Temporal and spatial variability in the sediments of a tidal flat, Queule River Estuary, south-central Chile

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ABSTRACT

Microtidal flood plain estuaries are well represented along the coast of south - central Chile (*ca.* 35 - 41°S). The Queule River estuary (39°23'S, 73°12'W) has a small tidal flat, which formed after the earthquake and tsunami of May 1960 and is made up of sandy and muddy areas. Previous studies carried out at the Queule estuary only represented the results of short term sampling, thus the objectives of this study are to assess the seasonal textural changes, in order to interpret possible simultaneous variations in both areas, and to relate the sedimentological variability to tide and river discharge variables. Both areas were sampled 27 times from November 1995 to December 1997. Standard laboratory procedures were applied to determine the texture of the samples. Metereological information was also obtained from a nearby station, as well as tide forecast from national tables. This information was used to examine the temporal variability of the sedimentological characteristics as well as their possible relationships to environmental variables, by means of one-way ANOVA, multiple regression and canonical analysis models. Two variables, mean sand size and the relative percentage of the organic fraction of the mud, showed no differences between the areas. Most of the sedimentological parameters, *i.e.*, percentages of organic sand, organic and inorganic mud, and mean sand size, changed simultaneously in both areas, but the variation was greater on the muddy flat. There are significant relationships between the variability of some sedimentological parameters, rainfall and tide range, and the most obvious changes were related to the rainy season caused by the 1997 El Niño event.

Key words: Microtidal estuaries, Tidal flats, Texture, Environmental variability, El Niño, Chile.

RESUMEN

Variabilidad espacial y temporal de los sedimentos de una planicie de marea, Estuario del río Queule, centro-sur de Chile. Los estuarios micromareales de planicie fluvial están numerosamente representados a lo largo de la costa de Chile centro-sur (*ca.* 35-41°S). El estuario Queule (39°23'S, 73°12'W) presenta una planicie mareal, originada después del sismo y tsunami de mayo de 1960, y está compuesta por áreas arenosas y fangosas. Los estudios anteriores en esta planicie fueron el resultado de muestreos de corto plazo; por esta razón los objetivos de este estudio incluyeron la evaluación de los cambios texturales estacionales, la interpretación del posible sincronismo de tales cambios en ambas áreas, y la determinación de la eventual relación entre las características sedimentológicas y la variabilidad de la descarga del río y la altura de la onda de marea. Ambas áreas se muestrearon 27 veces desde noviembre de 1995 a diciembre de 1997. Se aplicaron procedimientos estándar de laboratorio para determinar la textura

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de las muestras. También, se obtuvo información meteorológica desde una estación cercana, y además datos de proyecciones de marea de tablas nacionales. Esta información se usó para explorar la variabilidad temporal de las características sedimentológicas y las relaciones con las variables ambientales por medio de modelos estadísticos de análisis de varianza de una vía, regresión múltiple y análisis canónico. Dos variables, tamaño medio de la arena y el porcentaje relativo de la fracción orgánica del fango no presentaron diferencias entre ambas áreas. La mayoría de los parámetros sedimentológicos, *i.e.*, porcentajes de arena orgánica, fango orgánico e inorgánico, y tamaño medio de la arena variaron simultáneamente en ambas áreas, pero la variación fue más importante en la zona fangosa. Se detectaron relaciones significativas entre la variabilidad de algunas características de los sedimentos y la altura de la marea y la precipitación. Los cambios más conspicuos estuvieron relacionados con la temporada lluviosa del evento El Niño de 1997.

Palabras claves: Estuarios micromareales, Planicie de marea, Textura, Variabilidad ambiental, El Niño, Chile.

INTRODUCTION

The asymmetry of the tidal waves in estuaries and other shallow-water embayments, results in the transport and deposition of muddy sediments (fine sand, silt, clay and organic compounds: European Community Maine Science and Technology Report -EC-MAST, 1993) on tidal flats and salt marshes. The coexistence of mud and sand in these environments is usually explained as a result of their different behavior in suspension, and the variability of tidal currents (Pethick, 1984). In shallow water, the tidal velocity is out of phase with the tidal height, *i.e.* during high and low tide the current velocity is zero, whereas the maximum velocity occurs during flooding and ebbing. In these environments, deposition of fine sediments takes place only during high water level. This is dependent on the settling velocity and the suspended sediment concentration (McCave, 1970). During low water, the tidal flat is exposed. At the beginning of the flood, the energy of the tide is concentrated along the tidal creeks until these are full of water, with the water subsequently moving over the tidal flat. The part of the flat affected by the mid-flood tide is subjected to sand grain transport, because the energy reaches its maximum at that time. From the mid-flood tide to the high water level, the current velocity decreases, and fine sediments are deposited in the upper parts of the flat, close to the saltmarshes.

Due to the fact that mud is a cohesive sediment, erosion is not caused by individual grains being lifted into the current, but rather by mass failure. Thus, it is quite difficult to predict the balance between deposition and erosion in these environments (Amos, 1995).

Microtidal estuaries are well represented along the coast of south-central Chile (*ca.* 35-41°S; Pino, 1994). Most of them can be classified as plain flood estuaries. The majority of these estuaries get water from the Coastal Range, and only a few originate in rivers which drain water from lakes located in the foothills of the Andes (Campos and Moreno, 1991).

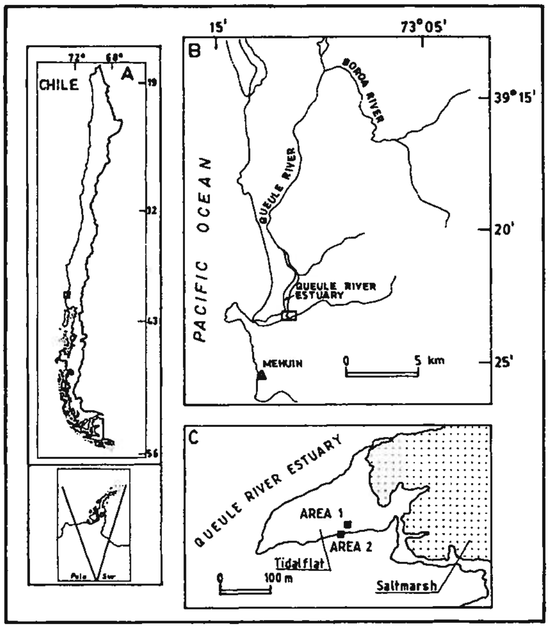

FIG. 1. Map of the Chilean coast **(A)**; Queule River Estuary **(B)**; sampling sites **(C)**; Numbers 1 and 2 indicate the sampling areas on the sandy and muddy tidal flat, respectively; ▲ meteorological station (1B).

The substrate of these estuaries is primarily sandy; finer sediments originated from soil erosion occur in protected areas where there is low current velocity (Pino and Mulsow,1983). The highest content of organic matter is associated with those fine sediments (Bertrán, 1984, 1989; Jaramillo *et al.*, 1985; Turner, 1984; Pino and Mulsow, 1983)

The very small tidal flat (about 2 ha) of the Queule River Estuary (Fig. 1) consists of two areas which developed more or less parallel to the main channel of its middle reach. The sandy flat is located in the inner part, close to the channel, whereas the muddy flat can be found farther towards the rocky shore of the estuary, including a tidal creek. Both areas are bounded by a saltmarsh towards the head of the estuary. A 0.5 m high small cliff separates the saltmarsh from the tidal flats. The sandy area comprises the higher zone of the flat, about 20 cm above the muddy area.

So far, the studies carried out at the Queule River Estuary are the results of short term samplings (Jaramillo *et al.*, 1985; Turner, 1984; Pino and Mulsow, 1983), *i.e.* the temporal variability in the sediment characteristics is not known. Thus, the goal of this study was to evaluate the seasonal textural changes, to interpret the possible synchronism of the changes in both areas, and to relate the sedimentological variability to environmental variables (tides and river runoff).

METHODS

During October 1994, 134 bottom sediment samples (5 mm depth) were collected from the tidal flat, over grid units of 18x18 m. Some of the textural characteristics of the samples (after Folk, 1980) were used to draw contour maps to characterize the facies of the tidal flat using SURFER 6.04 software .

Between October 1995 and December 1997 bottom sediments were also collected at two stations (areas 1 and 2, Fig. 1), located on the sandy and muddy tidal flat, respectively. In each of the 27 samplings, 3 replicated sediments were obtained in both areas. The sampling period mostly coincided with a spring tide (about every 28 days), but in some cases, samples were taken every 7 days to a maximum of 4 months (Table 1).

The samples were analyzed immediately by wet sieving using 62.5 micron sieves (Folk, 1980). The organic content of the sand and mud fractions was obtained by weight lost after ignition (550°C, 4 hours, Byers *et al.*, 1978). Granulometric parameters such as mean grain size and sorting were calculated for the sand fraction, using settling tube and moment methods (Emery, 1938, Gibbs *et al.*, 1971; Seward-Thomson and Hails, 1973). The variables used to characterize the sediment were: percentages of inorganic sand, organic sand (carbon organic matter), inorganic mud and organic mud. All these variables (A to D, respectively, Tables 1 and 2) were calculated in relation to the total weight of the sample. Furthermore, the relative percentage of organic mud was calculated in relation to the total weight of the mud (variable E). Mean grain size and sorting were expressed in phi units (variables F and G, Tables 1 and 2).

To show the high variability of the weather conditions (and thus river fresh-water discharge, *vide infra*) the authors used the amount of daily rainfall registered in the meteorological station in Mehuin belonging to the Instituto de Geociencias of the Universidad Austral de Chile, located about 5 km south of the tidal flat of the Queule River Estuary (Fig. 1). The first 3 variables calculated to represent the rainfall correspond to the daily maximum rainfall, the total cumulative rainfall and the mean daily rainfall, respectively, in all cases in relation to the whole sampling period.

In this estuary the rainfall in the catchment area is related directly to the fresh-water discharge (only 3 tributaries and a catchment area of 674 km^2). Unpublished data (M. Pino) obtained by long term measuring of the fresh-water discharge of one tributary of the Queule Estuary, showed that the best regression equation is obtained by using the cumulative rainfall in the four day period before measurement of the water discharge (discharge [m^{3}s^{-1}] = 4 days cumulative rainfall [mm] x 5.459 + 22.4; $r = 0.79$, $p > 0.05$). Thus, rainfall was calculated in a series of cumulative periods of 4 days each, covering a whole month. This means that 10 variables were calculated, representing *e.g.,* the cumul-

TABLE 1. TEXTURAL AND GRANULOMETRIC CHARACTERISTICS OF THE SANDY SEDIMENTS (AREA 1) OF THE TIDAL FLAT OF THE QUEULE RIVER ESTUARY.

Sampling date	Cumulative days	Sampling number	A Inorganic sand (%)	B Organic sand (%)	C Inorganic mud (%)	D Organic mud (%)	E Relative organic mud (%)	F Sand mean size (phi)	G Sand sorting (phi)
28.10.95	0	1	94.80	0.70	3.91	0.59	13.06	1.64	0.39
14.11.95	16	2	95.89	0.84	2.78	0.50	15.20	1.74	0.40
05.12.95	37	3	94.02	0.94	4.40	0.64	12.69	1.62	0.38
21.12.95	53	4	95.17	0.74	3.46	0.63	15.52	1.66	0.39
28.12.95	60	5	94.28	1.10	3.97	0.64	13.84	1.57	0.37
21.01.96	84	6	93.84	0.84	4.56	0.76	14.23	1.68	0.45
17.05.96	199	7	94.55	1.13	3.92	0.39	9.12	1.50	0.43
15.06.96	228	8	94.58	0.89	4.03	0.50	11.10	1.60	0.42
15.07.96	258	9	85.96	1.11	10.25	2.68	20.71	1.46	0.42
17.08.96	290	10	94.86	0.93	3.74	0.48	11.28	1.62	0.42
14.09.96	317	11	96.10	0.70	2.82	0.38	12.00	1.60	0.44
14.10.96	348	12	95.96	0.86	2.69	0.49	15.42	1.49	0.44
14.11.96	378	13	95.60	0.74	3.22	0.44	11.94	1.60	0.41
11.12.96	405	14	94.70	0.74	3.99	0.57	12.41	1.64	0.41
11.01.97	432	15	94.70	0.76	4.04	0.50	10.98	1.60	0.42
08.02.97	460	16	95.25	0.69	3.60	0.46	11.38	1.52	0.42
08.03.97	491	17	94.37	0.70	4.38	0.54	11.06	1.65	0.42
06.04.97	519	18	94.05	0.67	4.71	0.57	10.83	1.63	0.44
13.05.97	556	19	93.81	0.76	4.74	0.68	12.57	1.63	0.44
10.06.97	584	20	94.74	1.16	3.61	0.49	12.01	1.68	0.45
31.07.97	626	21	94.09	1.17	4.31	0.43	9.08	1.69	0.46
20.08.97	646	22	94.57	1.42	3.63	0.39	9.63	1.69	0.46
19.09.97	675	23	94.09	1.04	4.30	0.57	11.73	1.60	0.42
21.10.97	707	24	93.21	0.85	5.15	0.79	13.35	1.68	0.40
18.11.97	735	25	91.94	0.68	6.35	1.02	13.87	1.70	0.39
09.12.97	756	26	93.19	0.78	5.22	0.81	13.37	1.66	0.45
29.12.97	776	27	94.94	0.77	3.71	0.58	13.49	1.67	0.42

Variables A to D are expressed in percentages of the whole sediment, the variable E (%) is related to the mud fraction. The variables F and G (phi units) are calculated for the the sand fraction.

ative rainfall for the last 4 days before the sediment sampling (days 0 to 3), between the days 3-6, 6-9, 9-12, etc., up to 28-31 days before the sampling. These different variables represent the variability of the river runoff. They were calculated for short periods to avoid possible changes in the textural characteristics of the samples, produced by a river runoff event which had not occurred immediately before the sampling.

Tide height variables were calculated by using the daily predictions from the Servicio Hidrográfico y Oceanográfico de la Armada de Chile (S.H.O.A., 1995, 1996, 1997). These predicted tides were compared with numerous records of the tide on the tidal flat, and no significant differences could be found in the tidal range (maximum difference of 5 cm). The variables calculated in this case were mean high tide, mean low tide, highest high tide, lowest high tide, highest low tide and lowest low tide of the whole sampling period. The latter 4 variables were also calculated for the periods of four days described above, used in the determination of the rainfall events (40 variables).

Textural and granulometric variables were related to each other by means of linear models of regression analysis. Both sets of rainfall and tide variables were analyzed by Pearson product moment correlation to reduce the number of variables. Textural and granulometric characteristics of both areas were compared by means of a one-way analysis of variance (Fisher's least significant difference procedure) to determine whether the values of both parameters in the two sampled areas were the same. When the variance of both sets was inhomogeneous, the Kruskal-Wallis analysis was applied to test the null hypothesis that the medians of the variables within each of the two areas are the same. For each area, both sets of sedimentological and environmental variables were related by means of linear regression, stepwise multiple regression and canonical analysis. All the analyses were carried out with the software Statgraphics Plus for Windows.

TABLE 2. TEXTURAL AND GRANULOMETRIC CHARACTERISTICS OF THE MUDDY SEDIMENTS (AREA 2) OF THE TIDAL FLAT OF THE QUEULE RIVER ESTUARY.

Sampling date	Cumulative days	Sampling number	A Inorganic sand (%)	B Organic sand (%)	C Inorganic mud (%)	D Organic mud (%)	E Relative organic mud (%)	F Sand mean size (phi)	G Sand sorting (phi)
28.10.95	0	1	51.91	1.71	40.24	6.13	13.22	1.85	0.57
14.11.95	16	2	68.19	1.56	26.03	4.23	13.98	1.61	0.46
05.12.95	37	3	62.45	1.68	31.66	4.21	11.74	1.68	0.54
21.12.95	53	4	64.93	1.33	29.74	4.00	11.86	1.59	0.47
28.12.95	60	5	64.94	1.86	28.94	4.26	12.83	1.73	0.63
21.01.96	84	6	71.74	1.45	24.00	2.81	10.49	1.66	0.60
17.05.96	199	7	85.29	2.11	11.44	1.16	9.20	1.58	0.42
15.06.96	228	8	72.68	1.67	22.56	3.08	12.03	1.45	0.45
15.07.96	258	9	52.45	2.24	36.44	8.87	19.57	1.47	0.41
17.08.96	290	10	71.50	2.07	23.33	3.09	11.70	1.59	0.46
14.09.96	317	11	76.39	1.52	19.37	2.72	12.31	1.56	0.46
14.10.96	348	12	77.65	1.43	18.41	2.51	11.98	1.41	0.43
14.11.96	378	13	75.97	1.72	19.95	2.35	10.55	1.54	0.43
11.12.96	405	14	80.88	1.28	15.78	2.06	11.53	1.52	0.41
11.01.97	432	15	82.17	1.51	14.69	1.63	9.97	1.48	0.43
08.02.97	460	16	85.34	1.18	12.05	1.42	10.54	1.46	0.44
08.03.97	491	17	87.16	0.94	10.65	1.25	10.47	1.70	0.46
06.04.97	519	18	86.57	1.06	11.28	1.10	8.86	1.64	0.51
13.05.97	556	19	78.29	1.44	18.22	2.05	10.11	1.65	0.48
10.06.97	584	20	78.71	1.64	17.25	2.40	12.22	1.70	0.47
31.07.97	626	21	63.58	1.94	29.98	4.51	13.07	1.67	0.46
20.08.97	646	22	48.79	3.41	42.09	5.71	11.94	1.74	0.56
19.09.97	675	23	44.76	2.33	46.41	6.49	12.27	1.81	0.67
21.10.97	707	24	56.76	1.90	36.13	5.21	12.60	1.69	0.65
18.11.97	735	25	52.59	2.49	38.80	6.13	13.64	1.78	0.65
09.12.97	756	26	56.64	2.41	35.59	5.36	13.08	1.62	0.52
29.12.97	776	27	58.68	1.98	34.33	5.02	12.76	1.61	0.51

Variables A to D are expressed in percentages of the whole sediment, the variable E (%) is related to the mud fraction. The variables F and G (phi units) are calculated for the the sand fraction.

THE QUEULE RIVER ESTUARY

The Queule River Estuary (39°23'S, 73°12'W) consists of a catchment area of 674 km^2 in the Coastal Range of South - Central Chile (Fig. 1). The estuary has a mean depth of 2 m, and a maximum in the ebb- flood channel of 8 m (Rojas, 1986). The average fresh-water discharge is about 50 m^{3}s^{-1}, which varies from 17 m^{3}s^{-1} during dry summers to 200 m^{3}s^{-1} during rainy winters.

The tide in the estuary is semi-diurnal. The mean tidal range reaches 1.49 m near the tidal flat during spring tides, and falls to 0.85 m during neap tides. Maximum tidal ranges are 1.84 and 1.35 m in spring and neap tides, respectively. The tidal range decreases towards the head of the estuary and has a tidal reach of 25 km. The saline (33‰ at the mouth) and fresh water are partially mixed within the estuary. The salt water of the Southern Pacific penetrates the estuarine basin, but on average, is diluted to about 25‰ during high water up to the tidal flat (1.5 km from the mouth) and 0.1‰ at 15 km during dry summers. The penetration distance of brackish water decreases strongly with increasing river discharge. Frequently, the salinity of the whole estuary basin reaches zero during rainy winters.

The most common sediments of the estuarine subtidal bottoms are sand and muddy sand. Organic material varies in the intertidal sediments from 0.3 to 7% (Bertrán, 1984, 1989; Jaramillo *et al.*, 1985; Turner, 1984; Pino and Mulsow, 1983; Rojas, 1986)

The Queule River Estuary, in spite of its 1.8 m tidal range, has a small tidal flat and a saltmarsh. Both are developed in an area where the old town of

Queule and a prairie was located, before the coseismic subsidence associated with the earthquake and tsunami of May 1960 (Weischet, 1960; Tazzief, 1960, 1961; Wright and Mella, 1963; Pflafker and Savage, 1970; Rojas, 1986; Pino, 1995). Thanks to photographical records of the last 15 years, it is possible to observe the growing of the tidal flats and other subtidal banks, but the reasons for this steady increase are up to now unknown. The accretion process may be related to changes in the use of the landscape (Blackburn *et al.*, 1986; Harden, 1993) or recovery of the coseismic subsidence (Atwater *et al.*, 1992).

The deposition-resuspension on this tidal flat is produced by three different factors. Tide and river runoff variables are common to all estuaries, but a third factor here is a local wind blowing from the sea during the summer. This kind of local wind in the estuary basin is not well registered by the meteorological station, and it was not possible to measure *in situ* the effect of the wind in the resuspension process.

Tidal currents are very important during spring tides, especially near the mid-flood and ebb tide. The river discharge, which responds rapidly to the rainfall in the catchment area, is only important during the winter season, when more than 60% of the annual precipitation occurs. Finally, the wind blowing through the valley is caused by the differential heating between the ocean and the land. This is an important factor during spring and summer seasons, from midday to afternoon. This wind produces waves of a short period and height (1 sec, 10 cm) over the tidal flat, resulting in a very distinctive resuspension of the fine sediments. This process is especially strong at the beginning of the flood and at the end of the ebb, when the water depth is about 20 cm.

THE VARIABILITY OF PRECIPITATION

The mean monthly rainfall for the period 1967 to 1997 was 254 mm (Fig. 2a). This figure shows, first of all, that the mean rainfall calculated on the basis of the monthly accumulated precipitation was very homogeneous between the years 1967 and 1989, a period in which most of the years show a mean precipitation lower or close to the average; after 1990 there is an increase in the mean rainfall. Secondly, it can be observed that there is a change in the yearly variability (in this case represented by one standard deviation).

Figure 2b shows the monthly distribution of precipitation during the sampling period (October 1995 to December 1997), related to the historical monthly average of the past 30 years. It is obvious that the first months represent a dry summer, whereas during the fall and winter of 1996 (May and August) a surplus of precipitation was registered. From April 1997 a surplus of precipitation was registered in all months, showing a nearly 200% (June and July) increase compared to the historical monthly average. Furthermore, at the end of the spring season of 1997 (December) the precipitation was near the average.

SEDIMENTOLOGICAL FACIES OF THE TIDAL FLAT

Figure 3 shows the spatial distribution (before the periodical sampling) of the percentages of inorganic mud (Fig. 3a) and organic mud (Fig. 3b) related to the whole sample, and the percentage of organic mud in relation to the mud fraction (Fig. 3c). The first parameter varied around 5% in the sandy area, and between 5 and 50% in the muddy area. It is clear, as can be expected, that the first two parameters are strongly related, and also that the relation between the sandy and muddy areas is transitional. The relative amount of organic mud (Fig. 3c) is, however, very homogeneous over the entire tidal flat (average of 10.4%).

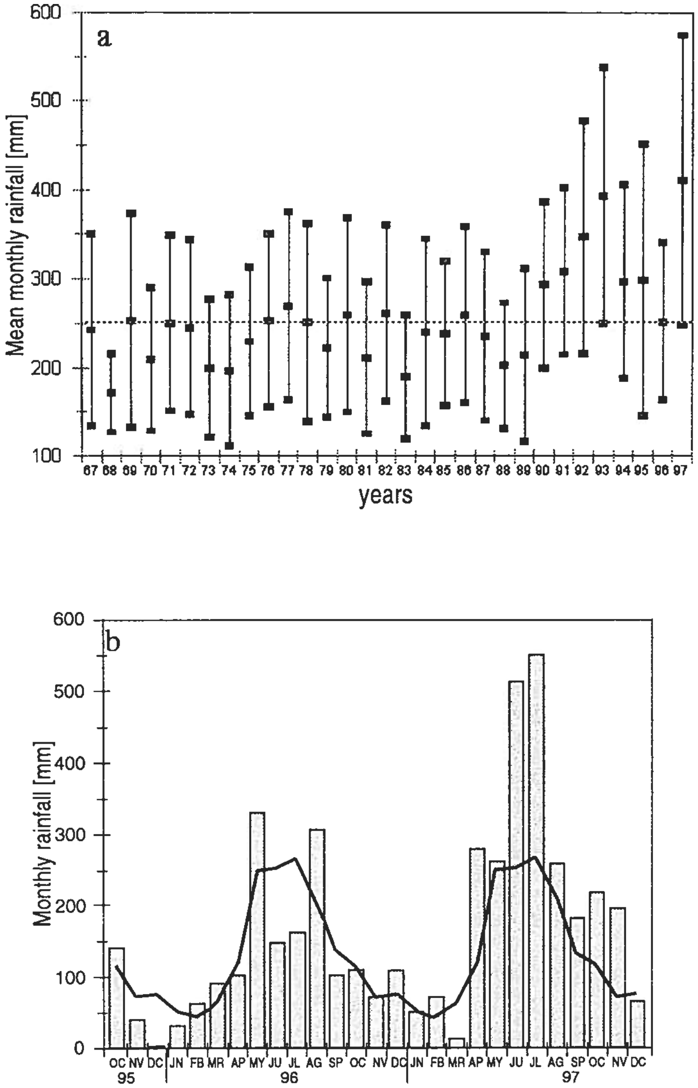

FIG. 2. **a-** long term variability (30 years) of the annual rainfall (monthly mean ± 1 standard deviation) in the study area. The dotted line represents the whole average for the period 1967-1997; **b-** monthly rainfall during the sampling period. The line represents the monthly average for the same 30 years period.

SEDIMENTOLOGICAL CHARACTERISTICS OF AREAS 1 AND 2

In both areas the percentages of inorganic sand and inorganic mud have a significant inverse relationship ($p<0.01$), because they represent the most important components (% inorganic sand = [-0.837 x % inorganic mud] + 83.26 ; $r=0.999$) (Tables 1 and 2).

In area 1 (sandy flat, Table 1) the average of the inorganic mud reaches 4.28%, and varies between 2.69 and 10.25%; in area 2 (Table 2) the same component has an average of 25.75% (10.65-46.41%). Table 3 shows a summary of the linear regression analysis carried out for all the textural variables (% inorganic sand excluded) from both areas. All the relationships have p value of <0.01, but most of them are only moderately strongly related. The exception are the relationships between organic and inorganic mud, in both areas (R^2= 87.41 and 86.21, Table 3).

Comparison of the textural and granulometric characteristics of both areas (one-way analysis of variance, Table 4) shows that only the values of the relative percentage of organic mud (variable E, Tables 1 and 2) and the sand mean size (variable F, Tables 1 and 2) display no significant differences between the areas ($p > 0.05$).

TABLE 3. SUMMARY OF LINEAR REGRESSION ANALYSIS CARRIED OUT FOR THE SEDIMENT CHARACTERISTICS OF BOTH AREAS.

Dependent variable	Area	Independent variable	Area	Intercept	Slope	R^2 %	p Value
Organic sand	1	Organic sand	2	0.455	0.239	40.91	< 0.01
Inorganic mud	**1**	**Organic mud**	**1**	**2.261**	**3.106**	**87.41**	**< 0.01**
		Relative organic mud	1	0.149	0.326	29.07	< 0.01
		Organic mud	2	2.734	0.417	32.79	< 0.01
		Relative organic mud	2	-1.158	0.452	39.94	< 0.01
Organic mud	1	Relative organic mud	1	-1.130	0.141	59.57	< 0.01
		Organic mud	2	0.149	0.135	38.04	< 0.01
		Relative organic mud	2	-1.348	0.166	59.52	< 0.01
Relative organic mud	1	Organic mud	2	10.289	0.642	28.37	< 0.01
		Relative organic mud	2	2.355	0.858	52.54	< 0.01
Sand mean size	1	Sand mean size	2	1.080	0.334	30.36	< 0.01
Organic sand	2	Inorganic mud	2	0.860	0.035	51.83	< 0.01
		Organic mud	2	1.124	0.176	44.44	< 0.01
Inorganic mud	**2**	**Organic mud**	**2**	**7.391**	**4.971**	**86.21**	**< 0.01**
		Relative organic mud	2	-12.507	3.183	36.73	< 0.01
		Sand mean size	2	-56.600	50.790	29.89	< 0.01
		Sand sorting	2	-18.380	87.923	43.77	< 0.01
Organic mud	2	Relative organic mud	2	-6.222	0.825	70.71	< 0.01
Sand mean size	2	Sand sorting	2	1.064	1.110	60.24	< 0.01

Area 1 corresponds to the sandy flat, whereas area 2 corresponds to the muddy flat. Only the inorganic and organic mud of both areas bear relation to each other, as reflected in a relatively strong correlation coefficient (in bold).

TABLE 4. TYPE OF ANALYSIS, MEANS AND PROBABILITY VALUES RESULTING FROM THE STATISTICAL COMPARISON BETWEEN THE SEDIMENT CHARACTERISTICS OF BOTH AREAS.

Variable	Statistical analysis	Mean area 1	Mean area 2	p Value
Inorganic sand (%)	Kruskal-Wallis	68.78	94.20	< 0.05
Organic sand (%)	Kruskal-Wallis	0.88	1.77	< 0.05
Inorganic mud (%)	Kruskal-Wallis	4.28	25.76	< 0.05
Organic mud (%)	Kruskal-Wallis	0.65	3.69	< 0.05
Relative organic mud (%)	Anova	12.02	12.66	> 0.05
Sand mean size(phi)	Kruskal-Wallis	1.62	1.62	> 0.05
Sand sorting (phi)	Kruskal-Wallis	0.42	0.50	< 0.05

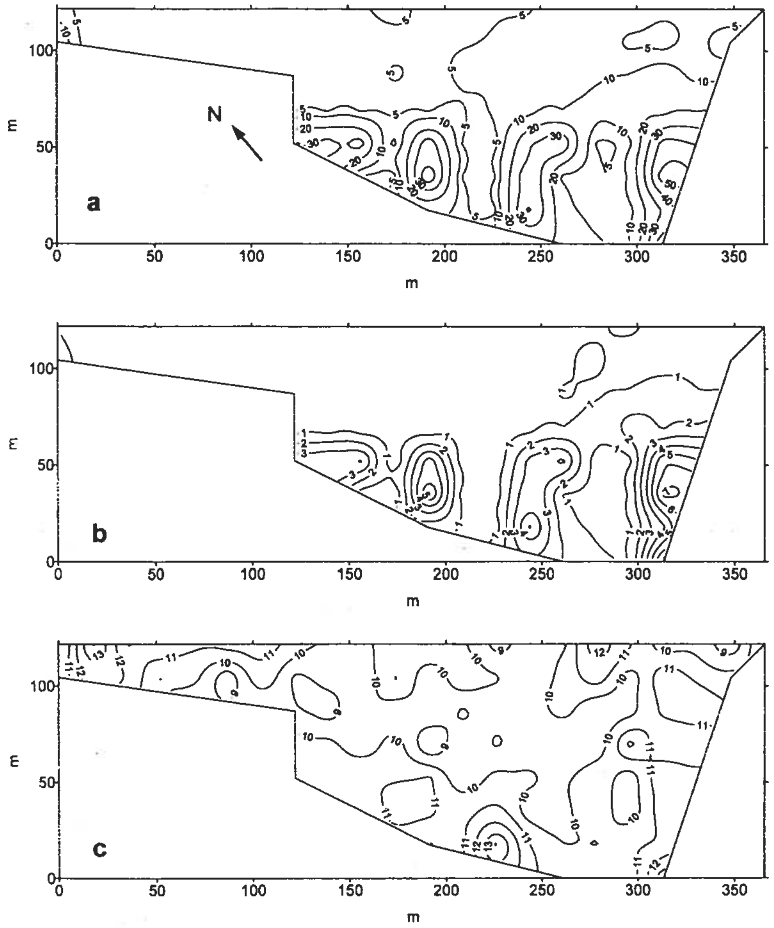

FIG. 3. Distribution in percentage of the inorganic (**a**) and organic mud (**b**) (% related to the whole sample), and percentage of organic mud (**c**) (% related to the mud fraction) in the tidal flat of the Queule River Estuary.

TEMPORAL VARIABILITY OF THE SEDIMENT CHARACTERISTICS

Between the spring seasons of 1995 and 1997 it was possible to recognize that most of the textural and granulometric variables of both areas follow the same trend, but the changes were more evident in area 2 (Fig. 4 and 5). The percentages of organic sand (variable B, Tables 1 and 2, Fig. 4) and inorganic mud (variable C, Tables 1 and 2, Fig. 4), and, therefore, the percentage of organic mud (Fig. 5), reached two peaks during the winter seasons of 1996 and 1997 (Fig. 4, Tables 1 and 2). The relative organic mud (variable E, Tables 1 and 2) had only one clear primary mode in the winter season of 1996, in both areas (sampling number 9, Tables 1 and 2, Fig. 5). The sand mean grain size showed a tendency to coarsen during the winter and spring of 1996 (samplings 8, 9 and 12) and fined during the spring of 1997, especially in area 2 (samplings 22, 23 and 25, Fig. 4, Tables 1 and 2). Finally, the sorting of the sand fraction showed very constant values in area 1 (near 0.75 phi), and in area 2 it became poor during the beginning of the summer of 1996 (samplings 5 and 6) and between the winter and spring seasons of 1997 (samplings 23, 24 and 25, Table 2).

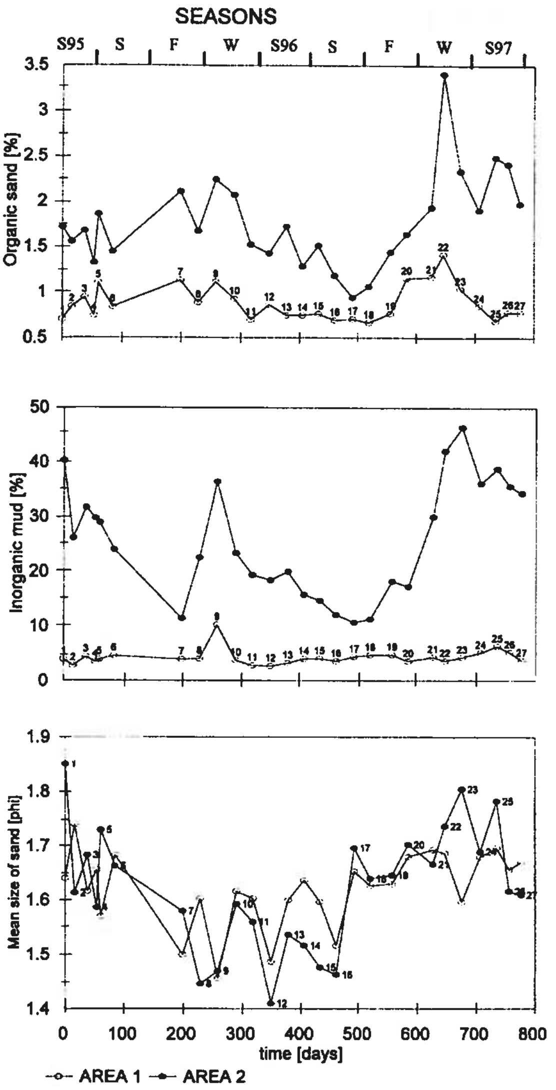

FIG. 4. Seasonal variability of the percentages of organic sand and inorganic mud, and mean sand size in both areas studied. These three variables were the only ones that vary synchronically ($p<0.05$) at both sampling areas. S, S, F, W = summer, spring, fall, winter.

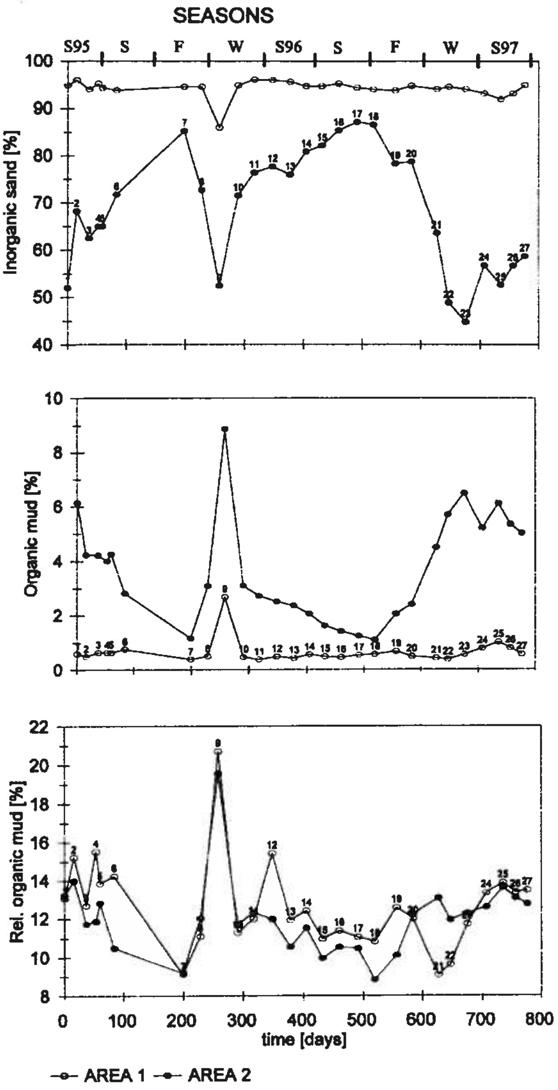

FIG. 5. Seasonal variability of the percentages of inorganic sand, organic mud, and relative organic mud in both areas studied. S, S, F, W = summer, spring, fall, winter.

PRECIPITATION AND TIDE VARIABILITY

After the analysis of 13 variables related to precipitation, and 40 variables related to tide elevations, using the Pearson product moment correlation, the number of independent variables was reduced to only 9. The first 5 variables (K to L, Table 5) represent the highest high or low tide for different periods of days between samplings, with the exception of variable J that represents the minimal ebb tide. The last 4 variables correspond to the maximum daily rain of the sampling period, and the accumulated rain in the last four days, between days 6 and 9, and between days 15 and 18 before the sampling date (variables M to P, respectively, and table 5).

TABLE 5. SELECTED VARIABLES RELATED TO TIDE (M) AND RAINFALL (MM) DURING THE SAMPLING PERIOD.

Sampling date	Number	Tide variables H	I	J	K	L	Rain variables M	N	O	P
28.10.95	1	1.44	0.45	0.04	1.24	0.28	65.7	0.8	20.4	13.0
14.11.95	2	1.35	0.41	0.41	1.38	0.38	33.1	0.0	2.7	0.0
05.12.95	3	1.58	0.49	0.22	1.19	0.21	0.6	0.0	0.0	4.0
21.12.95	4	1.48	0.48	0.24	1.34	0.20	7.2	0.0	0.0	0.0
28.12.95	5	1.65	0.32	0.32	1.38	0.22	2.3	0.0	0.0	0.0
21.01.96	6	1.87	0.44	0.03	1.16	0.32	0.0	0.0	1.7	14.3
17.05.96	7	1.68	0.47	0.06	1.25	0.37	0.0	52.5	36.4	7.2
15.06.96	8	1.78	0.47	0.12	1.32	0.36	0.0	49.6	1.4	103.9
15.07.96	9	1.84	0.44	0.16	1.30	0.36	25.2	0.0	17.4	17.1
17.08.96	10	1.83	0.39	0.09	1.48	0.39	31.7	38.6	43.5	15.1
14.09.96	11	1.74	0.33	0.06	1.34	0.33	78.8	13.7	5.8	10.4
14.10.96	12	1.61	0.39	0.02	1.41	0.29	49.9	0.0	14.2	0.0
14.11.96	13	1.67	0.46	0.13	1.48	0.33	12.7	3.6	0.5	12.7
11.12.96	14	1.74	0.51	0.12	1.42	0.31	2.2	9.1	64.9	0.3
11.01.97	15	1.85	0.49	0.02	1.56	0.33	3.3	0.5	2.5	10.5
08.02.97	16	1.81	0.44	0.03	1.43	0.29	27.5	0.0	40.4	13.1
08.03.97	17	1.83	0.35	0.11	1.32	0.13	8.5	0.0	0.0	0.0
06.04.97	18	1.73	0.36	0.12	1.12	0.12	0.0	0.0	0.0	0.0
13.05.97	19	1.68	0.40	0.38	1.46	0.33	82.7	0.4	0.3	9.9
10.06.97	20	1.45	0.45	0.28	1.23	0.41	123.4	60.3	127.6	7.1
31.07.97	21	1.53	0.47	0.21	1.27	0.17	76.3	149.4	57.1	32.8
20.08.97	22	1.52	0.39	-0.05	1.21	0.27	203.0	37.5	45.2	0.0
19.09.97	23	1.44	0.33	-0.17	1.17	0.23	146.9	0.0	2.6	22.0
21.10.97	24	1.43	0.37	0.14	1.15	0.29	53.5	8.0	12.7	61.2
18.11.97	25	1.51	0.39	0.20	1.11	0.37	49.8	0.6	123.3	0.0
09.12.97	26	1.42	0.45	0.37	1.51	-0.04	9.2	0.3	24.1	2.0
29.12.97	27	1.53	0.50	0.21	1.24	0.30	18.4	41.0	0.0	0.0

H- maximum high tide of the sampling period; **I-** maximum low tide of the sampling period; **J-** lowest low tide predicted for a four day period before the sampling period; **K-** maximum high tide for a four day period occurring 24 to 27 days before sampling; **L-** maximum low tide for a four day period occurring 27 to 30 days before the sampling; **M-** maximum daily rainfall during sampling period; **N-** accumulated rainfall during the last four days before the sampling; **O-** accumulated rainfall during a four day period occurring 6 to 9 days before sampling; **P-** accumulated rainfall during a four day period occurring 15 to 18 days before the sampling.

Figure 6 shows the temporary variation of these environmental variables. The precipitation was concentrated in two periods, decreasing from the winter to the beginning of the spring seasons of 1996, and with a set of strong modes (reaching 200 mm in one day) in the winter season of 1997 (Fig. 6a). The temporal variation of the tidal elevations is less clear. The maximum high tide of the sampling period (variable H) shows two peaks during the winter and summer seasons of 1996, and lower values at the end of the sampling period. The maximum high tide, between days 24 to 27 before the sampling (variable K), has a trend similar to variable H. Variables I and L, both related to maximum low tides, are very homogeneous, with a slightly distorted sine curve of four cycles. Finally, variable J, related to minimal low tide height, showed a lower peak in the winter season of 1997.

RELATIONSHIPS BETWEEN SEDIMENTS AND ENVIRONMENTAL VARIABLES

Table 6 shows a summary of the results of the multiple regression analysis carried out between independent variables (precipitation and tide height) and dependent variables (sedimentological characteristics). Of the 12 possible cases, only 8 had significant p values (< 0.01), but with an adjusted R^2 under 50%. For both areas significant models were obtained for percentages of the organic sand, sand

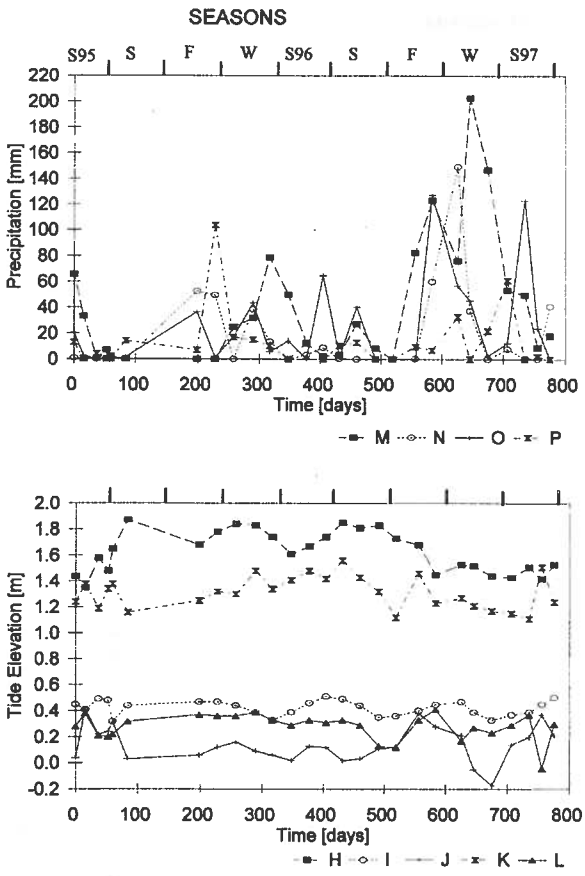

FIG. 6. Seasonal variation of the environmental variables that represent the rainfall **(a)**: **M**- maximum daily rainfall during sampling period; **N**- accumulated rainfall during the last four days before the sampling; **O**-accumulated rainfall during a four day period occurring 6 to 9 days before sampling; **P**- accumulated rainfall during a four day period occurring 15 to 18 days before the sampling; and the height of the tide **(b)**: **H**- maximum high tide of the sampling period; **I**- maximum low tide of the sampling period; **J** = lowest low tide predicted for a four day period before the sampling period; **K**- maximum high tide for a four day period occurring 24 to 27 days before sampling; **L**- maximum low tide for a four day period occurring 27 to 30 days before the sampling; **S95**-spring, **S**- summer; **F**-fall; **w**- winter.

TABLE 6. SUMMARY OF MULTIPLE LINEAR REGRESSION ANALYSIS CARRIED OUT BETWEEN SEDIMENTOLOGICAL CHARACTERISTICS (DEPENDENT VARIABLES) AND TIDE AND RAINFALL FEATURES (INDEPENDENT VARIABLES).

						Independent variables					
						Tide				Rain	
Dependent Variable	Area	Adjusted R²	r	P Value	Intercept	Slope var. H	Slope var. I	Slope var. J	Slope var. K	Slope var. M	Slope var. N
Organic sand	1	39.64	0.63	< 0.01	0.77	*	*	*	*	0.0016	0.0024
	2	27.84	0.53	< 0.01	1.54					0.0056	*
Inorganic mud	1			> 0.01							
	2	33.69	0.58	< 0.01	90.21	-36.5656	*	*	*	*	*
Organic mud	1			> 0.01							
	2			> 0.01							
Relative organic mud	1	27.85	0.53	< 0.01	12.48	*	*	5.5281	*	*	-0.0357
	2			> 0.01							
Sand mean size	1	21.36	0.46	< 0.01	1.96	-0.2118	*	*	*	*	*
	2	43.91	0.66	< 0.01	2.62	-0.2784	*	*	-0.4165	*	*
Sand sorting	1	35.56	0.60	< 0.01	0.31	0.0590	*	*	*	0.0002	0.0003
	2	49.33	0.70	< 0.01	1.31	-0.1504	-0.5075	*	-0.2685	*	*

* = variables not included in the model.

mean size and sand sorting. In area 2, the multiple regression model was significant only for inorganic mud, and in area 1 only for the independent variable of relative organic mud. In the 8 models, variable H (maximum high tide of the sampling period) was included four times, variable N (accumulated rain in the last four days before the sampling) and variable M (maximum daily rain of the sampling period) three times, variable K (maximum high tide between days 24 to 27 before the sampling) twice, and variables I and J (highest low tide of the sampling period and minimum low tide in the last 4 days before the sampling, respectively) only once. In general, the slopes (estimates) of the independent variables displayed positive values for precipitation variables, and negative ones for tide variables. When both type of variables are together in a model, the absolute values of the slopes related to tide are larger than those related to precipitation.

Figure 7 shows the results of the canonical analysis carried out for area 1, using environmental variables (tide and precipitation) for set 1 and sedimentological variables for set 2. In set 1 the most important coefficients in the first canonical function correspond to variable M (maximum daily rain of the sampling period). In the second set these coefficients correspond to variables **E**=% relative organic mud, **B**=% organic sand and **G**=sand sorting. The first canonical function between the two sets of variables in this area produces a strong correlation that appears linear, and is statistically significant (canonical correlation 0.891, $p < 0.05$) (Fig. 7). The relationships between each of the original variables are not simple, but from the graphical representation it is possible to interpret that the high figures on both sets (upper right) correspond to samples with poor sand sorting (G) and low percentages of relative organic mud (E), associated with high values of precipitation (M and N). The samplings located in the negative area of both sets (lower left) correspond to the opposite, good sorting, high relative organic mud percentages, and weak precipitation (Fig. 7, Tables 1 and 5).

The same analysis carried out in area 2 shows that for the first canonical function (canonical correlation 0.895, $p < 0.05$, Fig. 8), the most important coefficients in the first set correspond to variable I (maximum low tide of the sampling period) and variable O (accumulated rain between days 6 to 9 before the sampling). In the second set, the highest coefficients correspond to variables C, G and E (percentages of inorganic mud, sand sorting and relative organic mud, respectively) (Fig. 8). In this area, the first canonical function between the two sets of variables also produces a strong linear correlation (Fig. 8) where the environmental variables produce a clear separation on the x axis (tide and rain canonical scores), with more precipitation and low tides to the right. In the second set axis (sediment canonical scores), high figures are related to poor sorting and high percentages of relative organic mud (variables E and G, respectively), but the variable with the highest coefficient in the root (% inorganic mud, C) only tends towards high values in the upper right quadrant (Fig 7, Tables 2 and 5).

DISCUSSION

As most field-oriented environmental research programs operate on a short time scale, variability is usually measured over the course of the research program, but does not necessarily change. The subtle difference between variability and change was recognized in the joint workshop report by IGBP/PAGES and WCP/Climate Variability and Predictability (Duplessy and Overpeck, 1996). Only very long-term process studies or programs designed to look at changes as established in geological records (*e.g.*, the IGBP/PAGES program), truly provide the opportunity to examine responses to environmental change.

Estuaries hold a unique position among coastal systems, because they allow a relatively simplistic view of input-output processes, although they are subjected to complex time and space variations. Changing river flow is likely to represent the major estuarine impact in response to natural and anthropogenic alterations of climate (Milliman and Syvitski, 1992). The degree of fluvial influence (as a result of the rainfall in the catchment area) affects not only the distribution of the sediments, but also controls salinity, nutrients, pollutants and the distribution of biota.

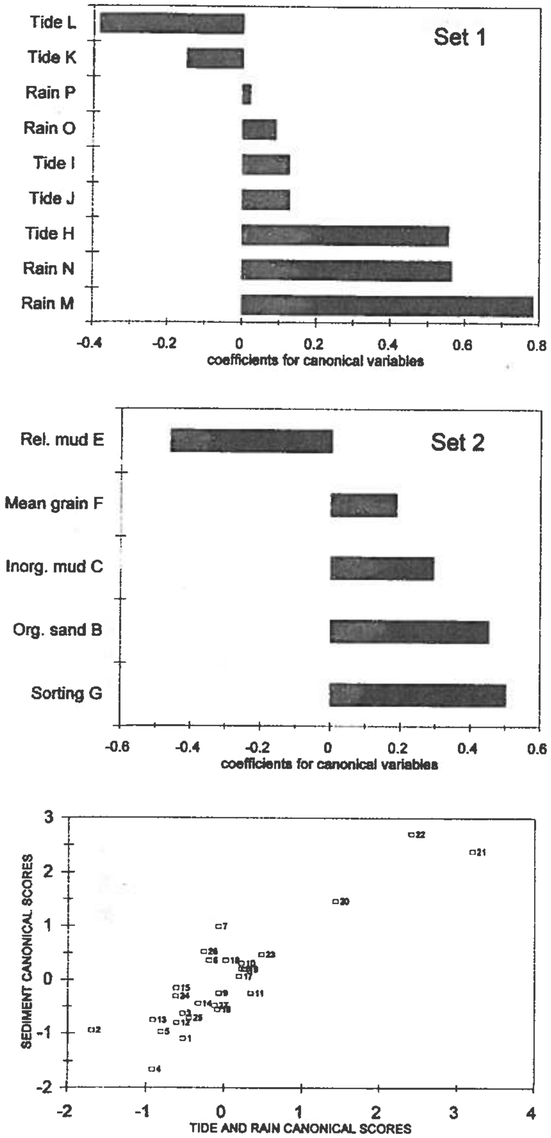

FIG. 7. Values of coefficients for canonical variables for set 1 (tide and rainfall) and set 2 (sedimentological variables, see figure 5 for identification of the variables), and graphical representation of the scores in the first canonical function of area 1. The numbers correspond to the 27 sampling periods.

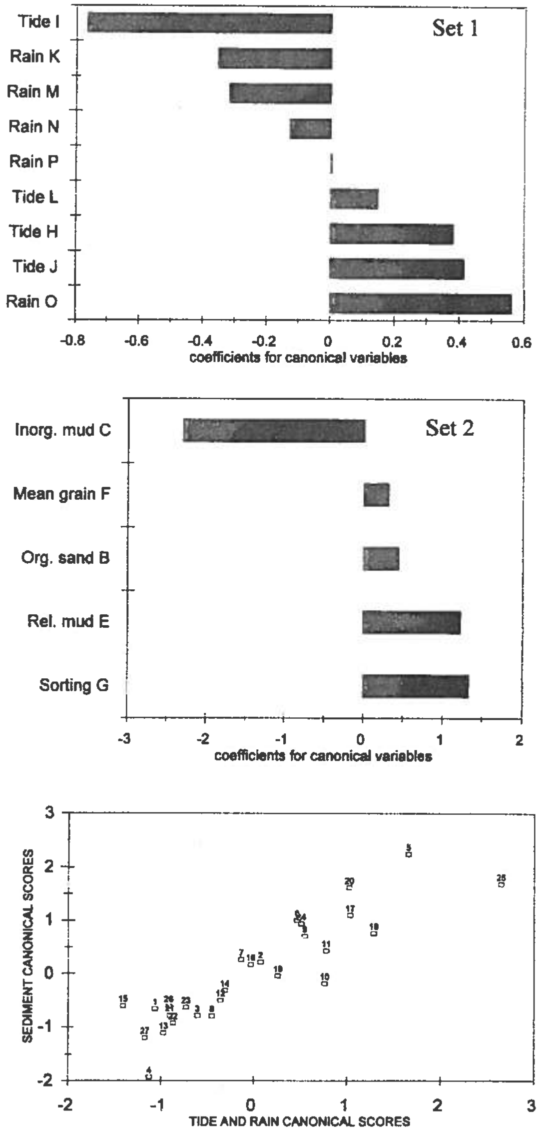

FIG. 8. Area 2, coefficients for canonical variables for set 1 (environmental variables) and set 2 (sedimentological variables, see table 5 for identification of the variables), and graphical representation of the scores in the first canonical function. The numbers correspond to the 27 sampling periods.

Despite the rainfall-river discharge variability expected in relation to El Niño events (Philander, 1990), in the study area the precipitation on a basis of year average (average of 12 months) shows that between 1967 and 1990, the typical El Niño years (1972-1973, 1982-1983, 1986-1987; Troup, 1965; Kousky and Leetmaa, 1989; Allan *et al.*, 1996) did not produce precipitation over the historical mean, and are similar to other years with no El Niño Southern Oscillation (ENSO).

The situation changes as of 1990, due to the unusually rapid succession of several El Niño events (from 1991 to 1993; McPhaden, 1993), which caused the notable increase in rainfall over the historical average (Fig. 2a). Following these events, a La Niña event developed (1995-1996), with no rainfall below the historical average being registered, as had occurred with La Niña of 1973-1974 and 1988-1989 (Allan *et al.*, 1996). The year 1997 presents the highest mean precipitation (close to 400 mm) related directly to the ENSO of this period (Walter and Timlin, 1998). While the La Niña event of 1995-1996 produced lower precipitation in the rainy season (June and July), the effects of the last El Niño event resulted in a surplus of precipitation registered during all months, with figures of nearly 200% (June and July) compared to the historical monthly average (Fig 2b). However, during the already mentioned La Niña event, two months (May and August) presented values of rainfall over the historical average.

The transition between sandy and muddy sediments on the tidalflat of the Queule Estuary (Fig. 3) is very common to intertidal flats and shallow water bottoms (Pethick, 1984; Anderson *et al.*, 1981; Amos, 1995), as is the direct relationship between inorganic and organic mud (Rashid *et al.*, 1972; Blatt *et al.*, 1980). The homogeneity of the relative percentage of organic mud figures shows that independently of the absolute value of inorganic mud, this parameter shows little variation in both areas. It is possible that it could be related to the degree of organic enrichment of the estuary, since those estuaries experience a greater impact of urban settlement in the zone, displaying also higher relative organic mud contents.

The relative percentage of organic mud and mean size of the sand fraction showed no difference between areas 1 and 2 (Tables 1, 2 and 4). In the first case the reason could be related to the previously discussed idea. On the other hand, the two sampling stations are very close (Fig. 1), but in spite of their vicinity, it was possible to expect a significant inverse relationship between the percentage of mud and mean sand size. It is possible that the mud and the sand were transported and deposited by two different mechanisms (*e.g.,* suspension and saltation). However, most of the time, at least, the fine sand fraction is transported together with the mud suspension. The homogeneity of the granulometric characteristics of the sand (Fig. 4) may be related rather to the origin of the sand in this region. All the coastal sand is composed primarily of volcanic components, which originated from Pleistocene marine terraces. These sediments have a mean size corresponding to medium sand and good sorting, thus all the sand of beaches, estuaries and dunes in the area are very similar in their granulometric distribution (Pino, 1988; Pino and Jaramillo, 1992).

The temporal variability of the sediment characteristics clearly showed that textures change seasonally, with marked peaks during the winters of 1996 and 1997. However, not all the variables follow the same temporal behavior. Thus, the percentage of organic mud and relative organic mud showed maximum peaks in the winter of 1996 (only sampling number 9, Table 2), while percentages of organic sand and inorganic mud reached maxima during the winter of 1997 (Tables 1 and 2, Fig 4). The mean size of sand reached figures between 1.4 and 1.5 phi during the first winter season, and figures up to 1.8 phi during the winter of 1997. In area 2, the sand showed moderately good sorting between the spring of 1995 and summer of 1996, and good sorting (Folk, 1980) during the winter of 1997 (Table 2). The sedimentological characteristics of sampling 9 could be related to a specific event which produced an increase in the percentage of organic mud (total and relative), together with a coarsening in the mean sand size. One possible interpretation could be related to resuspension and winnowing, which result in a high content of fine organic matter and a lag deposit of coarse sand, also better sorted in relation to the older deposits (McLaren, 1981). A temporal process is also possible, *e.g.,* first resuspension, and later arrival of new sediments. During the winter season of 1997, the high amounts of mud and the fining of the mean sand size could be linked to depositional processes derived from suspension, probably related to the new arrival of sediments, because of the improvement of the sorting. All erosion-transport processes produce a deposit with better sorting in relation to the source (McLaren, 1981).

When comparing both seasonal variations (sedimentological characteristics and the variables that represent the tide and the rainfall), it can be observed that for the last variables there is a temporal coincidence, at least in the same time frame. The variability related to the height of the tide does not possess a seasonal trend, though the high tides were highest during the winter of 1996 (variables H and K, Fig. 6), and the high and low tides were lowest during the winter of 1997 (variable H, J and K, Table 5, Fig. 6).

As noted earlier, the percentage of inorganic sand (variable A) follows the opposite behavior of inorganic mud (Tables 1 and 2), simply because both components account for more than 89% of the total weight (Anderson *et al.*, 1981). Between the springs of 1995 and 1997, it is evident that most of the textural and granulometric variables of both areas follow the same trend, but the changes were more obvious in area 2. The percentages of organic sand (variable B) and inorganic mud (variable C), and therefore the percentage of organic mud, reached two peaks during the winter seasons of 1996 and 1997 (Fig. 4, Tables 1 and 2). These values are greater than those published previously (Bertrán, 1984, 1989; Jaramillo *et al.*, 1985; Turner, 1984; Quijón and Jaramillo, 1993).

The relative organic mud (variable E) had only one clear maximum peak in the winter season of 1996, in both areas (sampling number 9, Tables 1 and 2). The sand mean grain size showed a tendency to coarsen during the winter and spring of 1996 (samplings 8, 9 and 12), and to fine during the spring season of 1997, especially in area 2 (samplings 22, 23 and 25, Fig. 4, Tables 1 and 2). Finally, the sorting of the sand fraction had a very constant value in area 1 (near 0.65 phi), and in area 2 deteriorated during the beginning of the summer season of 1996 (samplings 5 and 6), and between the winter and spring seasons of 1997 (samplings 23,24 and 25, Table 2).

The temporal variability of the variables chosen to represent the rainfall (and thus the river discharge) shows very clearly the effect of the 1997 El Niño event, and also the precipitation of May and August 1996 (Fig. 6). As expected, the variables that represent the tide did not show a seasonal trend, although some differences in height between the winters of 1996 and 1997 (Fig. 6), that do not have any relationship to climatic events, can be observed.

The statistical models used to relate sedimentological characteristics and environmental variables cannot explain all the variability, because one of the variables, the effect of the local wind, was not possible to measure *in situ*. Although variables such as the percentage of inorganic mud (area 2) are apparently related to the rainy season (Fig, 4 and 5), the multiple regression model showed that the only significant relationship is obtained with variable H (maximum high tide, slope -36.6). This means that in area 2 high tides can explain about a 34% of the variability of the amounts of inorganic mud, in an inverse relationship. In general, all these models explained no more than 50% of the sedimentological variability, and in most of the cases (with the exception of organic sand), tides were included in the models. Organic particles of sand size, derived from the palustrian and saltmarsh vegetation, are observed frequently in the estuary after heavy rains. The second statistical model (canonical analysis) used, had the advantage of relating simultaneously two sets of independent variables. In this case, the rainfall was included in both areas, as one of the most important variables in the canonical functions. In area 1, heavy rain and high tide were related to poor sorting of the sand, high contents of organic sand and lower relative percentages of organic mud; in area 2, higher figures of accumulated precipitation during a four day period, occurring 6-9 days before sampling, and lower values of maximum low tide were related to poor sorting of the sand, and high amounts of inorganic and organic mud. The textural variability observed is probably related to the fact that the lower mudflat is covered by tides during a larger number of hours *per* day, despite the fact that they show a difference of only 20 cm in altitude.

CONCLUSIONS

Some of the sedimentological characteristics (relative percentage of organic mud and mean size of sand) showed no significant differences between the two areas. Most of the studied parameters changed simultaneously in both areas, but there is a greater variability on the muddy flat.

The sedimentological variability displays a seasonal trend related to higher river runoff produced by heavy rainfall, but tides also contributed to the temporal changes. Finally, the most evident textural changes were related to the rainy season of the 1997 El Niño event.

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