used to analyze the evolution of the Delta Po lagoons.

Type	**Owner**	**Years**
Maps	Italian military geographical institute	1892 1934 *Scale 1:25.000*
Aerial orthophotos	Italian National Geoportal	1955 1973 1988 1994 2000 2006 2012 *Resolution 1:10000*
Satellite	Bing satellite	2015
Lidar Orthophotos	Veneto Region ** Only for the Caleri Lagoon*	2006* *pixel 1m* 2009* *pixel 0.5m* 2018 *pixel 0.2m*

Historically, salt marshes (NCEDS, 2003; Van der Wal *et al*., 2002; Castillo et al., 2002; Boyes, 2005) were analyzed using different indexes like percentage of salt marsh's cover, erosion/accretion of the marsh surface, but, as reported by Best et al. (2007), the determination of a baseline to define their extension and variation is difficult. In this study, the salt marshes' extensions were drawn by associating the high salt marshes, submerged only during the high sizial tides, with the low ones (Adnitt et al., 2007), flooded at each tidal cycle. In addition, the salt marshes have been identified by interpreting morphological evidences according to colour, contrast and texture evidence. The mapping operations were performed by two experts working at a scale 1:2,000. Furthermore, the two main dimensions of the lagoon (shore parallel and shore normal) and the lagoon's inlet, which drive to the classification proposed by Kjerfve (1994), were measured on each photo set.
It should be noted that the salt marshes were already drawn in the 1892 and 1934 maps. However, the subjectivity of the operator being inevitable in fuzzy boundary detection (Boak and Turner, 2005), the delimitation of the single salt marsh was uncertain, difficult, and problematic especially due to different salt marsh's reconstruction interventions. The reliability of the mapping operations has been validated by comparing the results of the photo interpretations with the available lidar data (2006, 2009, 2018) and in-situ observations.
Previous works explored classifications of salt marshes (Dijkema, 1987; Dijkema et al., 1984; Pye & French, 1993; Oertel and Woo, 1994; JNCC, 2004) in different ways, but, in our study, the mapping and classification of the salt marshes have been based on the geographical position and its implications on the lagoon system(Oertel and Woo, 1994; Fontolan et al., 2012). According to the location of the saltmarshes inside the lagoon, we define five classes of salt marshes, which are (1) isolated marshes; (2) fringing salt marshes; 3) salt marshes in recent paralagoonal basins (); 4) tidal channel-fringing salt marshes (); 5) back-barrier salt marshes.

(1) The isolated salt marshes can be easily identified because they generally develop as islands and patches, consequently they are clearly separated from other lagoon morphologies.

(2) The fringing salt marshes are generally located at the edge of the lagoon, and can be found on the back or bay sides of barrier islands. These wetlands may occur in small strips or may cover vast area

(3) The salt marshes in recent paralagoonal basins are relatively new and, as indicated by Fontolan et al. (2021), are found between the old barrier islands, partially embanked, and the new ones.

(4) Fontolan et al. (2012) defined the tidal channel-fringing salt marshes as marshes found along the edges of the channel networks, and in particular in the central part of the lagoon and develop on creek banks.

(5) According to Oertel and Woo (1994) the back-barrier salt marshes are found in the lee of spits or barrier islands.

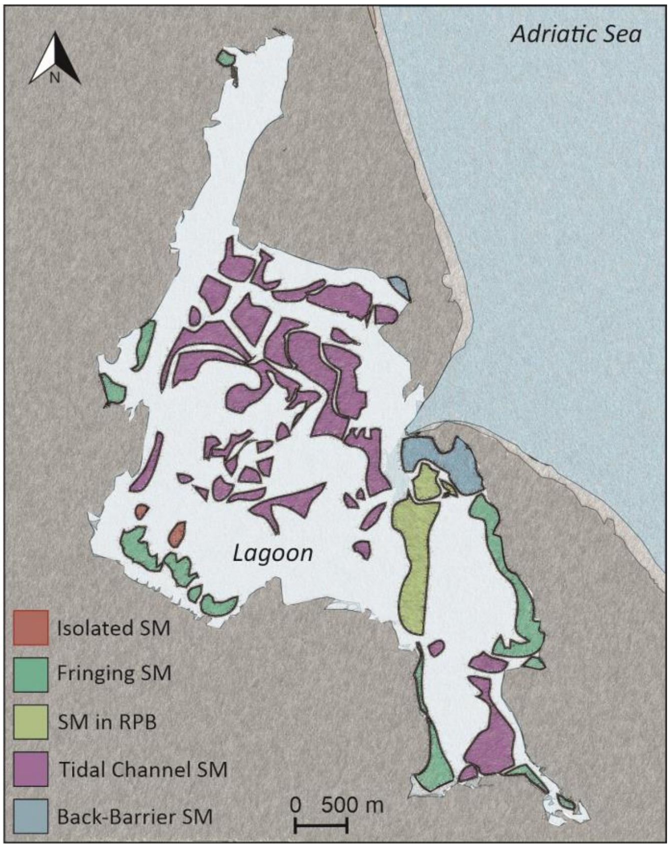


Figure 3: Sketch of the different salt marshes identified in the lagoons of the Po Delta. Please note that the sketch was based on the Caleri lagoon morphologies.

IV- RESULTS

IV-1 Lagoons and salt marshes characteristics

The main characteristics of the lagoons are reported in Table 3 and Table 4. The results indicate that the lagoons of Caleri, Vallona, Scardovari and Goro were already present in 1892 map, while Barbamarco and Canarin were first observed in 1934, the lagoon of Basson developed after 1934 and Burcio after 1978.
The lagoons are mainly oriented NS or NNW – SSE except Scardovari (NNE-SSW) and Goro (E-W) lagoons. They generally present one or two entrances-. The dimensions of the entrances are generally less than 10% of the shore parallel dimension besides the Scardovari and Goro lagoons (from 20 to 40%). They are mainly classified as restricted according to the classification of Kjerfve (1994); however, Vallona lagoon is defined as choked with a long narrow entrance channel (Table 3).
The dimensions of the lagoons range from a minimum of 110 ha to a maximum of 3,830 ha (Table 4) : Burcio and Basson (central part) are the smallest ones, while Goro and Scardovari, southward, are the

largest ones (Figure 1a). The dimensions of the lagoons were variable until 1988/1994.. However, it should be noted that the Scardovari lagoon increased until 1932 and then decreased in successive periods.
The shore-parallel length of the lagoons ranges from a minimum of 2,200 m (Basson) to a maximum of 10,400 m (Goro), while their width ranges from a minimum of 300 m (Vallona, Barbamarco) to a maximum of 7,700 m (Scardovari). In addition, while most of the lagoons are characterized by an alongshore dimension greater than its shore-normal dimension, the lagoon of Scardovari is characterized by a major shore normal dimension. The rate between the length and the width ranges between 2 (Caleri, Vallona, Basson and Goro) and 4.8 (Scardovari) except for Scardovari, which is characterized by a rate less than 1. Finally, it should be noted that just Burcio lagoon has not been stabilized while interventions have been performed on the other lagoons (nourishment, jetty at the lagoon inlets).

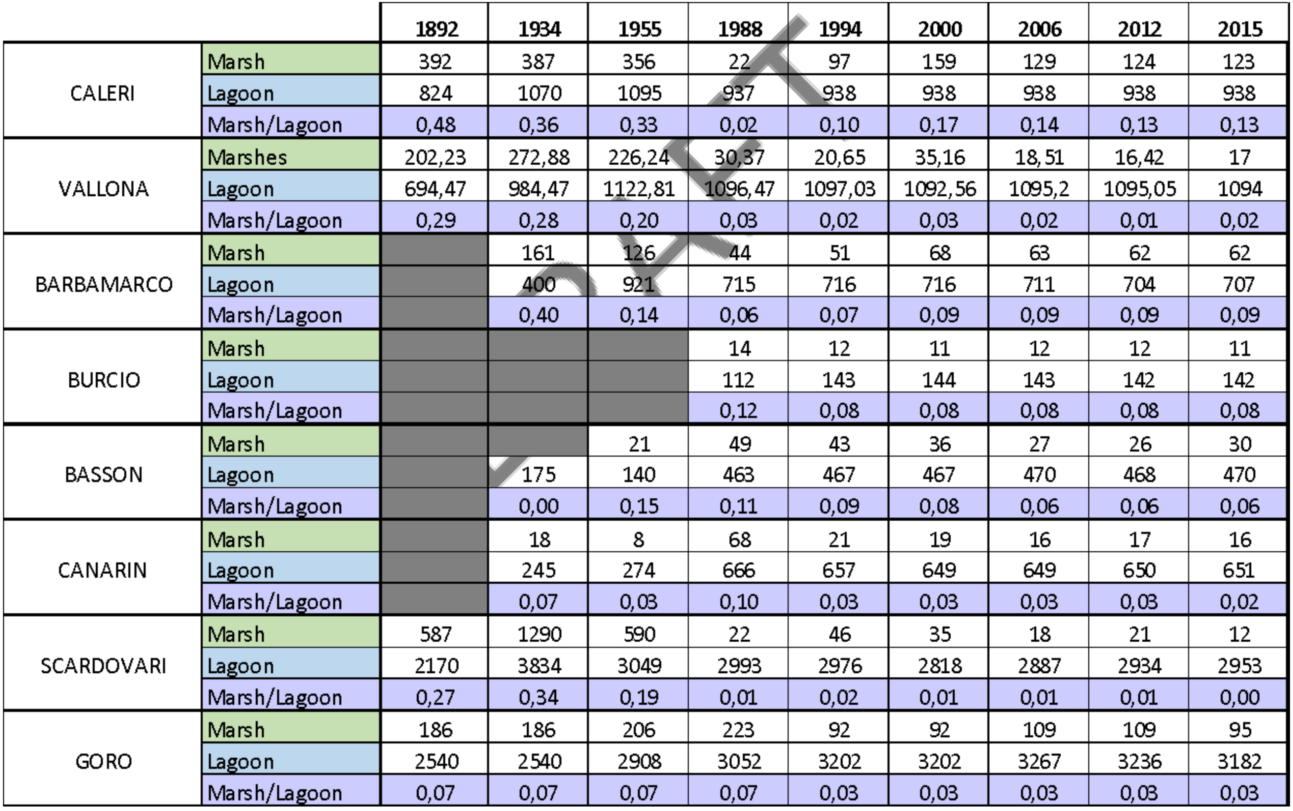
Table 3: Main characteristics of the lagoons, (all dimensions are expressed in meters)

	1892	1934	1955	1988	1994	2000	2009	2018
Caleri	Orientation North – South restricted							
Length Shore parallel	6950	7350	7400	6840				
Wide shore normal	3200	3275	3430	3200				
Inlet 1 (north)	245	165	180	145	130	125	125	100
Inlet 2 (south)	77	74	67	82	130	131	131	131
Vallona	Orientation NNW – SSE - 1892 restricted and then chocked							
Length Shore parallel	4370	6900	6700	6700				
Wide shore normal	300 - 921	800 – 3400	700 - 3400	700 – 3500				
Inlet	120	143	140	128	296	640	640	640
Barbamarco	Orientation NNW – SSE - Restricted							
Length Shore parallel		5220	9540	9580				
Wide shore normal		330 – 1350	330 - 2000	340 – 1975				
Inlet north		124	449	330	240	44	105	80
Inlet south		88	86	80	68	72	68	68
Inlet river				10	8	8	-	-
Burcio	Orientation NNW – SSE - Restricted							
Length Shore parallel	-	-	-	2220	2250			
Wide shore normal	-	-	-	600	594			
Inlet				206	220	212	214	217
Basson	Orientation NNW – SSE - Restricted							
Length Shore parallel		2280	2200	3800				
Wide shore normal		1300	905	1800				
Inlet	-	450	110	125	130	100	220	67
Canarin	Orientation North – South - Restricted							
Length Shore parallel		3010	3150	5420				
Wide shore normal		1225	1330	1550	1600			
Inlet 1		505	130	100S	72 S	12S	9	10
Inlet 2				320 N	566	520	115	160
Scardovari	Orientation NNE – SSW - Restricted							
Length Shore parallel	6200	6170	5400	5500				
Wide shore normal	4330	7700	7260	6350				
Inlet 1	890	1900	670	2430	1600 S	960 S	640 S	820
Inlet 2					250	255	250	250

Goro	Orientation East – West - Restricted – leaky							
Length Shore parallel		10440	10800	10900				
Wide shore normal		3700	4600	4600				
Inlet 1		2415	2430 E		863 E	455 E	605	3630
Inlet 2			2030 W		910 W	455	1560	
Inlet 3						140		
Inlet 4						700		

As observed in Table 4, the Po Delta lagoons are characterized by different salt marsh's distribution that has varied during the last 120 years. For instance, in the Caleri lagoon, the salt marshes represented about 48% of the lagoon's area in 1892 and reduced until 1988 (2%). The Scardovari lagoon presented a high percentage of salt marshes from 1892 to 1955 (with values ranging from 19 to 34%), but after 1955, the salt marshes almost disappeared representing only 1%. The lagoon of Goro was characterized by a low presence of salt marshes, with a value ranging from 7% to 3%. Today, the presence of the salt marshes is scarce (less than 10%) except in the Caleri lagoon.

Table 4: Relation between the lagoon and salt marsh. The dimensions of the lagoons and salt marshes are expressed in m^2, while the rate Marsh/Lagoon is adimensional



		1892	1934	1955	1988	1994	2000	2006	2012	2015
CALERI	Marsh	392	387	356	22	97	159	129	124	123
	Lagoon	824	1070	1095	937	938	938	938	938	938
	Marsh/Lagoon	0,48	0,36	0,33	0,02	0,10	0,17	0,14	0,13	0,13
VALLONA	Marshes	202,23	272,88	226,24	30,37	20,65	35,16	18,51	16,42	17
	Lagoon	694,47	984,47	1122,81	1096,47	1097,03	1092,56	1095,2	1095,05	1094
	Marsh/Lagoon	0,29	0,28	0,20	0,03	0,02	0,03	0,02	0,01	0,02
BARBAMARCO	Marsh		161	126	44	51	68	63	62	62
	Lagoon		400	921	715	716	716	711	704	707
	Marsh/Lagoon		0,40	0,14	0,06	0,07	0,09	0,09	0,09	0,09
BURCIO	Marsh				14	12	11	12	12	11
	Lagoon				112	143	144	143	142	142
	Marsh/Lagoon				0,12	0,08	0,08	0,08	0,08	0,08
BASSON	Marsh			21	49	43	36	27	26	30
	Lagoon		175	140	463	467	467	470	468	470
	Marsh/Lagoon		0,00	0,15	0,11	0,09	0,08	0,06	0,06	0,06
CANARIN	Marsh		18	8	68	21	19	16	17	16
	Lagoon		245	274	666	657	649	649	650	651
	Marsh/Lagoon		0,07	0,03	0,10	0,03	0,03	0,03	0,03	0,02
SCARDOVARI	Marsh	587	1290	590	22	46	35	18	21	12
	Lagoon	2170	3834	3049	2993	2976	2818	2887	2934	2953
	Marsh/Lagoon	0,27	0,34	0,19	0,01	0,02	0,01	0,01	0,01	0,00
GORO	Marsh	186	186	206	223	92	92	109	109	95
	Lagoon	2540	2540	2908	3052	3202	3202	3267	3236	3182
	Marsh/Lagoon	0,07	0,07	0,07	0,07	0,03	0,03	0,03	0,03	0,03

IV-2 EVOLUTION OF THE SALT MARSHES

Salt marshes have been mapped in relation to their position in the lagoon and temporal development. Generally, the most observed salt marshes are isolated and fringing types. All the types of salt marsh have only been observed in the Caleri lagoon from 1892 to 1955, while only two types develop in the Canarin and Basson lagoons.

IV-2.1 Caleri lagoon

In 1892, the Caleri lagoon was about 824 ha. As observed in Figure 4a, the Po di Tramontana fluvial branch was not in communication with the Po di Levante branch, which delimited the westward boundary of the lagoon, and the communication with the sea occurred through the Caleri harbor inlet and a small channel located southward. Today, the water exchange still occurs through the Caleri harbor inlet (about 190 m wide), and the Pozzantini breach (30-40 m wide) (Figure 4b).

In 1934, the lagoon's extension increased by about 246 ha with the formation of new wetlands in the western part, while in 1955 the lagoon reached its maximum extension (about 1,095 ha).

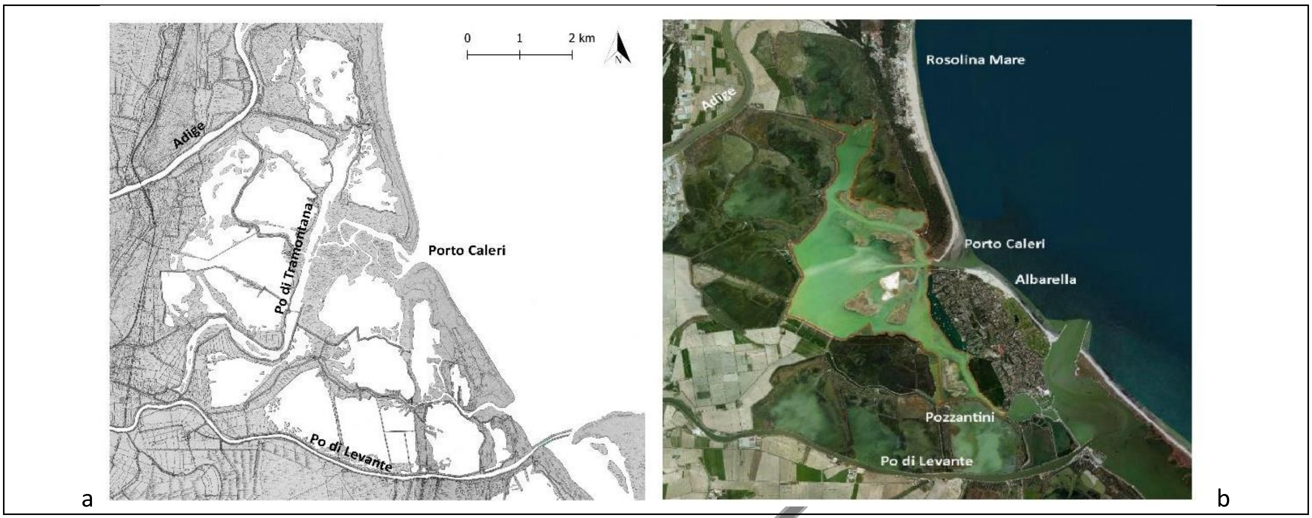


Figure 4: Caleri lagoon in 1892 (a: left) and 2015 (b: right) *The scale and orientation for both images are reported in the 1894 image*

The trend of the dimension of the salt marshes is reported in Figure 5. In 1892, they covered about 48 % of the lagoon area, and successively reduced, reaching a minimum of 2% in 1978 before increasing again to cover 13% of the lagoon area.

In 1892, fringing (55%) and tidal channel salt marshes (40%) were the two principal types, while isolated marshes covered only 5% of the lagoon area (Figure 5b). In 1934 and 1955, the five types of salt marsh were present. However, since 1978, only two types of saltmarshes were present: tidal channel salt marshes (principal type) and fringing salt marshes (less extended).

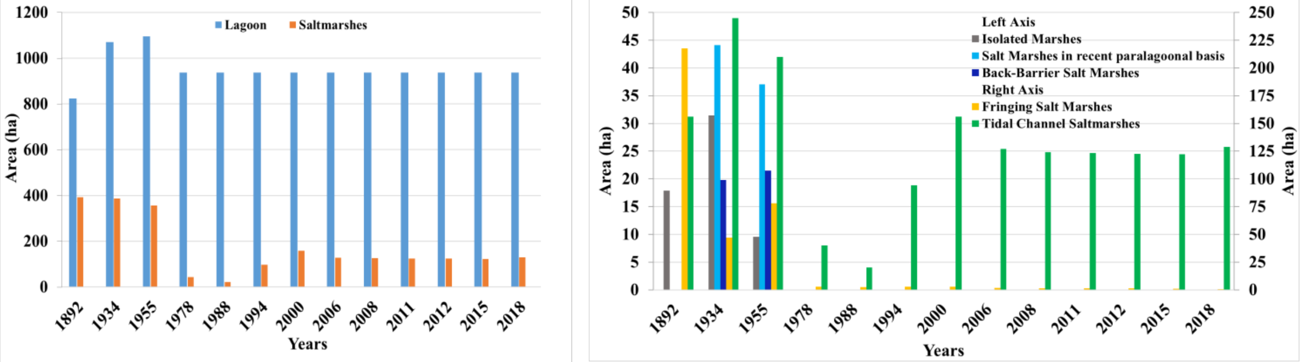


Figure 5: Caleri lagoon (a) Extension of the lagoons and salt marshes (in ha); (b) Extension of the different types of salt marsh (in ha).

In addition, the observations of the 1954, 1983 and 1998 aerial photos, used to map the channels present in the lagoon, indicate that the channels network was more complex in 1954 compared to 1998 (Figure 6).

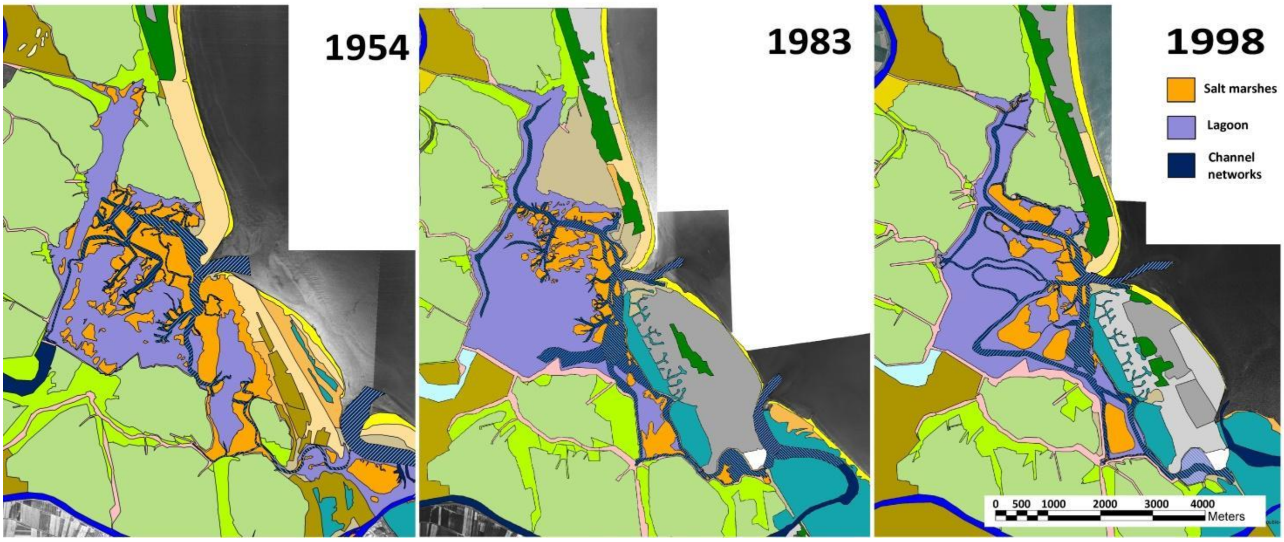
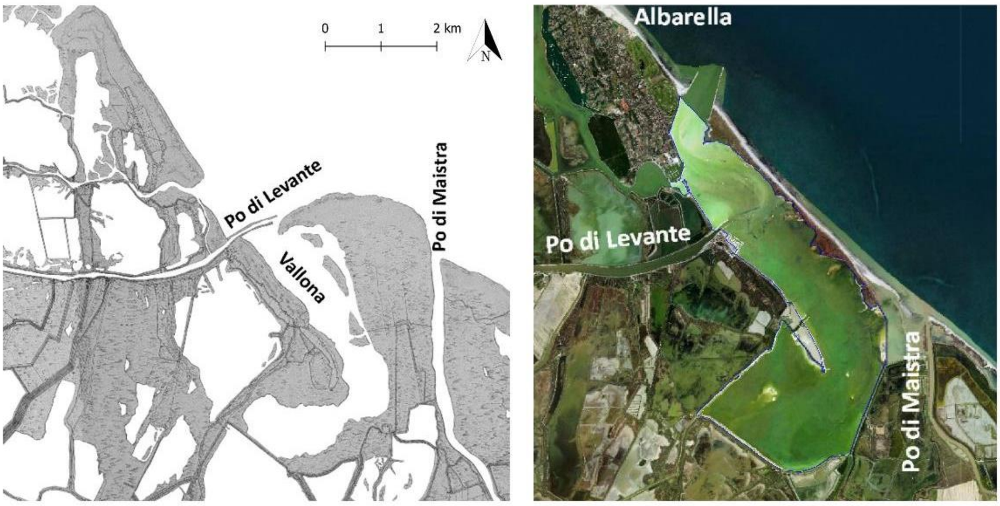


Figure 6: Organization of the channel networks in the Caleri lagoon

IV-2.2_ Evolution of the Vallona lagoon and salt marshes

The evolution of the Vallona lagoon is conditioned by the evolution of the spit as highlighted in Figure 7. In 1892, the lagoon was delimited by the Po di Levante river in the northern part and had an extension of 694 ha (Figure 8). Successively, the lagoon increased with the development of spit reaching its maximum (1123 ha) in 1955 and then remained stable (1095 ha, Figure 8)..

Salt marshes cover an extensive portion of the lagoon system until 1955. In 1892, marshes covered 202 ha (28% of the lagoon area), 272 ha in 1934 and 226 ha in 1955. Later, the salt marshes reduced drastically covering 18 to 50 ha (5 to 14% of the lagoon area). The main type was represented by the fringing salt marshes and secondarily the isolated marshes.



a b

Figure 7: Vallona lagoon in 1892 and 2015. *The scale and orientation for both images are reported in the 1894 image*

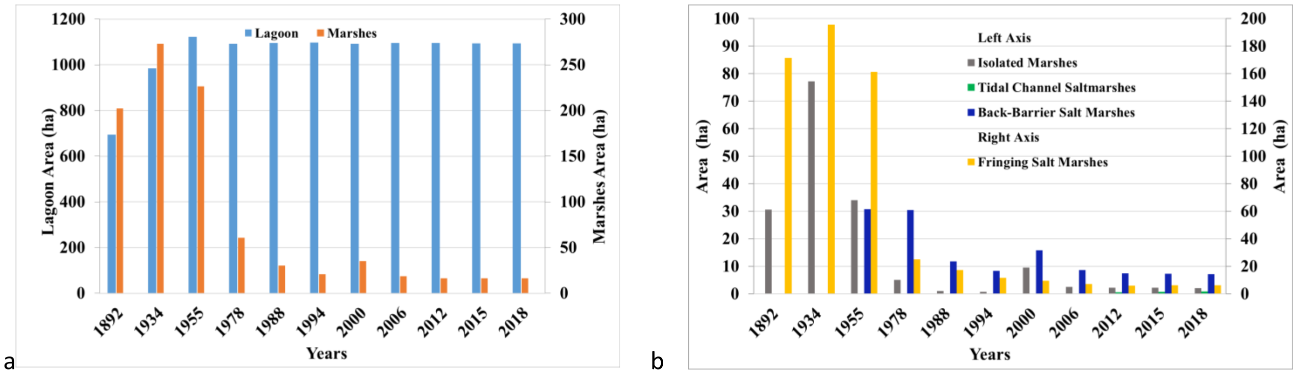


Figure 8: Vallona lagoon (a) Extension of the lagoons and salt marshes (in ha); (b) Extension of the different types of salt marsh (in ha).

IV-2.3_ Evolution of the Barbamarco, Burcio and Basson and Canarin lagoons and salt marshes

The lagoons of Barbamarco, Basson and Canarin were represented for the first time in 1934, while the Burcio lagoon appeared in 1988 (Figure 9). The dimension of the Barbamarco lagoon increased until 1955 and then reduced in 1978 and stabilized until 2015. The dimension of the Burcio lagoon increased until 1994 and remained constant. The dimension of the Basson lagoon developed until 1978 and then stabilized. Finally, the extension of the Canarin lagoon increased until 1978. Until 1978, the lagoon had two inlets; one well-developed at the north and the second one at the south), but the development of the southern spit has progressively reduced the lagoon entrance.

Figure 9: The lagoons of Barbamarco, Burcio, Basson and Canarin (1894 e 2015). *The scale and orientation for both images are reported in the 1894 image*

The salt marshes identified in the four lagoons generally covered less than 10% of the lagoon's area (Figure 10). In the Barbamarco lagoon, they covered 161 ha in 1934, reduced to 43 ha in 1988, and then increased and stabilized in the successive periods. In the 80s, the development of the salt marshes in the Burcio and Basson lagoons was limited, covering 12% and 10% of the lagoon's area, respectively. The salt marshes of the Canarin lagoon increased from 1934 to 1988, and then reduced to less than 3% of the lagoon extension. The salt marshes were principally fringing and isolated types, except in the Barbamarco lagoon, which was characterized by tidal channel salt marshes (Figure 11).

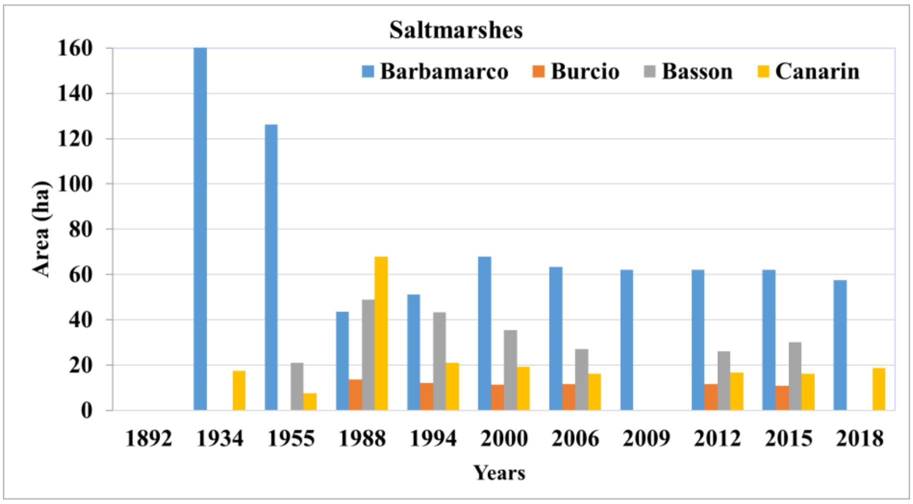


Figure 10: Extension of the salt marshes in ha (Lagoon of Barbamarco, Burcio, Basson and Canarin)

Figure 11: Salt marsh's typologies in the lagoons of Barbamarco, Burcio, Basson and Canarin

IV-2.4_ Evolution of the Scardovari lagoon and salt marshes

The dimension of the Scardovari lagoon was about 2,170 ha in 1892 increasing to 3800 ha in 1934. Later, the lagoon's area was reduced to about 3000 ha in 1955 (Figure 12 and Figure 13).

The salt marshes reached their maximum development in 1934 before reducing as observed in Figure 13a. After 1955, the salt marshes covered only 1 to 2% of the lagoon's area. The fringing salt marshes was the dominant type, while the isolated salt marshes, also mapped, were of minor extension. (Figure 13b).

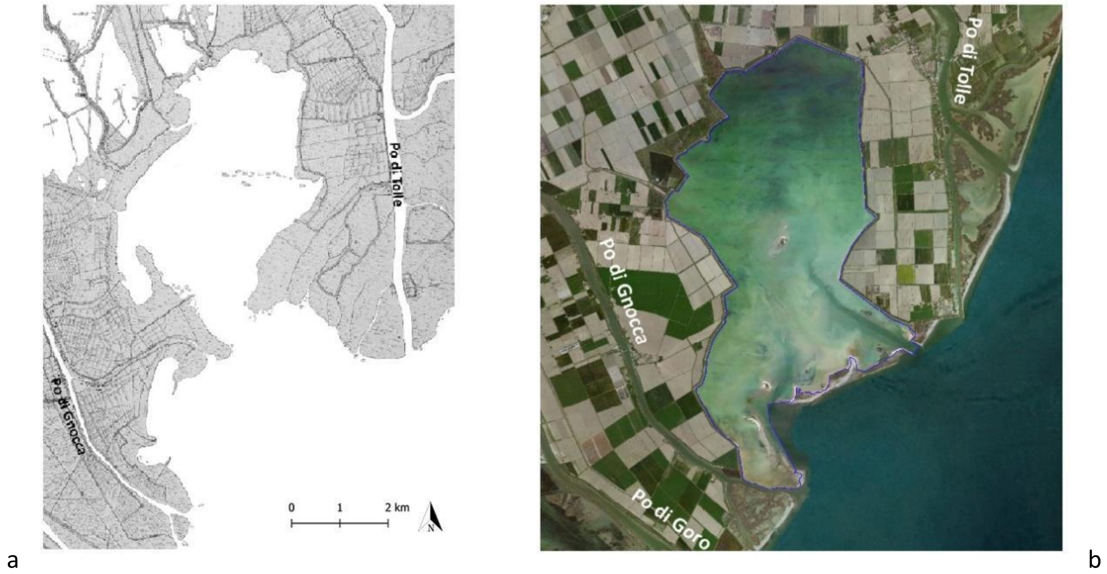


Figure 12: Scardovari lagoon in 1892 and 2015. *The scale and orientation for both images are reported in the 1894 image*

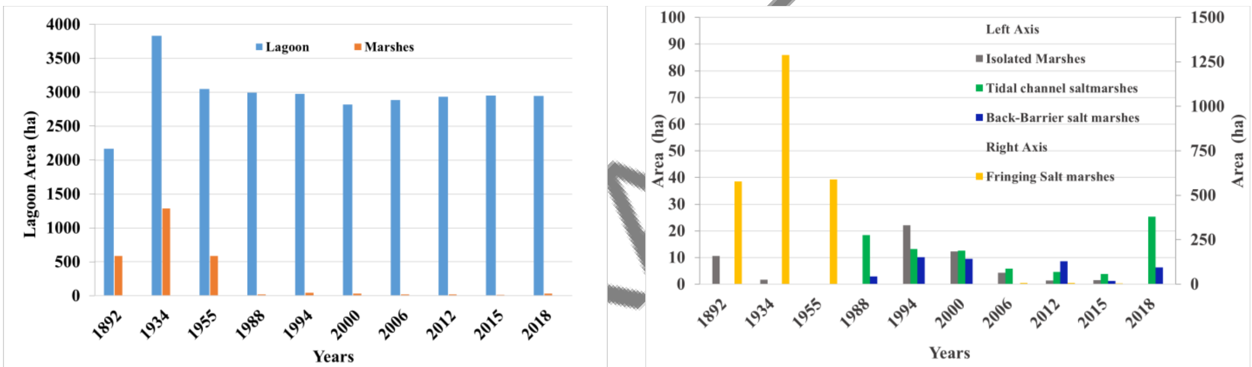


Figure 13: Scardovari lagoon (a) Extension of the lagoons and salt marshes (in ha); (b) Extension of the different types of salt marsh (in ha).

IV-2.5_ Evolution of the Goro lagoon and salt marshes

The dimension of the Goro lagoon (Figure 14) slowly increased from 1892 to 1994 and then remained constant. The salt marshes generally covered less than 10% of the lagoon. Its maximum extension, about 220 ha, occurred in 1988 and, then reduced in the successive periods to about 100 ha. From 1934 to 1994, isolated and fringing salt marshes were the two types of salt marshes present in the lagoon , while from , tidal channel salt marshes also developed (Figure 15)

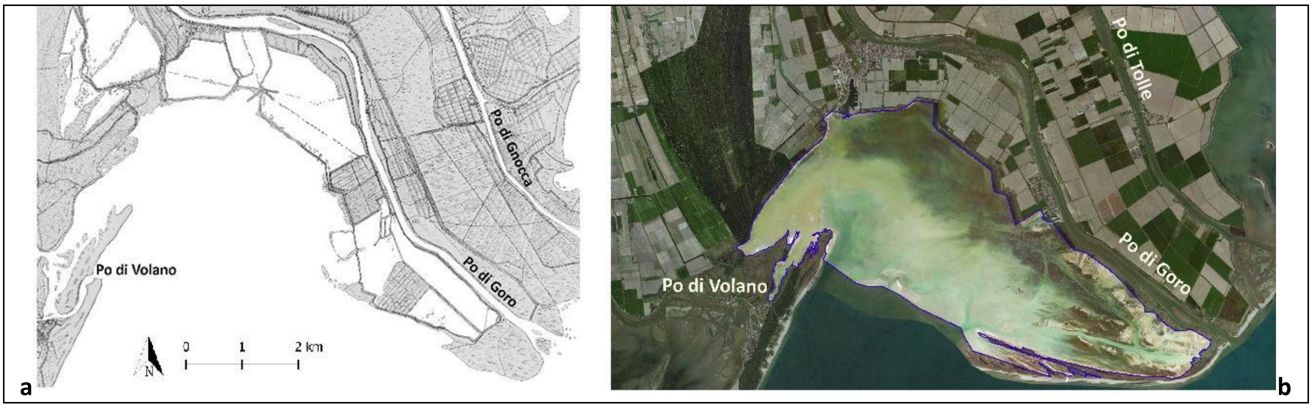


Figure 14: The Goro lagoon in 1892 and 2015. *The scale and orientation for both images are reported in the 1894 image*

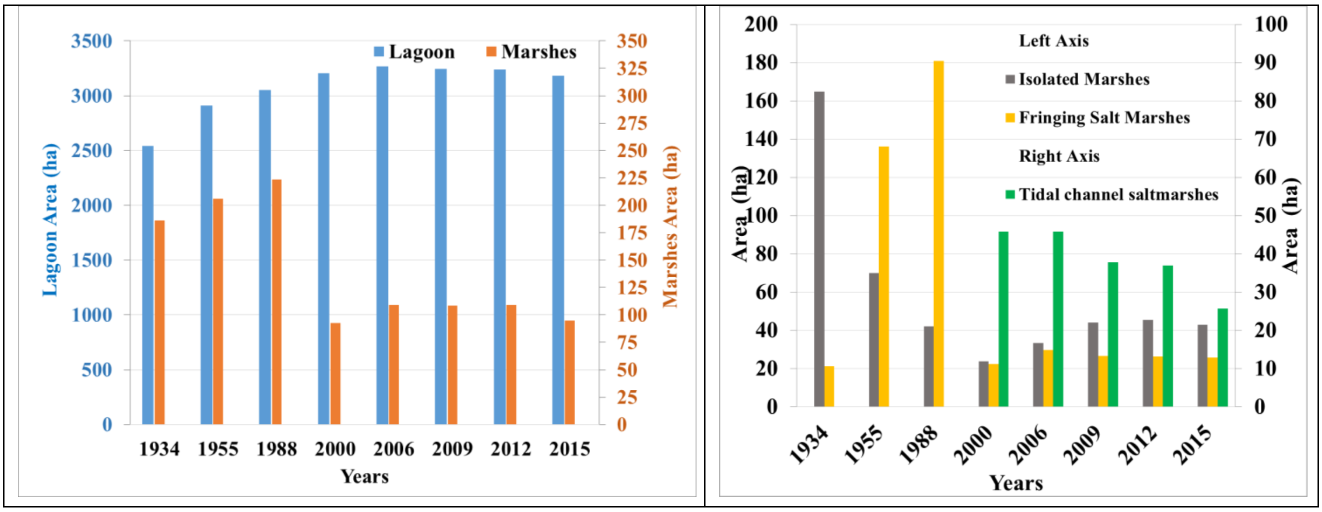


Figure 15: Goro lagoon (a) Extension of the lagoons and salt marshes (in ha); (b) Extension of the different types of salt marsh (in ha).

V- DISCUSSION

As reported by Pérez-Ruzafa et al. (2019) knowledge on lagoons, despite their important functions, is still limited. They are considered naturally ephemeral ecosystems that are dynamic, changing shape and size due to natural processes (De Wit, 2011). However, their lifespans are related to human manipulation of their morphology (Pérez-Ruzafa et al., 2019). Their evolution associated with the salt marsh could be assessed through aerial imagery analysis and mapping, allowing to assess their stability (Carrasco et al., 2021, Blount et al., 2021). Carniello et al. (2009) for instance analyzed the long-term evolution of the lagoon of Venice (Italy) and proposed a conceptual long-term evolution model highlighting its degradation during the last century. Blount et al. (2021) analyzed the long-term lateral evolution of salt marsh patches in the Ria Formosa coastal lagoon (Portugal) using aerial and satellite images.

The recent evolution of the Po Delta lagoons illustrates how their morphology has rapidly changed during the last 120 years. Indeed, the lagoons are recent features, with the lagoons of Barbamarco, Basson and Canarin being formed between 1892 and 1934, and the Burcio lagoon between 1978 and 1988. The lagoons are generally restricted according to Kjerfve (1994) and consequently may experience good tidal circulation amplified with wind-generated wave action. Vallona lagoon is however choked with a very narrow connection with the sea. In this case, as underlined by Duck and da Silva (2012) the channel acts as a filter damping out tidal currents and water level variations inside the lagoon and consequently, the tidal variations should be reduced.

Moreover, most of the lagoons reached their actual shape and dimensions by 1955 except the lagoon of Goro, which stabilized in 2000, and the lagoon of Burcio. From 1892 to 2015, the total extension of the lagoons has increased by about 9670 ha, but a major increase was observed between 1892 (about 3690 ha) and 1955 (about 9510 ha). The increase of the Po Delta lagoon's areas is probably related to the seaward progradation of the Po Delta, associated to high fluvial sediment input, that has allowed the formation of new lagoons associated with the development and elongation of the spits and barrier islands bordering the lagoons. In contrast, the stabilization or retreat of the lagoons observed after 1955 is probably related by the negative or low sediment budget of the Po river,, which is the main sediment delivery agent supplying sand to the bay-head delta. In addition, the relative sea level rise also contributes to the increase of the lagoon's areas by causing the flooding of farming land and the abandonment of some farming valleys (Caleri for instance), which progressively merge with the lagoons. The lagoon of Scardovari, however, is characterized by a different pattern characterized by a retreat of about 500 m (reduction of its size) and a southward extension, as observed by Matticchio (2009).The retreat of the Scardovari lagoon is most related to the reduction of the sediments apported by the Po river branch.

Therefore, our results highlight the importance of the fluvial sediment input and the wave actions in the formation and evolution of the lagoons as reported by Duck and da Silva (2012). In fact, the evolution of the delta Po lagoons is directly linked to the evolution of the Po Delta, which, during the last few decades, was characterized by a rapid progradation (Simeoni and Corbau, 2009; Stefani, 2017) associated with high fluvial sediment transport. The cartographic documents show the presence of consolidated fluvial systems characterized by mouth bars and spits attesting buoyancy-dominated environmental patterns as described by Wright (1977) and delimiting the seaside of the lagoons. Furthermore, the constructive dynamics observed during the first half of the 20th century, characterized by high fluvial efficiency, had repercussions in the “areal” evolution of the lagoons. The seaward progression of the river mouths associated with the development of barrier islands and spit due to the distribution of fluvial sediments by wave’s actions have allowed the development of the lagoons of Barbamarco, Burcio, Basson and Canarin, and the enlargement of the lagoons of Vallona and Scardovari. The development of a spit at the Po di Goro mouth has transformed a closed bay into the lagoon of Goro (Simeoni et al., 2007).

Similarly, to what happened to the Venice lagoon, the lagoons of the Po delta have also been experienced a general degradation, during the last 80 years. Such degradation was also analyzed by Corbau et al. (2019b). In addition, according to Simeoni and Corbau (2009), the Po delta suffered erosion after the 1950s due to the reduction of the solid supply of the Po, due to dam and barrier construction and to river bed excavation. According to the conceptual model proposed by Carniello et al. (2009), the degradation of the lagoons of the Po delta is in its first step consisting of salt marsh deterioration. Successively, without human interventions, the lagoons will most probably be characterized by the tidal flat erosion phase.

Salt marshes

Recently salt marshes have received considerable scientific attention in recent years due to a combination of factors, especially in relation to the accelerated sea-level rise as mentioned by Fagherazzi et al. (2021). Silvestri et al. (2018), analysing the evolution of the salt marshes in the Venice lagoon (Italy) also suggested that hydrodynamic changes and anthropic interventions play a crucial role in the survival of salt marshes. Fagherazzi et al. (2021) and Silvestri et al. (2018) further indicate the need to assess their evolution in order to inform government and local communities and implement protection strategies. Similarly, Carrasco et al. (2021) have studied the evolution of the salt marsh in the Ria Formosa lagoon (Portugal) based on aerial imagery analysis. They found that salt marshes have been strongly influenced by inlet dynamics and human interventions. In addition they observed that human pressures mainly occurred near stabilised inlets and dredged channels. Our results are partially in agreement with this results since we observed a strong reduction of the salt marshes located near the inlets, which are almost all stabilised. On the contrary we observed an increase of the tidal channel salt marshes that could be due the hydrodynamic variation induced by the realization of jetties at the lagoon’s inlet as explained by Silvestri et al. (2018).

Our results show that lagoons present different morphological characteristics with the lagoon of Caleri having a higher morphological variability due to the presence of salt marshes and a complex hydraulic network as also observed by Maicu et al. (2018). Today, these lagoons are subject to progressive hydro-morphological and environmental degradation. As a matter of fact, while the lagoons have increased and stabilized in terms of extension, salt marshes have progressively disappeared, passing from 32% of the lagoons' surfaces in 1892 to only 3% in the 21st-century Figure 16). In order to explain such a trend, it is important to point out that the salt marsh evolution depends on the interaction between several factors such as sediment availability, vegetation cover, topography, sea-level changes and hydrodynamic conditions. (Allen, 2000; Bartholdy, 2012). The variation of one of these factors determines a change in the hydro-sedimentary equilibrium causing the growth or disappearance of the salt marshes.

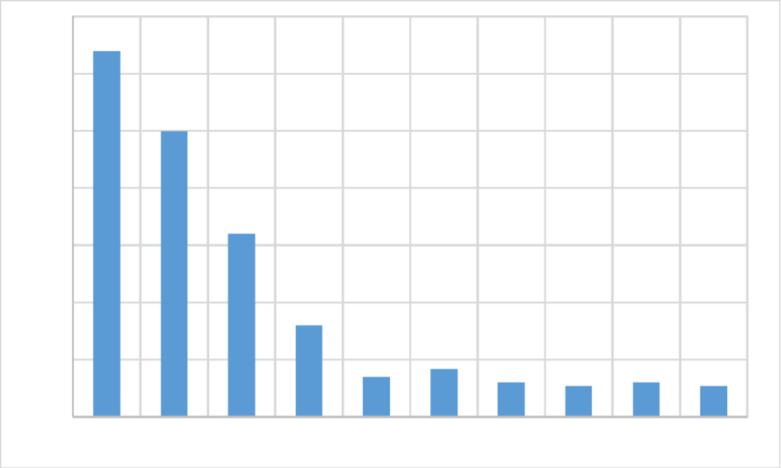


Figure 16: Percentage of the lagoon area occupied by salt marsh

Previous studies conducted in the United States and New Zealand (Kirwan et al., 2011) have demonstrated that an increase of sediment input determines an expansion of the salt marshes. For instance, Mudd (2011) highlights how a salt marsh environment has positive feedback to a significant increase in sedimentary budget. However, some studies (Day et al, 1998, Schwimmer & Pizzuto, 2000; Adam, 2002; Cox et al., 2003) reveal a strong impact of the local forcing, both natural and anthropogenic, on the evolution of the salt marshes. Reed (1995) observed the development of salt marshes in a negative sediment budget presenting widespread erosion. In fact, a short-term sediment compensation may result in erosional processes affecting the lower parts of the salt marsh providing sediment to feed their upper part. However, the conservation of lagoon morphologies is generally linked to a sedimentary budget that balances the relative sea-level rise and the self-compaction of sediments (Orson et al., 1987; Reed, 1988; Cahoon et al. 1995; Allen, 2000; Nielsen and Nielsen, 2002).

Furthermore, relative sea-level rise also induces fast disappearance of salt marshes (Kearney et al., 1988; Reed, 1995; Day et al., 1999; Hartig et al., 2002; Van der Waland Pye, 2004; Baily and Pearson, 2007; Ravens et al., 2009). In fact, if the sea level rise is not associated with sediment supply, then the salt marsh will have a rapid loss of elevation until it “drowns”. However, its maintenance will depend on the vegetation since below a depth less than the mean high tide level the halophilous plants die and consequently lose their important protection role against erosion processes (Fagherazzi et al., 2006; Mudd, 2011).

Based on the previous observations, the evolution of the salt marshes in the Po Delta lagoons allows us to identify three distinct phases. The first one, from 1892 to 1934, represents the baseline situation with salt marshes extension greater than in the two successive periods.. It is characterized by high fluvial sediment input associated with a fast seaward progression of the river mouths and by the first subsidence phenomenon linked to methane water extraction (Figure 17, Corbau et al., 2019a). Such conditions of high sediment input, as suggested by Mudd (2011), favor the growth of the salt marsh due to a major sediment trapping efficiency (Figure 17). In addition, the complex endo-lagoonal morphologies allow a reduction of the wave’s actions, consequently reducing the erosion at the edges of the lagoon explaining the predominance of the fringing salt marshes.

The second phase, characterized by a small increase of the lagoon extension associated with a reduction of the salt marsh, occurred between 1934 and 1978. In this period, the conditions changed significantly and were characterized by a negative sediment budget in the lagoons as a result of a gradual lowering of the seabed. In addition, as reported by Stefani (2017), the human induced alteration of the river due to dam construction and fluvial sand exploitation has almost gradually stopped the fluvial sediment input. Consequently, the reduction of the river sediment supply associated with the increase of the anthropic subsidence due to large withdrawals of methane-rich groundwater has caused the drawing of the lagoon morphologies and an increase of the wave impacts.

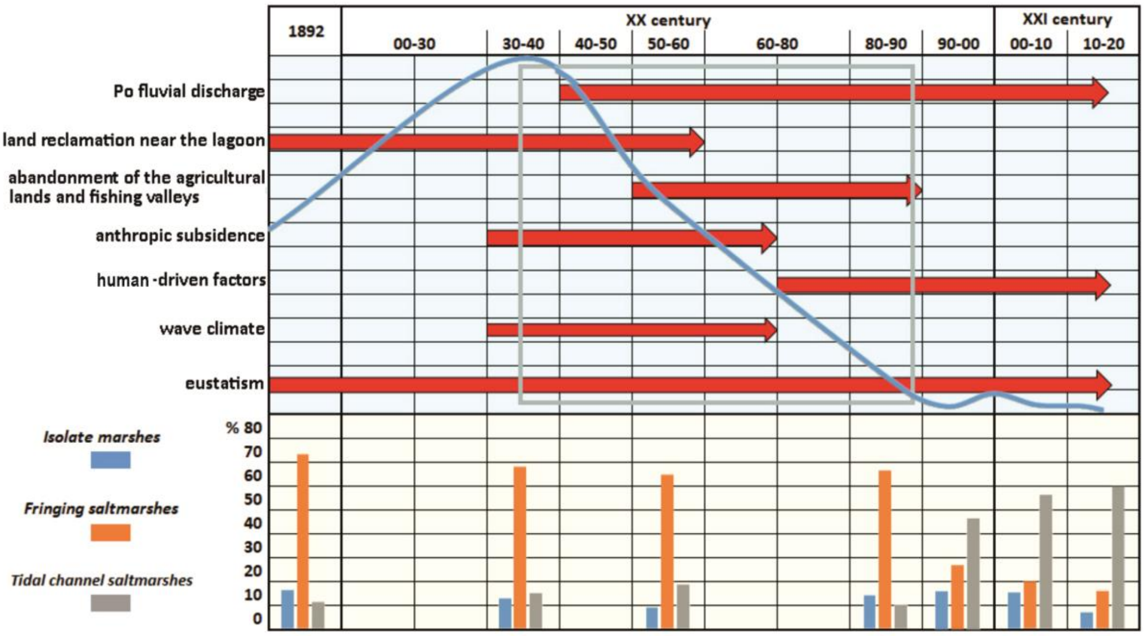


Figure 17: Factors influencing the evolution of the salt marsh present in the lagoons of the Po Delta. The red arrows represent the period of major intensity of the factors that have induced a reduction of the salt marshes. The blue line represents the evolution of the intensity of the factors controlling the loss/degradation of the salt marshes. The distribution of the three main salt marsh types is reported in the second graph**.**

Numerous studies have explored the impact of sediment starvation in tidal systems (Ganju et al.,2017). They assumed that the available sediment is not sufficient to compensate for the relative sea-level rise. Additionally, Ganju et al. (2017) have shown that a sediment deficit may result in the conversion of vegetated marsh portions into open water. Furthermore, Tessler et al. (2018) have found that currently all deltas receive substantially reduced sediment fluxes from upstream compared to pristine conditions. In the Goro lagoon, one of the most efficient sedimentary traps of the Po Delta (Simeoni et al., 2000), the sedimentary prism formed during the last century has been estimated at about 0.8 m corresponding to a mean sedimentation rate of 80 mm/yr (Fontolan et al., 2000) that obviously partially compensated the relative sea-level rise, which ranged from 1.10 to 1.6 m from 1900 to 2015 (Corbau et al., 2019a). D'Alpaos (2009) further identified a deepening of about 0.5 to 3 m of the seafloor of the Scardovari lagoon between 1950 and 1967. Such water depth increase is only partially related to the relative sea-level rise of about 0, 68 and 1.21 m (Corbau et al, 2019a), that was not compensated by. D'Alpaos (2009) further demonstrated that the water-depth increase has caused an increase in the wave climate and erosion phenomenon inside the lagoon. Once triggered, this process tends to feed itself, favouring the phenomenon of flattening of the lagoon seabed.

The combined effects of the relative sea rise and seabed erosion are due to the rapid development of the lagoons after 1934 (Canarin; Burcio; Basson). This process does not allow complete development of the marshes and then explain the loss of the salt marshes between 1934 and 1988, quantified in about 82% of the total. The effects of these components on the salt marshes are well documented in the Venice lagoon where a relative sea-level rise of about 23 cm has been recorded (Carbognin and Taroni, 1996). As a consequence, this relative sea-level rise associated with a negative sediment budget resulted in a reduction of more than 50% of the salt marshes between 1927 and 2002 (Favero, 1992; Day et al, 1998; Ravera, 2000; Pillon et al., 2003; Sfriso et al., 2005; Molinaroli et al., 2009; Sarretta et al., 2010).

The third phase, starting after 1978 and characterized by a stabilization of the lagoon extension and a drastic reduction of the salt marsh (representing less than 5% of the lagoon area), presents a low sedimentary budget and a diminution of the anthropogenic subsidence rate as shown in Figure 17. In addition, the transgressive trend of the coast has resulted in a shoreline retreat associated with a narrowing of spits and barrier islands, and thus reducing their function of protection and absorption of wave energy. For instance, erosion and breaching processes have been observed along the spits and barrier islands bordering the Scardovari or Goro lagoons (Ruol et al., 2016; Simeoni et al., 2007).

This period is further characterized by strong human control with the several interventions performed on the lagoon's entrances and the lagoon sea bed (Bonometto et al., https://www.bonificadeltadelpo.it/wp-content/uploads/2017/03/lagune_del_delta_del_po_ENG.pdf, Simeoni & Corbau, 2009, Cencini, 1988), while other interventions were performed to restore the hydrodynamics and internal morphology of the lagoons with excavations of canals, the creation of filled areas and the reconstruction of sandbanks as observed for the Caleri lagoon (Ruol et al., 2016). For instance, in 2011 over 110 ha of artificial sandbanks were realized in the Po lagoons (excluding Goro) corresponding to about 28% of their total extension (https://www.bonificadeltadelpo.it/wp-content/uploads/2017/03/lagune_del_delta_del_po_ENG).

Taking into account such interventions we should consider that the actual salt marsh status should be worse indicating the conversion of some lagoons to the open sea, in particular for the Scadovari and Goro lagoon. In fact, the disappearance of the salt marshes is due to the sea-level rise caused by the subsidence and the reduction of the fluvial discharge. Considering that the fluvial sediment supply is decreasing worldwide (Syvitski et al., 2005), a progressive increase of the open-water area compared to the salt marsh surface is expected (Oertel and Woo, 1994). This would determine a reversion of salt marsh to intertidal mudflat (French, 2006) and/or a simplification of the lagoon morphology becoming more similar to the marine system. In the Caleri lagoon, the human interventions have resulted in a diminution of the bifurcation channel indexes (Table 5), revealing a stabilization and conservation of the channel network.

Human economic activities should also be added to this scenario since the degradation of the salt marsh is also related to the impacts of economic exploitations that characterized this environment and in particular the shellfish exploitation and tourism activities (Simeoni and Corbau, 2009; Donati and Fabbro, 2013). Such impacts have also been observed in different studies (like Prahalad, 2014, Zhang et al. 2021). Murray et al. (2018), for instance, reported that coastal wetland reclamation by seawall construction and aquaculture land uses are the primary drivers for coastal wetland loss, resulting in a 16% loss of coastal tidal flats globally from 1984 to 2016.

Finally, human action is often an essential factor explaining the evolution of the salt marshes in the Po delta lagoons (Simeoni and Corbau, 2009; Corbau et al., 2019b). Firstly, as highlighted by Simeoni and Corbau (2009) land reclamation interventions have severely affected the salt marshes, which have been converted into agricultural areas. Secondly, the presence of isolated salt marsh reveals a fragmentation process as explained by the study of Baily and Pearson (2007) or Fontolan et al. (2012). Baily and Pearson (2007) reported that increasing fragmentation leads to the breakup of the isolated salt marsh during the ''attrition'' stage before eventual disappearance, while according to Fontolan et al. (2012), the reduction of the isolated salt marshes is mostly due to wave action erosion, that could be related to wind waves and or vessels. In addition, the evolution of the fringing salt marsh further attests their susceptibility to environmental and human impacts as reported by Morgan et al. (2009). According to these authors, fringing salt marshes are affected by urban development inland and by wave's actions seaward. Furthermore they also report that they represent easy access to open water for fishermen and boaters, because of their dimensions. Indeed, until the 1980s the fringing salt marshes was the prevalent type, while successively, we observe an almost equal distribution between fringing salt marshes, isolated salt marshes and tidal channel salt marshes, with a slight prevalence (between 1 and 12%) of the latter type (Figure 18). The reduction of the fringing salt marshes might be caused by human impacts as observed by Morgan et al. (2009) who studied a residential development which removed marshes to provide convenient access to fishermen. Similarly, the increase of tidal channels in salt marsh systems is also the result of human interventions. In fact, lagoon restoration activities involve channel dredging that impact salt marshes accretion and enhance water circulation.

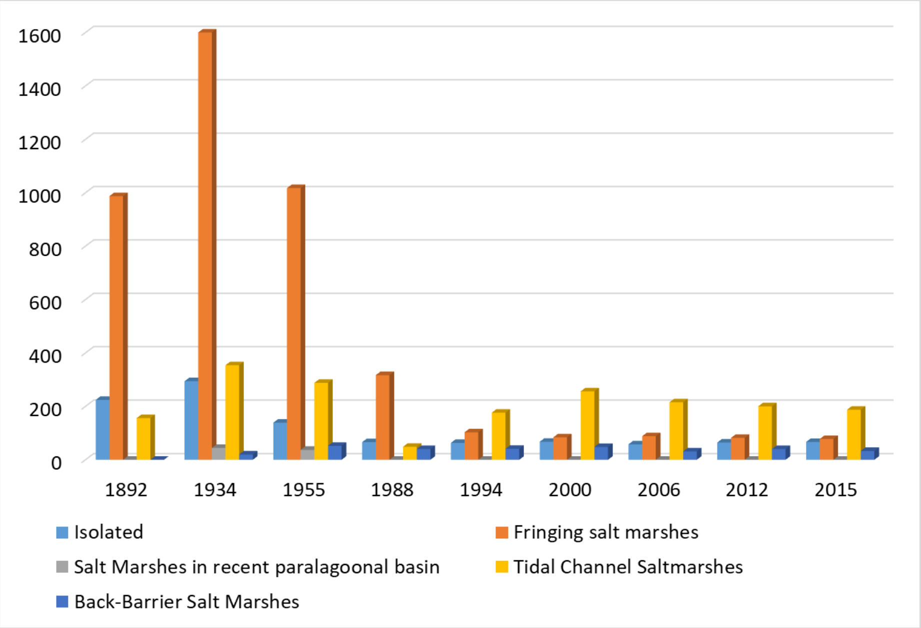


Figure 18: (b) estensione delle tipologie di barene.

VI - CONCLUSIONS

In this study, we analysed the centennial evolution of the lagoons and salt marshes of the delta Po through a spatial analysis using cartographic maps and aerial photographs. The results obtained reveal that

1) Some lagoons were already developed before the realization of the first cartographic document we studied (1892), while new lagoons were formed from 1934 to 1955 in relation to the seaward progradation of the Po Delta. Most of the lagoons have reach their actual shape and dimension since 1955
2) The maximum extension of the salt marsh was observed in 1934 (about 2315 ha). The rate between total salt marsh and lagoon areas ranges from a maximum of 25% in 1934 to a minimum of 3% 2012-2018, highlighting a significant decline of the salt marsh of about (2050 ha). The decline of the salt marsh is due to the reduction of the river sediment supply associated with human interference.
3) A decline of the fringing and isolated salt marshes that are highly susceptible to environment and human impacts. On the other hand, tidal channel salt marsh progressively became the main salt marsh type, mostly due to human interventions. Therefore, fringing salt marsh and tidal channel salt marsh may be used as an indicator to assess the health of the salt marsh because fringing salt marshes are particularly susceptible to environmental impacts, while tidal channel salt marshes are usually realized to restore or improve the hydraulic circulation inside the lagoon.
4) Considering the current sediment budget and the ongoing sea level rise, we assume that a progressive loss of the salt marshes will be observed, as well as tidal flat erosion. As a consequence, it is strongly recommended, since this study has shown a decline in salt marsh in almost all the areas mapped, to further monitor the evolution of the salt marsh. In particular, information on the vegetation should be obtained using, for instance, false colour infrared images in order to better assess and map the areas of loss and define the rates of loss.
5) Finally, we must highlight the importance of maintaining to maintain or enhancing the salt marsh to provide a long term and more sustainable approach to coastal defence especially in view of climate change. Consequently the management of all lagoons is essential. The data of the monitoring will be useful for determining the cause of the salt marsh's erosion and successively to define the best management approach for the lagoon: restoration of the degraded saltmarshes or recreation of salt marshes on areas where they have been lost. Our results suggest that we should favour the restoration/enhancement of the tidal channel salt marshes and eventually fringing salt

marsh. One option could be to dredge the lagoon inlets and channels to improve the water circulation. In addition, the dredged material could be to restore or enhance the salt marsh coupled with grazing operations. Their long and medium-term evolution will provide indication of the saltmarshes and channels morphometry.

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