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Hydrology, sediment yield, erosion and sedimentation rates in the estuarine environment of the Ria de Vigo, Galicia, Spain

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Abstract

The aim of this study is to provide a budget study with calculated erosion rates. Three methods have been used to calculate sediment yield and denudation rates in the Ria de Vigo: (1) measurements of sediment loads, (2) measurements of sediment accumulation rates at the coast, (3) theoretical calculations of potential denudation. Sediment loads and water discharge were measured over a period of 14 months from May 1997 to July 1998. Two of the tributaries entering the Ria de Vigo were monitored for 12 more months, from May 2000 to May 2001, to observe changes in discharge and sediment loads. This period corresponded with atypical precipitation, with peak monthly values (600 mm) three times higher than those on record.

Water rating curves are typically exponential. Suspended and dissolved loads vary for different rivers, showing values of 1.5 to 130 mg/l during 1997/1998. For 2000/2001, these values are twice as high. Suspended load versus discharge relationships for 1997/1998 were logarithmic, but data from 2000/2001 does not fit the same equation. Dissolved loads are several times higher than suspended loads in almost all cases. Dissolved load concentrations vary more widely with discharge than suspended loads. This is probably due to local pollution and contamination from marine spray in areas closer to the sea.

Second, erosion rates and bed load sediment yields were calculated from accumulation rates at the Ramallosa Complex. Well-preserved estuarine and tidal sediments, associated with the Minor River, have accumulated in this area during the Holocene. ^{14}C ages allow calculation of sedimentation rates (SR) for two intervals. The lower interval extends from 2001 to 484 years BP and yields an SR of 1.12 mm/a. The upper interval extends from 484 years BP to the present and has an SR of 3.3–4.4 mm/a. These differences may be explained by basin dynamics as the beach progressively encloses the area and also by human interference. From sedimentary facies analysis it is concluded that 90% to 95% of the accumulated deposits were transferred to the basin as bed load. Muddy deposits (mostly marshes) are better developed at the upper part of the sediment pile, and inner areas, indicating a progressive shallowing and filling up of the basin. Most of suspended load is exported to the ria, whereas the Ramallosa Complex acts as a sediment sink for bed load derived material.

Calculated potential erosion rates using Ahnert's [Am. J. Sci. 268 (1970) 243] equation show lower values than those estimated from river load concentrations. Potential erosion rates for the Minor River are higher than for the Lagares River which contrast with mechanical denudation rate values from river loads during 1997/1998 which are higher for the Lagares

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River. During 2000/2001 MDR values were higher than those of the potential erosion rates for both rivers, in line with the extremely high precipitation. Higher values in the Lagares could be in part due to human interference.

Keywords: Holocene; Sediment load; Sediment yield; Denudation rates; Estuary; Ria; Galicia

1. Introduction

The Ria de Vigo is located at the south of the Galician Rias Baixas. There are 36 individual tributaries draining the Ria de Vigo (Fig. 1). The largest, the Verdugo–Oitaven River, is located at the head of the ria and is oriented approximately parallel to its longitudinal axis. The rest are transversal river systems. In spite of being small, the numerous transverse rivers on both margins contribute substantially (>30%) to the total amount of fresh water and sediment load introduced into the ria. Nonchannellised areas occupy about 12.5% of total drainage area, in which diffusive runoff and mass wasting processes dominate (Perez-Arlucea et al., 2000a).

From preliminary research, conducted between May 1997 and July 98, 19 rivers were selected for systematic monitoring. The research was subsequently extended to a second 12-month period, from May 2000 to May 2001, but only the largest rivers of the transversal system were selected this time: the Minor and the Lagares. The Ramallosa Complex is located in the Minor River mouth, where estuarine and tidal deposits are well preserved. The Minor River is an example of a fairly natural system with little anthropogenic influence. It flows along forest and lowlands with only a small proportion of cultivated areas on the floodplain. Population density is low, and is concentrated mostly near the river mouth. In contrast, the Lagares River traverses the rather big city of Vigo and the catchment shows a much higher population density.

Previous hydrological and budget data on the rias are very scarce. Some hydrologic parameters are published by the Consello da Cultura Galega (1996). Most fluvial discharge data sources for the Ria de Vigo consist of theoretical calculations related to catchment size and meteorological records. Some discharge and sediment load measurements are provided by Nombela (1989), Rios et al. (1992), Alejo (1994), Pazos et al. (2000), Perez-Arlucea et al. (2000a,b, 2001). Additionally, there is a total lack of information about directly measured erosion, sediment yield and sedimentation rates in the whole of Galicia. The only available data are centred on specific contexts such as deforestation due to fires, in which the main issue was to evaluate soil damage caused by arson on Galician forests, mostly from the 1960s to 1980s (Bara and Vega, 1983; Benito et al., 1991; Diaz-Fierros et al., 1982, 1983, 1990, 1994; Soto Gonzalez, 1993; Vega, 1983; Vega et al., 1982). Other papers deal with erosion on small experimental erosion plots (Rodriguez Martinez-Conde et al., 1995, 1996a,b, 1998, 2001; Valcarcel Armesto, 1998; Vila Garcia, 1996). Most of these references have a very local character and the data have very limited use.

The aim of this study is to provide a budget study with calculated erosion rates based on (1) suspended sediment and dissolved loads, sediment flux and sediment yield; (2) sediment accumulation rates at the coast and (3) theoretical calculations of potential denudation rates based on catchments relief. Our study is thus a broad one, comprising geomorphologic, hydraulic and sedimentologic approaches to the main tributary rivers in the southern slope of the Ria de Vigo and associated sedimentary environments at the river mouths.

2. Methodology

There are no permanent gauging stations in the Vigo catchments apart from some private ones located at reservoirs. Consequently, stations were set up in both rivers. These stations were positioned to avoid tidal influence and at the same time to sample the maximum flow. Stage fluctuations were registered every week, from May 1997 to July 1998 and from May 2000 to May 2001.

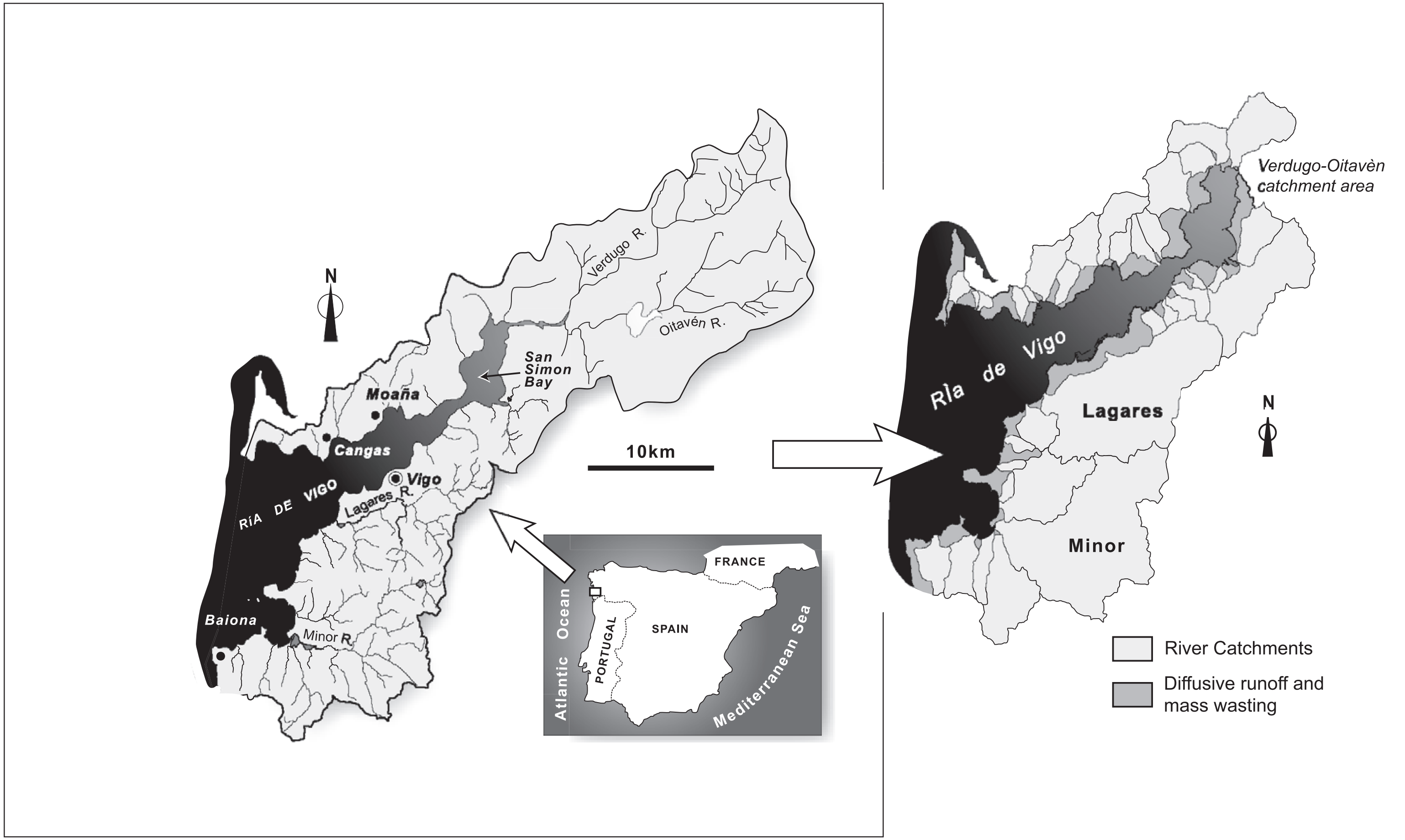

Fig. 1. Geographic sketch of the studied area, showing individual catchments and diffusive runoff areas in the Ria de Vigo.

Several discharge values (Q) were measured at different stages (H) over 2 years, using a propeller current meter. Transversal sections were surveyed with a topographic compass and rod. Mean discharge values were obtained using the rating curves H/Q. At both gauging stations water samples were collected for suspended and dissolved loads, using a special water bottle which allows to obtain representative samples of the whole water column. Suspended and dissolved materials were obtained by filtering water samples at the laboratory, using millipore filters. Bed load samples were obtained on channel bottoms across the total cross-sections to avoid hydrodynamic sorting problems, as in mid-channel sand bars.

Finally, sediment distribution and facies analysis were carried out by coring several transects in the estuarine and coastal environments, close to the river mouths. Forty-millimeter cores were extracted with a detachable TESS-1 suction corer (Méndez et al., 2003), developed ad hoc to optimize sediment extraction and subsequent analysis in the laboratory. The TESS-1 is based on the Van der Staay suction corer (van de Meene et al., 1979), but with the important modification of a detachable head (Fig. 2), designed to provide a mechanism to keep the sediment inside PVC pipes for later logging and sample analysis in the laboratory (Fig. 3). This method allows cores up to 4 m long to be extracted, from uncompacted mud to coarse pebbles as long as the sediment is wet or water saturated. Both land-based and underwater cores can be obtained. A significant advantage of this coring technique, apart from an immense time saving with respect to regular suction corers, is that the sediment is kept in the PVC pipes, sediment distortion is minimized and allows the extraction of finer cohesive material, which is almost impossible to extract from the pipes in the field due to plugging problems. Longitudinally sliced cores show fine, beautifully preserved layering. Sediment distortion by fluidification problems was minimal. Depth penetration was measured in the field and core thicknesses were corrected for compaction or dilatation.

Fig. 2. TESS-1 detachable head for the suction corer. PVC pipes are inserted from the lower end and adjusted with a bracket.

Fig. 3. Once separated from the TESS-1 head, PVC pipes filled up with sediments are sealed to be analyzed in the laboratory.

Cores from suction corer boreholes were sampled every 10–20 cm. Sediment sampling included textural and grain size analysis by mechanic sieving and sedigraph, organic matter, carbonates and metal contents. X-ray diffractograms and fluorescence were used to establish element and mineral composition. In order to obtain compositional data of the source area, 20 samples were collected in rock and soil at different locations in the catchments. Marine shells and wood fragments have been collected on the coastal sediments for ^{14}C dating, allowing calculations of sediment rates, accumulation rates and erosion rates for bed load and suspended load material. Age determinations were provided by Geochron Laboratories and calibrated using the University of Washington Quaternary isotope lab Radiocarbon Calibration Program Rev. 4.3 (Stuiver and Reimer, 1993).

3. Climatology and local meteorological conditions

Climatic conditions for the Southern Rias of Galicia (Fig. 4) can be described as oceanic with Mediterranean influence (drastic decrease in rainfall during July and August). Seasonal temperatures are fairly homogeneous over the whole area, apart from some local influence of elevation and proximity to the sea. Rainfall conditions respond to regional topography and penetration paths for oceanic humid winds. Dominant winds blow from SSW and NNW. There is rainfall all year, with maximum values from November to February and peak values in January. Low-stage conditions occur from July to September. The driest months are July and August. Data obtained from May 2000 to May 2001 show a very atypical meteorological year, with very high rainfall values for November (434.9 mm) and December 2000 (573.7 mm), January 2001 (323.1 mm) and March 2001 (562.0 mm), five times higher than the average of 110.4 mm. Total rainfall in a 12-month period between May 2000 and April 2001, was 2477.7 mm, which is very high compared to the average (1455.9 mm). These rainfall amounts are the highest on record and have had an important influence on river discharge and sediment loads as will be shown later.

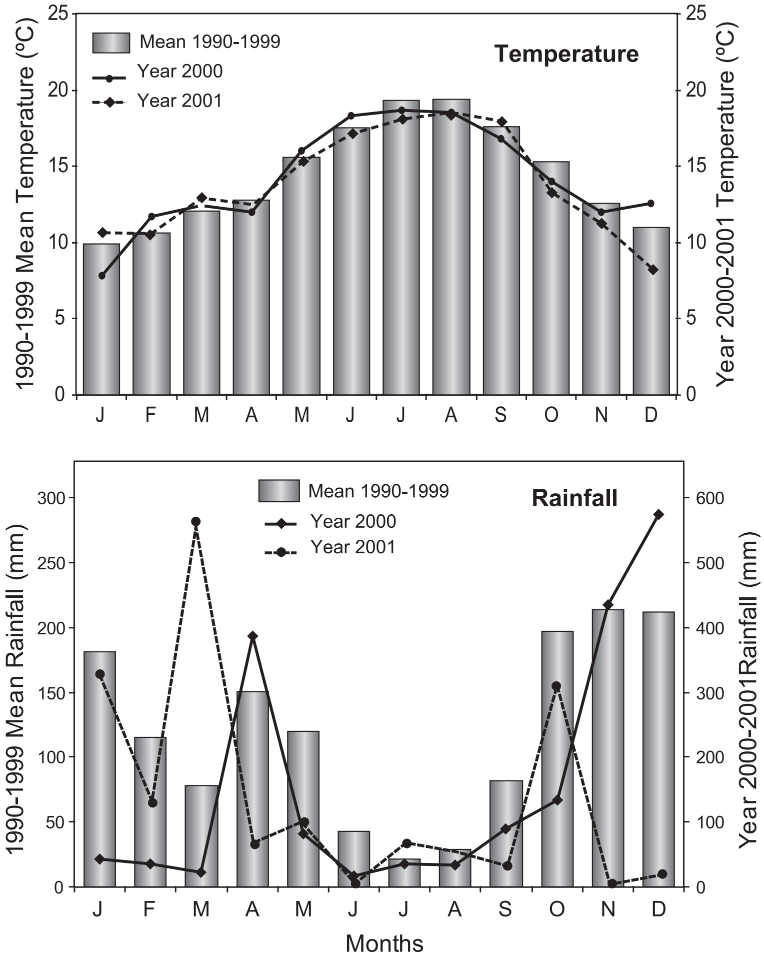

Fig. 4. Meteorological data at Gondomar station, showing mean temperatures and rainfall for the interval 1990–1999 and for years 2000 and 2001.

4. Catchment areas: composition, geomorphology and hydrology

In order to obtain denudation rates from river loads, several aspects have to be considered: lithology and weathering conditions in the source areas, hydrology, sediment loads, sediment flux and sediment yield, and geomorphological parameters such as slope, catchment areas, etc.

4.1. Rock and soil chemical composition

The geology of the source area is dominated by igneous (alkaline and calc-alkaline granites and metamorphic rocks (mainly schist and gneiss) of Precambrian to Paleozoic age. Sedimentary rocks comprise scarce Quaternary and recent fluvial-estuarine and coastal sediments. The Lagares catchment has higher proportions of metamorphic rocks, whilst the Minor's has a predominance of granites. Chemical composition of rocks and soils from the source area in the Lagares and the Minor River catchments (Table 1), show a predominance of silica (~60%), followed by Al_2O_3 (~30%), Fe_2O_3 (~5%), K_2O (3.5%) and Na_2O (~2%), and MgO, CaO and TiO_2 in minor proportions. Comparing both catchments, mean values for Si, Na, K, Rb and Sr, are higher for the Minor reflecting predominance of alkaline and calc-alkaline granites. To the contrary, the Lagares catchment shows higher values for Fe_2O_3, MgO, CaO, TiO_2 and MnO reflecting the dominance of gneissic rocks with ferromagnesian minerals such as biotite and/or riebeckite. These data are consistent with the values given by Turekian and Wedepohl (1961) and Taylor (1964). Trace elements (V, Cr, Co, Ni, Cu and As) are also higher for the Lagares catchment and some elements such as Cr, Cu and Ni surpass values defined as background by Rubio et al. (2000) for sediments deposited in the Ria de Vigo. This proportion of trace elements is in part due to soil pollution and is also reflected in water composition.

4.2. Geomorphology and hydrology

The total drainage area of the Ria de Vigo catchment is 709 km^2. The whole catchment has a rectangular shape with a NE–SW axis. The Verdugo

Table 1
Chemical composition of rocks and soils

Elemental composition	Total	Minor River	Lagares River
SiO_2	57.34±9.90	57.86±7.19	56.70±12.93
Al_2O_3	27.25±6.72	25.58±5.87	29.31±7.45
Fe_2O_3	4.48±3.00	4.14±2.68	4.90±3.47
K_2O	3.51±1.18	4.02±0.89	2.89±1.24
Na_2O	1.81±1.34	1.92±1.19	1.68±1.57
CaO	1.03±1.64	0.56±0.29	1.61±2.38
MgO	1.43±1.53	0.97±0.50	1.99±2.16
TiO_2	0.69±0.51	0.64±0.35	0.75±0.67
MnO	0.06±0.00	0.05±0.04	0.08±0.07
V	96.55±109.20	75.71±82.85	122.03±135.69
Cr	102.02±125.06	70.32±82.11	140.76±160.17
Co	11.59±12.59	9.03±11.35	14.71±13.98
Ni	34.24±39.45	23.37±23.76	47.52±51.29
C	30.05±25.66	21.30±14.04	40.73±32.93
Z	74.27±32.65	84.35±34.17	61.94±27.61
A	24.67±18.16	17.89±5.84	32.95±24.50
Rb	89.63±117.26	229.92±107.07	140.39±115.61
Sr	99.77±79.86	139.70±84.64	50.96±36.34
Ba	625.86±162.49	626.65±196.08	624.88±121.02
Pb	32.76±18.49	42.52±18.54	20.83±9.54

Chemical composition (mean±standard deviation) of rocks and soils from the source area at the Minor and Lagares catchments. Oxides are in % and elements in mg/g.

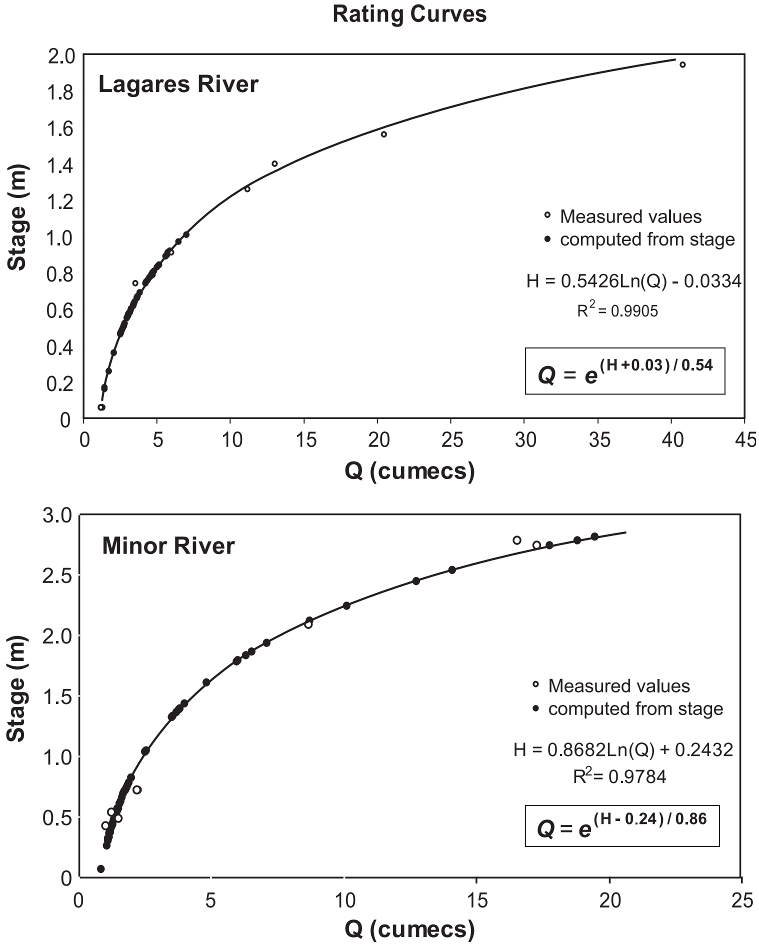

Fig. 5. Rating curves for the Lagares and Minor Rivers obtained during 1997/1998 and 2000/2001, showing measured data and fitted stage values.

and Oitaven Rivers, which merge 4.5 km upstream from their common estuary in San Simon Bay (Fig. 1), are located at the ria head and follow the same orientation. The permanently flooded marine basin area of the Ria de Vigo is 149 km^2 so that the AD/AB index equals 4.8 (AD=drainage area; AB= basin area). This means that the catchment areas are large compared to the marine basin area, implying that the potential sediment input should be high. Longitudinal rivers constitute 45% of the total catchment area, the remainder is taken up by minor transverse drainage systems. Most of the transversal catchments form a mosaic of small catchments at the north and south margins. The largest rivers are the Minor and the Lagares, located between Baiona and Vigo (Fig. 1).

The Minor River, 15 km long, along with the right main tributary, the Zamans River, 16.5 km long, drains an area of 75.8 km^2. An asymmetric distribution of the channels is apparent, with channels better developed at the right margins. The major divide is at an altitude of up to 600 m. Longitudinal profiles along the channels have a concave-up profile and they are not regularly graded (Perez-Arlucea et al., 2000a). Several steps occur along the river thalweg at altitudes of 50, 100 and 300 m. Lithological contacts in the catchments have a N–S trend and do not affect network distributions as observed in other Galician catchments (Pages, 2000). Many of the tributary rivers follow fracture trends, which suggests that the drainage network is in part controlled by tectonics. Average

Table 2
Hydrologic data for the Lagares and Minor Rivers

Year	$\bar{H}$ (m)	H_{max} (m)	$\bar{u}$ (m/s)	$\bar{Q}$ (m^3/s)	Q_{max} (m^3/s)	Slope	τ_0 (Pa)	ω (W/m^2)
Lagares River								
1997–1998	0.64	1.26	0.70	3.60	11.15	0.20°	21.90	15.30
2000–2001	0.68	1.96	1.00	5.45	41.50		23.30	23.30
Minor River								
1997–1998	0.82	2.45	0.20	2.53	12.70	0.25°	35.00	7.00
2000–2001	1.40	2.80	0.33	6.70	19.50		60.00	19.80

Physical and hydraulic parameters for the Minor and the Lagares rivers, including average depth ($\bar{H}$), maximum depth H_{max}, slope, average velocity ($\bar{u}$), average discharge ($\bar{Q}$), peak discharge (Q_{max}), bed shear stress (τ_0) and stream power (ω).

slope in the lower reach is about 0.25° and in the upper reach 7.6°.

The Lagares catchment is 69.3 km^2 in area (Fig. 1). Maximum elevations at the divides are located at the western and southern margins, where they reach 300 and 450 m. Mean elevation is lower than that of the Minor. The Lagares River, 17.6 km long, and main tributaries show also disequilibrium longitudinal profiles, with steps at 50, 100 and 250 m. The average slope for the upper reach is about 1.8° and 0.2° for the lower reach.

Weekly stage measurements show important variations over the year, although channel cross-sections are quite stable. All 19 previously studied rivers at the Ria de Vigo show similar stage tendencies over the year (Perez-Arlucea et al., 2000a). There is a well-defined low stage from June to September and two high-stage periods, the first from November to January and the second in March to April. Measured stage fluctuations correlate with seasonal variations in precipitation. Meteorological data from 2000 and January to May 2001 show very atypical precipitation mean values. Peak monthly values (600 mm), recorded in November–December are about three times higher than average over the last 10 years (data from the Galician Territorial Meteorological Centre and private meteorological station at Gondomar). Different rivers show variable minor fluctuations reflecting local meteorological conditions. Direct measurements show mean discharge values for the Verdugo River from 13 to 17 cumecs (i.e., Lopez-Jurado, 1985). The transverse, minor rivers have average discharges from 0.05 to 3.6 cumecs. In spite of these small values it is important to remember that there are 35 tributary rivers and total fresh water

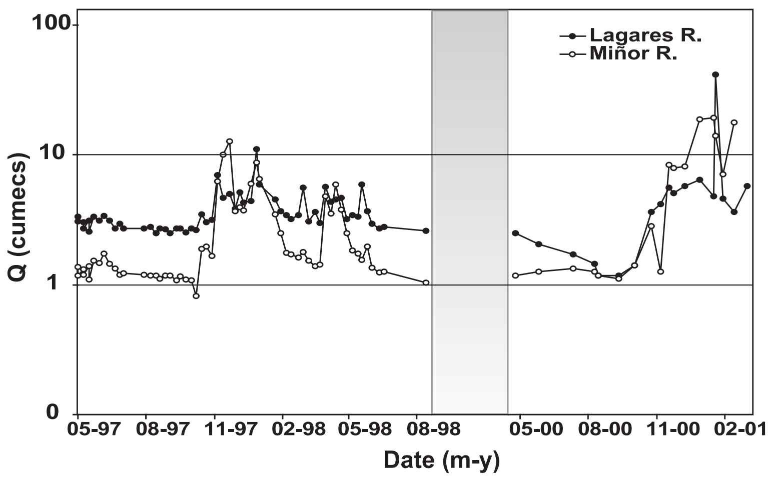

Fig. 6. Time series diagram showing discharge fluctuations obtained from the rating curves for the Lagares and Minor rivers during 1997/1998 and 2000/2001 measured intervals.

input into the ria is substantial (30% to 40% of the total flow, Perez-Arlucea et al., 2000b).

Concentrating now on the two largest transverse tributaries, the Minor and the Lagares, the main object of this study, H/Q rating curves are typically exponential (Fig. 5):

$$Q = e^{(H+a)/b}$$

where Q is discharge, H stage and a, b constant values.

Mean river discharge (Table 2) increased up to 2.5 times due to the unusually high precipitation during November and December 2000 (Fig. 6). Rating curves are very stable, with good correlation values (R^2=0.98). Having established the discharge variation ranges for both rivers it is possible to obtain average values for both 1997/1998 and 2000/2001 periods. During 1997/1998 the Minor River had an average discharge of 2.5 $m^3\ s^{-1}$; for 2000/2001 this figure was 6.7 $m^3\ s^{-1}$. Mean values for the Lagares River were 3.6 and 5.5 $m^3\ s^{-1}$, respectively. For both rivers, discharge values obtained in 1997/1998 are more consistent with previous data (i.e., Nombela, 1989; Fraga, 1996), and can be considered good-weather average values. Those obtained for 2000/2001 should be considered as extreme values. Peak registered discharges were 19.5 cumecs for the Minor River and 41.5 cumecs for the Lagares River during this time. The most important physical and hydraulic parameters for both rivers are summarised in Table 2.

5. River sediment loads and sediment flux

All tributaries have low sediment loads during normal fair weather conditions. Bed materials consist chiefly of boulders and cobbles at the heads of rivers, grading to very coarse granules, pebbles and medium-coarse sand toward estuarine areas. Quartz

Table 3
Calculated values for sediment yield and erosion rates from river loads

Minor						
Period	SLC (mg/l)	CA (km^2)	SF (ton/a)	SSY (ton/km^2 a)	MDR (m^3/km^2 a)	PErosion (mm/ka)
1997–1998	22.9	75.8	1947	25.8	9.5	26.1
2000–2001	50.0		10564	139.7	51.8	
Period	DLC (mg/l)	CA (km^2)	DF (ton/a)	DSY (ton/km^2 a)	QDR (m^3/km^2 a)	PErosion (mm/ka)
1997–1998	97.0	75.8	8259	109.3	40.5	
2000–2001	73.0		15424	204.0	75.6	
Lagares						
Period	SLC (mg/l)	CA (km^2)	SF (ton/a)	SSY (ton/km^2 a)	MDR (m^3/km^2 a)	PErosion (mm/ka)
1997–1998	71.6	69.3	8287	119.5	44.3	21.5
2000–2001	105.6		18179	262.3	97.1	
Period	DLC (mg/l)	CA (km^2)	DF (ton/a)	DSY (ton/km^2 a)	QDR (m^3/km^2 a)	PErosion (mm/ka)
1997–1998	120.7	69.3	13970	201.5	74.6	
2000–2001	94.1		16208	157.2	58.2	
Verdugo						
Period	SLC (mg/l)	CA (km^2)	SF (ton/a)	SSY (ton/km^2 a)	MDR (m3/km^2 a)	PErosion (mm/ka)
1997–1998	3.5	331.5	1888	27.2	10.1	NA
Period	DLC (mg/l)	CA (km^2)	DF (ton/a)	DSY (ton/km^2 a)	QDR (m^3/km^2 a)	PErosion (mm/ka)
1997–1998	52.7	331.5	28752	414.8	153.6	

Estimated values in relation with sediment yield and erosion rates. Suspended load concentration (SLC), dissolved load concentration (DLC), catchment area (CArea), sediment flux (SF), suspended sediment yield (SSY), dissolved sediment yield (DSY), mechanical erosion rates (MDR), chemical denudation rates (QDR), potential erosion (PErosion) (Ahnert's, 1970 equation).

and feldspar grains dominate, although metamorphic rock fragments, mainly schists and slates, can be locally quite abundant. The Minor and the Lagares Rivers have the highest proportion of sand size particles of all the transversal tributaries.

Up to 43 water samples were taken from each river to determine suspended sediment and dissolved loads and composition (Table 3). Typical suspended sediment compositions are kaolinite (22%), muscovite (17%), quartz (15%), orthoclase (13%), anorthite (11%) with minor proportions of albite (8%) and microcline (6%). Individual rivers show important fluctuations in stage and sediment load concentrations. Fig. 7 shows stage fluctuations, represented in nondimensional form (H/H_{max}), and suspended load concentrations for the Lagares, the Minor and the Verdugo rivers for 1997/1998. During 1997/1998, the Lagares had the highest concentrations of all the rivers: 71.6 mg/l with a sediment flux of 8287 ton/a. Second was the Minor with 22.9 mg/l and 1947 ton/a. The remaining rivers showed typical average concentrations with flux values smaller than 60 ton/a (Perez-Arlucea et al., 2000a). It is important to note that the Lagares River had a sediment flux about four times higher than the much larger Verdugo River (3.5 mg/l and 1888 ton/a for an average discharge of 17.3 cumecs). The Lagares and the Minor rivers, are about the same size and have discharges and catchment areas approximately of the same order. Nevertheless, the Lagares had an average sediment flux an order of magnitude higher.

Suspended load versus discharge relationships are power law (Lagares) or linear (Minor) but data are strongly scattered, resulting in low correlation indexes for 1997/1998 (R^2~0.6). This can in part be explained by flow and load variations. During 2000/2001, additional measurements were taken at the Lagares and Minor Rivers. The SLC for the Minor was 50.0 mg/l and sediment flux was 10,565 ton/a. The Lagares had a SLC of 105.6 mg/l and a sediment yield of 18,179 ton/a for the same period of time. Those figures can be considered as extreme maximum values for an extremely wet year.

A most important conclusion is that dissolved loads (weight per unit volume) are several times higher than suspended loads in almost all 19 measured rivers, from 10 mg/l to extreme values of 1300 mg/l during 1997/1998, although most typical values are 10–50 mg/l (Fig. 8). Average values for the Minor and Lagares are depicted in Table 3. The Verdugo River yields higher amounts of dissolved materials than any of the transversal rivers. During 2000/2001 concentrations were lower for both the

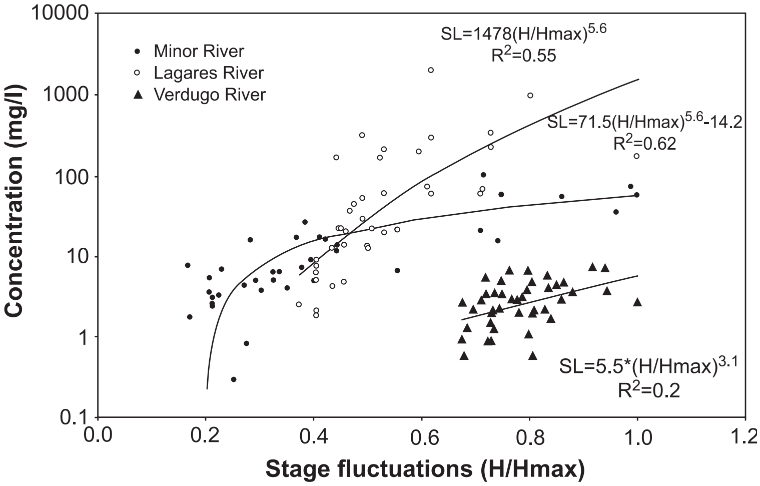

Fig. 7. Concentration versus stage fluctuations (H/H_{max}; H: stage; H_{max}: maximum recorded stage for one particular river) for the Lagares, Minor and Verdugo rivers. The Verdugo River, being the main longitudinal river, shows a smaller stage fluctuation range and also lower concentrations than the minor transverse Lagares and Minor Rivers.

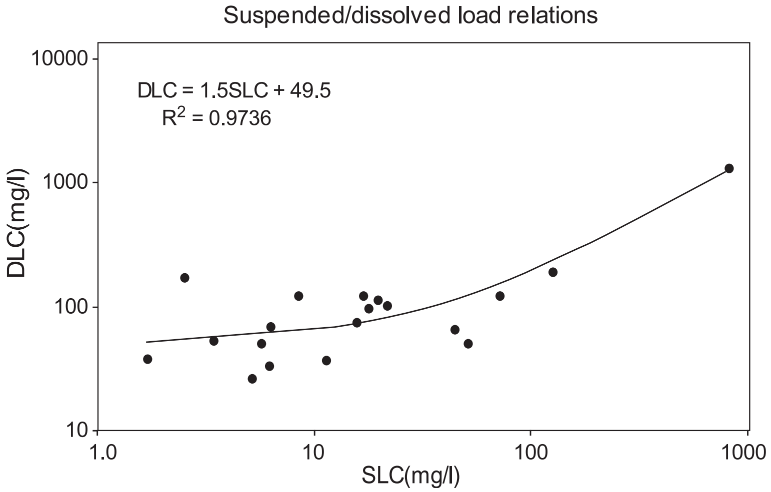

Fig. 8. Suspended load concentrations (SLC) versus dissolved load concentrations (DLC) for the 19 biggest rivers flowing into the Ria de Vigo.

Minor and the Lagares, than those of 1997/1998, but a considerable increase in the discharge allowed higher dissolved material fluxes during the year (Table 3). Dissolved load concentrations (DLC) vary more widely with discharge than suspended loads. Water chemistry shows high values for sodium, calcium, potassium, magnesium, silica and chlorine and minor proportions of aluminum, iron and manganese. DLC versus discharge (Q) graphs show large scatter and very low correlation indexes (R^2<0.5), but in all cases, trends show systematic linear trends with negative correlations. This tendency is due to dilution of the DLC as the water discharge increases.

Poor correlations in both SLC and DLC may be due to pollution, mostly in the Lagares River. Human activities such as road and building construction (increasing suspended loads due to deforestation, soil breaking and ground piling up during works), sewage inputs, chemical waste from industries (increasing chemical loads) and agricultural activities may account for the difference in load concentrations, as indicated also in previous results (Pazos et al., 2000). Another factor to consider is the input from marine spray or wet winds blowing from the sea (NW winds) which may explain in part the high proportions of chlorine in the water, and the observed exponentially decreasing values versus distance toward the sea (Perez-Arlucea et al., 2001).

6. Sediment yield and erosion rates from river loads

To estimate short-term erosion rates from river loads, average discharges for the Minor and the Lagares rivers, sediment flux, suspended and dissolved sediment yields were calculated for both study periods. Solid suspended sediment yield (SSY) mean values for the Minor near Baiona Bay were 25.8 ton/km^2 a for 1997/1998 and 139.7 ton/km^2 a for 2000/2001. Values for dissolved sediment yields (DSY) were 109.3 and 204.0 ton/km^2 a, respectively. Considering an average rock density of 2.7 g/cm^3, mechanical denudation rates (MDR) of 9.5 m^3/km^2 a during 1997/1998 and 51.8 m^3/km^2 a have been estimated for 2000/2001. Chemical denudation rates (QDR) are 40.5 m^3/km^2 a for the first period and 75.6 m^3/km^2 a for the second.

In spite of having a smaller area and lower slopes, the Lagares River shows higher values for suspended sediment yield and erosion rates than those of the Minor and the Verdugo rivers (see Table 3). This applies even for 1997/1998 when the average discharge was smaller than that of the other two rivers. Dissolved sediment yield was 201.5 for 1997/1998 and 157.2 ton/km^2 a for 2000/2001. MDR data obtained during the 2000/2001 interval can be considered as maximum values, bearing in mind the very unusual high rainfall conditions. Average MDR data for the Minor River are of the same order as those described by Gunnell (1998) and Riebe et al. (2001) for granitic terrains, whereas the Lagares shows generally higher values.

7. Coastal deposits: the Ramallosa Complex

7.1. Sedimentology of the coastal deposits

Coastal deposits are not very prominent in the Ria de Vigo. Beach and aeolian sand dunes are preserved in protected bays along margins between low cliffs (Nombela et al., 1995). Generally, high cliffs dominate the coast line. Several rivers form prominent estuaries such as the Verdugo-Oitaven, the Minor and the Lagares. Tidal flats are well preserved in the San Simon embayment and small areas of tidal flats and marshes can be found elsewhere associated with estuaries and protected by sandy spits (Nombela et al., 1995).

Both the Minor and the Lagares river estuaries show associated tidal marsh deposits, although those associated with the Lagares are not well preserved, as they were partially used for artificial salt mining in the past and are thus modified by human activities. By way of contrast, the Minor River has well-preserved estuarine and tidal sedimentary environments that we describe as the Ramallosa complex.

7.2. The Ramallosa Complex

The Ramallosa Complex is located in a tide-dominated environment protected by a spit (Ladeira Beach, Figs. 9 and 10). There are two rivers entering the Complex, the Minor and the Groba (Fig. 9). The Minor River has a single, 22-m-wide, meandering channel at the upstream reach. Further downstream, about 3 km from the coast, it develops into an estuary entering the Ramallosa Complex from the north. The estuarine reach shows a fairly straight, 54-m-wide channel with several alternate bars evolving downstream to a multichannel braided system. Several

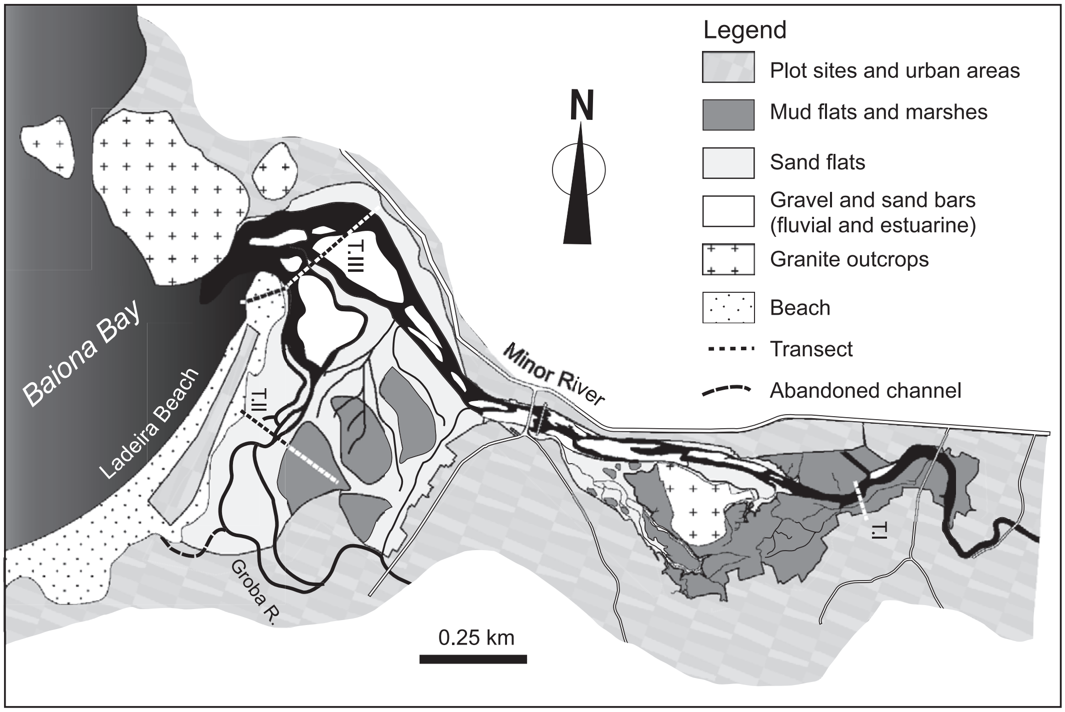

Fig. 9. Ramallosa Complex simplified map, showing the Minor and the Groba rivers estuarine areas, the intertidal areas and the spit. Locations of Transects I, II and III, depicted in Fig. 10, are shown.

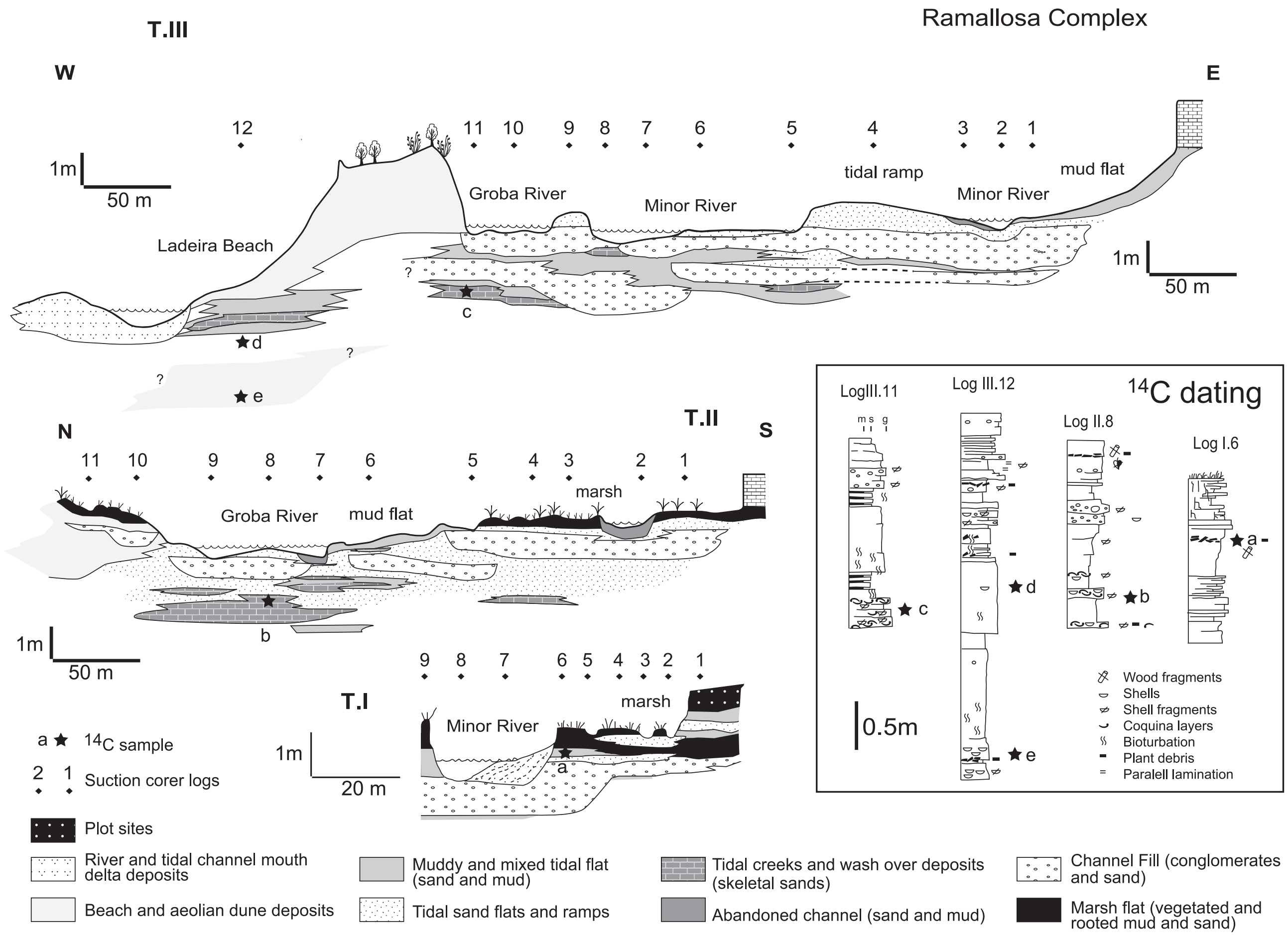

Fig. 10. Transects I, II and III of the Ramallosa Complex. Facies distributions, borehole positions and ^{14}C age data are shown. Inset shows detailed logs with ^{14}C samples.

flood and ebb midchannel ramps are present. The Groba River is a moderately sinuous channel about 9 m wide at the upstream reach. It enters the complex on the southern margin showing a discrete anastomosing pattern. Individual channels are about 35 m wide. Nowadays, the Groba River flow is forced parallel to the beach, although in the past it crossed the area of the present beach about 1 km south of the present outlet. Fluvial deposits are preserved under the modern beach sediments at this location. The Minor and the Groba rivers merge close to the narrow outlet located at the north end of the beach.

Tidal deposits consist of sub to intertidal sand flats and midchannel ramps, mixed intertidal mud–sand flats and intertidal to supratidal marshes. Sandy deposits are dominant in the north and in the back barrier area. Muddy deposits are better preserved toward the inner, south part of the complex. Tidal range is 2–3 m. During average tides about 90% of the complex is flooded giving rise to a wide lagoon.

Facies distribution was examined in three cross-sections to show the most representative environments in the complex (Fig. 10) and to determine parameters for the calculations of bed load fluxes. Transect I is a North–South, 75 m long, cross-section representing the proximal fluvial/estuarine area in the inner part of the complex (T.I, Fig. 10). Transect II is 418 m long (T.II, Fig. 10), and is a more distal section crossing the Groba River from the low supratidal marshes toward the spit back-barrier. Transect-III is 672 m long (T.III, Fig. 10) and crosses the distal part of the complex, from mud flat deposits in the east, through the estuarine part of the Minor and Groba rivers toward the distal part of the spit at the west. Thirty-two suction corer boreholes were obtained with lengths varying from 1 to 4 m, and spaced from 7 to 50 m (Fig. 9). Lithofacies descriptions based on borehole logging and correlations are described below.

7.2.1. Channel fill

Channel fills consist of light gray to tan, very coarse sand, granules and pebbles (20% gravel, 78% sand, 2% mud). They form isolated, lenticular sand bodies separated by tidal deposits (T.II and T.III, Fig. 10). Mud clasts are frequently preserved at the base of channel bodies. Channel bodies formed by the ancestral and present Minor River are 240–260 m wide, larger than those of the Groba, which are 80–150 m wide. Channel deposits show very similar thickness from 0.8 to 1 m. Abandoned channel deposits, as in the North Groba channel, consist of very fine sand, silt and clay forming lenticular deposits. Up to 0.4-m-thick muddy sediments are preserved (2% gravel, 66% sand, 32% mud). Bioturbation ranges from moderate to intense.

7.2.2. Sand flats and ramps

Sand flats and ramps consist of dark to medium gray, medium to fine mica-rich sands (3% gravel, 96% sand, 1% mud). Bioturbation by *Arenicola marina* is frequent although not very intense. Well-preserved centimeter-scale layering is usually observed in the cores. At the surface, sand waves, dunes and ripples are preserved. Nonarticulated bivalve shells and shell fragments, plant and wood debris are common.

7.2.3. Mixed and mud flat

Mud flats are not well developed. They are thin, black, organic-rich or dark grey mud layers along the Minor River and small flat areas close to the marshes. Mixed environments with interlayered muds and fine and medium sand (0% gravel, 97% sand, 3% mud) are much more common and are present between channel bodies at the estuarine area (T.II and T.III). Layers are typically several centimeters thick. Plant remains, black wood fragments, inarticulate shells and shell fragments (chiefly bivalves) are abundant in some layers. Moderate bioturbation may occur.

7.2.4. Marshes

This lithofacies typically consists of black, organic-rich clay, silt and sand layers (0% gravel, 69% sand, 31% mud). Bioturbation by roots is commonly intense and oxidation occurs locally. Plant and wood remains are abundant. Some gastropod and bivalve shells may be present. Modern marshes are colonized by *Spartina* and *Juncus maritimus* (Alejo et al., 1990). They are better developed at the upper, proximal part of the Ramallosa Complex and South areas (T.I and T.II, Fig. 10).

Table 4
Ages and sedimentation rates (SR) for the Ramallosa Complex deposits

Sample	Location	Depth (m)	Age				SR(mm/a)
			^{14}C age (years BP)	Cal. years BP	Max. P. (years BP)	Calendar age	
a	T.I, Log6	0.6	210±110	230–132	–	1720–1818AD	2.60–4.50
b	T.II, Log8	1.71	730±40	459–286	388	1562 AD	4.40
c	T.III, Log11	1.86	2790±40	2691–2353	2496	547 BC	0.75
d	T.III, Log12	1.74	850±40	526–427	484	1466 AD	3.60
e	T.III, Log12	3.44	2390±40	2115–1914	2001	52 BC	1.12

Ages (AMS ^{14}C age determinations) for samples a to e taken at the Ramallosa Complex. Sample location is shown in Fig. 10.

7.2.5. Tidal channels

Tidal channels form a dense dendritic network crossing the marshes and the tidal flats, flowing toward the north and east. Tidal channels and creek deposits range from 3 to 25 m in width and from 100 to 400 m in length. Lithology varies from very coarse sand and granules to medium to fine sands. They have a coarser bed load at the locations closer to T.I, whereas at the most distal areas (T.II and T.III) they are finer and show abundant shell and plant debris (Fig. 9). Some tidal channels are becoming abandoned and infilled by muddy deposits.

7.2.6. Beach

Beach deposits consist of light tan, medium to fine, well sorted sand (1% gravel, 99% sand, 0% mud). Toward the north the beach sands are poorly sorted, and medium to coarse due to local influence of fluvial sediments from the Minor and Groba rivers (Fig. 9), coming out from the outlet (18% gravel, 82% sand, 0% mud). Particles are chiefly siliciclastic although some bioclastic, carbonate-rich layers occur. They are finer at the upper part, where some aeolian, vegetated dunes exist. Beach deposits form wedge-shaped sand bodies, with a maximum thickness of 2 to 2.6 m (T.III, Fig. 10).

7.3. Geochronology (^{14}C dating)

Five samples have been ^{14}C dated. Sample locations are shown in Fig. 10. Data is summarized in Table 4. Sample *a* consisted of wood fragments and was located at 0.6 m below the surface, at the base of marsh deposits, in Transect-I. The rest of the samples collected for ^{14}C analysis were marine bivalve shells and shell fragments. Sample *b* was collected in core 8 at T.II, at 1.71 m below the surface. Sample *c* was taken in T.III, at 1.86 m. Finally, samples *d* and *e* in T.III, with depths of 1.74 and 3.44 m, respectively. Ages provided by Geochron laboratories (MA, USA) were analyzed by accelerator mass spectrometry (AMS). Radiocarbon ages were calibrated using the University of Washington Quaternary isotope lab Radiocarbon Calibration Program Rev. 4.3.

In sample *a*, the error margin is large and the age is not very precise. With the exception of sample *c*, all samples, including *a*, show consistent ages (Fig. 10). Sample *c* is far too old compared to samples *b* and *d*,

Table 5
Estimated values related to the Ramallosa Complex and erosion rate calculations

Rock density (ton/m^3)	Grain density (ton/m^3)	Porosity	Sediment density (ton/m^3)	Sedimentation area (km^2)		
2.7	2.66	0.2	2.1	0.88		
Interval	Time interval (years)	$\overline{SR}$ (mm/a)	AR (ton/km^2 a)	SF (ton/a)	SY (ton/km^2 a)	DR (mm/ka)
Upper	484	3.7	7.8×10^3	6.8×10^3	90.2	33.4
Lower	1517	1.1	2.3×10^3	2.1×10^3	27.3	10.1

Upper part: rock density, sediment parameters and Ramallosa Complex sedimentary area. Lower part: estimated values for the two defined intervals of average sedimentation rates ($\overline{SR}$), accumulation rates (AR), sediment flux (SF), sediment yield (SY) and denudation rates (DR) based in the Ramallosa Complex sediments.

which were located at similar depths and show reasonable ages (Table 4). Possibly, sample *c* is composed of reworked older material, and thus should be rejected.

8. Sediment budget

Calculated sedimentation rates (SR) are shown in Table 4. SR estimations have been made with depths measured in the cores corrected for compaction (a linear decompaction was made considering penetration depths measured in the field when coring) and sediment ages. Apart from the oldest and deepest sample *d* which yields 1.1 mm/a, sedimentation rates vary from 3.3 to 4.4 mm/a. Accumulation rates (AR) (sediment weight per area and unit time; Table 5) have been estimated using an SR/AR conversion diagram (Einsele, 2000). We consider average grain density 2.66 ton/m^3, sediment density 2.10 ton/m^3, porosity 0.2 and average sedimentation rates of 1.1 for the older dated interval (1517 years) and an average of 3.7 mm/a for the younger interval (484 years). Resulting values for sediment accumulation rates are 2.3×10^3 ton/km^2 a. Allowing for an area of 0.88 km^2 for the Ramallosa basin, total sediment flux was 2.1×10^3 ton/a. If we consider now the Minor catchment area (75.8 km^2) sediment yield would be 27.3 ton/km^2 a. Now to convert this figure into an erosion rate, we use an average rock density of 2.7 ton/m^3, resulting in a rate of 10.1 m^3/km^2 a. The same calculations for the younger interval yields erosion rates of 33.4 m^3/km^2 a.

Most of this sediment is fluvial-derived siliciclastic material. Basin carbonate production and marine sediment input occur during storms (washover deposits) but are not very high (Fig. 10). Sediments accumulated in the Complex are mainly bed load derived coarse material, and thus, resulting values can be used to approximate bed load sediment yield to the basin. Considering the proportion of coarse to fine material defined for different facies and facies distributions (Fig. 10) we estimate that between 90% and 95% of the total sediments correspond to bed load material. This implies that from the total amount of eroded material (10.1 m^3/km^2 a or 10.1 mm/ka) about 9.1–9.6 m^3/km^2 a would correspond to bed load derived erosion and only 1.0–0.5 m^3/km^2 a will correspond to suspended load for the lower interval. This means that 90% of the mud coming from the rivers as suspended load is exported out toward the Ria during normal weather conditions. For the upper interval 30.1–31.7 m^3/km^2 a should correspond to bed load and 1.7–3.3 m^3/km^2 a to suspended load eroded material. In this case, 73.8% of the suspended particles are exported to the marine environment.

The Ramallosa sedimentary area is very small (0.88 km^2) compared to its Minor River catchment (75.8 km^2) and nowadays forms a semienclosed sedimentary basin. To evaluate the proportion of sediments preserved over time is not yet possible, but a dynamic model involving progressively more restricted conditions simultaneous to the evolution of the spit may apply. Differences in sedimentation rates from the first interval (2001–484 years BP) and the second (484 years BP to present) may be interpreted also in part by accelerated human influence in the last 480 years, like progressive deforestation, fires, cultivation, building and road construction, etc. Pollen data presented by Tornqvist et al. (1989) suggest that climatic changes during the last 2500 years are not very significant and vegetation changes (which can alter erosion rates and sediment yield) are due mostly to human influence. There is no direct evidence in the studied sediments that indicates significant climatic changes which could alter erosion and sedimentation rates although this must remain a possibility.

Calculated potential erosion rates, using Ahnert's (1970) equation for the Minor are higher (26.1 mm/ka) than for the Lagares (21.5 mm/ka) which contrast with mechanical denudation rate values (MDR) from river loads during 1997/1998 (Table 3). During 2000/2001 MDR values were higher than those of the potential erosion rates for both rivers, in relation to the recorded extremely high precipitations. Higher values of mechanical denudation rates in the Lagares during 1997/1998 may corroborate human influence.

9. Conclusions

The objectives of the proposed budget study with calculated erosion and sedimentation rates were completed. The most important results and conclusions are:

– Data obtained for May 2000 to May 2001 show a very atypical meteorological year. Rainfall conditions were the most intense on record and had an important influence on river discharge, sediment loads and yields, which can all be considered as extreme historic values. For both the Lagares and Minor rivers, discharge values obtained in 1997/1998 are more consistent with previous data and may be considered good-weather average values.

- Suspended load (SLC) versus discharge relationships are linear or power law with low correlation indexes. Dissolved load concentrations (DLC) are higher than suspended load concentrations (SLC) in almost all rivers entering the Ria de Vigo. Both tributaries show higher concentration values than the main longitudinal river, which has a much larger catchment area. DLC versus discharge (Q) curves show a high data scatter. In all cases data show linear trends with negative correlations. This tendency is due to dilution of the DLC as the water discharge increases. Possibly, poor correlations are due to pollution, especially in the Lagares River, where chemical soil composition shows higher proportions on trace elements, indicative of contamination.
- Estimated sediment yield and mechanical denudation rates estimated from suspended loads were higher also during 2000/2001 than for 1997/1998. Those figures can be considered as maximum values for an extremely wet year.
- 5 age determinations by ^{14}C dating have been used to calculate sedimentation and accumulation rates in the Ramallosa Complex. Sedimentation rates are lower from 2001 to 484 years BP than from 480 years BP to present. We conclude that about 90–95% of the preserved sediments have been introduced into the complex by bed load, with 90% of fluvial-derived mud exported out to the Ria as suspended load during normal weather conditions.
- Several factors could be involved in the observed increase in sedimentation rates (apart from minimal compaction for deeper sediments): (1) progressive changes in the degree of basin confinement by lateral growth of the spit (Ladeira Beach), evolving as a dynamic system and influencing sediment preservation in the area and (2) anthropogenic causes like progressive deforestation, cultivation and construction activities leading to soil exposure and degradation.

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References

Alejo, I., 1994. Estudio dinamico y sedimentario de la Bahia de Baiona. Tesis Doctoral inedita. Universidad de Vigo, Vigo. 264 pp.

Alejo, I., de Ramon, M.I., Nombela, M.A., Reigosa, M.J., Vilas, F., 1990. Complejo intermareal de a Ramallosa, (Bahia de Baiona, Pontevedra): I. Ecologia y evolucion. Thalassas 8, 45–56.

Ahnert, F., 1970. Functional relationships between denudation, relief, and uplift in large mid-latitude basins. Am. J. Sci. 268, 243–263.

Bara, S., Vega, J.A., 1983. Effects of wildfire on forest soil in the northwestern Spain. Proc. II Symp. Fire Ecol. Freiburg.

Benito, E., Soto, B., Diaz-Fierros, F., 1991. Soil erosion studies in NW Spain. In: Sala, M., Rubio, J.L., Garcia-Ruiz, J.M. (Eds.), Soil Erosion Studies in Spain. Geoforma Ediciones, Logroño, pp. 55–74.

Consello da Cultura Galega (1996), As augas de Galicia. Concello da Cultura Galega, Santiago de Compostela. 611 pp.

Diaz-Fierros, F., Gil Sotres, F., Cabaneiro, A., Carballas, T., Leiros de la Peña, M.C., Villar Celorio, M.C., 1982. Efectos erosivos de los incendios forestales en suelos de Galicia. Anales de Edafologia y Agrobiologia, vol. XLI 3-4, pp. 627–639.

Diaz-Fierros, F., Benito, E., Vega, J., Castelao, A., Soto, B., Perez, R., Taboada, T., 1990. Solute loss and soil erosion in burnt soil from Galicia (NW Spain). In: Goldammer, J.G., Jenkins, M.J. (Eds.), Fire in Ecosystem Dynamics. SPB Academic Publishing, The Hague, pp. 103–116.

Diaz-Fierros, F., Basanta, M., Casal, M., 1983. Incendios forestales en Galicia. Sus causas y efectos sobre el medio ambiente. Xunta de Galicia.

Diaz-Fierros, F., Benito, E., Soto, B., 1994. Action of forest fires on vegetation cover and soil erodibility. In: Sala, M., Rubio, J.L. (Eds.), Soil Erosion and Degradation as a Consequence of Forest Fires. Geoforma Ediciones, Logroño, pp. 163–176.

Einsele, G., 2000. Sedimentary basins. Evolution, Facies and Sediment Budget, 2ª Ed. Spinger-Verlag, Berlin. 792 pp.

Fraga, F., 1996. As rias. As augas de Galicia. Consello da Cultura Galega. 611 pp.

Gunnell, Y., 1998. Present, past and potential denudation rates: is there a link? Tentative evidence from fission-track data, river sediment loads and terrain analysis in the South Indian Shield. Geomorphology 25, 135–153.

Lopez-Jurado, 1985. Notas climatologicas e hidrologicas de las Rias Bajas. Inf. Téc.-Inst. Esp. Oceanogr. 23, 1–13.

Méndez, G., Pérez-Arlucea, M., Stouthammer, E., Berensden, H., 2003. The TESS-1 suction corer: a new device to extract wet, uncompacted sediments. J. Sediment. Res. 73, 1078–1081.

Nombela, M.A., 1989. Oceanografia y sedimentologia de la Ria de Vigo. PhD thesis, Universidad Complutense, Madrid. 292 pp.

Nombela, M.A., Vilas, F., Evans, G., 1995. Sedimentation in the mesotidal rias of Galicia (North-Western Spain). Ensenada de San Simon, inner Ria de Vigo. Spec. Publ. Int. Assoc. Sedimentol. 24, 133–149.

Pages, J.L., 2000. Origen y evolucion geomorfologica de las rias atlanticas de Galicia. Rev. Soc. Geol. Esp. 13, 393–403.

Pazos, O., Nombela, M.A., Vilas, F., 2000. Continental contribution of suspended sediment to a ria: Ria de Vigo. Sci. Mar. 64, 295–302.

Perez-Arlucea, M., Filgueira, M., Freijido, M., Mendez, G., 2000a. Parametros morfometricos e hidrologicos de las cuencas de drenaje y rios tributarios a la ria de Vigo. Estimacion de las variaciones anuales en las cargas en suspension y en disolucion. J. Iberian Geol. Cuadernos de Geologia Iberica, vol. 26, pp. 171–187.

Perez-Arlucea, M., Freijido, M., Mendez, G., Filgueira, M., 2000b. Hydraulics and morphology of the tributary rivers entering the Ria de Vigo. Estimation on the annual variations in suspended and dissolved loads.—Hidraulica y geomorfologia de los tributarios de la Ria de Vigo. Estimacion de las variaciones anuales en las cargas de fondo y en disolucion. 3° Simposio sobre a Margem Continental Iberica Atlântica. Universidade do Algarve, CIACOMAR y Centro de Investigação Marinha e Ambiental, Faro (Portugal), pp. 53–54.

Perez-Arlucea, M., Freijido, M.T., Mendez, G., Nombela, M.A., Rubio, B., Filgueira, M., Fernandez-Bastero, S., Gimenez, R., 2001. Tasas de erosion, transporte y sedimentacion en un medio estuarico: el rio Miñor (Ria de Vigo, Pontevedra). XIV Congreso Nacional de Sedimentologia - IV Coloquio del Cretacico de España. Jaen, 10–16 de septiembre, 2001, Geotemas Vol. 3 (2), pp. 17–21.

Riebe, C.S., Kirchner, J.W., Granger, D.E., Finkel, R.C., 2001. Minimal climatic control on erosion rates in the Sierra Nevada California. Geology 29, 447–450.

Rios, A., Nombela, M.A., Perez, F.F., Roson, G., Fraga, F., 1992. Calculation of runoff to an estuary Ria de Vigo. Sci. Mar. 56, 29–33.

Rodriguez Martinez-Conde, R., Puga Rodriguez, J.M., Vila Garcia, R., 1995. Runoff on traditional ploughing. First results (Galicia, NW Spain). III Conference on Erosion and Land Degradation in the Mediterranean: The impact of Agriculture, Forestry and Tourism. Proceedings, University of Aveiro, (Portugal), pp. 169–177.

Rodriguez Martinez-Conde, R., Puga Rodriguez, J.M., Vila Garcia, R., 1996a. Informe Final del Proyecto "Estudio de la degradacion de suelos cultivados en Galicia y posible formulacion de un modelo predictivo de erosion". Conselleria de Educacion e Ordenacion Universitaria. Xunta de Galicia. Inedito.

Rodriguez Martinez-Conde, R., Puga Rodriguez, J.M., Vila Garcia, R., Cibeira Friol, A., 1996b. La erosion en campos cultivados en Galicia (NW España). Cadernos do Laboratorio Xeoloxico de Laxe T, vol. 21, pp. 147–162.

Rodriguez Martinez-Conde, R., Puga, J.M., Vila, R., Cibeira, A., 1998. Comportamientos de la escorrentia en un medio oceanico y de uso agricola (Galicia España). V Reunion Nacional de Geomorfologia. Granada, pp. 547–556.

Rodriguez Martinez-Conde, R., Vila Garcia, R., Puga Rodriguez, J.M., Cibeira Friol, A., 2001. Las perdidas de suelos en zonas cultivables de Galicia (España): una aproximacion a su temporalidad. En: F. Manero (coord.) Espacio natural y dinamicas territoriales. Homenaje al Dr. D. Jesus Garcia Fernandez. Universidad de Valladolid, Valladolid, pp. 149–159.

Rubio, B., Nombela, M.A., Vilas, F., 2000. Geochemistry of major and trace elements in sediments of the Ria de Vigo (NW Spain): an assessment of metal pollution. Mar. Pollut. Bull. 40, 968–980.

Soto Gonzalez, B., 1993. Influencia de los incendios forestales en la fertilidad y erosionabilidad de los suelos de Galicia. Tesis de Doctoral. Universidade de Santiago. Inedita.

Stuiver, M., Reimer, P.J., 1993. Extended 14C database and revised CALIB radiocarbon calibration program. Radiocarbon 35, 215–230.

Taylor, S.R., 1964. Abundance of chemical elements in the continental crust: a new table. Geochim. Cosmochim. Acta 28, 1273–1285.

Tornqvist, T.E., Janssen, C.R., Perez-Alberti, A., 1989. Degradacion antropogenica de la vegetacion en el noroeste de Galicia durante los ultimos 2500 años. Cuad. Estud. Gallegos 38, 175–198.

Turekian, K.K., Wedepohl, K.H., 1961. Distribution of the elements in some major units of the Earth's crust. Geol. Soc. Am. Bull. 72, 175–192.

Valcarcel Armesto, M., 1998. Variabilidade espacial e temporal da erosion en solos de cultivo. Tesis doctoral. Universidad de Santiago. Inedita.

van de Meene, E.A., van der Staay, J., Hock, T.L., 1979. The Van der Staay suction-corer: a simple apparatus for drilling in sand below groundwater table. Rijks Geol. Dienst. Haarlem (Netherlands) 24 pp.

Vega, J.A., 1983. Erosion despues de un incendio forestal. Memoria interna del Departamento Forestal de Zonas Humedas de Lourizan. CRIDA 01. I.N.I.A.

Vega, J.A., Bara, S., Villamuera, M.A., Alonso, M., 1982. Erosion despues de un incendio forestal. Departamento Forestal zonas humedas de Lourizan.

Vila Garcia, R., 1996. A erosion en cultivos tradicionais de Galicia. Universidade de Santiago. Memoria de Licenciatura. Departamento de Xeografia. Inedita.