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# Sedimentation Rates: Anthropogenic Impacts and Environmental Changes in Transitional Water Systems

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**Abstract:** The trophic evolution of the Venice lagoon was analyzed by studying the particulate collected monthly with sedimentation traps in many areas of the Venice lagoon since 1989, and at Goro in 2018–2019. Sedimentation rates were strongly related to the presence of macrophytes, which reduced sediment resuspension, and to anthropogenic pressures, such as clam harvesting and naval-boat traffic, that triggered sediment resuspension and loss. The highest mean annual sedimentation rates (from 2000 to over 4000 g DWT $m^{-2}$ $day^{-1}$) have been recorded in many areas of the Venice lagoon between 1998–1999 to 2001–2002, during the intense fishing activities of the clam *Ruditapes philippinarum*. High values (daily peaks up to 5224 g DWT $m^{-2}$ $day^{-1}$) were also recorded in areas affected by marine and/or recreational traffic, due to the high wave motion. In contrast, the presence of high biomasses of macroalgae, or seagrasses, reduced significantly sediment resuspension and settlement, with mean annual sedimentation rates ranging between 40 and 140 g DWT $m^{-2}$ $day^{-1}$ and minimum values of 6–10 g DWT $m^{-2}$ $day^{-1}$. High sedimentation rates were strongly related to a lower sediment grain-size, with loss of the fine fraction and dispersion of nutrients and pollutants in the whole lagoon.

**Keywords:** sedimentation rates; anthropogenic pressures; grain-size changes; nutrient spread; transitional water systems

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**Citation:** Sfriso, A.; Buosi, A.; Juhmani, A.-S.; Tomio, Y.; Mistri, M.; Munari, C.; Sfriso, A.A. Sedimentation Rates: Anthropogenic Impacts and Environmental Changes in Transitional Water Systems. *Water* **2022**, *14*, 3843. https://doi.org/10.3390/w14233843

Academic Editor: Bommanna Krishnappan

Received: 25 October 2022
Accepted: 22 November 2022
Published: 26 November 2022

## 1. Introduction

The ecological conditions of transitional water systems (TWS) are strictly related to many anthropogenic pressures, such as morphological variations [1,2], habitat destruction [3–5], pollutant loads [6–8] and the introduction of alien species [9–13].

The population density and/or the river outflows in these areas are also very important. Presently, about 40% of the world's population lives within 100 km of the coast [14], and by 2025 that figure is likely to double [15].

High population density increases the discharge of organic particulate and the resuspension of sediments coming from commercial and tourist ports, nautical traffic and fishing activities, such as clam harvesting. Rivers convey high quantities of sediments [16,17] that come from the hinterland making the restoration of coastal environments problematic [7].

The Venice lagoon and the lagoons and ponds of the Po Delta are two examples of these conditions. In the first case, the ecological conditions were affected by the direct pressures of the population, while the transport of sediments by rivers is negligible because they were diverted in the sea by Serenissima Repubblica of Venice [18]. In the second example, environment quality is affected both by the river particulate transport and the intense fishing of the Manila clam *Ruditapes philippinarum* (Adams and Reeve) [19].

The Venice lagoon has more than a millennial history. Since the fifteenth century, the Republic of Venice has removed the main rivers that flowed into its basin, flowing them directly into the sea, in order to avoid the progressive burial that would have nullified the natural defenses due to its lagoon [18]. As a consequence, the amount of particulate suspended in this basin, and the sedimentation rates, are driven mainly by anthropogenic activities.

A study by Serandrei-Barbero et al., 2006 [20], reports a chronology for the accumulation of subtidal and intertidal sediments in the lagoon of Venice in various palaeo-environments, by studying the changes in benthic foraminiferal assemblages in cores of approx. 1 m deep over various time-spans. The long-term sedimentation rates (SRs), inclusive of subsidence and eustasy, were about 1.1 mm year$^{-1}$ between 2500 and 1500 y BP (before present) and about 0.5 mm year$^{-1}$ from 1500 y BP, to the present. No information on the quantities of sediments or particulate that are resuspended and fall back into the lagoon bottom, and on their composition and pollutant content, is reported. A more recent study on the impact of exceptional tides, using the radionuclide method, reports similar results [21]. Other researchers studied historical changes in sedimentation by bathymetric variations during the last century [22], or modelled sediment entrainment, transport and deposition caused by the combined action of tidal currents and wind waves in shallow micro-tidal basins [23].

Scarce information is available on the quantities of resuspended sediments or particulates that settle on the lagoon bottom [24,25], specifically, a gap exist in knowledge about changes in composition on medium-long term time scales.

A study on the sediment resuspension in the Venice lagoon, and the concentrations of nutrients in the resuspended particulate matter (SPM), was carried out by Sfriso et al., 1990 [26]. Particle resuspension was determined in different areas of the Venice lagoon from undisturbed sediment cores by using a portable device, which produced shear stresses from 5 to 10 dynes cm$^{-2}$, reproducing the water turbulence generated by normal windy storm events in the lagoon. The resuspended sediment varied from 4.22 ± 2.83 mg cm$^{-2}$ (6.6 dynes cm$^{-2}$) to 7.34 ± 4.53 mg cm$^{-2}$ (9 dynes mg cm$^{-2}$), accounting for a layer thickness varying from 0.011–0.036 to 0.059–0.165 mm, depending on sediment characteristics. The concentrations of organic carbon (Corg), total nitrogen (Ntot) and total phosphorus (Ptot) determined in the resuspended matter were 2–5 times higher than in the 5-cm surface sediments.

In the following years, SRs were determined directly in the field by means of sedimentation traps, providing continuous data on sediment and nutrient spread on an annual, monthly, daily, or other time unit basis.

The purpose of this work is to make an analysis of the SRs recorded in the Venice lagoon by our research team from 1989 to 2021. The variations of SPM, grain-size and nutrient concentrations that have occurred in individual stations in different years, and globally, for the entire period 1989–2021, are analyzed according to the different scenarios that have characterized this lagoon: (i) the period of hyper-dystrophic conditions [27] and macroalgal dominance [28] (up to 1993); (ii) the period of the fishing of the Manila clams *Ruditapes philippinarum* Adams and Reeve with destructive dredging tools [24,25] (1993–2010); and (iii) the period of anthropogenic impact decrease [29,30] (2011–2021). A comparison with the SRs detected in three stations affected by high trophic conditions and intense clam farming in Sacca di Goro in the Po Delta, between 2018 and 2019, was also performed.

## 2. Materials and Methods

### 2.1. Study Areas

The determination of the amounts of particulate matter settled on the lagoon bottom (SPM), sedimentation rates (SRs) and nutrient spread by SPM on different time scales started in 1989–1990 in the Venice lagoon. However, some samples were also performed at Sacca di Goro in the Po Delta to check the impact of consolidated clam farming activities.

### 2.1.1. Venice Lagoon

The lagoon of Venice (Figure 1) with a surface of 549 km$^2$ (sexagesimal coordinates: 45° 12–34′ N, 12° 08–38′ E) is the largest lagoon in the Mediterranean Sea. It includes most of the different ecological conditions present in the Italian TWS [31].

In 1989–1990 three stations dominated by different primary producers were sampled. The first station (Alberoni), located near the middle Venice lagoon inlet, was dominated by seagrasses. The second (San Giuliano), mainly colonised by phytoplankton, was selected close to the mainland on the northeast side of the bridge connecting Venice historical center to the mainland. The third station (Sacca Sessola), placed in the Lido watershed, was colonised by a luxuriant growth of macroalgae, especially Ulvaceae. In the following years SRs were determined in several stations (Figure 1) characterized by different ecological conditions, obtaining 79 years of data with monthly samples (Table S1). Many stations were sampled in different years allowing to reconstruct SRs, SPM grain-size and SPM nutrient concentrations changes both in the single stations and in the whole lagoon during the last 30 years.

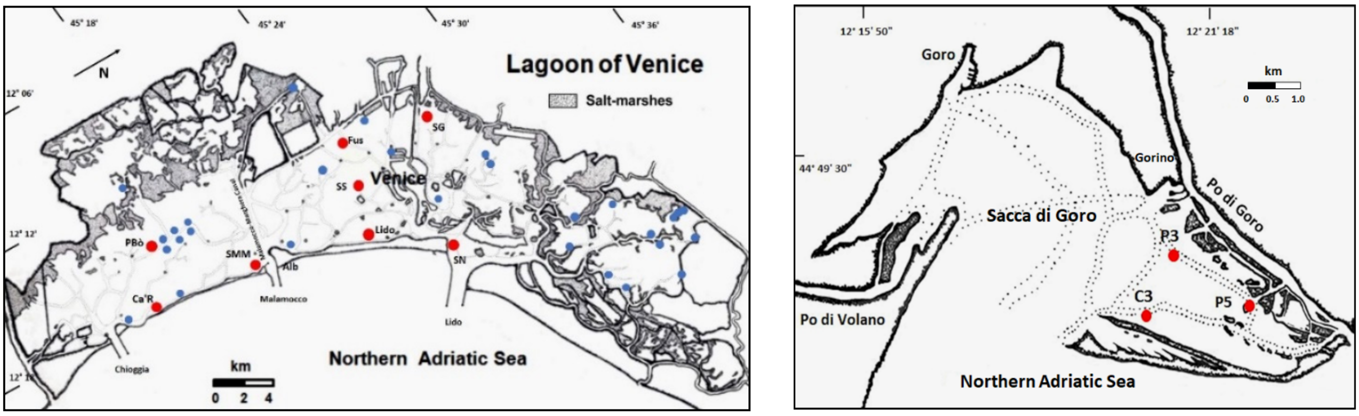

**Figure 1.** On the left: Lagoon of Venice and sampling sites. In red stations with 3 years of sampling at least. In blue stations with 1–2 sampling years. On the right: Lagoon of Goro and the three sampling sites.

### 2.1.2. Goro Lagoon

This is a small lagoon of approx. 27 km$^2$ (sexagesimal coordinates: 44° 47–50′ N, 12° 15–24′ E) placed in the southern part of the Po Delta, between Po di Goro and Po di Volano (Figure 1), which strongly affects the morphology and ecological conditions of this TWS. The lagoon is characterized by high trophic conditions and is largely used for the breeding of clams [19].

Sedimentation rates were measured in three stations (P3, P5 and C3) between 2018 and 2019, sampled in the framework of the Life AGREE- coAstal laGoon long teRm managEmEnt (LIFE13 NAT/IT/000115).

All three stations were located on the edges of the canal dug to increase water circulation and avoid anoxic crises. The station P5 was located near a canal that connect Po di Goro to the lagoon. The station P3 was placed near the mainland of Gorino, whereas the station C3 was selected near the sandy shore that separates the lagoon from the sea.

## *2.2. Sedimentation Traps*

Sedimentation rates were determined by means of sedimentation traps (Figure 2) set up for the lagoon shallow bottom, which can also emerge at low tide. They have a quadrangular shape with a side of 20 cm × 20 cm, height of 10 cm and a mouth of 15 cm × 15 cm covered with a 1–2 cm net to prevent the entry of fish to lay eggs (Figure 2). Traps were usually made of Plexiglas, or stainless steel. Plexiglas traps were used to determine nutrient and pollutant concentrations, wheras stainless steel traps were emploied to determine microplastic contamination. Indeed, the latter are affected by corrosion and unsuitable for the analysis of metals while those in Plexiglas could distort the study of microplasics.

Traps were left in each station for one year and sampled each month to determine the SRs, the percentage of Fines (fraction < 63 μm), the concentrations of nutrients and possibly of pollutants [32].

**Figure 2.** Sedimentation traps in Plexiglas to the left and in stainless steel to the right.

### 2.3. SPM Monitoring

The SPMs were collected on a monthly basis and transferred into measuring containers. After homogenization, two sub-samples of known volume were retained, marking the ratio between the total sample and the sub-sample. One subsample, after freeze-drying, was used for the determination of the SPM dry weight and for nutrient or other pollutant analysis. The other one was retained for the determination of Fines (fraction < 63 μm). Data were referred to the square meter taking into account both the volumetric ratio between the total sample and the sub-sample and the surface of the trap mouth (conversion factor: $10000/225\ \mathrm{cm}^2 = 44.44$). The final values were increased by 10% to compensate for the loss of SPM due to the various transfer operations of the samples, and the use of a frame with net to avoid the entry of fish and crabs into the trap.

Finally, because samples were collected in different dates, the SRs were reported on a monthly basis taking into consideration the number of days and SRs belonging to the first and second month. Samples were integrated accordingly in order to obtain the SRs of each month following the formula:

$$\text{Monthly SRs} = \text{g DWT day}^{-1} \times \text{N}^{\circ} \text{ days of month 1} + \text{g DWT day}^{-1} \times \text{N}^{\circ} \text{ days of month 2}.$$

In this way, the data of each year can be compared on any time basis: second, hour, day, month and year.

## 3. Results

### 3.1. Venice Lagoon

The SRs were obtained by our research team in the whole lagoon of Venice in the framework of many research projects starting from 1989–1990. The SRs recorded in stations with three sampling years at least are displayed in Figure 3, to highlight changes recorded over time.

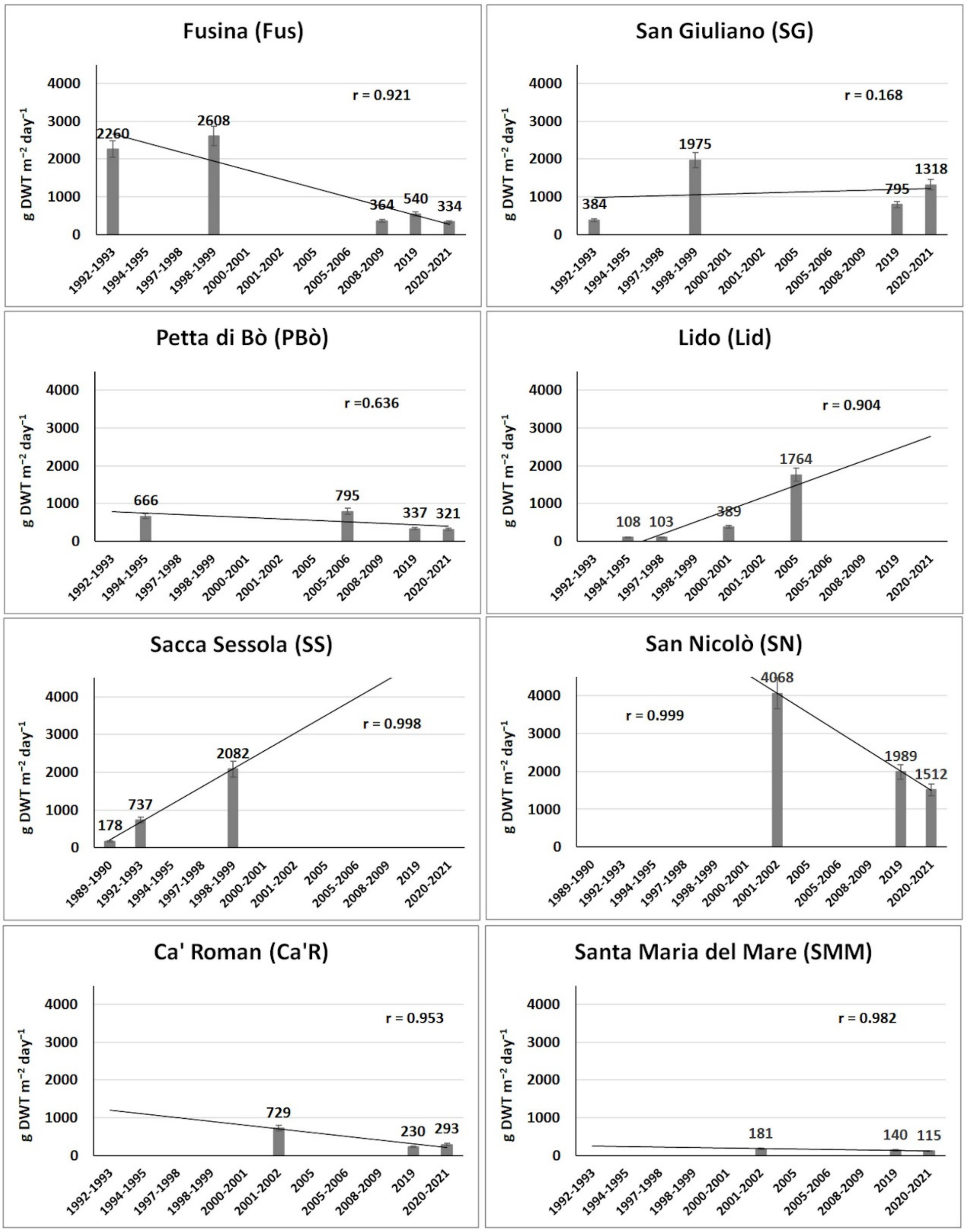

**Figure 3.** Sedimentation rates recorded in some stations of the Venice lagoon with 2–5 years of data. Bars are the coefficient of variation of the measures.

At Fusina (Fus), near the Malamocco-Marghera canal, we have recorded five sampling years: 1992–1993, 1998–1999, 2008–2009, 2019 and 2020–2021. In 1992–1993 the mean amount of SPM was 2260 g DWT $m^{-2}$ $day^{-1}$ (i.e., 825 Kg DWT $m^{-2}$ $year^{-1}$). This already relevant value increased up to 2608 g DWT $m^{-2}$ $day^{-1}$ in 1998–1999 during the highest clam fishing activities. In 2008–2009, SRs decreased to 364 g DWT $m^{-2}$ $day^{-1}$ (i.e., 133 Kg DWT $m^{-2}$ $year^{-1}$) and fluctuated between 540 and 334 g DWT $m^{-2}$ $day^{-1}$ in 2019 and 2020–2021, after the construction of some artificial salt marshes to reduce the wave motion due to the intense maritime traffic of the canal. The correlation coefficient (r = 0.921) of the linear regression of the different years was significant ($p < 0.049$).

San Giuliano (SG), with four sampling years, showed a similar trend. The highest SR was recorded in 1998–1999 (1975 g DWT $m^{-2}$ $day^{-1}$) whereas the lower one was found in 1992–1993 (384 g DWT $m^{-2}$ $day^{-1}$) in the presence of a macroalgal biomass ranging from 3 to 8 Kg FWT $m^{-2}$. In 2019 and 2020–2021 the SR values were intermediate due to the strong reduction of macroalgal biomass and the absence of clam fishing activities. The correlation coefficient (r = 0.168) of the linear regression was low and not significant ($p < 0.919$).

Petta di Bò (PBò), placed far from the direct impact of anthropogenic pressures, was sampled during four periods between 1994–1995 and 2020–2021. This station was colonized mainly by the seagrass *Zostera noltei* Hornemann, thus the SPM fluctuations were less relevant. The reduction of clam fishing and sediment resuspension in the nearest areas contributed to reduce significantly the sedimentation rates that changed from 666–795 g DWT $m^{-2}$ $day^{-1}$ in 1994–1995 and 2005–2006 to 337–321 g DWT $m^{-2}$ $day^{-1}$ in 2019 and 2020–2021. The correlation coefficient (r = 0.636) of the linear regression was not significant ($p < 0.172$).

Lido, placed in the Lido watershed, was sampled during 4 years between 1994–1995 and 2005. In 1994–1995, and 1997–1998, the area was covered by 5–12 Kg FWT $m^{-2}$ of Ulvaceae that reduced the sediment resuspension and sedimentation to 108–103 g DWT $m^{-2}$ $day^{-1}$ (i.e., 38–39 Kg DWT $m^{-2}$ $year^{-1}$) [28]. In the following years, clam fishing and the almost disappearance of macroalgal biomass progressively increased SRs to 389 (2000–2001) and 1764 g DWT $m^{-2}$ $day^{-1}$ (2005), i.e., approx. 16 times the SRs found in 1994–1995 and 1997–1998. No data are available for the following years, however clams disappeared and macroalgae recolonized this area with a biomass of 2–3 Kg FWT $m^{-2}$. The correlation coefficient (r = 0.904) of the linear regression was good but not significant ($p < 0.109$).

The three year sampling trend recorded at Sacca Sessola was very similar with a strong SR increase: from 178 (1989–1990) to 737 (1992–1993) and 2082 g DWT $m^2$ $day^{-1}$ (1998–1999). No other data are available but at present the area is not affected by clam fishing activities and has a negligible macroalgal biomass. The correlation coefficient (r = 0.998) of the linear regression of the different years was significant ($p < 0.028$).

The other three stations were colonized by seagrasses and placed near the lagoon mouth, one (SN) close to the port-entrance of Lido and the other two (Ca'R and SMM) in the shallow bottom, far for canal influence (Figure 1), near the port-entrances of Chioggia and Malamocco. The first SR determination in these stations took place in 2001–2002 and was replicated in 2019 and 2020–2021.

At San Nicolò (SN), affected by an intense maritime traffic and colonized by a dense prairie of *Cymodocea nodosa* (Ucria) Ascherson, the highest SRs were recorded. Indeed, in 2001–2002 the mean SRs were 4068 g DWT $m^{-2}$ $day^{-1}$ (i.e., 1485 Kg DWT $m^{-2}$ $year^{-1}$). However, SRs decreased to 1989 and 1512 g DWT $m^{-2}$ $day^{-1}$ in 2019 and 2020–2021, respectively. The correlation coefficient (r = 0.999) of the linear regression was very good but slightly not significant ($p < 0.051$).

Ca' Roman (Ca'R), and above all Santa Maria del Mare (SMM), are the stations that have suffered the least anthropogenic impacts, so the SRs were significantly lower. Ca'R showed mean SRs of 729 g DWT $m^{-2}$ $day^{-1}$ in 2001–2002, that decreased to 230 and 293 g DWT $m^{-2}$ $day^{-1}$ in 2019 and 2020–2021, respectively. A slight decrease was also observed at SMM, but the SRs of this station were significantly lower ranging from 181 g DWT $m^{-2}$ $day^{-1}$ in 2001–2002 to 140 and 115 g DWT $m^{-2}$ $day^{-1}$ in 2019 and 2020–2021. In both stations the correlation coefficient (r = 0.953 and 0.982, respectively) of the linear regression was good but not significant ($p < 0.135$ and $p < 0.184$).

The amount of Fines (fraction < 63 μm) and nutrient concentration in SPM varied in accordance with the SRs and generally were higher in the presence of low SRs. The values of Fines and the concentrations of nutrients found in the SPM of six stations, three placed close to the mainland (San Giuliano, Fusina, Petta di Bò) and three close to the port-entrances (Lido, Santa Maria del Mare, Ca' Roman) sampled in 2019 and 2020–2021 (Figure 4) are a good example.

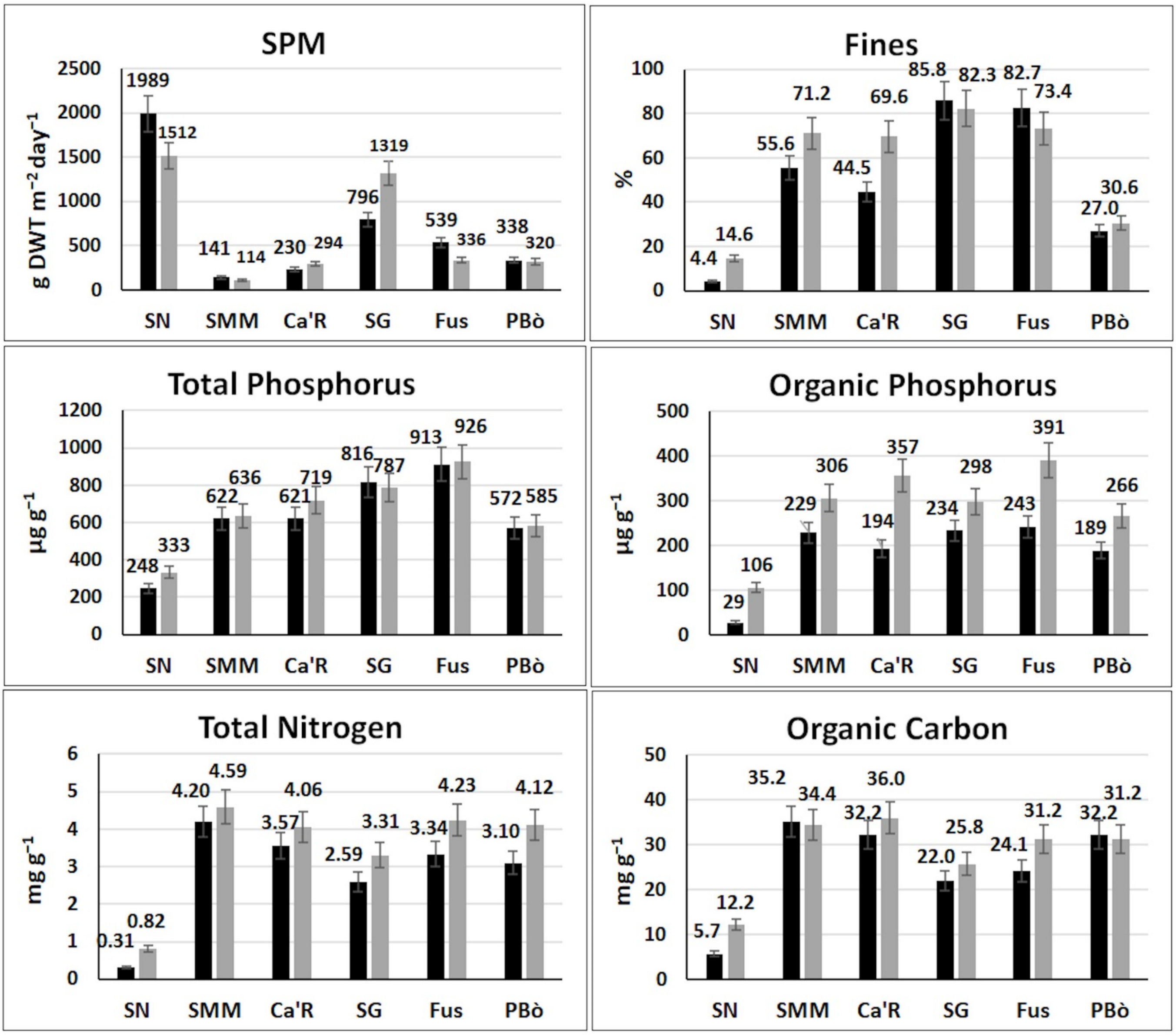

**Figure 4.** Mean values of SPM, SR, Total Phosphorus (Ptot), Organic Phosphorus (Porg), Total Nitrogen (Ntot) and Organic Carbon (Corg) in six stations sampled in 2019 and 2020–2021. Bars are the coefficient of variation of the measures.

Indeed, the SRs recorded in 2019 and 2020–2021 at SN had the highest amounts of SPM (1989 and 1512 g DWT m$^{-2}$ day$^{-1}$, respectively) and the lowest values of Fines (4.4 and 14.6%), Total Phosphorus (Ptot: 248 and 333 µg g$^{-1}$), Organic Phosphorus (Porg: 29 and 106 µg g$^{-1}$), Total Nitrogen (Ntot: 0.31 and 0 82 mg g$^{-1}$) and Organic Carbon (Corg: 5.7 and 12.2 mg g$^{-1}$). On the contrary, SMM that displayed the lowest mean SPM (141 and 114 g DWT m$^{-2}$ day$^{-1}$) showed relatively high amounts of Fines (55.6 and 71.2%), Ptot (420 and 459 µg g$^{-1}$), Porg (229 and 306 µg g$^{-1}$) and the highest concentrations of Ntot (4.20 and 4.59 mg g$^{-1}$) and Corg (35.2 and 34.4 mg g$^{-1}$, respectively). The other stations showed intermediate trends.

These strong relationships were confirmed by the Pearson's correlation analyses (Table 1). In both the sampling years (2019 and 2020–2021) SPM was inversely correlated to Fines, Corg, Ptot, Porg, Ntot concentrations. On the other hand, Fines were positively correlated to nutrient concentration and Corg. In 2019 the most significant ($p$ < 0.05) correlations were recorded between SPM and Ntot, Corg (r = −0.98) and Porg (r = −0.86), whereas Fines were significantly correlated to Ptot (r = 0.95) and Porg (r = 0.85). In 2020–2021 the significant correlations were similar but slightly smaller (Table 2).

**Table 1.** Pearson's coefficients between the amounts of SPM, Fines and nutrient contents in six stations sampled in 2019 and 2020–2021 in the Venice lagoon. In red significant values $p < 0.05$.

| | 2019 | | | | | | | 2020–2021 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **SPM** | **Fines** | **Porg** | **Ptot** | **Ntot** | **Corg** | | **SPM** | **Fines** | **Porg** | **Ptot** | **Ntot** | **Corg** |
| **SPM** | 1.00 | | | | | | **SPM** | 1.00 | | | | | |
| **Fines** | −0.49 | 1.00 | | | | | **Fines** | −0.34 | 1.00 | | | | |
| **Porg** | −0.86 | 0.85 | 1.00 | | | | **Porg** | −0.70 | 0.83 | 1.00 | | | |
| **Ptot** | −0.62 | 0.95 | 0.92 | 1.00 | | | **Ptot** | −0.44 | 0.86 | 0.93 | 1.00 | | |
| **Ntot** | −0.98 | 0.56 | 0.88 | 0.66 | 1.00 | | **Ntot** | −0.87 | 0.67 | 0.88 | 0.72 | 1.00 | |
| **Corg** | −0.98 | 0.35 | 0.77 | 0.48 | 0.95 | 1.00 | **Corg** | −0.89 | 0.65 | 0.87 | 0.66 | 0.97 | 1.00 |

**Table 2.** Pearson's coefficients between the amounts of SPM, Fines and nutrient contents in three stations sampled in 1989–1990 and 1998–1999 in the Venice lagoon. In red significant values $p < 0.05$.

| **Three Stations (1989–1990/1998–1999)** | | | | |
|---|---|---|---|---|
| | **SPM** | **Fines** | **Ptot** | **Ntot** |
| **SPM** | 1 | | | |
| **Fines** | −0.88 | 1 | | |
| **Ptot** | −0.39 | 0.34 | 1 | |
| **Ntot** | −0.68 | 0.52 | 0.91 | 1 |

Similar results were obtained in three stations placed close to the mainland (San Giuliano), the Lido watershed (Sacca Sessola), and the Malamocco port-entrance (Alberoni) sampled in 1989–1990 and 1998–1999 (Figure 5). In the presence of clam fishing activities, from 1989–1990 to 1998–1999 the amount of SPM increased significantly in all three stations, especially at Sacca Sessola (11.6 times), where clam harvesting was higher, ranging from 178 to 2079 g DWT $m^{-2}$ $day^{-1}$. At Alberoni and San Giuliano SPMs grew 5.58 (from 112 to 625 g DWT $m^{-2}$ $day^{-1}$) and 5.14 times (from 384 to 1975 g DWT $m^{-2}$ $day^{-1}$), respectively.

As a result, the amount of Fines decreased slightly in all the three stations. With the increase of SRs and the decrease of Fines also the concentrations of Ptot and Ntot decreased, especially at Sacca Sessola, where the sediments were affected by intense clam harvesting activities. In this station, Ptot decreased from 719 to 473 µg $g^{-1}$ and Ntot was reduced by almost a third, from 3.37 to 1.14 mg $g^{-1}$.

The correlation coefficients (Table 2) showed trends similar to the results reported for the six stations monitored in 1919 and 2020–2021. Indeed, SPMs were inversely correlated to Fines, Ptot and Ntot, whereas Fines were positively correlated to nutrient concentrations. In this period, characterized by intense clam fishing activities, significant coefficients were only recorded between SPMs and Fines (r = −0.88) but not with nutrient concentrations.

The global trend of the sedimentation rates in all the stations monitored in the Venice lagoon between 1989–1990 and 2020–2021 is highlighted in Figure 6. On the whole, the mean value of the 79 years of SR sampling was 706 g DWT $m^{-2}$ $day^{-1}$, accounting for 258 Kg DWT $m^{-2}$ $year^{-1}$. The global trend highlighted by the regression line showed a significant ($p < 0.0064$) decrease.

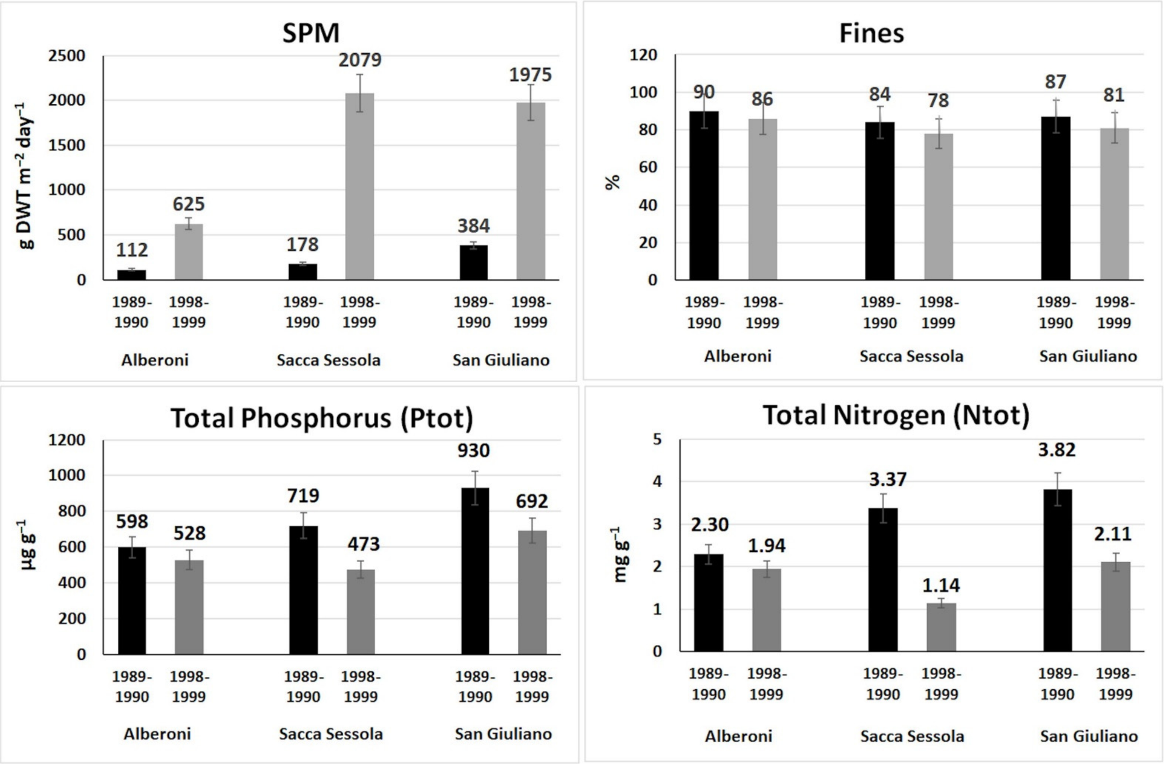

**Figure 5.** Mean values of SPM, Fines, Total Phosphorus (Ptot) and Total Nitrogen (Ntot) in three stations sampled in 1989-1990 and 1998-1999. Bars are the coefficient of variation of the measures.

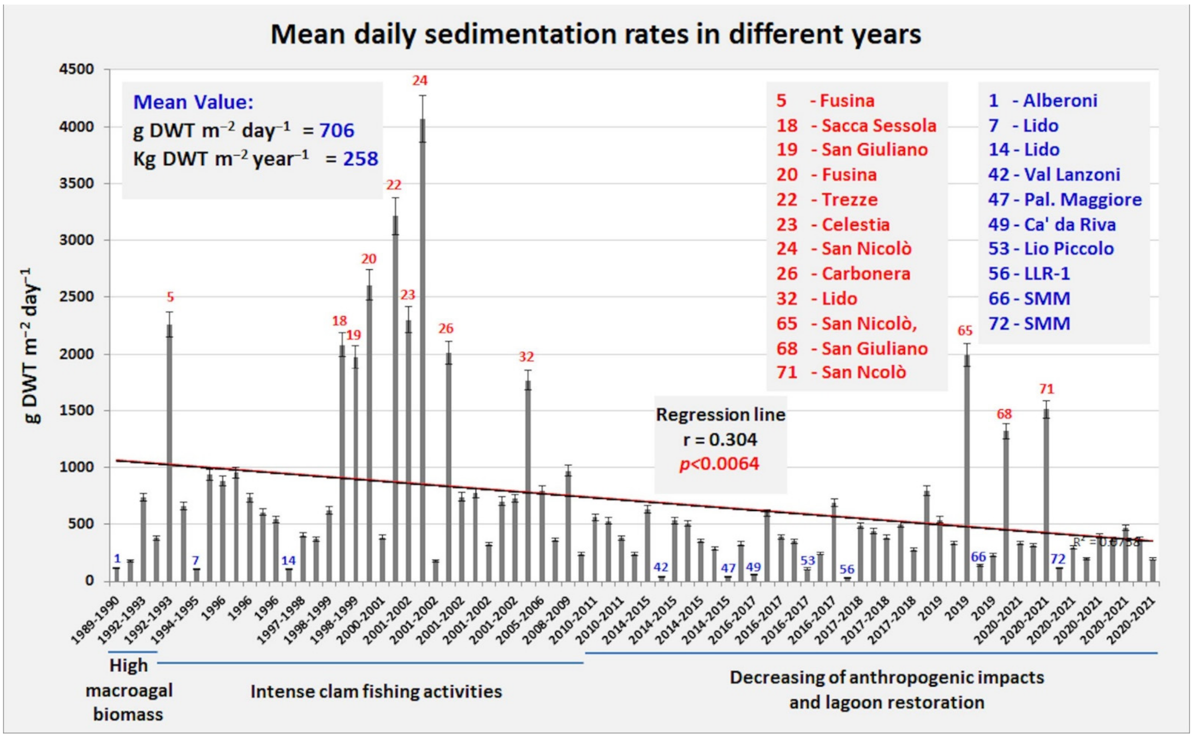

**Figure 6.** Mean daily sedimentation rates in 79 stations sampled between 1989 and 2020–2021 in the Venice lagoon. In red the stations with the highest SRs (>1319 g DWT m$^{-2}$ day$^{-1}$). In blue stations with the lowest sedimentation rates (<141 g DWT m$^{-2}$ day$^{-1}$). Bars are the coefficient of variation of the measures.

### 3.2. Sacca di Goro

In 2018–2019 the sedimentation traps were also used in three stations (C3, P3, P5) of Sacca di Goro in the framework of the project Life AGREE, whose objective was to increase the water exchange in the choked areas of the lagoon by digging a new canal. The SPM amounts are shown in Figure 7, together with the flow rate values of the Po river recorded at the ARPAE sampling station in Borgoforte (available at ARPAE Open Database). The values were very variable in the different seasons but the means annual SRs of the three stations were very similar ranging from 153 to 208 and 211 g DWT $m^{-2}$ $day^{-1}$ in P3, P5 and C3, respectively. The highest SPMs were recorded from August to November in sts C3, P3, P5 with 583, 578 and 489 g DWT $m^{-2}$ $day^{-1}$, respectively. Figure 7 also shows the flow of the Po river which, except for November in st P5, does not seem to have affected the sedimentation rates of the different stations (no correlation).

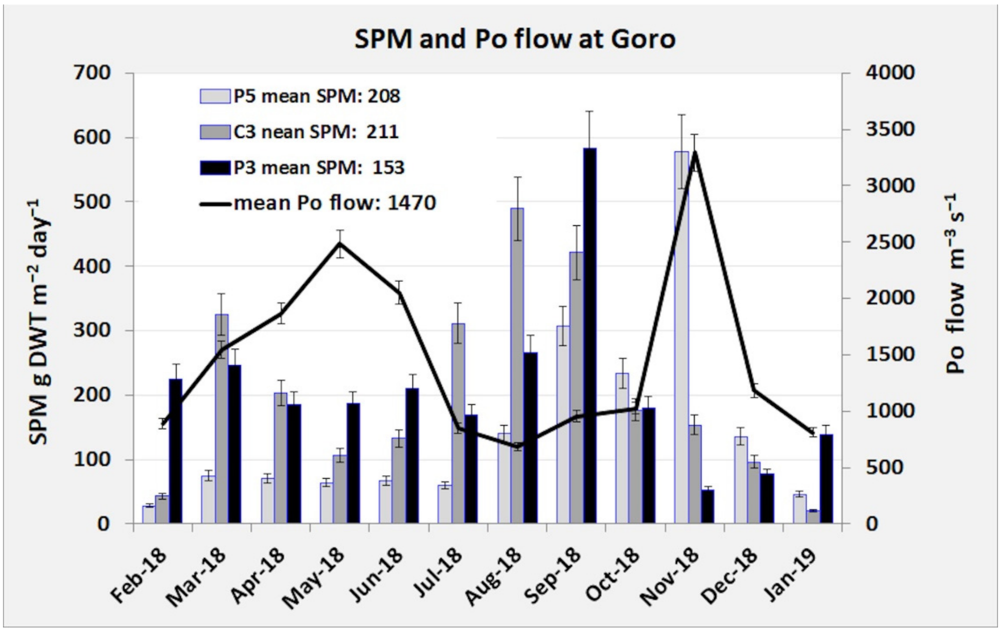

**Figure 7.** SPM trend in tree stations of the Po Delta and river flow on monthly basis.

## 4. Discussion

Water transparency is one of the most important parameters which control the primary production of macrophytes in the TWS [31]. It mainly depends on the phytoplankton concentration and the amount of suspended particulate [24,25]. Sedimentation traps allow to integrate over time the quantities of organic and inorganic particles that settle on the bottom, giving more significant values than the values obtained by filtering a certain volume of water during the sampling campaigns. Sampling traps are emptied every month on an annual basis and sedimentation rates can be extrapolated to any time unit (annual, daily, instantaneous, etc.). If these measures are repeated in the same stations in different years, they can also give important long-term information. Therefore, the determination of the SPM was a routine measure done in our sampling campaigns. Now we have a remarkable series of SR sampling years that allow to understand the trophic evolution of the lagoon under different anthropogenic pressures, and make predictions for the following years. Furthermore, the SPM analysis of the concentrations of nutrients [30] and pollutants [32–34], gives us information on the spread of these elements.

SR trends sampled in different years in some stations (Figure 3), although they cover different periods, showed a general increase from 1989 to 2003 and then a gradual decrease. This period corresponded to the maximum disturbance of the superficial sediments due to the uncontrolled and illegal harvesting of the Manila clams. In this case, approx. 120 fishing boats (up to 10 tonnes) with heavy (up to 600 kg) and large dredges (140–160 cm) and

6–700 small boats, equipped with dredges approx. 60 cm large, dredged the first 10–15 cm of the lagoon superficial sediments, resuspending enormous quantities of material [24,25]. The finest sediments (Fines) were dispersed throughout the lagoon increasing up to 16 times the SPM collected by sedimentation traps (see sts. Lido and Sacca Sessola) or were transferred into the sea by tidal exchanges. In the following years clam stocks depleted and aquatic angiosperm recolonized the lagoon bottom [35], reducing sediment resuspension and increasing water transparency. However, it should be emphasized that the growth of macrophytes is favored not only by the presence of clear waters but also by low SRs, as the resuspended sediments cover the leaves and thalli of the macrophytes, reducing the photosynthetic activity.

In contrast, the presence of aquatic angiosperms such as at Petta di Bò, Santa Maria del Mare and Ca' Roman, prevented sediment resuspension, therefore in these stations SR changes were lower and unsignificant.

The global analysis of the data collected from 1998 to 2021, albeit with considerable differences based on the stations considered (Figure 6), confirms a general decrease in the SRs ($p < 0.0064$). As already reported, three different periods can be identified. A period dominated by a luxuriant growth of nuisance macroalgae between the 1970s and the early 1990s [28]. During this period, in the presence of a biomass of Ulvaceae ranging from 5–20 Kg FWT $m^{-2}$, the sediment resuspension and settlement was averagely quite low (112–737 g DWT $m^{-2}$ $day^{-1}$) with the lowest values (7–10 g DWT $m^{-2}$ $day^{-1}$) recorded in late spring when the biomass was the highest. Unfortunately, for this period the availability of data is poor, but the presence of high biomass of free-floating laminar macroalgae such as *Ulva rigida* C. Agardh and *Ulva australis* Areschoug prevented the resuspension of sediments [36]. Subsequently, between the early 1990s and the beginning of the 2010s, SRs increased markedly, especially in the areas closest to the lagoon edges [24,25,30]. The introduction of the clam *Ruditapes philippinarum* Adams and Reeve in 1983 for commercial purposes [37], and its rapid spread in the lagoon, triggered an intense harvesting of this species with hydraulic and mechanical dredges and a strong impact on the biological communities [3,36,38], sediment [24,25] and nutrient spread [30]. The highest impact was in the late 1990s and the early 2000s, with a clam harvesting up to 40,000 tonnes [39,40], a sediment resuspension in many stations ranging from 2000 to over 4000 g DWT $m^{-2}$ $day^{-1}$ (Figure 6) and a sediment loss of 405,000 $m^3$ [39].

In the following years, due to over-exploitation, this resource, mainly harvested from illegal open access fishing, declined and clams continued to be raised and fished only in concessionary areas. With subsequent authorization deeds, the total area subject to concession (approx. 2589 hectares) was defined in 2009, divided into macro-areas and distributed over the lagoon surface [41]. Inside the concessionary areas, clam harvesting on average takes place every two years and not daily, with a drastic reduction of the environmental impacts. This confirms the results also found by Pessa et al., 2002 [42] in the lagoon of Venice showing that the environmental impact of clam farming is about an order of magnitude less than illegal fishing and equivalent to the effects of a few days of strong atmospheric perturbations.

In the following years (third period), except in some stations affected by high wave motion (San Nicolò) or characterized by fine sediments with a scarce macroalgal cover (San Giuliano), average SRs decreased to values lower than 500 g DWT $m^{-2}$ $day^{-1}$. In this period, the lagoon showed a general environmental recovery [29,35] with a significant aquatic angiosperm re-colonization and a replacement of opportunistic macroalgae with species of high ecological value [29]. The contribution of the Life SERESTO (Life12 NAT/IT/000331, www.lifeseresto.eu, accessed on 4 October 2022) and the Life LAGOON REFRESH (Life16 NAT/IT/000663, www.lifelagoonrefresh.eu, accessed on 4 October 2022) projects was also important. Indeed, in the context of these two projects, more than 101,000 rhizomes of aquatic angiosperms (*Zostera marina* Linnaeus, *Zostera noltei*, *Ruppia cirrhosa* (Petagna) Grande and *Cymodocea nodosa*) were transplanted in the northernmost part of the northern lagoon. Plants, after 5 years, have colonized more than 15 km$^2$ of lagoon bottom with a mean cover of 40%, and are again increasing.

SPM amounts were also linked to Fines amounts and nutrient concentrations. The latter were lower in the presence of high SRs, reducing the sediment contamination in surface sediments [30] with a significant decrease on the lagoon trophy, favoring the reduction of the opportunistic macroalgae such as Ulvaceae, and increasing the spread of aquatic angiosperms and macroalgae of high ecological value [29].

The results obtained in Sacca di Goro showed that in this lagoon SRs were relatively low (mean range 153–211 g DWT m$^{-2}$ day$^{-1}$), despite the fact that clam farming in concessionary areas were intense. Indeed, as we have seen for the concessionary areas of the Venice lagoon, in Goro clams are not continuously and illegally harvested affecting the superficial sediments, but they are reared with a drastic reduction of environmental impacts.

## 5. Conclusions

Seventy nine years of SPM collected by sedimentation traps from many stations spread in the whole Venice lagoon, and more recently in three stations of the Po delta, showed a strong variation of SRs, SPM grain-size and SPM contamination.

A high trophy with abundant production of laminar macroalgae, such as Ulvaceae, or the presence of seagrasses, reduced the phenomena of sediment resuspension and the spread of nutrients and pollutants. Vice versa, anthropogenic activities affecting the superficial sediments, such as clam harvesting and the high turbulence created by naval-boat traffic and port activities, resuspended large quantities of sediments, increasing the dispersion of the finest particles rich in nutrients and pollutants. Finally, clam farming in concessionary areas reduced SRs and SPM by approx. an order of magnitude.

Overall, the sedimentation trends recorded in single stations and in the whole period in the Venice lagoon allowed us to understand the strong relationship between anthropogenic pressures and the trophic evolution of this basin, and to hypothesize positive short-term changes.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w14233843/s1, Table S1: List of SRs recorded in the Venice lagoon.

**Author Contributions:** Conceptualization, A.S.; formal analysis, A.B., A.-S.J., Y.T. and A.A.S.; funding acquisition, A.S. and M.M.; investigation, A.S. and M.M.; methodology, A.S.; project administration, A.S. and M.M.; resources, A.S.; supervision, M.M., C.M. and A.A.S.; visualization, A.B., A.-S.J. and Y.T.; writing—original draft, A.S.; writing—review and editing, A.B., A.-S.J., Y.T., M.M., C.M. and A.A.S. All authors have read and agreed to the published version of the manuscript.

**Funding:** Scientific activity performed in the Research Programme Venezia2021, coordinated by CORILA (Consortium for Coordination of Research Activities concerning the Venice Lagoon system), with the contribution of the Provveditorato for the Public Works of Veneto, Trentino Alto Adige and Friuli Venezia Giulia.

**Institutional Review Board Statement:** Not acceptable.

**Informed Consent Statement:** Not acceptable.

**Data Availability Statement:** Not acceptable.

**Acknowledgments:** Most of the data collection and elaboration was obtained in the framework of the scientific activity performed in the Research Programme Venezia2021, coordinated by CORILA (Consortium for Coordination of Research Activities concerning the Venice Lagoon system), with the contribution of the Provveditorato for the Public Works of Veneto, Trentino Alto Adige and Friuli Venezia Giulia. The research program: Venezia 2021.

**Conflicts of Interest:** The authors declare no conflict of interest.

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