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Relative sea level rise and Venice lagoon wetlands

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Abstract. Over the past century, the Venice lagoon has experienced a high rate of wetland loss and a strong net export of sediments; currently the local Authority is running several projects for beneficial use of dredging materials. From March 1993 until March 1995 the accretionary response of wetlands in the lagoon to changing water levels was studied. Vertical accretion, short term sedimentation and surface elevation change were measured at six sites with varying sediment availability and wave energy. Short term sedimentation averaged 6.85 g m^{-2} d^{-1} with a minimum of 0.06 g and a maximum of 72 g during periods of high tides and storms. Over two years accretion ranged from 0.3 to 2.3 cm/yr and surface elevation change ranged from +0.7 to – 3.7 cm/yr. The sites with highest accretion were near a river mouth and a site with strong wave energy and rapid erosion of the marsh edge with a high resuspended sediment availability. The rate of accretion at three sites was clearly sufficient to offset relative sea level rise, but a saline site with low sediment availability had the lowest accretion. A sediment fence significantly increased accretion at one site. The results suggest that reduction of turbulent motion or increasing sediment availability are needed to offset wetland loss in different areas of the lagoon.

Keywords: Accretion; Erosion; Mediterranean; Salt marsh; Sedimentation.

Abbreviation: RSLR = Relative sea level rise; SET = Sedimentation erosion table.

Introduction

The objective of this project was to study the accretionary response of wetlands in the Venice lagoon to relative sea level rise, and to determine the effectiveness of different management approaches in maintaining wetlands with accelerated sea level rise. Measurements included accretion rates on different time scales, and changes in the surface elevation of wetlands of the Venice lagoon. The stimulus for this research is based on experiences in the Mississippi delta, the Camargue, the Ebro delta and the Nile delta where, due to high rates of geologic subsidence, there are relative rates of sea level rise (RSLR) greater than the rate of eustatic rise. Several studies indicate that global warming will cause an acceleration in the rate of eustatic sea level rise (Warrick & Oerlemans 1990). Evidence indicates that rising sea level will first affect regions with large areas of near sea-level land – such as deltaic and lagoonal systems – and areas with low tide range –such as the Mediterranean (Day & Templet 1989). In addition, a number of coastal areas, such as the Po delta/Venice lagoon area, have experienced enhanced subsidence due to subsurface fluid withdrawal, thus exacerbating the problem of relative sea level rise (cf. Brivio & Zilioli 1996).

The objectives of the study were**:**

(1) to measure vertical accretion and vertical elevation change on varying time scales in different areas of Venice lagoon;
(2) to determine mechanisms leading to accretion and elevation change;
(3) to compare rates of accretion and elevation change with relative sea level rise (RSLR) to determine if wetlands are threatened by present and predicted future rates of RSLR.
(4) To evaluate the effectiveness of different management options in offsetting the impacts of RSLR.

Study area

The Venice lagoon is a shallow coastal lagoon located along the Adriatic Sea in northeastern Italy (ca. 45° N,12°E) which has an area of ca. 550 km ^{2}. The lagoon originated nearly 6000 yr ago when the rising sea level flooded the upper Adriatic Wurmian paleoplain (Gatto & Carbognin 1981). Two barrier islands separate the lagoon from the sea and water is exchanged through three large inlets (Fig. 1). Over the past five centuries, sediment dynamics of the lagoon have been greatly altered. The Brenta and Piave rivers presently flow into the sea to the south and north of the lagoon ecosystem but previously they discharged into the lagoon. Only one small river, the Dese, presently discharges to the northern lagoon although there is considerable agricultural drainage into the lagoon. Thus riverine sediment input to the lagoon has been almost completely eliminated. Long jetties constructed in the inlets at the end of last century have greatly reduced the import of marine sediments into the lagoon. As a result of these alterations, there is a net loss of sediments from the lagoon system of ca. 1.1×10^6 m^3/yr of sediment (Bettinetti et al. 1995). Most of the lagoon area is occupied by a large central waterbody (ca. 400 km^2) which is partially vegetated by macroalgae and seagrasses. The mean depth of the lagoon is 1.1 m and the tidal range during spring tides is ca. 1m ; there are extensive intertidal salt marshes, especially in the southwestern and northern portions of the lagoon. The dominant marsh species include *Limonium serotinum*, *Salicornia* spp., *Arthrocnemum fruticosum*, *Halimione portulacoides*, *Puccinellia palustris* and *Spartina maritima*. These marshes are considered very important in Europe due to their aerial extent, high productivity, and habitat value for vegetation (e.g. Dijkema 1984) and breeding birds (Scarton et al. 1994). The salt marsh area in the lagoon, however, has decreased in size, from ca. 12000 ha at the beginning of the century to ca. 4000 ha at present (Favero 1992; Runca et al. 1993), due to reclamation, erosion and natural and human-induced

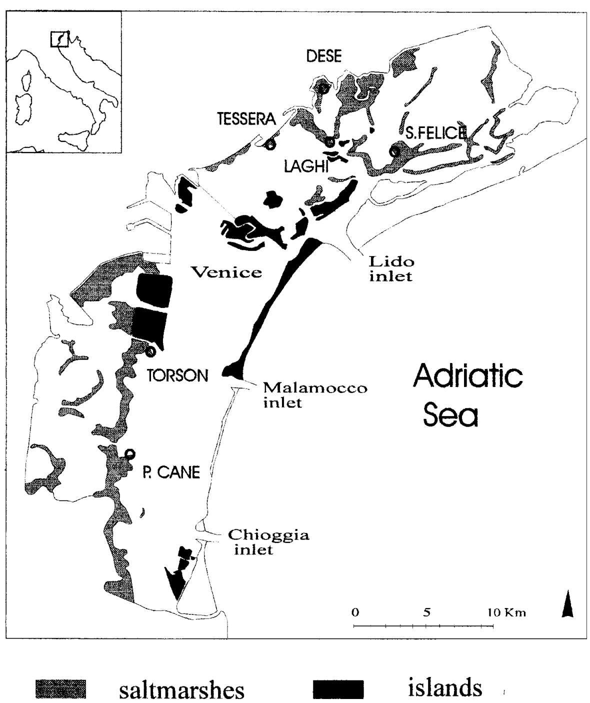

Fig. 1. Location of study sites in the Venice Lagoon.

subsidence. In the Po delta area just south of the lagoon the estimated rate of subsidence is ca. 5 mm/yr (Sestini 1992) while in Venice the current estimates range from 1.1 mm/yr (Rusconi et al. 1993) to 1.3 mm/yr (Pirazzoli 1987). Within the next 100 years, it is predicted that accelerated eustatic sea level will cause a 35-70 cm rise in sea level (Warrick & Oerlemans 1990).

The marshes of the Venice lagoon occur in a highly variable environment with respect to mean salinity, sediment availability and hydrodynamic forces. In order to determine the effects of this variability on accretion and erosion processes, we selected sites in a number of representative marsh areas of the lagoon (Fig. 1).

1. *San Felice.* This salt marsh site is located near the Lido inlet and before the construction of jetties there was probably an input of coarser sediments from the near-shore Adriatic Sea, with a development of saltmarshes along the main lagoon channels (Albani et al. 1983). Nevertheless, now salt marshes in this area exist mainly as relatively narrow fringes along tidal creeks while interior zones between creeks are shallow ponds. These ponds formed over the last few decades due to the disappearance of interior marsh. The study site is located between a tidal creek and a shallow pond. Measurement plots were set up in two vegetation zones, a higher *Arthrocnemum-Limonium* stand nearer the tidal creek (S. Felice 1) and a lower *Spartina* area nearer the pond (S. Felice 2).

2. *Isola dei Laghi.* This is a salt marsh wetland opposite Torcello Island. This site is intermediate between the mouth of the Dese River and the San Felice site and probably receives sediments from both the sea and river. Wetland vegetation at the site includes *Juncus maritimus*, *A. fruticosum* and several *Salicornia* species, including *S. maritima*. One station was established in the marsh adjacent to a small tidal creek.

3. *Dese.* This site is a fresh water marsh near the mouth of the Dese River composed of nearly pure stands of *Phragmites australis*. This area receives sediment from the river. Two stations were established, one on the edge of a creek near the mainland several hundred meters away from the Dese River (Dese 1) and a second on the edge of the Dese River (Dese 2).

4. *Tessera.* This site is a relic salt marsh, located on the western edge of the lagoon adjacent to Marco Polo airport, which is experiencing edge erosion due to wind wave attack. The vegetation at the site is composed of *P. palustris*, *L. serotinum*, and *J. maritimus* and the marsh edge is being eroded by wind waves. Two marsh plots were established in March 1993. The marsh shoreline is characterized by two very similar small embayments. A sediment fence was constructed across one of these embayments in 1994 to enhance accretion, following the instructions of Boumans et al. (1997). SET stations (see

Methods) were established in the area, both in the saltmarsh (Tessera 1 and 3) and in the adjacent tidal flat, one behind the sediment fence (Tessera 2) and a second in a control area without a sediment fence (Tessera 4).

5. *Torson di Sotto.* This site is a constructed wetland area in the southern lagoon formed when dredged spoil was pumped into a confined area in 1992. After two years the site was sparsely covered with *A. fruticosum*. Stations were established in an adjacent natural wetland (Torson 1) and in the constructed wetland (Torson 2).

6. *Punta Cane.* This site is a deteriorating wetland in the southern part of the lagoon in an old delta of the Brenta River. Vegetation at this site includes *P. palustris*, *S. maritima*, *L. serotinum* and *A. fruticosum*. The marsh edge is being eroded by wind waves and tidal channels are cutting into the wetland. Two small tidal channels about 10 m long are developing near the stations. Duplicate plots were established in the marsh just behind the eroding marsh edge. Two additional SET stations were established about 4 m in front of the marsh where erosion is taking place. A number of additional markers were put in to determine horizontal erosion rates of the marsh edge, the enlargement of the tidal channels, and changes in the size of small ponds in the marsh.

Methods

At each study site, a 50m $\times$ 50 m area was marked off in a representative area of the marsh, and duplicate, randomly-placed 4m $\times$ 4 m plots were established for measurement of short-term sedimentation patterns, vertical accretion, and change in surface elevation. Short-term sedimentation was measured as the accumulation of material on 9 cm Whatmann ashless filters placed on the marsh surface (Reed 1992) from March 1993 to February 1995. Three pre-weighed, numbered filters were placed in each plot at various times throughout the study period and left in place for 2-4 weeks. Where parts of filters were lost, we estimated the percentage area lost and corrected for this. After collection, the filter pads were dried at 60 °C for 48 h and weighed to obtain total sedimentation. The filters were then combusted at 550 °C and re-weighed. The loss on combustion was considered organic matter and the remaining inorganic material. Because measurements were made on a short-term basis, the effect of particular types of events (such as storms, high river flow, rainfall, etc.) could be determined.

Vertical accretion was measured as the accumulation of material over artificial marker horizons laid down on the marsh surface (Cahoon & Turner 1989). The marker horizons consist of 0.25 m^2 plots of white feldspar clay spread on the marsh surface to an approximate depth of 1 cm. Three horizons were randomly laid down in each plot for a total of six markers. The markers were set up in March 1993 and sampled by coring in February and June 1994, and January 1995. Surface elevation changes were measured using a sedimentation erosion table (SET) developed for high precision measurements of surface elevation changes in wetlands (Boumans & Day 1993). The SET has an accuracy of about 0.2 cm. One SET station was established in each marsh plot in March 1993 (November 1993 in Torson di sotto) and surface elevation was measured every three months until March 1995 (for consistency between SET and markers measurements, rates reported in the text refer to the March 1993- January 1995 period). SET stations were also established on the eroding marsh front at Punta Cane which had been denuded of vegetation. Organic content was determined from three cores of the upper 15 cm of the soil from each station. Organic percentage was evaluated by ignition loss. Bulk density was determined from three to five micro cores (2 cm diameter) 5 cm deep, taken at each site. The vertical accretion rates obtained from the above measurements were compared with the rate of relative sea level rise (RSLR) for the area to determine if accretion is less than RSLR. The rate of RSLR has been determined from regression analysis of tide gauge data, long term cores and dating of historical markers (Sestini 1992). If there is a vertical accretion deficit (vertical accretion < RSLR), then estimates will be made of the effect of rising water level on wetland vegetation. Because coastal wetland vegetation grows only within a given elevation range (McKee & Patrick 1988) it can be calculated when the elevation will fall below that range given the vertical accretion deficit. Thus, we estimated when different wetland areas area likely to become stressed and begin to deteriorate.

Results and Discussion

Short-term sedimentation patterns

Short-term sedimentation at the different sites was highly variable, ranging from 0.1-73gm $^{-2}$ d^{-1}. This variability reflects the importance of high energy events, such as strong storms and river floods, in mobilizing and transporting sediments. The highest sedimentation (73 g m^{-2} d^{-1}) occurred in October 1993 at Punta Cane during a heavy storm with southeast winds of 100 kph (Fig. 2). High sedimentation rates associated with storms also occurred at Tessera and Laghi; and at Dese associated with river floods (Fig. 2). The lowest mean values (1.7 and 2.2 g m^{-2} d^{-1}) occurred at San Felice. Short-term sedimentation was uniformly low at this site indicating that high energy events do not promote sediment input

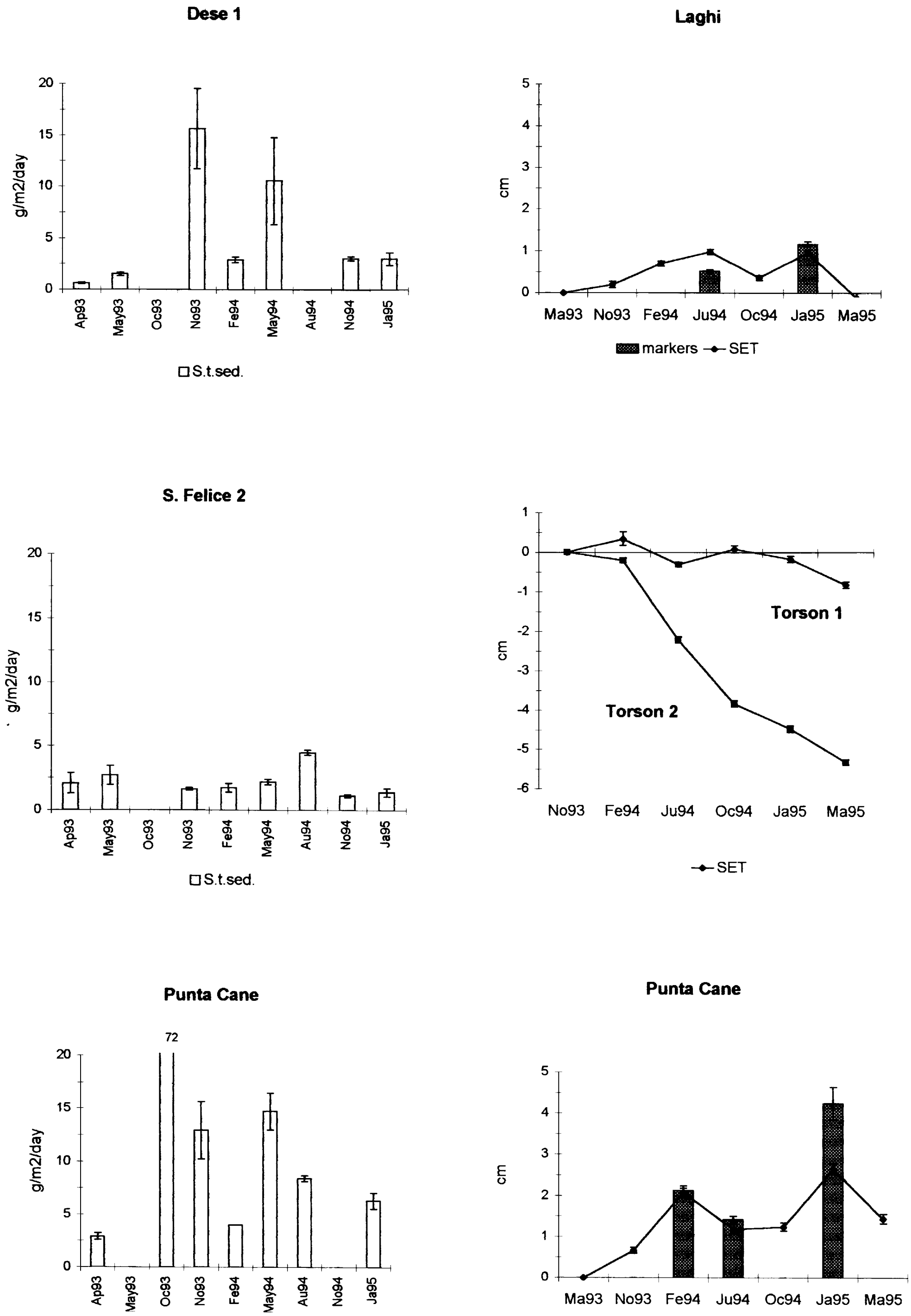

Fig. 2. Short-term sedimentation (left column), accretion and marsh surface elevation change (right column) at several sites in the Venice Lagoon (means ± standard errors are shown).

to this area (Fig. 2). This is probably the result of the jetties in the Lido inlet which restrict the input of sediments from the near shore Adriatic. Thus, this deteriorating saltmarsh has very low sediment input. A similar situation was reported for a coastal area in North Carolina where inlet dredging led to a reduction in sand input and a loss of salt marshes (Hackney & Cleary 1987). Short-term sedimentation in the Venice lagoon was in the range reported from other areas. In the Mississippi delta, Reed (1989, 1992) reported rates ranging from 0-40 g m^{-2} d^{-1}, with higher rates occurring near the coast and during winter frontal passages. Boumans & Day (1994) reported that mean annual short term sedimentation rates were 3.8 g $m^{-2}d^{-1}$ at a site near the coast and 1g $m^{-2}d^{-1}$ at a site far from the coast in the Mississippi delta; sedimentation rates were significantly lower in impounded areas which restricted tidal flow. In the Rhone delta, short term sedimentation ranged from zero to ca. 65 gm $^{-2}d^{-1}$, with the highest values occurring during a 10 year flood (P. Hensel pers. comm.)

Vertical accretion and surface elevation change

As with short term sedimentation, the results for vertical accretion and surface elevation change also showed strong differences among sites (Table 1, Figs. 2 and 3). The sites which experience high short term pulses of sediment input (Dese, Tessera 1, Laghi and Punta Cane) also had high rates of vertical accretion. The highest rate of vertical accretion (2.32 cm/yr) was at Punta Cane where strong wave energy leads to high sediment input. Vertical accretion was lower at San Felice, Torson and Tessera 3 (0.2-0.4 cm/yr). These results compare with accretion rates reported from other coastal areas. Pethick (1992) measured accretion rates of more than 2.0 cm in two years in an English salt marsh. Cahoon et al. (1995a) reported vertical accretion rates of 1.9-6.1 cm in coastal marshes of the Mississippi delta during a six-month period which included the passage of hurricane Andrew compared to 0.17-0.96 cm for the same marshes during six month periods prior to and after the hurricane. Baumann et al. (1984) found that in deteriorating marshes of the Mississippi delta, vertical accretion was less than the local rate of ESLR. Cahoon (1994) reported rates of accretion were 5 - 10 times lower in impounded Mississippi delta marshes as compared to non-impounded areas. Hackney & Cleary (1987) reported that salt marshes in a coastal lagoon in North Carolina had low accretion rates and disappeared when the sediment source was eliminated.

Surface elevation was, in all cases, less than vertical accretion, indicating that the accreted material was undergoing compaction and consolidation (Fig. 3). In several of the sites with high rates of vertical accretion (Punta Cane, Dese 2 and Laghi) there was an increase in surface elevation > 0.5 cm/yr. The increase was especially pronounced at Punta Cane (1.4 cm/yr) due to the high sediment input. At the rest of the sites, elevation change was near zero or negative, indicating that the vertical accretion was not sufficient to offset RSLR. Decrease in surface elevation was very high at Torson 2 - 3.8 cm/yr), a result of the rapid consolidation of the dredge spoil material used in the construction of this site. At times surface elevation changed very little (e.g., Torson 1) while at others, the rate of change was very consistent (as at Torson 2) (Fig. 2). At other sites, there were increases and decreases in both surface elevation and the depth of accreted material (e.g. Punta Cane, Fig. 2). We believe that this is the result of sequential erosional and depositional events (Day et al. 1998). These elevation changes are comparable to results from the middle Atlantic coast of the USA (Childers et al. 1993) and the Mississippi delta (Cahoon et al. 1995a,b). Childers et al. (1993) found that sediment elevation increase was 2-3 times local RSLR in areas near direct freshwater inputs (such as Dese), while at most other sites elevation was comparable to RSLR. In the Mississippi delta, some sites showed high seasonal variability as in Punta Cane, while the highest elevation increases followed hurricane Andrew.

The high rate of vertical accretion and surface elevation increase at Punta Cane was accompanied by rapid retreat of the edge of the marsh due to wave induced erosion. Over two years of measurements, the vegetation edge retreated at a rate of about 1 m/yr. The erosion of the marsh edge is proceeding in two phases. First, the

Table 1. Site characteristics, rates of accretion and surface elevation change observed on vegetated marshes in the Venice Lagoon.

Site	Elevation a.s.l. (m)	Rate of elevation change (SET) (cm/yr)	Rate of accretion (markers) (cm/yr)	Bulk density g dw/cm^3	Organic content (%)
Dese 1	0.30	0.34	0.82	0.35	25.81
Dese 2	0.28	0.58	0.81	0.31	28.25
Laghi	0.32	0.53	0.64	0.46	26.53
S. Felice 1	0.34	0.04	0.35	0.50	24.95
S. Felice 2	0.26	– 0.08	0.23	0.40	24.07
Tessera 1	0.30	–0.20	0.63	0.42	26.62
Tessera 3	0.32	–0.27	0.25	0.48	25.01
Torson 1	0.10	–0.14	0.44	0.49	21.89
Torson 2	0.60	–3.82	erosion	1.54	3.38
Punta Cane	0.51	1.45	2.32	0.30	24.18

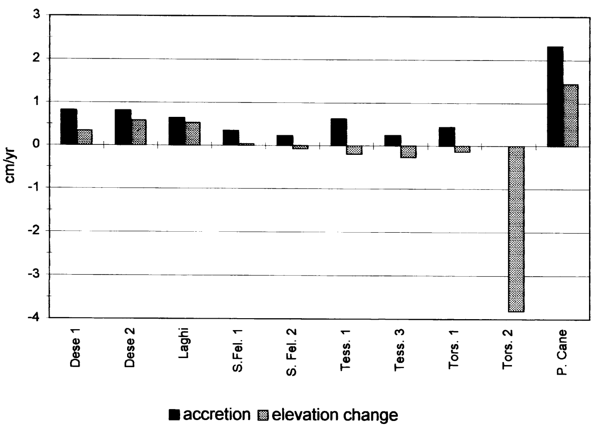

Fig. 3. Rates of accretion and surface elevation change between March 1993 and January 1995.

vegetation is eroded exposing an elevated intertidal bench about 5 m wide at approximately the level of the marsh surface which is devoid of vegetation. The substrate is composed of relatively firm peaty-clay material. Subsequently, this bench is eroded back along its seaward margin resulting in a sub-tidal elevation. Within our immediate study area, two new tidal channels are rapidly cutting into the marsh. The two channels are lengthening at a rate of 0.22 and 0.60 m/yr and widening at a rate of 0.48 m/yr and 0.26 m/yr, respectively. We observed distinct depositional layers in the exposed erosional surface on the edge of the forming tidal channel. Material of relatively recent origin such as plastic sheeting was buried 0.3-0.4 m deep indicating that this marsh formed rapidly over the past several decades by vertical accretion (Day et al. 1998). Pethick (1992) reported similar results for a salt marsh along the Essex coast of England where rapid retreat of the marsh edge due to wave erosion was accompanied by rapid vertical accretion on the marsh surface.

At present, eustatic sea level rise is between 1 and 2 mm/yr (Gornitz et al. 1982). If RSLR in Venice is 1.5 mm/yr (1.3 of subsidence + 0.2; minimum estimates by IPCC, in Warrick & Orlemans 1990) then Dese, Laghi and Punta Cane have a current rate of elevation gain sufficient to offset the present RSLR. The other stations are close to zero and if this rate persists in the long term, then these stations will lose elevation. If RSLR increases significantly, ca. 4 mm/yr 1.3 + 2.7 (mean IPCC estimates) only Dese, Laghi and Punta Cane will survive. The lack of sufficient levels of sediment input in areas such as San Felice is thus a critical factor affecting the survival of these marshes. Low sediment input has been reported to be responsible for loss of coastal marshes in other areas (Hackney & Cleary 1987; Day & Templet 1989; Day et al. 1993; Moorhead & Brinson 1995).

Sediment fence

Sedimentation in the fenced embayment was 4.3 cm/yr between June 1994 and January 1995, although there was variable sedimentation on either side of the fence and along the water's edge. Sedimentation in the unfenced control site during the same period was 0.3 cm/yr. New vegetation establishment was observed in the area where the fence joined the existing marsh. In this area, the fence had induced sediment deposition and vegetation had spread several meters into a previously unvegetated intertidal flat area. Vegetation was also spreading from the original marsh edge onto the intertidal flat in the embayment protected by the sediment fence. This vegetation is composed mainly of *Salicornia* spp. and *A. fruticosum*. We believe that vegetation spread is enhanced both by the decrease of water depth and reduction of wave energy. Both rapid accretion and vegetation spread have been noted in other areas with sediment fences (Schoot & de Jong 1982; Boumans et al. 1997).

Management suggestions

Wetland deterioration in the Venice lagoon is generally a result of either erosion by strong waves or low sediment deposition in marshes so that vertical accretion is inadequate to balance RSLR. Punta Cane is an example of wave erosion while San Felice has a sediment deficit. To reverse the trend of wetland loss will require both sediment management and management of wave energy. Sediment management includes trapping suspended sediments and re-use of dredged spoil. Over the last 10yr, CVN (Consorzio Venezia Nuova) and MAV (Magistrato alle Acque di Venezia) have constructed about 280 ha of artificial salt marsh in the Venice lagoon (Bettinetti et al. 1995).

Management of wave energy involves such approaches as use of breakwaters for strong waves and sediment fences for lower wave energies. We will now discuss each of these. Throughout this century, the Venice lagoon has deepened due to subsidence, eustatic sea level rise, and erosion of the bottom (Cavazzoni & Gottardo 1983). Some of the subsidence is geologic but most is the result of subsurface fluid withdrawal. In some parts of the lagoon, there has been strong erosion and sediment export to the sea. This problem has been exacerbated by the dredging of deep navigation channels in the 1960s. In the central basin where the deepening is highest (30 cm since the 1950's; Anon. 1993), the edge of most of the exposed salt marsh is eroding due to north-east winds because of the long fetch. By comparing official maps, Cavazzoni & Gottardo (1983) calculated that between the years 1933 and 1970 these marshes retreated at a rate of 0.8-2.7 m/yr. The tidal creek system in these marshes is expanding. The formation of new tidal creeks at Punta Cane is an example. Pethick (1992) reported a similar situation for saltmarshes along the Essex coast in England. He concluded that higher tidal and wave energy due to deeper water caused by rising sea level was responsible for the expansion of the tidal creek system. The creek network dissipates energy and a mature system is in equilibrium with the existing energy regime. Deeper water leads to higher physical energy levels and thus to an expansion of the tidal network.

Sediment management can be either active or passive. The most aggressive and active form of sediment management is the use of dredged spoil to form new marshes. In the Venice lagoon, this is normally done by creating a containment area with closely spaced posts covered with geotextile and then pumping spoil into the area, up to the level of mean high tide. This technique has been used to form shallow subtidal flats as well as intertidal areas where marsh vegetation can grow. The site of Torson 2 is an example of a created wetland. As our results show, these areas have a high rate of subsidence at first due to consolidation and compaction. At Torson 2, the spoil had a high sand content and higher bulk density which resulted in a rather poor soil. In cases such as this, enriching the soil may speed vegetation growth. In marsh areas which are experiencing an accretion deficit, periodic application of a thin layer of sediment to the marsh surface can maintain these areas. This has been done in the Mississippi delta, where a jet spray has been used to apply sediment over a large area of marsh (Cahoon & Cowan 1988). The marshes at San Felice are an example of a wetland where this technique would be useful; a project was approved by MAV to jet spray part of this area in the spring of 1996. Looking to the future, diversion of sediment laden river water is a possibility for bringing new sediments into the lagoon (Day & Templet 1989).

The enhanced sedimentation behind the sediment fence at Tessera, as well as results from elsewhere (Schoot & de Jong 1982; Boumans et al. 1997), indicate that this management technique holds great promise for the creation and restoration of intertidal wetlands. The fences work better, however, under certain environmental conditions. The success of sediment fences is a function of wave energy, water depth and sediment supply. They work better in areas where there is moderate to low wave energy. Because they are constructed of vegetation material, they will not sustain high wave energies. In such cases, wave energy should be controlled by breakwaters as described above. Water depth is another important consideration when using sediment fences. Accretion rates which can be achieved behind fences are generally in the order of 3-5 cm/yr. The fences generally last for 3-5 years before they have to be rebuilt. Therefore, the total accretion over the life time of a single fence will range between about 10-25 cm. Thus, fences will be most successful in shallow water. If the fence is adjacent to an existing marsh, the elevation of the bottom will often slope gently up to the marsh and the marsh will serve as a source of plant propagules to colonize the adjacent accreting mud flat. Finally, sediment fences will work best if there is an adequate source of suspended sediments. In the coastal zone, there are two primary sources of suspended sediments, riverine input and sediments resuspended by winds and waves from the bottom of coastal bays and the near-shore zone. Sediment fences should be constructed in areas where there are suspended sediments from either of these two sources. Management of wave energy is necessary for both control of erosion and trapping of sediments. The higher wave energy caused by the deepening of the lagoon is causing accelerated erosion for many existing and created salt marshes. For this reason, the use of breakwaters in front of natural and artificial salt marshes would be beneficial for protecting the marsh edge and also the frontal tidal flat. As indicated above, sediment fences are a means of reducing wave energy. Basically, the fence serves to reduce turbulent motion so that suspended sediment deposition is enhanced.

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