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Estuaries in Northern Spain: An Analysis of Their Sedimentation Rates

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Abstract: This review presents an analysis of recent sedimentation rates (SRs) in the Atlantic estuaries of northern Spain. Sedimentation rates were derived from sediment core dating using radiometric methods, including 210-Pb, 137-Cs, and 14-C, and were compiled from the existing literature. The observed SRs are consistent with global estimates, ranging from 0.04 to 55.1 mm/year. No correlation was found between SRs and estuarine morphology, basin size, or estuary size, and no apparent geographical pattern emerged. However, certain SRs were directly linked to human activities in the catchment area or the estuarine environment. Temporally, a general increase in SRs has occurred since the early 20th century, particularly notable from the mid-20th century, with indications of stabilization or reduction in the 21st century. Further research is essential to investigate these relationships more comprehensively to ensure the sustainability of these fluvial–marine environments.

Keywords: radiometric dating; sedimentation rate; estuary; rias; northern Spain

1. Introduction

Estuaries represent a key component in the geo-ecological interaction between terrestrial and marine systems and provide essential ecosystem services necessary for socioeconomic development. Therefore, both their evolution and current state are of significant scientific interest. These systems are both highly productive and vulnerable to global change. The rise in mean sea level, water temperature and salinity, intensity of astronomical tides, and riverine inputs directly influence sedimentation rates (SRs) and, therefore, the sustainability of these areas. Changes in land use in the watersheds and the restoration of marshes can help improve the quality and productivity of these areas [1].

Detrital materials of fluvial–marine origin are the primary components of the sedimentary sequences in the estuaries located in the southern Bay of Biscay; the organic materials present on their vegetated surfaces are quickly consumed during burial [2]. These sedimentary systems preserve valuable records for reconstructing past environmental conditions. The temporal evolution of these depositional environments is influenced not only by long-term and regional driving forces—such as freshwater discharge and relative sea-level positions—at millennial and centennial scales, but also by more recent human interventions at decadal and local scales.

Some studies on the northern Spain estuaries have a paleoclimatic perspective, focusing on environmental evolution during the last 10,000 years [3–8], while others, the majority, have traced their ecological and chemical evolution over time, with a particular interest in the influence of anthropogenic activities [9–15]. One of the most common approaches in the literature is the determination of SRs, i.e., sediment deposition ages [16–22]. Most estuaries have experienced notable changes over the past century due to direct land reclamation and activities in their river catchments [8,10,15,23–30]. Combined with sea-level rise [1,7,31–37],

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all these factors have greatly impacted the SRs of estuaries. Some studies utilize radionuclides such as 137-Cs and 210-Pb to establish a geochronology [2,10,11,15,31,38,39]. However, to corroborate the dating results, some works adopt a multiproxy approach, incorporating sediment grain size [40], micropaleontology (usually benthic foraminiferal) [2,10,34] and pollen content [41], geochemical composition [2,10,34], organic and inorganic carbon contents [33,42,43], total nitrogen content [44], trace metals [19,45–47], microplastics [48], stable isotopes (δ13-C) [49,50], or bulk magnetic susceptibility (BMS) [51,52], among other methods.

The following aspects have been analyzed regarding the study of estuarine sedimentary deposits in the north of Spain:

- Sedimentation rates (SRs) are used to accurately reconstruct coastal hydrographic responses to climatic and relative sea-level changes.
- Anthropogenic impact, including land reclamation, sewage, industrial, urban, and mining waste disposal, dredging, and changes in watershed use. This also involves determining the sources and timing of anthropogenic pollution, especially heavy metal contaminants.
- Contribution of specific episodes corresponding to well-known and dated catastrophic events.
- The role of salt marshes as drivers of variability in blue carbon stocks and burial rates across European estuarine habitats.

A global review of publications, from 1977 to 2020, was conducted by [21,22]. The authors applied dating methods such as 137-Cs and 210-Pb; most studies pertained to areas in the Northern Hemisphere. In addition to an extensive bibliography, they provide a detailed database that includes relevant information, such as main process studied in the publication, heavy metals of interest analyzed if the main process focused on contaminants and pollution, country where the study was conducted, geographical coordinates, information about core environment, and so on. In their work, these authors show 17 records (11 publications) for Spain, covering study environments, such as lakes, lagoons, floodplains, marshes, and coastal or estuarine areas. Only five of these papers include some of the areas studied in the present work [19,53–55]. Therefore, the present study should contributes to enhancing the global research conducted by [21,22] and facilitate the comparison of SRs found in different parts of the world.

The aim of the present work is to conduct a comprehensive analysis of data published in recent years regarding SRs recorded in several estuaries in northern Spain:

1. Generate a comprehensive database with all the survey records conducted to date in northern Spain.
2. Investigate the potential presence of a geographical or spatial pattern of SRs in the estuaries of northern Spain and of a correlation with global SR data. Additionally, examine the relationship between SRs and each estuary's geomorphological characteristics, including size, morphology, and sediment accumulation.
3. Analyze whether any temporal trend can be observed in SRs in different estuaries and determine whether any relationship exists between SRs obtained in each estuary and the sea-level rise recorded at different tide gauges.

Study Area

The estuaries analyzed in this work are located along the north–northwest coast of Spain (Figure 1; Table 1), from the Bay of Biscay (border with France) to the mouth of the river Minho in Galicia (border with Portugal) [56,57]. This represents 2429 km of coast [58], about the 27% of the Spanish coastline [59]. The area can be geologically split into two regions: the western region, Galicia, features gently undulating terrain with Precambrian to Paleozoic metamorphic and granitic bedrock; the central and eastern regions, including Asturias, Cantabria, and the Basque Country, in contrast, show a predominance of Paleozoic and Cenozoic sedimentary rocks, such as limestone, sandstone, and marl [56,59].

Table 1. Characteristics of estuaries in northern Spain and administrative region in which these are located (Figure 1). On the left, estuaries for which data on SR are available. On the right, estuaries where no core data have been collected.

No.	Estuary with Cores	Area (km^2)	Basin Area (km^2)	Geographical Region	No.	Estuary without Cores	Area (km^2)	Basin Area (km^2)	Geographical Region
1	Miño	23	17,081	Galicia	2	Baiona	0.92	128	Galicia
3	Vigo	156	414	Galicia	7	Camariñas	17	323	Galicia
4	Pontevedra	145	576	Galicia	8	Corme	27	487	Galicia
5	Arousa	230	1542	Galicia	17	Foz	2.8	295	Galicia
6	Muros	125	1611	Galicia	18	Eo	8.5	1023	Galicia
9	A Coruña	24	124	Galicia	19	Porcía	0.05	143	Asturias
10	Betanzos	19	404	Galicia	20	Navia	3.6	2578	Asturias
11	Ares	13.1	281	Galicia	21	Barayo	0.04	20.2	Asturias
12	Ferrol	27	526	Galicia	22	Río Negro	0.015	62	Asturias
13	Cedeira	4.7	117	Galicia	23	Esva	0.41	461	Asturias
14	Ortigueira	38	127	Galicia	26	Villaviciosa	6.7	170	Asturias
15	Barqueiro	10	201	Galicia	28	Tina Mayor	0.7	1194	Cantabria
16	Viveiro	28	310	Galicia	33	Mogro	2.2	656	Cantabria
24	Nalón	7.62	4903	Asturias	34	San Juan de la Canal	0.03	9.4	Cantabria
25	Avilés	1.45	199	Asturias	37	Galizano	0.07	9.2	Cantabria
27	Ribadesella	4.2	1287	Asturias	38	Ajo	1.02	95	Cantabria
29	Tina Menor	1.5	431	Cantabria	39	Joyel	0.9	8	Cantabria
30	San Vicente	3.09	111	Cantabria	40	Victoria	0.5	11.8	Cantabria
31	Oyambre–La Rabia	1	43	Cantabria	42	Aguera–Oriñón	0.6	157	Cantabria
32	San Martín–Suances	3.89	1043	Cantabria	46	Bakio	0.006	24.1	Basque country
35	La Maruca	0.12	2.02	Cantabria	48	Laga	0.00161	16.3	Basque country
36	Santander	22.4	508	Cantabria	49	Ea	0.012	10.7	Basque country
41	Asón–Santoña	18.7	740	Cantabria	50	Lea	0.5	89	Basque country
43	Barbadun	0.8	120	Basque country	51	Saturraran	0.0016	11.2	Basque country
44	Nervión–Bilbao	21.7	1783	Basque country	52	Artibai	0.5	172	Basque country
45	Butrón–Plentzia	1.6	172	Basque country	55	Inurritza	0.015	22.1	Basque country
47	Oka–Urdaibai	10.3	143	Basque country	56	Oria	2	863	Basque country
53	Deba	0.7	522	Basque country	57	Urumea	1.4	275	Basque country
54	Urola	1	342	Basque country	59	Bidasoa	7.6	713	Basque country
58	Oiartzun	1	75	Basque country					

Cantabrian (southern Bay of Biscay) and North Atlantic regions are characterized by a narrow continental shelf (approximately 4 and 17 km, respectively), tending to widen towards the east; in the northwest region (Galicia), the continental shelf is wider (30 km).

In general, rivers discharging into this sector of the Spanish Atlantic coast are relatively short, with the Minho and Navia rivers as notable exceptions, measuring 310 and 159 km, respectively. Their short length can be initially attributed to the Cantabrian Mountains (with a maximum altitude of 2648 m), a mountain range extending from east to west close to the coast and serving as a natural barrier.

Population density (Table 2) for the study area is around 140 inhabitants per km^2 (hab./km^2). The highest population densities are concentrated in Biscay, home to nearly half of the Basque Country's population; in particular, in the industrial areas surrounding the Nervión–Bilbao estuary.

According to [1,60], 93 estuaries of different types (rias, coastal plain estuaries, bar-built estuaries, deltaic estuaries, and ephemeral floods) can be identified along the Spanish coast, of which 59 are located in northern Spain (Figure 1). A primary definition of an estuary that is now widely accepted was proposed by [61]: "a partially enclosed coastal body of water that is connected to the ocean and where ocean water mixes with freshwater from land sources". In fact, according to [62], from a hydrographic and sedimentological perspective, only the inner part of the Galician rias can be considered estuaries, as these correspond to river valleys flooded by the rise in sea level during the Holocene [63]. For other authors [59], rias are estuaries with little to no sediment fill.

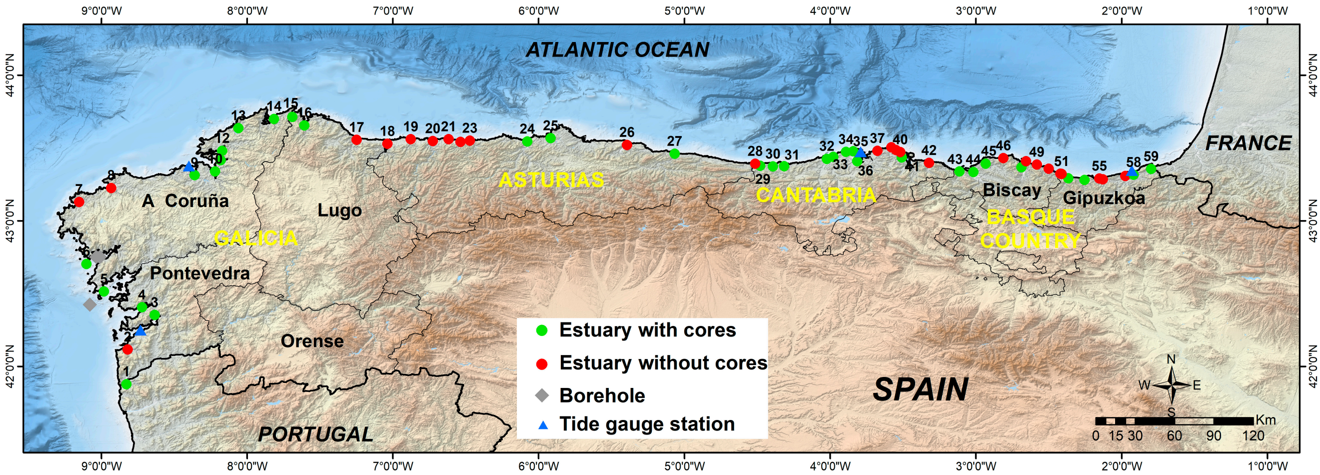

Figure 1. Estuaries located in the Spanish North Atlantic coast. In green, estuaries for which data on sedimentation rates (SRs) are available. In red, estuaries where no core data have been extracted. Numbers correspond to the reference in the first column in Table 1. Base map obtained from [64].

Table 2. Sociodemographic data of provinces where estuaries are located, coastline length, and population density in the river basin [58,65].

Region/Province	Area (km^2)	Population	Density (hab./km^2)	Coastline Length (km)
Galicia/Pontevedra	4495	946,710	210.61	398
Galicia/A Coruña	7950	1,123,884	141.37	956
Galicia/Lugo	9856	324,267	32.90	144
Asturias/Asturias	10,604	1,006,060	94.88	401
Cantabria/Cantabria	5321	588,387	110.58	284
Basque Country/Biscay	2217	1,153,282	520.20	154
Basque Country/Gipuzkoa	1909	726,712	380.68	92
Total	49,625	6,173,865	138.50	2429

2. Material and Methods

The most commonly used methods for estimating SRs are well-documented dating techniques based on excess 210-Pb and 137-Cs [20,66–71]. Both methods are useful for determining the age of recent lake, marine, and estuarine sediments. While excess 210-Pb is effective for dating sediments up to around 100–150 years old, 137-Cs can only estimate sediment age for the past 50–70 years [19]. In general, all boreholes are extracted manually and usually reach a depth of 50–60 cm.

The radioactive isotope 210-Pb is formed in the upper atmosphere from the decay of Rn-222, and then deposits on land or water bodies through precipitation, appearing in sediments as either total 210-Pb (from the decay of U-238) or excess 210-Pb (from recent atmospheric deposition). The radioactive isotope 137-Cs was produced by the atmospheric nuclear tests in the 1950s and 1970s in the Northern Hemisphere and shows a peak concentration around 1963, coinciding with the highest nuclear test activity. The presence of this peak allows for the estimation of the age of sediment from that point onward. This latter method is mainly used to cross-check results obtained with 210-Pb.

When data are imprecise (precise chronology cannot be established), other methods are often used—e.g., study of foraminifera species associations, which lived during specific periods and under certain environmental conditions, or the concentration of certain metallic elements—to establish chronostratigraphic boundaries. In other cases, when attempting to cover a broader period, 14-C dating—the accumulation of organic carbon in the soil—is used [43,72]; this usually requires longer sediment cores, capturing a longer sedimentation period, specifically for the Holocene (up to 11,700 years) and Pleistocene (up to 2.58 million years).

We selected the different relevant works and generated a database by compiling and incorporating all the studied cores into a geographic information system (GIS). All points are represented on the existing EMODnet bathymetry map viewer [64], funded by the European Commission. Cores without chronological information were not considered. Data from some cores recovered on the continental shelf, which could be used for comparison with those extracted from estuaries, were included.

For most cores, the concentrations of 210-Pb and 137-Cs were plotted along the sediment core. Plots were digitized using the open-source software WebPlotDigitizer-4.6 [73], allowing the retrieval of excess 210-Pb and 137-Cs concentrations in sediment. In some cases, when provided by the authors, data on SR were also extracted; we included rates not represented in graphs but were mentioned in text.

We obtained SRs recorded in 1900, 1950, 1965, 2000, and present time to analyze how SRs have varied over different periods. Present time data refer to rates shown by the most recent sediment cores, covering the early years of the 21st century. Additionally, average SR was calculated across different cores by dividing the length of the core by the time period in years spanned from the base to the top of the core. In estuaries with multiple cores available, average SR was calculated from the mean rate reflected in the different cores, ensuring the same time period was recorded in all of them.

The GIS enables to graphically show how SRs vary in the different estuaries over time; we used the inverse distance weighted (IDW) interpolation method for this purpose. This technique is easy to apply and directly interpretable. In addition, SRs obtained were compared with those presented by [3,21,74–78] at similar environments.

We analyzed the SR of each estuary by plotting it on an XY graph (the x-axis indicates the year; the y-axis indicates the SR) to identify any temporal trends or periods of higher or lower SR in these estuaries. Additionally, data recorded from tide gauges at various points along the Atlantic coast over time (Figure 1) were used to compare sea level variations with the obtained SRs. The objective is to determine whether a relationship exists between these two variables.

Finally, the different SRs obtained for each estuary were compared with the size of the estuary and its basin area (Table 1). A relationship was investigated between the different sedimentary behaviors of the analyzed estuaries (based on their SRs) and their various geomorphological characteristics. For this purpose, we used the classifications developed by the Institute of Natural Resources and Territorial Planning (INDUROT for its Spanish acronym) for Lugo, Asturias, Cantabria, and Basque Country estuaries [79,80], using the morphology and state of infilling as criteria.

Size: The dimensions of each estuary (in hectares, ha) were calculated encompassing environments included in the marine, aeolian, and estuarine realms, artificial fills over these environments, and water surfaces within the estuary, including large tidal channels, lateral bays, and fluvial–marine channel sections. The defined groups are as follows:

(a) Embryonic estuaries: surface area <15 ha.
(b) Small estuaries: 15–60 ha.

(c) Medium estuaries: 60–200 ha.
(d) Large estuaries: 200–600 ha.
(e) Very large estuaries: >600 ha.

Morphology: One of the main factors conditioning the morphological characteristics of an estuary is the geological/geomorphological context in which it was formed. The combination of the structural characteristics of the materials with their differential behavior towards erosion is such that softer lithologies favor the development of open and wide estuaries, while more resistant rocks tend to generate smaller highly entrenched estuaries whose dimensions are more conditioned by the width of the river valley that discharges into them. Within the coastal segment between the provinces of Lugo and Gipuzkoa, the following estuarine morphologies can be distinguished:

(a) Rias: Funnel-shaped, narrowing towards the continent, and bounded by cliffs. Rias are long incised-valley embayment's, with a characteristic funnel-shaped morphology completely open to the sea without rocky or sedimentary closures, with high surrounding reliefs [62,81].
(b) Open estuaries: Significantly larger than the associated river valley, with the widening extending upstream, showing large inlets or lateral bays. Usually located in soft substrates and linked even to geological structures such as faults and thrusts that favored their widening (e.g., Avilés).
(c) River valley estuaries: The estuary's width is comparable to that of the associated river valley, often bounded by steep slopes.
(d) Mixed: Generally, with a head zone shaped as a valley and an intermediate or outer zone with an open morphology.

Sediment filling: This criterion refers to the sediment production capacity of the river basins and the amount of material that reaches and is deposited at the estuary mouth. The greater the amount of sediment delivered by the basin and deposited at the mouth, the higher the degree of sediment infilling in the estuary, and, consequently, the smaller the extent of estuarine environments. Therefore, the fluvial load delivered to the mouth or the degree of sediment infilling in the estuary is one of the factors responsible for the types of environments that develop within it [82]. The degree of sediment infilling defines the environments found within the estuary. The following classes can be defined based on the sediment state of infilling:

(a) Tidal estuaries: Systems with minimal sediment infilling occupying a large part of the estuary alongside relatively deep-water bodies and characterized by a smaller representation of marshes compared with that of bare intertidal flats (mudflats or sands).
(b) Juvenile estuaries: In these systems, the area occupied by marshes is equal to or even greater than that occupied by bare intertidal flats.
(c) Mature estuaries: These estuarine terrains are topographically higher and primarily present marshes with little representation of bare intertidal flats.
(d) Urban estuaries: Given the difficulty in classifying estuarine terrains when their degree of urbanization is very high, we defined them as urban estuaries.

3. Results

In the present work, a literature review of nearly 70 publications analyzing SR in the estuaries of the Spanish Atlantic coast is performed (Figure 2a). Most of them correspond to publications in internationally recognized journals mainly by prestigious research groups from the universities of Galicia, Asturias, Cantabria, and the Basque Country. PhD and undergraduate or Master's dissertations were also consulted.

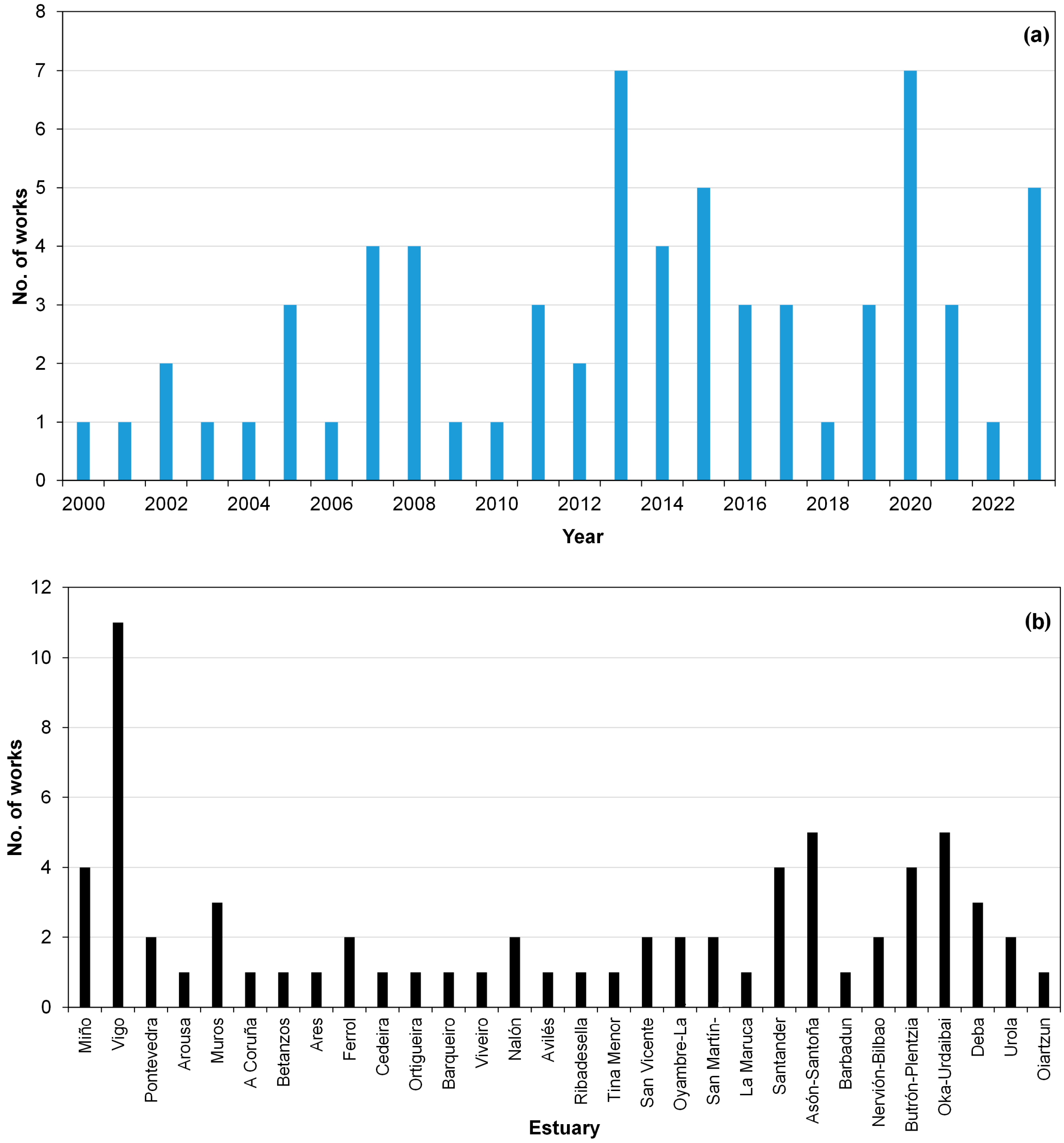

Figure 2. (**a**) Distribution of number of works on northern Spain estuaries published by year. (**b**) Number of works published on each estuary.

All the analyzed information, including a total of 82 cores and three boreholes from the estuaries in northern Spain, is presented in Table 3. These studies involved the extraction of sediment cores, to which dating methods such as Pb-210, Cs-137, and C-14 were applied to determine SRs for recent periods. Only those cores that provided reliable information have been considered.

The literature review produced core data from 30 of the 59 existing estuaries in the northern Atlantic area of Spain (about 50% of the estuaries with data available). Further investigation is recommended to extend the analysis to estuaries for which no information is available (Table 1). For the estuaries of Muros and Arousa, we considered data obtained from long boreholes drilled close to their mouth; however, 12 boreholes extracted on the Basque French continental shelves from deep-sea drilling [83] were not included.

Some estuaries have been the subject of more extensive studies—mainly due to their larger size, high population density in their surroundings and their touristic, economic/industrial, or natural interest—such as Santander and Vigo (nine cores each), Asón–

Santoña (eight), Oka–Urdaibai (seven), Nervión–Bilbao (six), Ferrol, Muros, Oyambre–La Rabia, San Martín-Suances (four each), or Butrón–Plentzia (three). For the remaining estuaries, one or two cores are available (Figure 2b).

Table 3. Estuaries analyzed. Period covered by each core, geographical location, bibliographic references, SRs at different times, and average SR (mm/year).

No.	Estuary	Core Code	Period	Lat. N	Long. W	References	SR 1900	SR 1950	SR 1965	SR 2000	SR 20xx	SR Average
1	Miño	Miño	1900–2000	41.87	8.82	[19,33,42]	0.6	0.6	0.6	0.6	—	0.6
3	Vigo	C1	1963–1999	42.34	8.61	[19]	—	—	—	—	—	4.3
3	Vigo	C2	1963–1999	42.34	8.61	[16,19]	—	—	1.1	6.5	—	5.9
3	Vigo	C3	1963–1999	42.34	8.61	[19]	—	—	—	—	—	5.1
3	Vigo	M2	1963–1999	42.35	8.63	[9]	—	—	5.0	5.0	—	5.0
3	Vigo	M3	1963–1999	42.35	8.63	[9]	—	—	5.0	5.0	—	5.0
3	Vigo	SS10	1950–2010	42.34	8.61	[84]	—	4.0	6.6	6.8	5.6	5.3
3	Vigo	q	1930–2005	42.35	8.63	[85]	1.5	1.5	4.0	4.0	6.1	2.3
3	Vigo	SSMPA	1940–2003	42.34	8.61	[5,19,31]	—	6.0	3.1	6.2	—	6.6
3	Vigo	T	1900–2006	42.35	8.61	[86]	0.04	0.1	2.0	1.7	5.5	2.3
4	Pontevedra	Core 1	1963–1999	42.40	8.72	[46]	—	1.0	1.0	1.0	1.0	1.0
5	Arousa	KIGX13	1960–1999	42.42	9.07	[83]	—	—	3.0	3.0	3.0	3.0
6	Muros	M12BC	1960–2009	42.77	8.97	[39]	—	—	2.6	3.9	3.2	3.1
6	Muros	M5BC	1900–2009	42.73	9.02	[39]	1.5	0.8	0.8	2.5	3.8	1.8
9	A Coruña	L	1923–2012	43.31	8.35	[13]	—	5.3	5.3	7.8	7.8	6.7
10	Betanzos	Betanzos	1910–2012	43.33	8.21	[87]	0.9	3.0	3.0	6.2	8.4	3.8
11	Ares	Ares	1910–2012	43.41	8.18	[87]	3.4	3.4	6.0	6.0	14.5	7.2
12	Ferrol	Ferrol	1880–2012	43.51	8.15	[88]	1.4	4.4	6.6	5.0	6.7	6.2
12	Ferrol	FEN	1940–2021	43.47	8.17	[30]	—	1.1	1.2	4.5	6.1	6.2
12	Ferrol	NED	1946–2021	43.50	8.16	[30]	6.0	6.0	6.0	10.0	14.0	6.6
12	Ferrol	XUV	1880–2021	43.51	8.16	[30]	—	1.8	2.6	5.8	7.1	3.5
13	Cedeira	Cedeira	1976–2012	43.63	8.05	[87]	—	—	—	11.0	16.0	13.0
14	Ortigueira	Ortigueira	1910–2002	43.69	7.81	[47]	12.0	12.0	12.0	25.0	—	12.0
15	Barqueiro	Barqueiro	1910–2002	43.71	7.68	[47]	9.0	10.0	10.0	10.0	—	9.0
16	Viveiro	Viveiro	1910–2002	43.65	7.60	[47]	11.0	11.0	11.0	10.0	—	10.5
24	Nalón	MSE-1	1900–2017	43.54	6.07	[55]	3.1	2.6	2.7	3.6	4.3	3.1
24	Nalón	MSE-2	1900–2017	43.54	6.08	[55]	2.7	3.0	3.3	4.2	6.0	3.6
24	Nalón	Junquera	1858–2022	43.54	6.08	[15]	3.0	6.6	4.5	4.5	4.5	3.0
24	Nalón	Muros	1965–2020	43.54	6.08	[15]	—	—	8.1	10.8	10.8	8.1
25	Avilés	Avilés	1860–2020	43.56	5.91	[28]	0.4	0.4	0.4	0.4	0.4	0.4
27	Ribadesella	Ribadesella	1900–2021	43.46	5.06	[89]	1.4	3.9	5.3	7.8	13.0	6.0
29	Tina Menor	TM	1900–2015	43.37	4.47	[90]	0.8	2.0	2.5	5.6	7.2	3.7
30	San Vicente	SV	1900–2015	43.37	4.39	[90]	0.6	1.4	1.4	3.3	3.5	1.6
31	Oyambre–Capitán	A1M1	1960–2018	43.38	4.32	[43]	—	—	0.6	0.6	0.6	0.6
31	Oyambre–Capitán	A2M3	1960–2018	43.38	4.33	[43]	—	—	3.3	3.3	3.3	3.3
31	Oyambre–La Rabia	n	1904–1998	43.38	4.31	[56]	0.8	2.2	2.2	2.2	—	1.5
31	Oyambre–La Rabia	NM3	1960–2018	43.38	4.31	[43]	—	—	2.9	2.9	2.9	2.9
31	Oyambre–La Rabia	NP2	1960–2018	43.38	4.31	[43]	—	—	3.5	3.5	3.5	3.5
31	Oyambre–La Rabia	o	1880–2005	43.37	4.31	[56]	1.8	4.3	4.3	4.3	—	3.1
32	San Martín–Suances	Edar	1930–2016	43.40	4.02	[27]	—	5.0	5.0	2.5	2.5	4.2
32	San Martín–Suances	Miengo 1	1880–2016	43.41	4.02	[27]	3.1	2.9	2.9	2.9	2.9	3.0
32	San Martín–Suances	Miengo 2	1930–2016	43.41	4.02	[27]	—	2.6	2.6	3.2	1.0	3.7
32	San Martín–Suances	Suances	1974–2003	43.42	4.02	[38]	—	—	17.0	17.0	—	17.0
35	La Maruca	Sa	1900–2014	43.47	3.84	[91]	1.6	6.1	3.3	7.5	7.3	5.1
35	La Maruca	Sb	1900–2014	43.47	3.84	[91]	1.6	3.0	4.7	6.9	6.6	6.0
36	Santander	BS1B1	1959–2019	43.43	3.75	[43]	—	—	1.8	1.8	1.8	1.5
36	Santander	BS2A1	1959–2019	43.45	3.74	[43]	—	—	0.9	0.9	0.9	1.5
36	Santander	C1-Raos	1954–1997	43.42	3.81	[53]	—	10.0	10.0	10.0	—	10.0
36	Santander	C2-Maliaño	1900–1997	43.41	3.82	[53]	2.0	2.0	2.0	2.0	—	2.0
36	Santander	C3-Astillero	1964–1997	43.39	3.81	[53]	—	11.0	11.0	11.0	—	11.0
36	Santander	C6-Elechas	1954–1997	43.42	3.78	[53]	—	11.0	11.0	11.0	—	11.0

Table 3. *Cont.*

No.	Estuary	Core Code	Period	Lat. N	Long. W	References	SR 1900	SR 1950	SR 1965	SR 2000	SR 20xx	SR Average
36	Santander	C9-Pedreña	1900–1997	43.44	3.75	[53]	2.6	2.6	2.6	2.6	—	2.6
36	Santander	P4	1900–1997	43.40	3.81	[16,17]	0.6	1.6	1.5	3.3	—	4.0
36	Santander	P9	1900–1997	43.44	3.75	[16,17]	1.0	2.2	2.0	3.6	—	5.0
41	Asón–Santoña	C	1900–2000	43.40	3.46	[85]	0.9	1.8	3.8	6.5	—	4.0
41	Asón–Santoña	Carasa	1950–2011	43.38	3.46	[36,92]	—	18.0	13.0	4.8	4.8	7.0
41	Asón–Santoña	Escalante	1900–2011	43.43	3.50	[11,36]	0.1	0.1	0.4	1.2	1.2	1.0
41	Asón–Santoña	Lastra	1911–2011	43.45	3.47	[36]	0.2	1.6	1.9	2.5	2.5	2.2
41	Asón–Santoña	MS1A2	1960–2019	43.36	3.42	[43]	—	—	2.8	2.8	2.8	2.8
41	Asón–Santoña	MS2A3	1960–2019	43.41	3.48	[43]	—	—	2.4	2.4	2.4	2.4
41	Asón–Santoña	MS2B2	1960–2019	43.41	3.48	[43]	—	—	1.5	1.5	1.5	1.5
41	Asón–Santoña	S	1900–2000	43.45	3.46	[85]	0.5	2.1	2.8	8.3	—	4.6
43	Barbadun	B	1900–2001	43.33	3.11	[23]	0.8	2.8	4.3	7.8	—	4.5
43	Barbadun	M	1900–2003	43.34	3.11	[23]	0.8	1.8	1.8	1.8	—	1.8
44	Nervión–Bilbao	Abra 1	1959–2015	43.33	3.01	[27,93,94]	—	3.0	6.5	8.1	7.0	11.3
44	Nervión–Bilbao	Abra 2	1978–2015	43.33	3.01	[27,94]	—	—	—	5.6	5.7	9.7
44	Nervión–Bilbao	Abra 3	1971–2015	43.33	3.01	[27,94]	—	—	—	10.2	8.6	12.3
44	Nervión–Bilbao	Abra 4	1959–2015	43.33	3.01	[27,93,94]	—	—	—	8.9	10.8	12.5
44	Nervión–Bilbao	Abra 5	1999–2015	43.33	3.01	[27,94]	—	—	—	30.0	30.0	29.4
44	Nervión–Bilbao	Abra 6	1994–2015	43.33	3.01	[27,94]	—	—	—	29.5	29.5	29.5
45	Butrón–Plentzia	ISKZ	1980–2006	43.39	2.91	[24,33,34]	—	—	15.0	15.0	—	15.0
45	Butrón–Plentzia	O	1880–1997	43.39	2.93	[2]	0.6	0.6	3.2	3.2	—	4.2
45	Butrón–Plentzia	T	1880–1997	43.40	2.95	[2]	1.0	1.0	0.5	0.5	—	2.5
47	Oka–Urdaibai	AX	1900–2008	43.37	2.68	[11]	2.8	21.0	21.0	1.0	1.0	3.7
47	Oka–Urdaibai	BA	1900–2008	43.35	2.66	[10]	3.0	4.0	1.1	1.1	1.1	2.2
47	Oka–Urdaibai	BU	1900–2003	43.37	2.68	[10]	1.8	1.8	13.3	4.4	4.4	3.6
47	Oka–Urdaibai	IS	1900–2008	43.35	2.67	[10]	2.4	19.0	2.7	2.7	2.7	4.1
47	Oka–Urdaibai	Ka	1900–2004	43.36	2.67	[33,34]	1.0	1.0	1.0	1.0	1.0	1.0
47	Oka–Urdaibai	Ma	1958–2007	43.36	2.68	[33,34]	—	10.0	10.0	10.0	10.0	10.0
47	Oka–Urdaibai	Muc	1900–2010	43.35	2.67	[7]	0.7	0.7	4.0	3.4	3.4	1.8
53	Deba	DB-3; D1	1911–2016	43.29	2.36	[26,29]	1.1	2.0	3.0	5.1	28.7	5.5
53	Deba	Deba 2	1950–2016	43.28	2.36	[95]	—	2.3	2.3	4.8	23.0	7.9
54	Urola	Z1	1900–2018	43.28	2.24	[29]	6.0	6.0	2.2	2.2	2.2	4.0
54	Urola	ZM, Z2	1900–2015	43.29	2.25	[29,96]	0.7	2.1	4.7	6.5	5.9	2.9
58	Oiartzun	PAS2	1968–2015	43.32	1.90	[8]	—	—	9.3	9.3	9.3	9.3

3.1. Sedimentation Rates (SRs)

The analyzed cores cover variable time periods, ranging from 16 years (Nervión–Bilbao; 29.5 mm/year) to 160 years (Avilés; 0.4 mm/year). According to data presented in Table 3, 24 of the estuaries analyzed contain 44 cores with sediment records spanning the entire 20th century (Figure 3a). In three estuaries—Pontevedra, A Coruña, and Nervión–Bilbao—cores record data only from 1950 to the year 2000 (Figure 3a). As shown in Figure 3b, apparently, higher SRs can be found in cores where a shorter period of time is recorded. Maximum and minimum SRs found in the different cores for each estuary are presented in Table 4.

Average SR is lower when a higher number of years is recorded in the core. The limited number of years (less than 40 years) recorded in some of the extracted cores is due to high SR in recent periods (ranging between 9.7 and 29.5 mm/year), specifically in the estuaries of Cedeira, Nervión–Bilbao, Butrón–Plentzia, and San Martín–Suances. Conversely, estuaries showing longer periods of time (more than 100 years in 35 cores) in their records provide SRs ranging from 0.4 to 12.0 mm/year on average. SR is constant (0.4 to 29.5 mm/year) over the whole period covered in 31 cores.

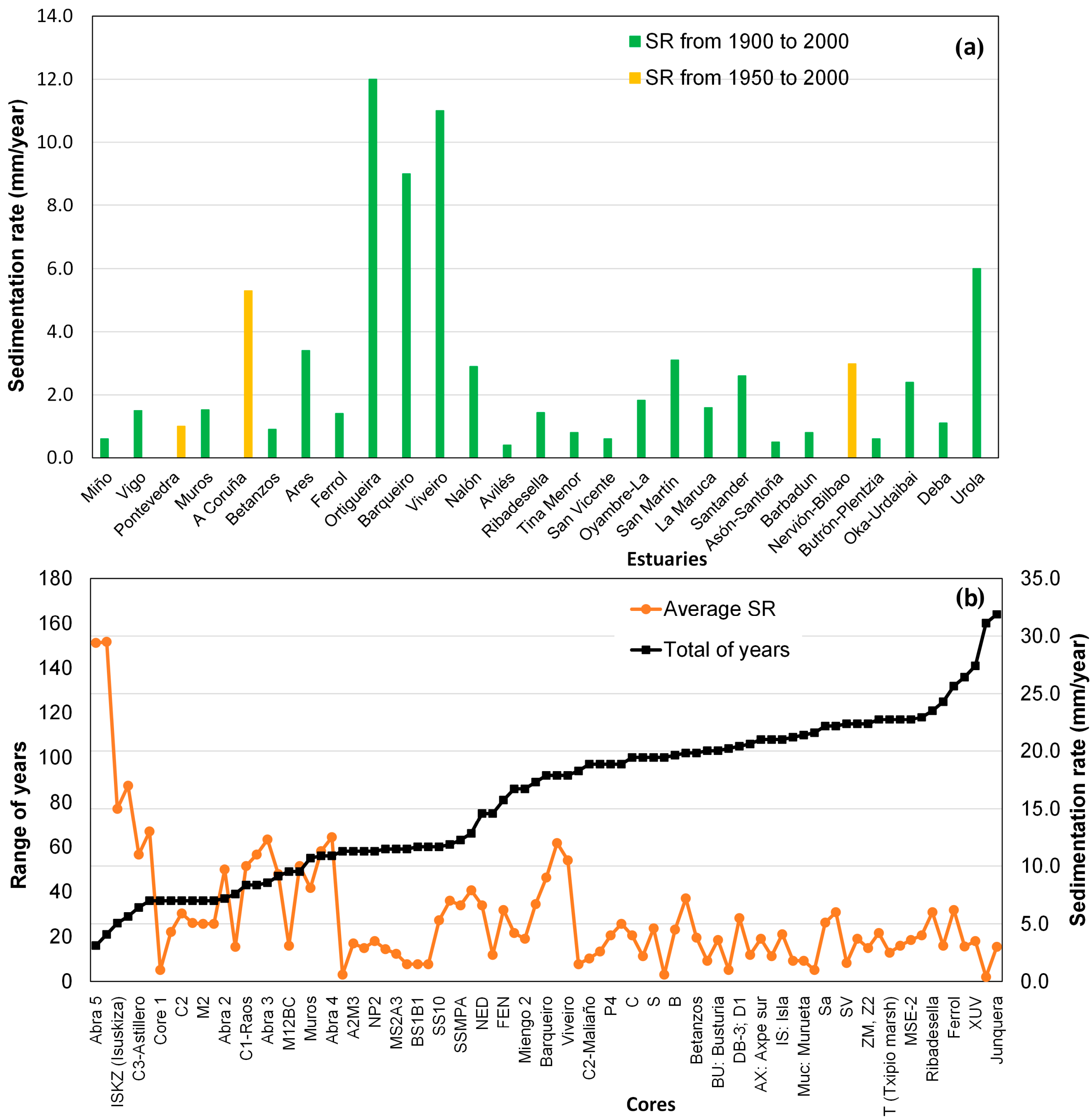

Figure 3. (**a**) Estuaries with complete records on SRs covering the entire 20th century (green) and estuaries with complete records only from 1950 onwards (orange). (**b**) Comparison between core average SRs and number of years recorded in the core.

Table 4. Estimations of maximum and minimum SRs in each estuary and their morphology and state of infilling (N/D: No Data for that estuary).

No.	Estuary	Maximum SR	Minimum SR	Morphology	State of Infilling
1	Miño	0.6	0.60	Ria	N/D
3	Vigo	11.0	0.04	Ria	N/D
4	Pontevedra	1.0	1.00	Ria	N/D
5	Arousa	3.0	3.00	Ria	N/D
6	Muros	6.2	0.70	Ria	N/D
9	A Coruña	7.8	5.30	Ria	N/D
10	Betanzos	16.0	3.40	Ria	N/D
11	Ares	8.4	0.90	Ria	N/D
12	Ferrol	19.9	0.40	Ria	N/D
13	Cedeira	16.0	11.00	Ria	N/D
14	Ortigueira	25.0	12.00	Ria	N/D
15	Barqueiro	10.0	9.00	Open estuary	Tidal
16	Viveiro	11.0	10.00	River valley estuary	Juvenile
24	Nalón	10.8	0.80	River valley estuary	Juvenile
25	Avilés	0.4	0.40	Open estuary	Urban
27	Ribadesella	13.0	1.40	River valley estuary	Mature
29	Tina Menor	7.2	0.90	Mixed	Juvenile
30	San Vicente	3.5	0.90	Open estuary	Juvenile
31	Oyambre–La Rabia	4.3	0.60	Open estuary	Juvenile
32	San Martín–Suances	17.0	1.00	Mixed	Juvenile
35	La Maruca	10.3	1.50	Mixed	Tidal
36	Santander	11.0	0.60	Open estuary	Juvenile
41	Asón–Santoña	18.0	0.10	Open estuary	Juvenile
43	Barbadun	8.7	0.80	Mixed	Mature
44	Nervión–Bilbao	45.0	2.90	Mixed	Urban
45	Butrón–Plentzia	15.0	0.50	Mixed	Juvenile
47	Oka–Urdaibai	19.0	0.70	Open estuary	Juvenile
53	Deba	55.1	1.10	River valley estuary	Mature
54	Urola	7.3	0.80	River valley estuary	Mature
58	Oiartzun	10.6	10.60	Mixed	Urban

3.2. Spatial Pattern

As can be seen in Figure 4, the estuaries with the highest SRs over time are those in northern Galicia, where these have remained almost constant from 1900 to the present day. Other factors, such as human influence, regional climatic characteristics, or differences in the geology of each basin, have not been analyzed, as these fall beyond the scope of this study. Some papers indicate possible causes for these SRs.

As shown in Figure 4, in 1900, estuaries with the highest SRs were those in Ortigueira, Viveiro, and Barqueiro, followed by Urola. In 1950, Oka–Urdaibai stood out with the highest rates, followed by Ortigueira, Viveiro, and Barqueiro. At the end of the century, the high rates in the Nervión–Bilbao estuary are of note; in 2000, the highest rates are found in Nervión–Bilbao and Ortigueira, followed by Suances; for the 21st century, Nervión–Bilbao and Deba show the highest values, while the highest average SRs are located in the estuaries of the Nervión–Bilbao, San Martín–Suances, and Butrón–Plentzia.

When the obtained SRs are correlated with the size of the estuary or the basin, no relationship can be established between these variables. Therefore, a direct relationship cannot be confirmed between the sedimentation of the estuaries and the size of the basin that drains them (Figure 5a). Furthermore, no relationship is observed between the recorded SR and morphology of the estuary (Figure 5b; Table 4), or the sedimentary evolutionary process (Figure 5c; Table 4).

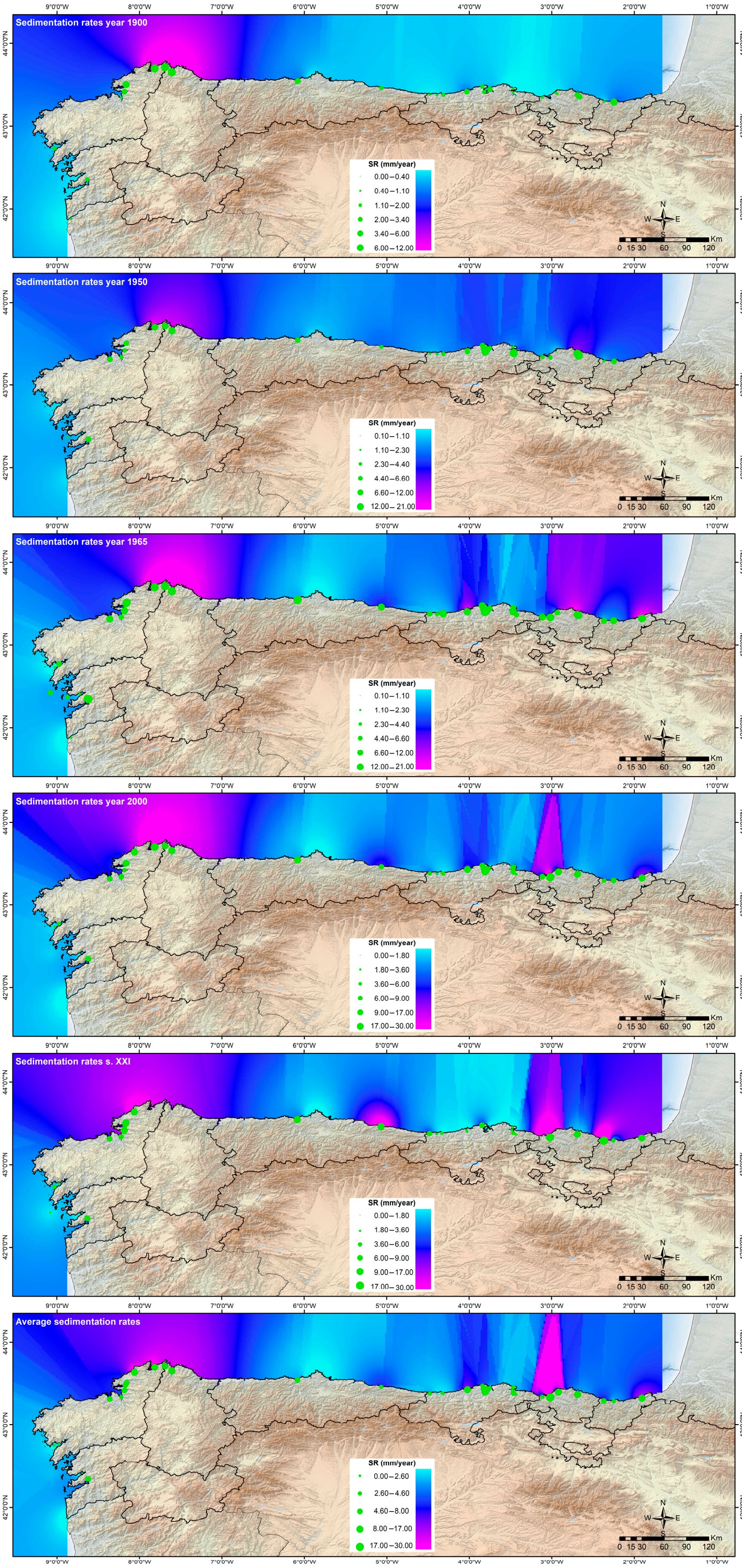

Figure 4. Spatial interpolation from estuaries SRs in different time periods. Note that SRs have been extrapolated to the ocean for a better visualization.

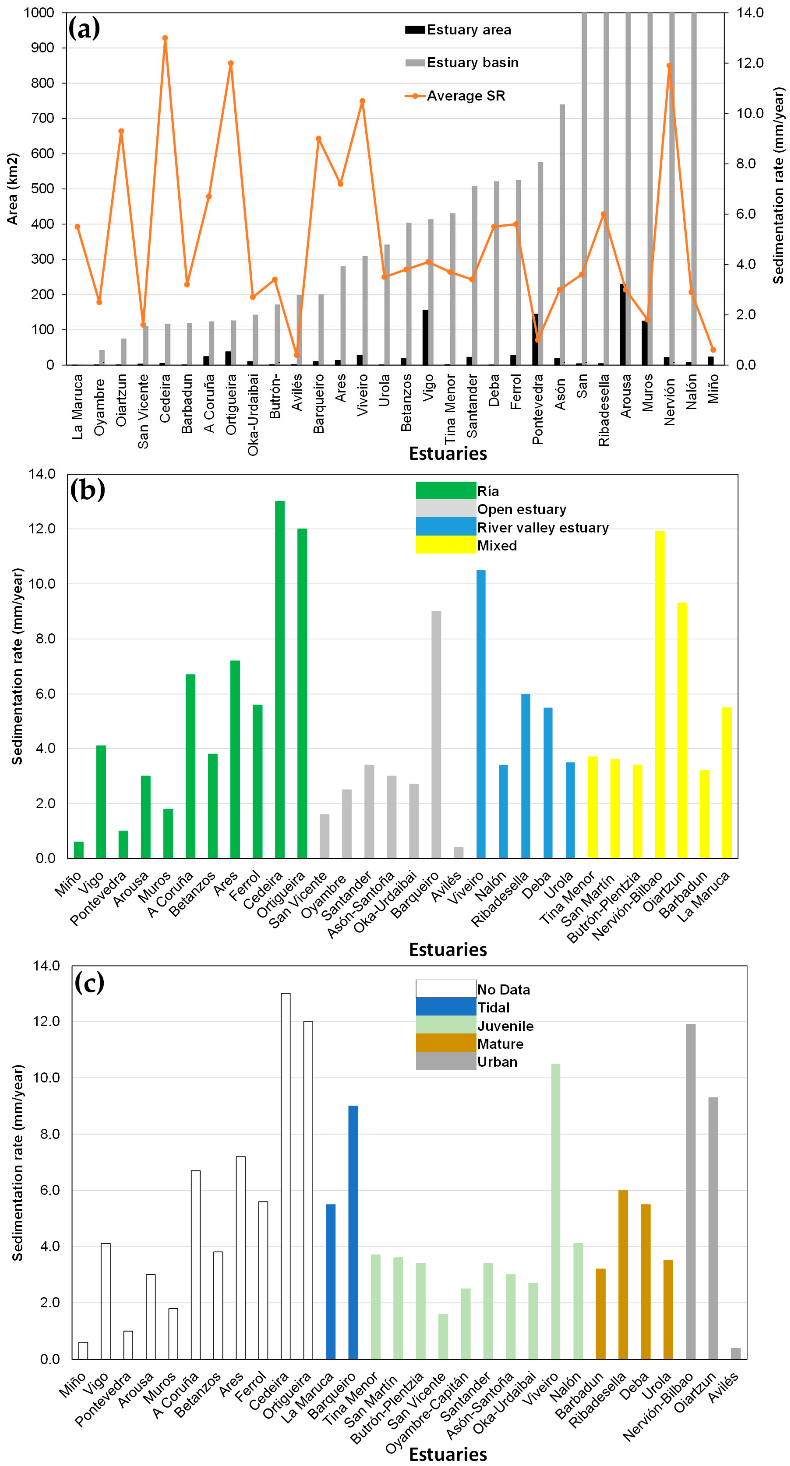

Figure 5. Comparisons between SRs and (**a**) basin area or estuary area; (**b**) estuary morphology; (**c**) state of infilling.

3.3. Temporal Evolution

A representation of the SRs obtained from the different papers reviewed (Table 3) is shown in Figure 6, where core id (No.), name, and code are represented (i.e., 35-La Maruca-Sa). The sole purpose of this figure is to show the published SRs for each core or borehole. To the best of our knowledge, no previous studies have graphically represented SRs within a geographical context similar to the one analyzed in the present work. This presentation facilitates the direct comparison of SRs among different cores and, consequently, among various estuaries or geographical regions.

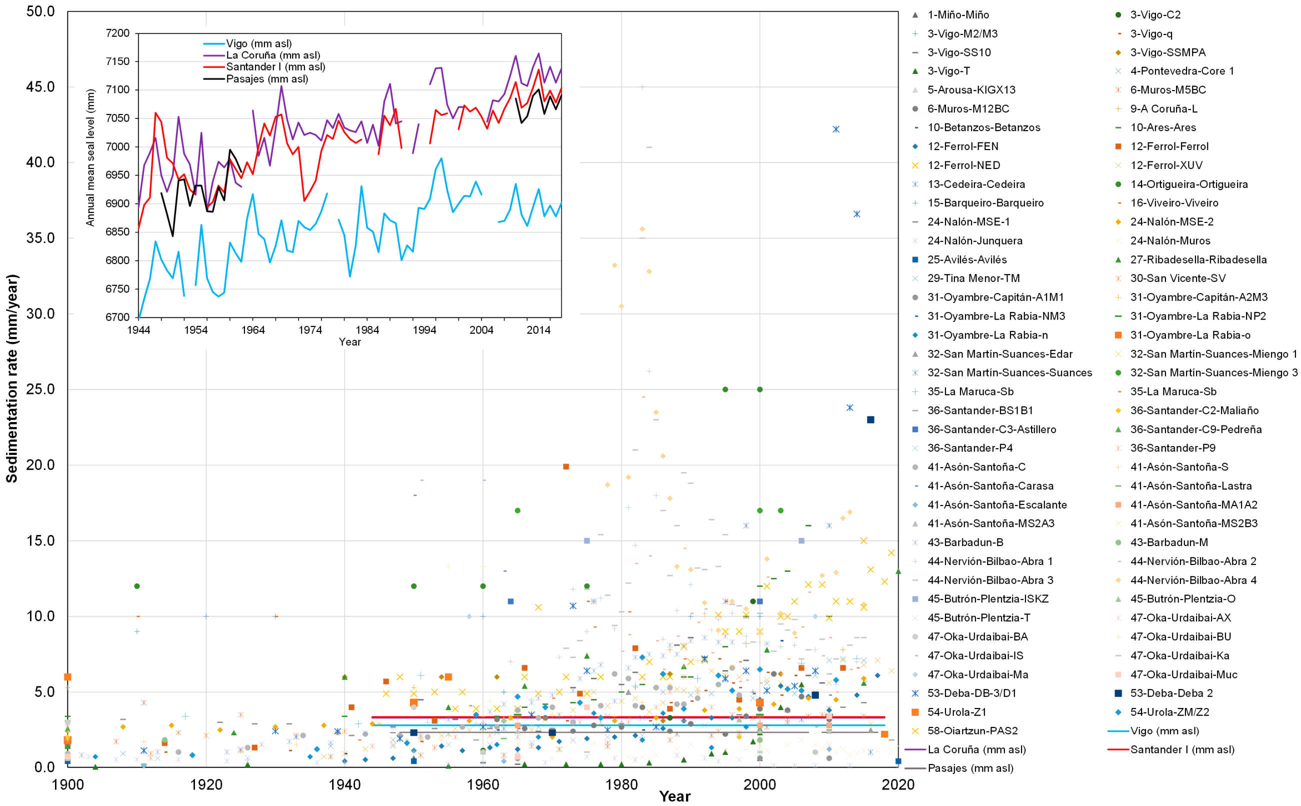

Figure 6. Average SRs from cores analyzed (symbols) and sea level in different tide gauges of the region (lines). The graph shows the variation of the annual mean sea level (referred to reference sea level in Spain) since the middle of the last century in those tide stations.

A higher density of data points is present for the period between the 1980s and 2000s. In the 1980s, some SRs obtained in the Nervión–Bilbao estuary show values up to 50 mm/year, while most of the cores present rates below 20 mm/year. In general, rates appear to exhibit an increasing trend from the second half of the 20th century.

To better visualize data in Figure 6, we represented the numerical data through its quartiles, grouping the data in periods of 20 years (Figure 7). Although the variance is significant, a clear growth in SRs throughout the 20th century and a stabilization and/or reduction in this century can be observed. Figure 7 shows SRs to have significantly increased throughout the 20th century, peaking between 1981 and 2000, and then stabilizing at a high level in the 2000–2020 period. This behavior is similar to that described for the set of sedimentation and denudation processes throughout the world in [97].

An upward trend can be observed in mean SRs from the period 1900–1920 to 1981–2000, and a steady increase in median SR. After 1981–2000, SRs seem to stabilize or show a slight decrease in the period 2000–2020, although this is still high compared with that in previous periods; the median is similar to that of the previous period, indicating a possible stabilization. Note that the 1981–2000 and 2000–2020 periods show a higher variability in SRs compared with that in the earlier periods.

To analyze the relationship between SRs and recent sea level variations, the most comprehensive and longest-term data available [98] are those from tide gauges in Vigo (Pontevedra), A Coruña (A Coruña), Santander (Cantabria), and Pasajes (Gipuzkoa) (Figure 1). Figure 6 shows a sea level rise in Vigo of 15.5 cm from 1944 to 2018 (2.1 mm/year) when applying the trend line to the obtained graph; in A Coruña, the rise is 19 cm for the same period (2.5 mm/year); and, in Santander, the rise is 15 cm (2 mm/year). The Pasajes tide gauge, with a discontinuous record, shows a rise similar to that observed in A Coruña. From 1970 to 2001, the sea level increased 1.31 mm/year in Vigo, 2.26 mm/year in A Coruña, and 2.5 mm/year in Santander [99]. A regional sea-level rise of 1.9 ± 0.3 mm/year since 1923 for the Bay of Biscay is shown in [32].

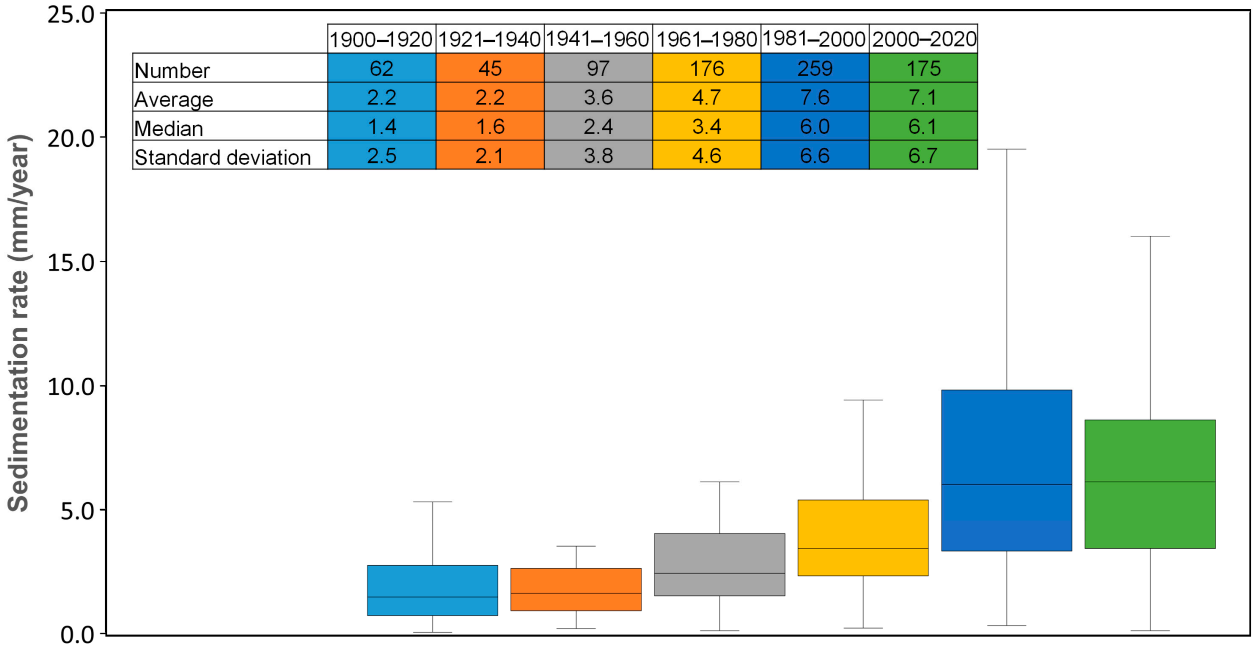

Figure 7. Box plot diagram of SR data in Figure 6. Different values of SRs per period are plotted: amount of data (dating points considering the total cores analyzed for each time interval) and mean, median, and standard deviation values.

4. Discussion

Data collected in the present study can be compared with those presented by different authors for the same sedimentary environment in different parts of the world. Two surveys conducted in [74] for the eastern coast of Spain obtained rates varying between 2.3 and 13.9 mm/year. Another study, although covering Holocene periods, has reported rates of 1.0 mm/year for the Tinto–Odiel estuary, 1.0 to 1.5 mm/year for the Guadalete estuary, and less than 2.5 mm/year for the Guadalquivir estuary [3]. For the Palmones River estuary, ref. [75] indicate rates of 7.0–12.0 mm/year. On the Barcelona continental shelf, ref. [76] report accumulation rates between 1.6 and 10 mm/year.

For an estuary in Cyprus, [74] indicate ranges from 1.6 to 3.0 mm/year, and for Turkey, between 0.8 and 3 mm/year. In the estuaries of Sado and Mira, in Portugal, SRs varying between 1.2 and 4.3 mm/year have been obtained [33]. In European countries, average SRs very similar to those found in the present work (1.6–12 mm/year) have been recorded [21,22]. The same database shows SRs ranging from 0.7 to 20 mm/year for America (only USA and Brazil). For Africa, SRs between 4.8 and 8.3 mm/year have been found, with data from only two countries. In Asia, the rates vary from 0.7 to 54 mm/year. In Oceania, with data only from New Zealand, the values range between 4.0 and 5.7 mm/year [21,22,77,78].

The observed SR values exhibit significant spatial disparities, attributable to two primary variables. Firstly, the interestuarine differences stem from environmental conditions (and their fluctuations) heavily influenced by local factors, in particular the direct impact of anthropogenic disturbances on the estuary and the indirect effects on its river basins. Most estuaries have experienced notable changes over the past century due to land reclamation and occupation resulting from human activities in the estuary and in the river catchment areas that flow into them. In fact, low SRs coincide clearly with estuaries with limited human presence such as Oyambre–La Rabia, which was declared a Natural Park in 1988.

Secondly, the variability in SRs within each estuary is a consequence of differing hydrodynamic conditions arising from distinct morphodynamic contexts. Hydrodynamic circulation within estuaries plays a critical role in shaping sedimentation patterns, leading to differential sediment relocation. Consequently, local sedimentological changes may affect specific areas of the estuary but are not necessarily reflected in the sedimentary records of other locations within the same estuary. As a result, more isolated salt marshes exhibit lower sediment accumulation rates, whereas salt marshes adjacent to channels tend to show higher sediment accumulation rates [36,92].

The rise in sediment accumulation rates during the last decades aligns with the regional tendency observed along the Cantabrian coast, which is attributed to anthropogenic influence. Besides the trends obtained, another clear indicator of high sediment supply is the intense dredging operations performed in the navigation channels of San Martín–Suances, Santander, Urola, and Oiartzun, among others. In some estuaries (e.g., Bilbao), the recent decrease in SRs and contamination levels is interpreted as a result of the adoption of environmental protection regulations from the European Union, leading to better production systems and a reduction in human pressure on the ecosystems. However, these general trends are compounded by local factors unique to each area and catastrophic events resulting from accidents and extreme weather events.

In ancient periods, the increase in SRs is often related to agricultural activities developed around the estuary and the resulting deforestation of nearby hills, which increased the sediment load transported by river tributaries due to soil loss, as observed in Ribadesella, Muros, and Oka–Urdaibai. Paradoxically, the same result can be observed from reforestation plans involving the introduction of anthropogenic plant species—initially Pinus and later Eucalyptus—for industrial purposes—paper pulp and cellulose production—initiated in the 1940s. In Ferrol, this affected an area formerly covered by heathland, while in Cedeira, it led to a transition from an agricultural watershed to an intensive timber production area.

In other cases, and in places with greater economic dynamism, the rapid growth of the population and industrialization in and around these areas, where large amounts of land were converted from agricultural to urban and industrial uses, resulted in intense construction activity (San Martín–Suances, Santander, Vigo). More recently, tourism activity associated with the coast has led to the accelerated expansion of the population in neighboring villages, mainly due to holiday visitors. This has probably led to the increased clearing of significant land areas in the catchment area, as seems to be happening in Asón–Santoña.

Particularly relevant is the influence of mining activities, which cause significant spills from mineral washing (Santander, San Martín–Suances, Ferrol) or increased weathering due to slope alteration and instabilities (Ares). Additionally, the closure of mining activities is not usually followed by a drastic decrease in SRs or contamination, as can be observed in the sedimentary records of the Nalón and Ferrol estuaries. In the Nalón estuary, this implies that the river drainage basin retains some memory, affecting riverine sediments. Part of this anthropogenic load remains in different compartments of the river basin and is gradually released into the fluvial environment [55,88].

Direct intervention in the estuary includes land reclamation through fillings for various uses, which change the volume and morphology of the estuary. Two extreme examples are the construction of an oil refinery in the early 1970s (Barbadun) and, notably, the physical transformation of the Oiarzun estuary into a subtidal port with its entire perimeter dedicated to docks, loading platforms, and warehouses [100]. Other examples are related to the construction and maintenance of infrastructure (bridges, tunnels, or roads) and restoration works developed in the surrounding area, as is the case for Betanzos, Ferrol, or Deba, or the remodeling of the river channel, as in the Urola estuary. Additionally, physical barriers such as bridges or dams cause various environmental perturbations leading to the evolution of these intertidal areas toward more confined and brackish conditions, involving higher SRs by limiting sediment transport toward the ocean, as interpreted for the estuaries of Ferrol and Minho.

Increased amounts of wastewater suspension due to residual urban waters is another factor that could have influenced the bays of Santander, Santoña, and Vigo, where municipal sewage from a large number of inhabitants was discharged directly into the estuary. One important factor in the San Martín–Suances estuary is the effluent from the Solvay factory, with a temperature of over 30 C, which contributes to the flocculation of fine-grained sediment.

Among the aforementioned catastrophic events, the most relevant ones are the sudden spills of material, usually mining waste deposits located upstream of estuaries due to the collapse of waste dumps. This occurred in 1960 in the Suances estuary [27], with a torrent of contaminated mud of at least 50,000 to 100,000 m^3 of sediment [101]. Similarly, the breakage of a mining settlement pond situated inside the Xubia River basin (Ferrol estuary) in the early 1960s could have introduced significant amounts of sediment into the estuary [30,88].

Natural catastrophic events have also left their fingerprint in the sedimentary record. Certain peaks in SRs (Oyambre–La Rabia and Muros) have been attributed to sudden increases in sediment inputs due to significant fires in the region followed by heavy rainfall events, which caused the deposition of a relatively thick sedimentary layer in a short period of time. An event of extremely high SR, clearly identified in the Bilbao and Zumaia (Urola) estuaries, was the catastrophic floods of August 1983, confirming the potential of natural events for sediment relocation [27,93,94]. Although with a lower degree of certainty, SRs in the bay of Santander also show an important increase that could be attributed to the floods of the years 1982 and 1984 [16,17].

Regarding the relationships between SRs and sea level variations, all stations indicate a trend in sea level rise in northern Spain during the last decades (Figure 6). In this figure, a sea level rise can be observed, assuming a constant trend, recorded at the four tide gauge stations. At first glance, the increase in sea level is clearly surpassed by the rise in sedimentation in the Atlantic estuaries. In general, in Europe, the sea level has risen by 2–4 mm/year on average over the past 30 years [102]. From 2000 to 2015, sea level variations of 2.67 mm/year in Rias Bajas, 1.31 mm/year in Rias Altas, 0.52 mm/year in Asturias, and 2.63 mm/year in Cantabria and Basque Country were registered [1]. According to the National Oceanic and Atmospheric Administration (NOAA), from 1943 to 2018, the sea level increased 2.05 $\pm$ 0.38 mm/year in Vigo, 2.43 $\pm$ 0.36 mm/year in A Coruña, and 2.22 $\pm$ 0.34 mm/year in Santander [103]. For the period 1944–2001, sea level variations were 2.5 $\pm$ 0.2 mm/year in Vigo, 1.4 $\pm$ 0.2 mm/year in A Coruña, and 2.0 $\pm$ 0.2 mm/year in Santander [104].

5. Conclusions

A literature review of about 70 published contributions was performed to investigate sediment core dating of estuaries in northern Spain for the 2000–2024 period. The collected data, assessed in 30 of the 59 estuaries of the study area, illustrate the changes in recent sedimentation within estuarine environments from the early 20th century to the present day. SRs have been estimated with radiometric techniques (mainly Pb-210 and Cs-137) in 82 cores and three boreholes. Data density is high, especially when considering that environmental and socioeconomic conditions are quite homogeneous within the region. Average SRs range from 0.4 to 29.5 mm/year, with minimum and maximum recorded values of 0.04 mm/year and 55.1 mm/year, respectively. Overall, sedimentation rates are comparable to those observed in other estuaries both in Spain and globally.

The analysis of SRs in this study does not reveal a clear spatial pattern. Additionally, these rates do not appear to be related to the morphology, type, or size of the estuary or its catchment area. However, we found a clear increase in SRs throughout the region since the beginning of the 20th century, with a stabilization and/or slight reduction during the current century. This increase is similar to that registered in most estuaries and other sedimentary environments in the world.

The increase in sedimentation rates coincides with a significant rise in sea level over the studied period, likely influencing estuarine sedimentation. Moreover, these rates seem to exceed the recorded sea level rise. Alternative drivers of variation in SRs over time are related to socio-economic factors (e.g., land reclamation, land use changes in the catchment, anthropogenic pollution, etc.), or even to specific natural/human catastrophic events. Other factors of global change warrant further investigation, such as changing climate and increasing human activity, as suggested. These results suggest improving management by proposing mitigation measures to address impacts in response to global change.

Author Contributions: J.B. conceived the idea of the work and the methodology. J.R. and V.R. implemented the methodological development and supervised the findings of this work. J.B. wrote the original draft. J.R. and V.R. reviewed and edited the final work. All authors discussed the results and contributed to the final manuscript. All authors have read and agreed to the published version of the manuscript.

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