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Pesquisas em Geociências, 30 (1): 65-81, jan./abr., 2003.

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Publicado por

Instituto de Geociências



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Data de publicação - jan./abr., 2003.

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Determination of Net Sediment Transport Patterns in Lirquén Harbor, Chile, Through Grain-size Trend Analysis: A Test Of Methods

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Abstract - During June 1997, bottom sediment samples were collected at 76 stations on a rectangular grid in a small port (Lirquén Harbor, south-central Chile) facing siltation problems. The spatial changes in grain-size parameters, analyzed by using three different methodologies to infer net sediment transport paths, are compared with the measured water circulation of the study area and sediment dispersal patterns on aerial photographs. A Geographical Information System (GIS) is used to determine the degree of similarity between the results of the three grain-size trend methodologies. The results of this study confirm that because of its formulation and underlying assumptions, the McLaren-Bowles methodology tends to confuse the space-scale of sediment transport processes. In this way, the obtained transport patterns are in poor correlation with the observed hydrodynamics and aerial photographs and they seem to represent a combination of the spatial macroscale and mesoscale sediment transport processes existing in Concepcion Bay and in Lirquén Harbor, respectively. On the contrary, because the results yielded by the Gao-Collins and Le Roux methodologies correlate well with these studies, it is suggested that both methodologies be applied in combination to allow a better representation of local net sediment transport patterns, especially in estuarine environments where multiple sediment sources exist. Spatial analysis suggests that transport pathways obtained through these two methodologies represent the mesoscale sediment circulation existing in Lirquén Harbor. This study also emphasizes the importance of applying a statistical test to the transport trend vectors obtained using the GSTA program of Gao (1996), as these may erroneously reflect sediment transport direction. Lastly, the analyzed data and the results of the models are combined to determine the sediment transport regime existing in Lirquén Harbor.

Keywords - Sediment transport patterns, grain-size trends, GIS, Lirquén Harbor, southern Chile.

INTRODUCTION

Over the last two decades there has been a rapid development of methods employed to identify net sediment transport paths in coastal marine environments (McLaren, 1981; McLaren and Bowles, 1985; Gao and Collins, 1992, 1994a; Le Roux, 1994b). All of these techniques are based upon spatial changes (trends) in the grain-size parameters of bottom sediments, which result from sediment transport processes.

Between 1930 and 1980, attempts were made to relate the variation of one single grain-size parameter to sediment transport paths (Pettijohn and Ridge, 1932; Pettijohn *et al.*, 1972; McCave, 1978), but this approach did not always produce good results, because grain-size parameters vary in different sedimentary environments (Friedman, 1979). More recent studies showed that a combination of three grain-size parameters (mean size, sorting and skewness) produces better results (McLaren, 1981; McLaren and Bowles, 1985). The "McLaren Model" determines the transport direction along a

sampling track by comparing the sedimentological parameters of all possible pairs of samples on the sampling line, resulting in a one-dimensional sediment transport model. This model has been tested in many natural environments by different authors, who have obtained results that agree with their interpretation of sediment transport in these environments (Haner, 1984; McLaren *et al.*, 1993). Nevertheless, some authors have questioned the universal applicability of the model, suggesting that its use is limited to certain specific environments (Masselink, 1992; Lessa, 1994).

Gao and Collins (1991) suggested modifications to the original approach of McLaren and Bowles (1985), proposing a two-dimensional model for the analysis and introducing the concept of transport vectors into the grain-size trend analysis. This new technique differs from the previous methods in that it creates a grid of dimensionless trend vectors by comparing the grain-size parameters of "neighboring" stations, which are later transformed into transport vectors by applying a filtering technique. According to Gao and Collins (1991, 1992),

the implementation of the vector approach produces more meaningful results and reduces the implied “bias” in the selection of the sampling lines inherent in the line-by-line approach of McLaren and Bowles (1985). The potential of this methodology is supported by its successful application in different coastal environments (Gao *et al.*, 1994b; Pedreros *et al.*, 1996).

The main shortcoming of this procedure is that only two sampling sites are compared at a time, which does not allow for the fact that sediment transport probably takes place within zones and not from point-to-point. Thus the relative location of any two stations within a transport zone will determine the resultant vector. Another problem lies in the fact that the Gao and Collins method assigns a vector of unit length between all sampling points, which obscures the significance of the vector magnitude obtained by subsequent filtering. The method thus has a low probability of determining the true transport directions (Le Roux, 1994a). Le Roux *et al.* (2002) also pointed out that the filtering procedure included in the Gao and Collins method may produce statistically valid trends which do not actually exist in nature. They suggested that filtering should be carried out only if the non-filtered trends are proven to be statistically significant.

In an attempt to circumvent these problems, Le Roux (1994b) proposed an entirely different approach based on conventional vector analysis. In this method, trend vectors are obtained by comparing groups of five stations (one central and four satellites) at a time and the grain-size parameters are integrated so that each assumes equal status. Finally, only those overall patterns produced by trend types or combinations of trend types with a vector magnitude exceeding a value determined by the non-parametric Watson test, are accepted (Le Roux *et al.*, 2002). Presently, only a few authors have tested the real-world validity of this model (Carriquiry and Sánchez, 1999).

Over the last two decades, Lirquén Harbor has experienced the effects of continuous siltation at its mooring sites, necessitating frequent and costly dredging operations with an average of 20,000 m³ of sediments having to be removed periodically. As this has to be done without the benefit of knowing the existing sediment transport regime, the object of this investigation is to determine the net transport routes and the location of depocenters within the harbor by comparing the sediment transport patterns

obtained through the methodologies of McLaren & Bowles (1985), Gao & Collins (1992) and Le Roux (1994b).

To test the validity of this concept, the results of the grain-size trend analyses are compared with short term (obtained during the winter and summer of 1997) and ‘long-term’ current measurements as well as known sediment distribution patterns as observed on aerial photographs of the study area. Lastly, the methods are discussed on the basis of their applicability as predictive tools in understanding the natural sedimentary processes of this harbor.

STUDY AREA

Lirquén Harbor, located within the southeastern part of Concepción Bay (36°40’S; 73°02’W) Chile, has two pile-supported piers with six mooring sites. Due to its infrastructure and depth, it is one of the most important commercial ports in Chile (Fig. 1). Concepción Bay is a shallow (maximum depth about 48 m) coastal embayment located in the south-central part of the Chilean coast. It is characterized by an almost rectangular shape with a gentle slope increasing toward the north, where it joins the Pacific Ocean. The bay has a surface area and water volume of 190 km² and 2.4x10⁹ m³, respectively.

The climate of the area is influenced by anticyclonic winds associated with a high-pressure cell centered in the South Pacific Ocean. During the austral winter, strong, consistently northerly winds with a mean velocity of 12.86 m/s prevail, whereas summer winds are predominantly southwesterly with lower speeds (9.78 m/s) and more variable directions (Saavedra, 1980).

Concepción Bay has semi-diurnal tides within a microtidal range (tidal range during spring tides is 1.6 m; SHOA 1994), which are strongly influenced by wind events, especially during the passage of frontal systems in winter (Sobarzo, 1993). The oceanography of the region is influenced by the surface Humboldt Current, which is sub-Antarctic in origin and flows northward along the coast. Below this surface water the equatorial subsurface water mass flows southward. Within Concepción Bay itself, the sub-Antarctic surface flow prevails during late fall to early spring, whereas the equatorial subsurface flow dominates between late spring and early fall (Ahumada and Chuecas, 1979). The maximum significant wave

height (1.6 m) occurs during winter, when waves from north-northwesterly directions and a mean period of 4.8 s predominate. Due to its sheltered nature, the bay is largely protected from west-southwesterly waves (CICLO, 1992).

Current measurements in the eastern part of Concepción Bay showed patterns that vary with seasonal changes. During winter months, northerly winds carry surface water into the bay, causing a compensating bottom flow out to sea. During the passage of strong frontal systems from the north, a great part of the water column in the southeastern part of the bay is forced towards the head (southwest). In summer, winds from the southwest cause an outgoing layer on surface and a circulation bottom layer entering the bay. The circulation in Concepción Bay is tide-dominated; winds and meteorological effects make secondary contributions (Arcos and Wilson, 1984; Sobarzo, 1993).

The littoral zone is composed of a Paleozoic basement of crystalline rocks, granites and shales partly covered by sedimentary rocks from the Cretaceous-Tertiary Periods (Aguirre *et al.*, 1972). The bottom sediments of Concepción Bay are dominated by black, organic-rich muds covering a large part of the area. The sediments along the coast are sandy, derived from rocky outcrops and erosion of the continent (Ahumada *et al.*, 1984). Experiments conducted along the coast of Lirquén Harbor using natural minerals as tracer materials identified a net southward sediment transport direction (EULA, 1994).

MATERIALS AND METHODS

Sampling Procedures

Current and wind data

Winds and mean currents were investigated in order to evaluate their potential effect on net sediment movement. Directions and velocities of surface and near-bottom currents were determined by two current meter moorings deployed in the study area for a period of 8 days during June and December 1997 (Fig. 1). The first deployment (June) was designed to represent winter storm conditions, whereas the second (December) represented summer fair-weather conditions. Moorings A and B were deployed in mean water depths of 20 and 9 m, respectively. At mooring A, currents were measured at 5 and 15 m depths, while at mooring B the cur-

rent was recorded at 6 m depth. In December 1997 moorings A and B were deployed in 17 and 8.5 m, respectively. There were current meters at 4, 11 and 16 m depths at site A, while at site B the current was measured at 7 m depth. The Sensor-Data 6000 current meters were programmed for a 10 minute sample frequency. Wind data for the period of current meter deployment were collected from a nearby coastal weather station.

Sedimentological data

A total of 76 bottom sediment samples were collected on a grid with an average spacing of 80 m between each station (Fig. 1), using a Petit-Ponar grab sampler (225 cm²). The existence of a rocky substratum in some sectors of the study area impeded the use of a regular sampling grid. A subsample of the top 10-cm of each grab was used to analyze the grain-size distributions. The positioning of the sampling stations was determined with a Differential Global Positioning System (DGPS).

Analytical Procedures

Current and wind data

Prior to the graphical and basic statistical analysis of the current and wind time series, the orthogonal components (u, v) of current and wind velocity were aligned with true north. For coordinate axes the right-handed system described by Pond and Pickard (1978) was used where u is positive to the east and v is positive to the north.

Sedimentological data

Separation of the samples into their textural fractions (gravel, sand and mud) was accomplished through wet sieving using standard sieves of -1 and 4 phi. The gravel and sand fractions were oven-dried and weighed to determine their relative percentages (Lewis, 1984). The coarse fraction was analyzed with a digital settling tube (Emery, 1938; Gibbs *et al.*, 1971; Syvitski *et al.*, 1991), providing the frequency distribution of equivalent particle diameters at intervals of 0.5 phi. The analysis of the mud fraction was carried out with an Electrozone system using apertures of 48 and 120 microns over intervals of 0.5 phi. The grain-size data obtained with these two instruments were merged to obtain complete grain size distributions. The method of moments (McManus, 1988) was used to obtain the basic statistical size parameters (mean, μ ; sorting coefficient, σ^2 ; and skewness, Sk).

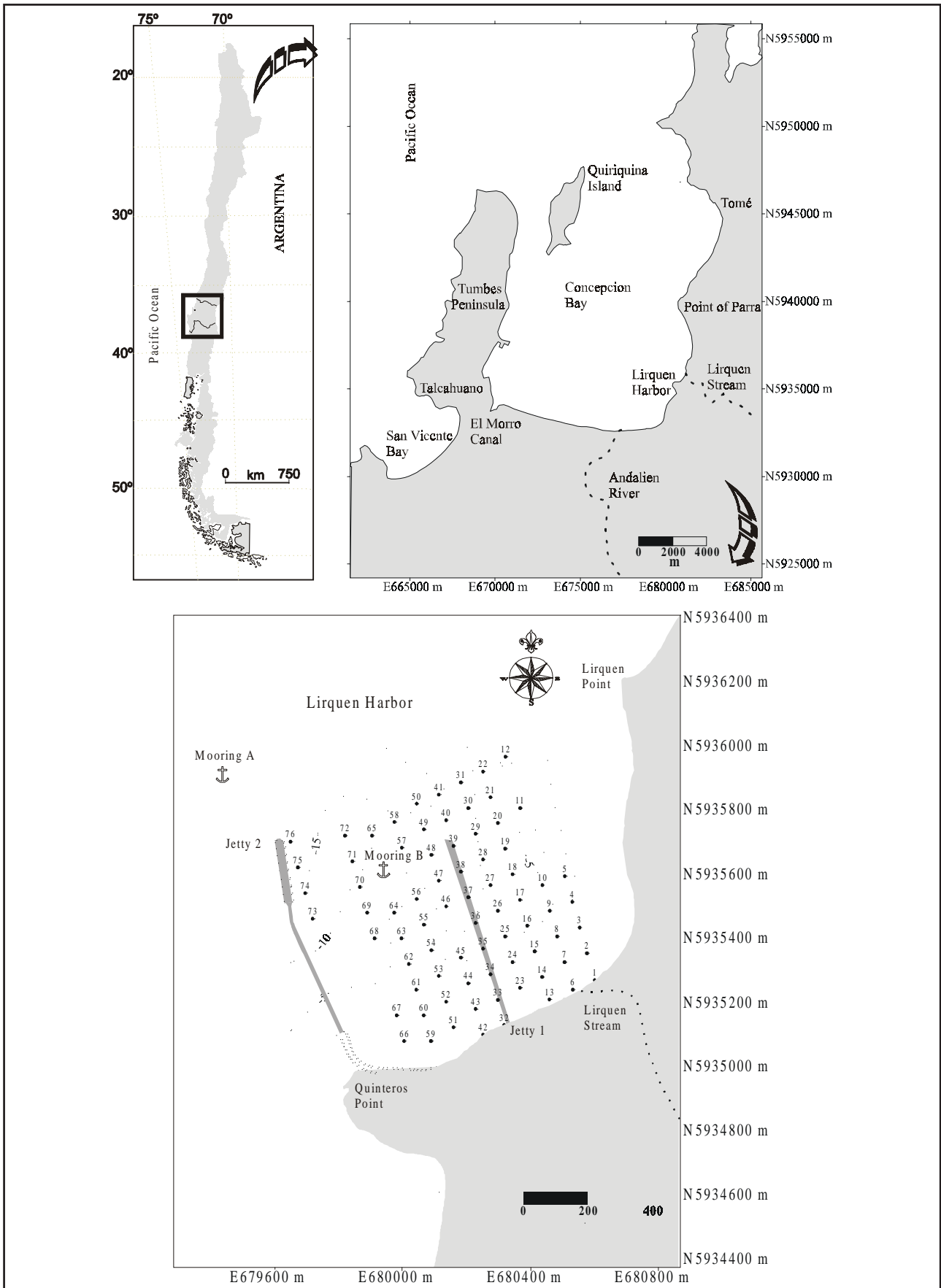


Figure 1 - Location map of the Lirquén Harbor study area. Dots represent sampling grid. Mooring A and B are the locations of current meters (bathymetry in meters).

The grain size data are expressed in the logarithmic phi ($\phi = -\log_2 \text{diameter in mm}$) scale which in comparison with the linear scale, provides better statistical measures for the determination of sediment transport directions (McLaren and Bowles, 1985).

Interpolation of grain-size data

To analyze for two dimensions the McLaren and Bowles (1985) methodology requires a regular grid of 9 x 9 samples; therefore a linear multiple regression model was used to create the required regular set of grain-size data. This interpolation model used the values of grain-size parameters and the position of the sampling stations to estimate the data gap. According to Gao and Collins (1992), increasing the density of sampling improves the results of the grain-size trend analysis. Therefore the interpolated grain-size data were also used in the application of the other two methodologies (Gao and Collins, 1992; Le Roux, 1994b) employed in this study to determine the existing sediment transport patterns in Lirquén Harbor.

Description of grain-size trend methodologies

Table 1 summarizes the three grain-size trend methodologies. The McLaren and Bowles (1985) methodology determines the net sediment transport direction comparing the sedimentological parameters (μ , σ^2 , Sk) of all possible pairs of samples located on a sampling line. For every pair of samples compared, eight possible trends exist, each having a probability of random occurrence equal to 1/8. According to the assumptions of this methodology, only two trends are indicative of transport: Compared to sample 1, sample 2 may be finer, better sorted and more negatively skewed (Case B) or coarser, better sorted and more positively skewed (Case C). Both cases indicate that energy decreases in the direction of transport, but case B represents a low-energy transfer process while case C is a high-energy one. Case B may also indicate that energy is increasing in the direction of transport as down-current fine deposits may remain to be observed as a result of cohesion in fine sediments, which difficulties their resuspension. A significant test (Z-score) is used to determine a preferred transport direction with a certain level of confidence. The transport direction is accepted if Z is larger than the corresponding value for different levels of confidence:

$$Z = \frac{x - Np}{\sqrt{Npq}} \begin{matrix} >1.645 \text{ (0.05 level of significance)} \\ \text{or } >2.33 \text{ (0.01 level of significance)} \end{matrix} \quad (1)$$

where x is the number of pairs representing a particular case in one of the two opposing directions, N

is the total number of possible pairs ($N = \frac{n^2 - n}{2}$),

n is the number of samples in a sequence, and p is the probability of random occurrence, which is equal to 0.125, and q = 1 - p)

The final acceptance or rejection of a trend is made by the qualitative evaluation of a multiple correlation coefficient (R^2) between the mean, sorting and skewness of each sample contained in the sequence (McLaren *et al.*, 1993).

The procedure proposed by Gao and Collins (1992) defines trend vectors for a grid of sampling sites using grain size trends that differ slightly from those proposed by McLaren and Bowles (1985). According to these authors, four grain-size trends are associated with net transport directions:

Type 1: F, B, - (finer, better sorted and more negatively skewed)

Type 2: C, B, + (coarser, better sorted and more positively skewed)

Type 3: C, B, - (coarser, better sorted and more negatively skewed)

Type 4: F, B, + (finer, better sorted and more positively skewed)

Trend vectors are defined comparing the grain size parameters of each sample with its neighbor. Neighboring sampling sites are identified on the basis of a characteristic distance that represents the space scale of sampling. The analysis considers only those sampling sites lying within the characteristic distance. Dimensionless trend vectors are drawn for those sites that present any of the four trend types, the direction of the vector running from the site with higher sorting coefficient. Vector summation produces a single vector at each sampling site, which are then filtered applying an averaging operation in order to remove any high frequency noise. The application of the filtering procedure produces "transport vectors" that represent net transport paths. The transport vectors were obtained using the Grain-Size Trend Analysis (GSTA) program published by Gao

Table 1 - Summary of grain-size trend methodologies.

| AUTHOR | FORMULATION | OUTPUT |
|------------------|--|--|
| McLaren & Bowles | One dimensional trend model (line-by-line approach). Two grain-size trends (Cases C and B) are related to direct sediment transport. Transport trend vectors are derived by comparing the grain-size parameters of all possible pairs of samples located on a sampling line regardless of the distance between them. A significance test (Z-score) is used to determine the preferred transport direction. | Transport direction along sampling lines. Case trends provide information on the relative energy of the transport regime. |
| Gao & Collins | Two-dimensional trend model (vector approach). Four grain-size trends are associated with net transport directions. The grain-size parameters of samples lying within the maximum sampling spacing, are compared to produce a grid of dimensionless trend vectors. Only two samples are compared at a time. The application of a semi-quantitative filtering technique and of a statistical significance test produces a residual pattern representing net sediment transport paths. | A grid of dimensionless transport vectors. Depocenters are identified by the convergence of transport vectors. |
| Le Roux | Two-dimensional model based on conventional vector analysis. Considers the same four grain-size trends defined by Gao & Collins or a combination of them all. Transport is inferred to take place along wide, unidirectional fronts rather than from point-to-point with the maximum gradient lying normal to the fronts. Grain-size parameters are integrated so that each assumes equal status. Transport vectors are obtained by comparing groups of five "neighboring" stations at a time. Valid transport patterns are determined by the nonparametric Watson test. | A grid of dimensional transport vectors. Vector magnitudes indicate existing energy conditions allowing the identification of depocenters. |

(1996). As this program does not include an appropriate significance test of the transport vectors, the modified Grain-Size Trend Analysis with Significance Test (GSTAST) program of Chang *et al.* (2001) was used to statistically test the results of the GSTA program. The significance test randomly re-allocates the grain-size parameters in the original stations to different stations in order to generate many empirical data sets prior to calculating a series of the transport trend vectors in each data set. The vector length (L) at the sampling stations calculated using the original data set is statistically tested by a critical value ($L_{\text{critical value}}$, e.g. L_{95} , 95% confidence interval) from the frequency distribution of the vector lengths calculated using all the data sets. If L is greater than $L_{\text{critical value}}$, the trend vector is accepted and kept at the sampling station as a preferred transport vector, otherwise, the trend vector is rejected. The trends identified represent the net sediment transport pathways with a high level of confidence

The method of Le Roux (1994b) is based upon the premise that if a transport trend is defined by an increase or decrease in the values of specific grain-size parameters or a combination of parameters, it must lie along the maximum gradient of these values. Transport in shallow marine environments is inferred to take place along wide, unidirectional fronts rather than from point-to-point as assumed in the previous methods, with the maximum

gradient lying normal to the fronts. Groups of five stations are therefore used to determine the vector mean azimuth and vector strength of the transport paths.

The grain-size parameters (μ , σ^2 , Sk) for each station are first combined into a single, dimensionless number, with each parameter considered to be of equal importance. However, the concept also allows for differential weighting of the parameters if needed. The basic method requires that there should be a central station and four satellite stations located on the principal radials (360° , 90° , 180° and 270°), at equal distance from the center, so that the dimensionless grain-size parameters can be substituted for the proportional frequencies of recorded directions in conventional vector analysis. To allow for an irregular distribution of station localities, however, an iterative trigonometric technique is used to determine the values at these localities. The four trend types described above can be analyzed, with the option to either use individual trend types or to employ the trend type with the maximum vector strength for each group of stations. The distribution of the resultant vectorial data is analyzed using the Watson non-parametric test, to determine whether it is preferential or uniform. This test for modulo 360° azimuth data is stronger than the Kuiper test and uses the following statistic (Watson 1966). The vectorial data, q_i (modulo 360°) are first sorted from the

smallest to the largest value and given indices from $i = 1$ to $i = n$. The test statistic u^2 is given by:

$$u^2 = (u_*^2 + 0.1/n^2 - 0.1/n)(1 + 0.8/n) \quad (2)$$

where $u_*^2 = \sum(\theta_i/360)^2 - 2/n\sum(i\theta_i/360) + 1/n\sum(\theta_i/360) + n\{1/n\sum(\theta_i/360) - [1/n\sum(\theta_i/360)]^2 + 1/12\}$.

The critical value of the test statistic, $U\alpha^2$, is 0.187 for $\alpha = 5\%$ and 0.267 for $\alpha = 1\%$. If u_*^2 is less than u_{α}^2 , the null hypothesis can be rejected with a confidence of $(100-\alpha)\%$ and the alternative hypothesis (i.e. that the distribution is non-random) can be accepted.

Raster analysis of transport trends

In order to detect the degree of similarity between the transport patterns obtained through the three grain-size methodologies, a spatial analysis was made using the software ILWIS 3.0. The raster models define the geographic space in a simple and uniform fashion, i.e. cells of same size, and they have great analytical power (Eastman, 1995). Thus, vector maps of trend vectors were transformed into raster maps, which were then overlaid, and the correlation coefficients were calculated between the directions of transport vectors (Sokal and Rohlf, 1981).

RESULTS

Wind and Current Characterization During Extreme Weather Conditions

The statistical characteristics of the winds and currents measured during the sampling period are summarized in Boxes 2 and 3.

Northwesterly winds dominated throughout the winter survey, with a mean velocity of 9.1 m/s. Recorded maximum near-bottom current velocities exceeded 15 cm/s at both moorings. Between June 19 and 23 a frontal weather system with wind speeds exceeding 20 m/s pushed the whole water column towards the interior of the harbor (Fig. 2). Light winds from the southwest prevailed during the summer survey, with an average speed of 5.3 m/s (Fig. 3). Weak currents (<5 cm/s) were recorded, especially at the bottom levels. On December 13 stronger winds (>15 m/s) established a circulation cell of water, forming a surface layer at the 4 m level at mooring A leaving the harbor (NW) and a bottom compensation flow entering into the harbor (SE-SW) at the near-bottom levels of both stations. As a result of the intensification of the southwesterly winds, the near-

bottom current at Mooring B reached 23.8 cm/s. Currents and winds measured were consistent with those measured by Sobarzo (1993).

The progressive vector diagrams (PVD) show the residual circulation at the different levels of measured currents. Until June 22 the water circulation pattern was towards the harbor (SW) at the 5 and 15 m levels (Fig. 4). By the end of day 22 these patterns changed to the northeast (out of the harbor). However, the water circulation at the near-bottom level of station B registered no changes during this period, remaining towards the SW. The current at all three levels was unsteady, especially at station A, due to the greater variability of the winds measured in June (Table 2). The residual current direction at all levels was to the southwest mainly as a result of the intense forcing of the northwesterly winds. During summer, the southwesterly trend persisted at the 4 and 11 m levels of station A and at the 7 m level of station B. Until day 15, the water circulation at the bottom level of 16 m was towards the southeast, changing to northwesterly at the end of day 16 (Fig. 5). The current at this level presents the greatest variability of all (Table 3). The residual current direction for all levels remained to the southwest, with the exception of the current at 16 m, which flowed towards the southeast.

A linear correlation analysis between the mean and tidal current (obtained through a short high-pass filter) revealed that the flow regime observed in Lirquén Harbor during the survey period is primarily tidally forced. The high-pass current velocity data indicate that the peak flood currents are stronger than the peak ebb currents at all levels (flood-ebb asymmetry). During the strong wind periods, wind forcing was especially evident as the strongest near-bottom currents were recorded during these events.

Sedimentological Characterization of the Study Area

The spatial distribution of textural classes reveals that most of Lirquén Harbor is dominated by sandy sediments. The mean size distribution pattern shows that coarse-grained sediments (0.4 to 4.1 ϕ) occur in the eastern sector whereas fine-grained sediments with a mean grain-size of 4.1 to 6.1 ϕ occur in the western sector. Consequently, the bottom sediments tend to become coarser, better sorted and more positively skewed towards the east (Fig. 6).

Table 2 - Descriptive statistics for winter wind and current.

| | | WIND (m/s) | CURRENT (cm/s) | | |
|------------------------------|--------------|------------|------------------|-------|-----------------|
| | | | Mooring A | | Mooring B |
| | | | Water depth 20 m | | Water depth 9 m |
| | | | 5 m | 10 m | 6 m |
| SPEED | Mean | 9,1 | 6,0 | 6,1 | 4,6 |
| | Variance | 24,1 | 11,4 | 15,5 | 13,4 |
| | Minimum | 0,4 | 0,0 | 0,8 | 0,6 |
| | Maximum | 24,2 | 21,2 | 24,4 | 27,6 |
| | Stability(%) | - | 21 | 27 | 34 |
| EAST-WEST COMPONENT | Mean | -4,6 | -0,2 | -0,8 | -1,2 |
| | Variance | 31,0 | 12,5 | 13,9 | 17,2 |
| | Minimum | -15,7 | -12,6 | -14,6 | -25,1 |
| | Maximum | 5,8 | 9,3 | 11,4 | 13,7 |
| NORTH-SOUTH COMPONENT | Mean | 3,7 | -1,3 | -1,5 | -1,0 |
| | Variance | 40,7 | 33,6 | 36,2 | 14,6 |
| | Minimum | -6,3 | -20,5 | -23,1 | -22,8 |
| | Maximum | 24,0 | 12,8 | 13,2 | 17,7 |

Table 3 - Descriptive statistics for summer wind and current.

| | | WIND (m/s) | CURRENT (cm/s) | | | |
|------------------------------|--------------|------------|-----------------|-------|------|------------------|
| | | | Mooring A | | | Mooring B |
| | | | Water depth 17m | | | Water depth 8.5m |
| | | | 4m | 11m | 16m | 7m |
| SPEED | Mean | 5,3 | 4,9 | 2,6 | 1,8 | 2,6 |
| | Variance | 15,7 | 12,2 | 3,2 | 1,6 | 3,7 |
| | Minimum | 0,3 | 0,2 | 0,2 | 0,8 | 0,6 |
| | Maximum | 16,9 | 17,8 | 12,4 | 8,6 | 23,8 |
| | Stability(%) | - | 45 | 44 | 29 | 32 |
| EAST-WEST COMPONENT | Mean | -1,9 | -1,1 | -1,0 | 0,3 | -0,8 |
| | Variance | 7,0 | 10,7 | 2,0 | 0,9 | 5,6 |
| | Minimum | -9,1 | -15,3 | -8,5 | -3,6 | -19,4 |
| | Maximum | 2,1 | 5,6 | 4,0 | 2,8 | 6,8 |
| NORTH-SOUTH COMPONENT | Mean | -2,5 | -1,9 | -0,5 | -0,4 | -0,2 |
| | Variance | 27,2 | 20,7 | 6,8 | 3,7 | 4,0 |
| | Minimum | -15,2 | -14,8 | -12,4 | -7,9 | -16,0 |
| | Maximum | 6,5 | 14,0 | 7,2 | 8,4 | 6,7 |

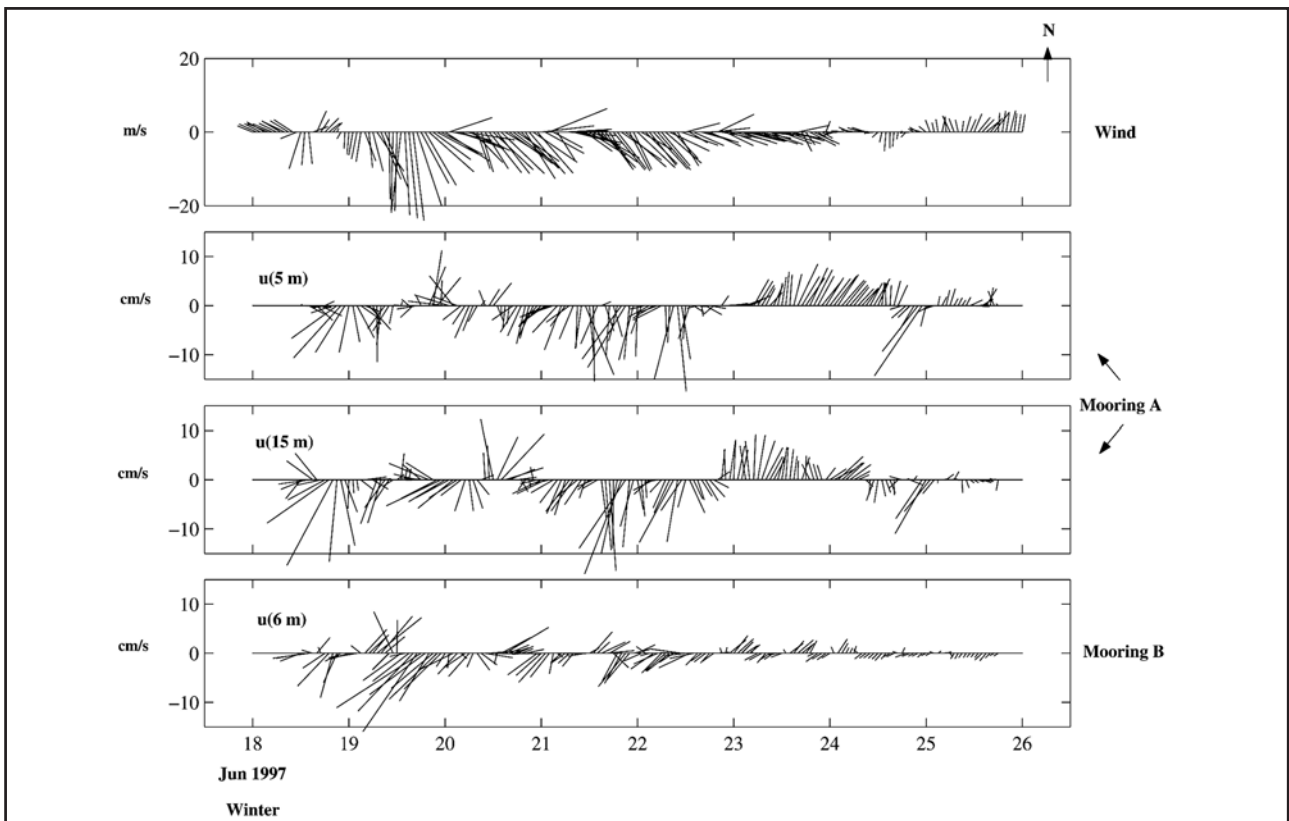


Figure 2 - Vector plots of wind and currents at different depths measured during the winter season (wind plotted in the oceanographic sense).

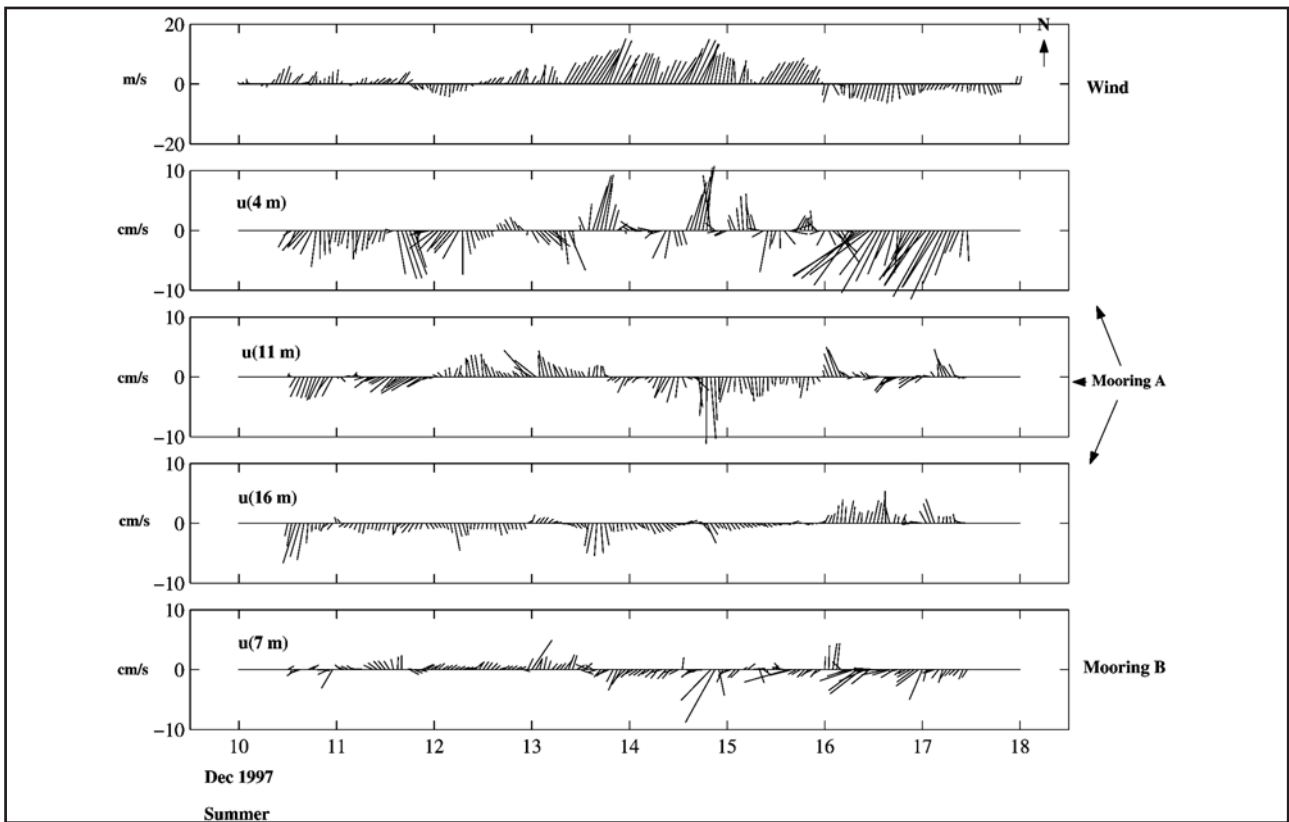


Figure 3 - Vector plots of wind and currents at different depths measured during the summer season (wind plotted in the oceanographic sense).

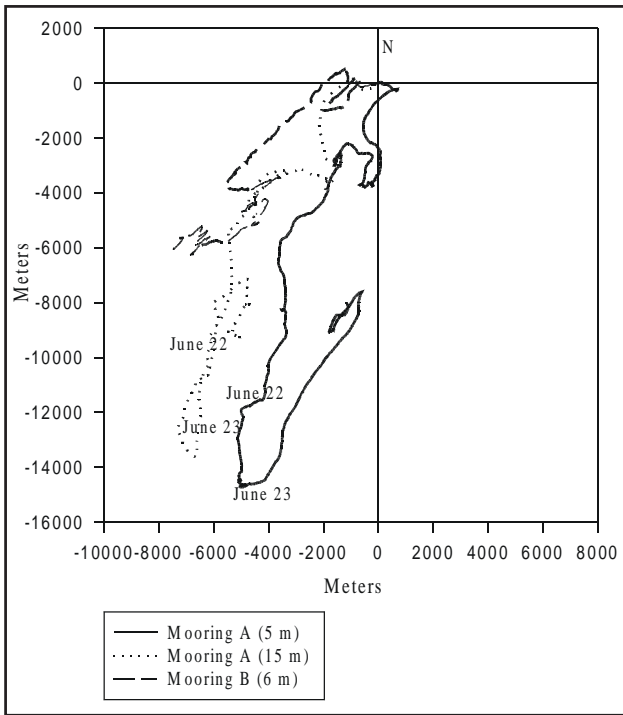


Figure 4 - Progressive vector diagrams at the three levels of measured currents during the winter survey.

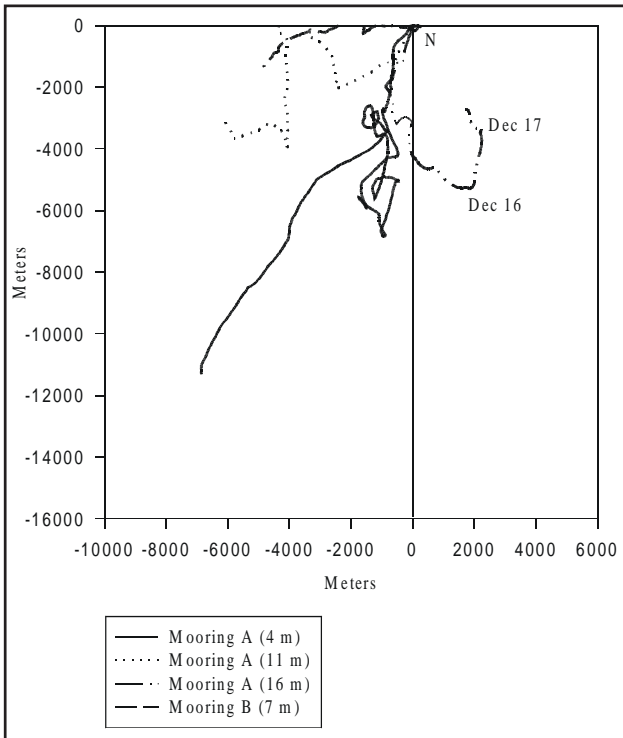


Figure 5 - Progressive vector diagrams at the four levels of measured currents during the summer survey.

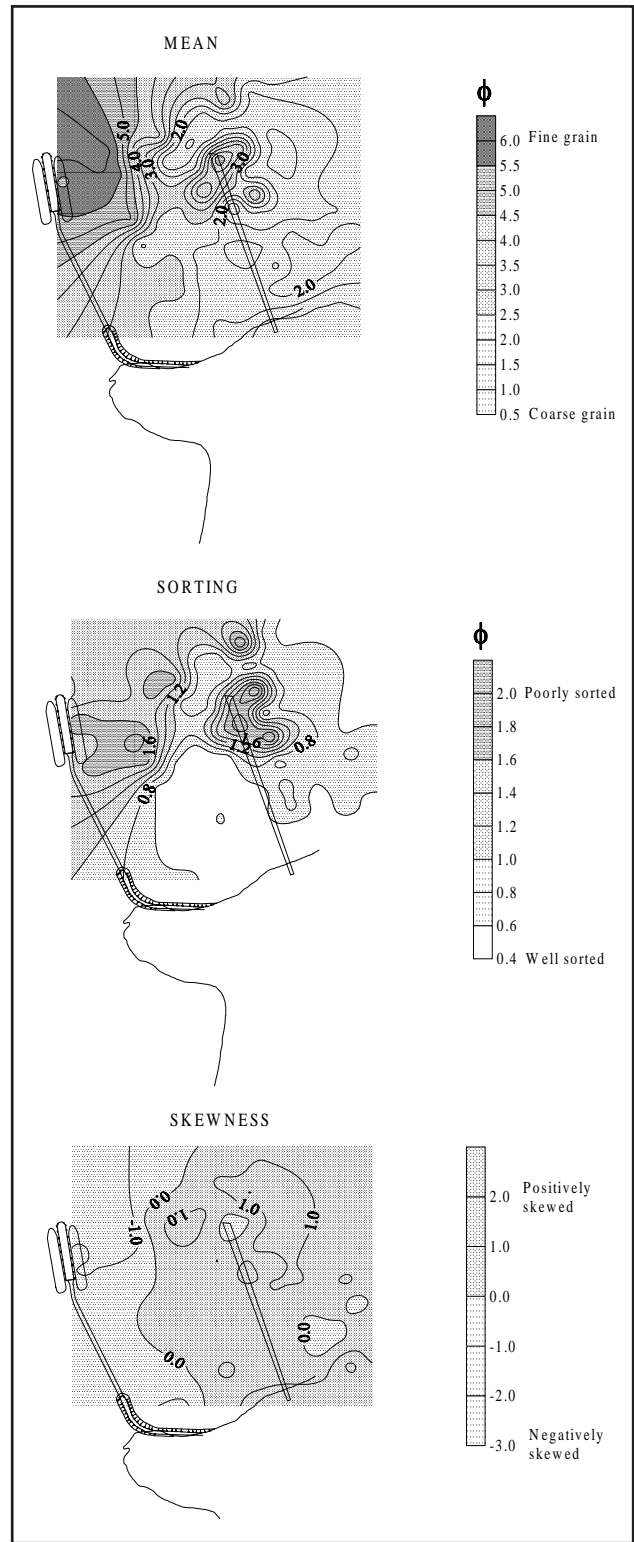


Figure 6 - Spatial distribution of mean grain size (in ϕ units), sorting coefficient (in ϕ units) and skewness of superficial sediments of Lirquén Harbor.

Sediment Transport Pattern Determination Through Grain Size Trend Analysis

McLaren-Bowles Methodology

Figure 7 shows the sampling lines used to determine the sediment transport directions by this methodology. A total of 28 lines were identified as having their Z-scores exceeding the 95% significance level on the basis of $p=1/8$ (Eq. (1)). The use of a low probability criterion resulted in most lines exceeding the accepBox significance level for both directions. This situation was overcome when a higher probability criterion ($p=1/4$) was applied. As a result only those lines with Z-scores exceeding the 95% level of significance at $p=1/4$ were used to infer the sediment transport direction. In order to facilitate the final acceptance or rejection of the trends, a multiple correlation coefficient was calculated between the three grain-size parameters of each sample present along a sequence.

The inferred sediment transport pathways are shown in Figure 8. Two main sediment transport

directions are observed. The analysis of the north-south and northwest-southeastern sample lines indicates significant trends of transport in a southerly and southeasterly direction, respectively, most of these representing type C trends. On average, the R^2 values for these lines are high (mean R^2 of 0.87) indicating a good transport relationship among the sediment samples. The analysis of the lines oriented in a west-east direction produced strong Case C trends showing net eastward transport, although the R^2 values for the lines closer to the shoreline are relatively low, decreasing to 0.66. Lastly, a north-eastward component was identified by the trend analysis of a southwest-northeastern line.

Gao-Collins Methodology

As it was not known at the time of the study which of the four grain-size trends dominated in the study area, all trend types were considered in the analysis. A characteristic distance of 150 m was used to define neighboring samples.

The sediment transport pathways in a two-dimensional sample grid calculated from the GSTA pro-

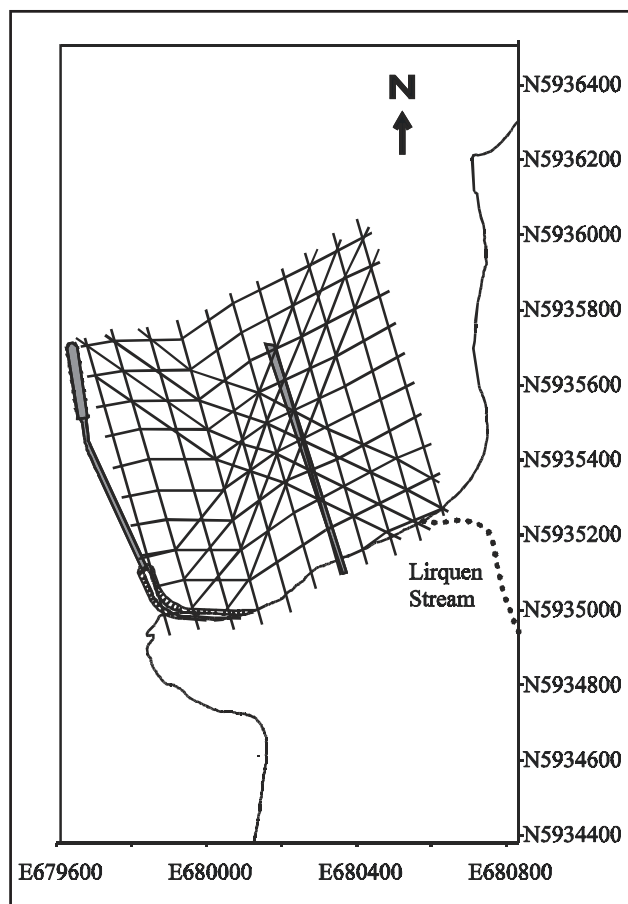


Figure 7 - Sampling lines used to determine sediment transport pathways through the McLaren-Bowles methodology.

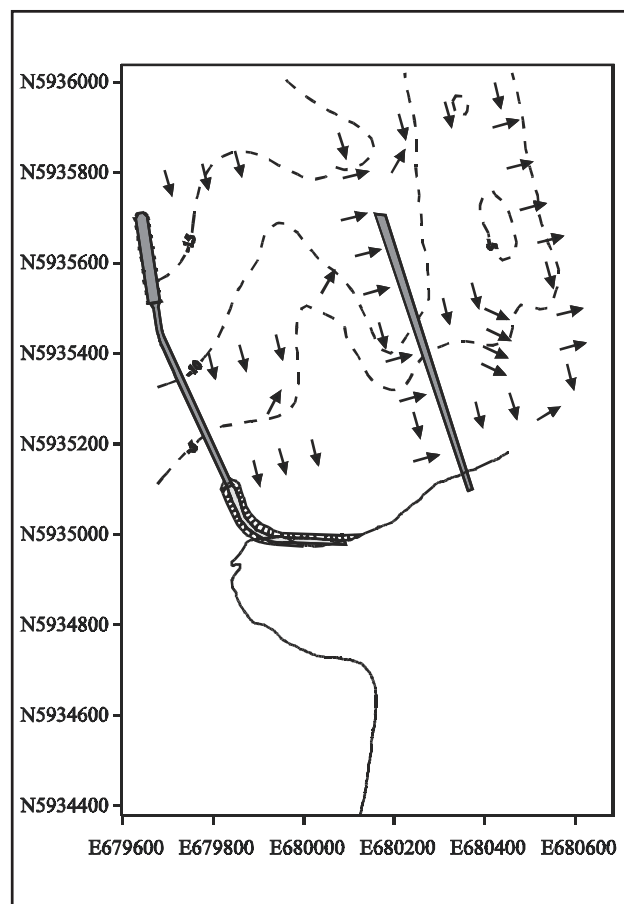


Figure 8 - Net sediment transport pathways obtained through the McLaren-Bowles methodology (bathymetry in meters).

gram are shown in Figure 9a. The application of this procedure revealed an alignment of transport vectors with depth contours. To the west of Jetty 1 transport is dominantly to the southeast and east, whereas along the shoreline transport was northeastward. To the east of the jetty, including the shoreline, transport to the south and southwest seems to exist. In the southern sector of the jetty, the presence of converging vectors from the northwest and northeast suggests that sediment deposition is taking place. However these sediment transport pathways have not been statistically tested.

The significant test on transport pathways was performed with a one-tailed 95% confidence level utilizing 1000 empirical data sets (the original and 999 empirical data sets). The results of the GSTAST analysis are shown in Figure 9b. As a result of the test, 81% of residual vectors were rejected at the 95% confidence interval because they are not significant compared with the randomly generated data sets. In the western sector of the study area the southeastward trend was calculated as the preferred direction of sediment transport, while along Jetty 1 the southward component was statistically distinguished as the valid direction. In the eastern sector, southward and southwestward transports were identified as being significant.

Le Roux Methodology

In this case all four-trend types as well as a combination of all four types were employed in the analysis. A search radius (defining the maximum distance between the central station and its satellite stations) of 2 times the average distance between stations was used to calculate transport vectors. The Watson (1966) non-parametric test rejects the null hypothesis of random variability at the 99% confidence level for all four trends, while the pattern yielded by combined vectors was rejected by the Watson test.

For our data, the different trend types yield the following unsmoothed vector means and magnitudes, with no filter employed: Type 1: 220°, 33%; Type 2: 96°, 40.3%; Type 3: 95°, 32.9%; Type 4: 152°, 48.4%. Three of the four trend types indicate a vector mean in the southeastern quadrant, with type 4 having the highest vector magnitude. Both type 2 and 3 trends show east-southeasterly transport in the westernmost part of the harbor, swinging towards the south-southeast along Jetty 1. East of the latter, trends are more variable but more towards the south and east (Fig. 10). Type 4 produces a very well developed pattern towards the south-southeast

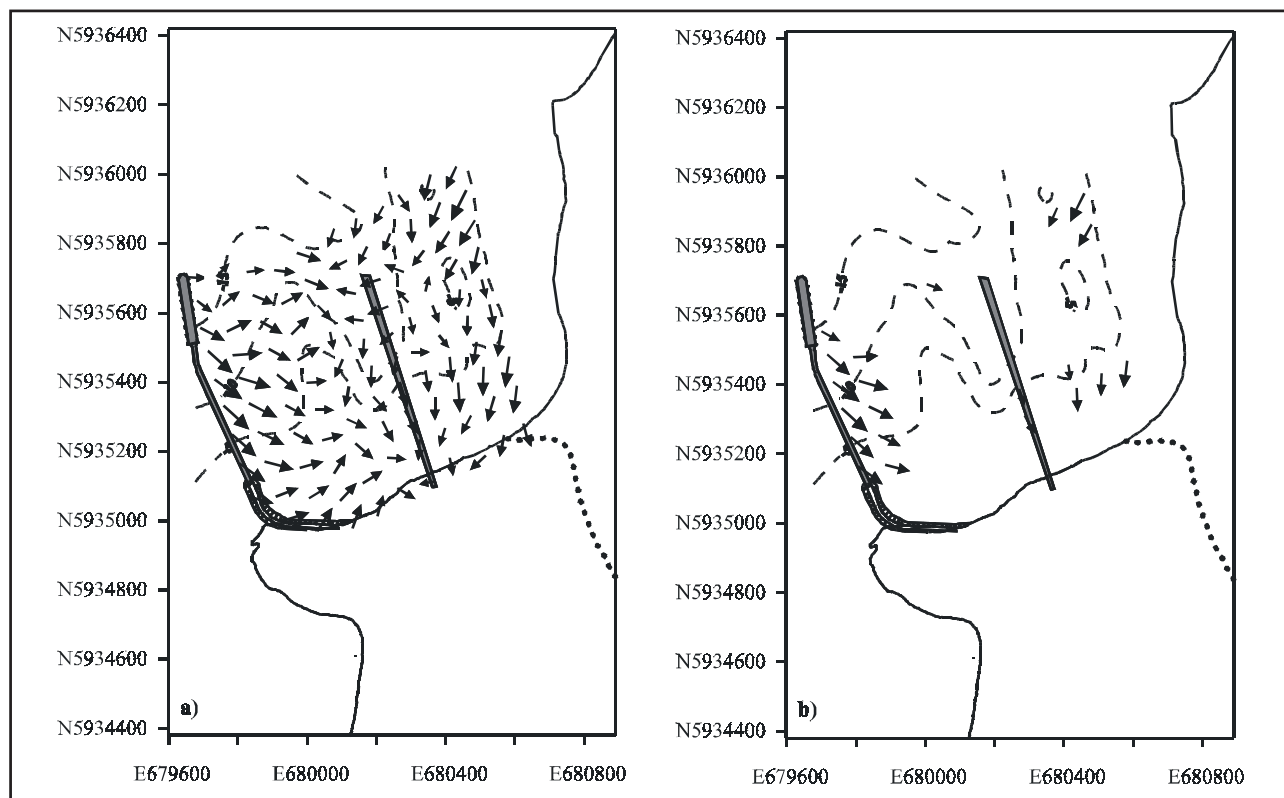


Figure 9 - Net sediment transport pathways obtained through the Gao-Collins methodology and calculated from GSTA (a) and GSTAST (b) programs.

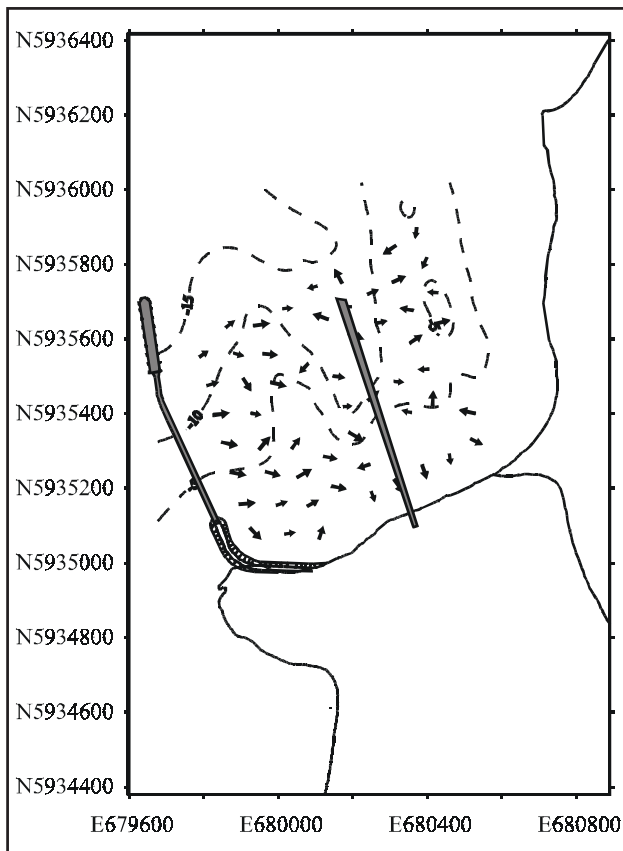


Figure 10 - Net sediment transport paths obtained through the Le Roux methodology and produced by Type 2 trend.

in the western part of the study area, with very variable and weakly developed vectors in the east. A summary of the practical results of the three methodologies is given in Table 4.

Raster Analysis

The transport patterns obtained through the Gao-Collins and the Le Roux methodologies present a moderate correlation ($r=0.53$, $n=13$, $p<0.05$), whereas a weak negative correlation exist between the transport trends obtained by the Gao-Collins and the McLaren-Bowles approaches ($r=-0.1$, $n=13$, $p<0.05$). No correlation exists between sediment transport trends inferred through the Le Roux and the McLaren-Bowles models (Table 5).

DISCUSSION & CONCLUSIONS

Use of Skewness Parameter in the Recognition of the Sedimentary Environment

The skewness parameter provides information on the dynamic status of the sedimentary regime. According to Duane (1964), positively skewed sediments predominate in low-energy areas, therefore the

predominance of such sediments in the study area is a clear indication that Lirquén Harbor is undergoing active sedimentation. The low energy patterns that operate in the sector throughout most of the year are in dynamic disequilibrium with the continuous supply of fine sediments received by the area.

McLaren - Bowles Methodology

According to the results obtained by the McLaren-Bowles procedure, the dominant transport directions in the study area are southward, south-eastward and eastward. In comparison with the near-bed residual water circulation, there is a poor correlation with the sediment trends; nevertheless, the detected southward trend seems to be controlled by the flood tidal current that dominates the bay. This transport direction would indicate a weak but constant movement of material into the harbor from the interior of Concepción Bay. With respect to the eastward transport, 'long-term' current measurements made in the head of Concepción Bay (EULA, 1993) indicate that in summer under the influence of winds from the southwest, the surface current in the western part of the head is induced towards the north. Thus the eastward transport detected could represent fine sediments transported in suspension from the Andalien River (see Fig. 1) by this surface current. The sediments from the Andalien River could finally find their way into the study area through the interaction of the mean flow with oscillatory currents. However, a more extensive sampling grid would be required to support this hypothesis. The limitations of the line-by-line approach applied to a bi-dimensional sampling grid and the subjectivity involved in the selection of the sampling sequences probably prevent the identification of other net sediment transport components that might also exist. Moreover, the consideration by this methodology of only two grain-size trends (Cases C and B) indicative of net sediment transport could prevent the identification of the whole dispersal pattern. It is possible that the comparison of samples spaced too far apart could confuse the spatial scale represented by the grain-size trends. In this way the results obtained by this procedure could represent a combination of the spatial macroscale and mesoscale sediment transport processes (as defined by Larson and Kraus, 1995) existing in Concepción Bay and in Lirquén Harbor, respectively. The predominance of the C trends indicates that a high-energy transport process is required to transport most of the bottom sediments present in the area.

Table 4 - Practical results obtained through the use of the three grain-size trend methodologies.

| METHODOLOGY | PRACTICAL RESULTS |
|------------------|--|
| McLaren & Bowles | Inferred sediment transport directions are in poor conformity with residual water circulation. Detected southward trend seems to be controlled by flood tidal current. The obtained transport patterns may represent a combination of sediment transport at different spatial scales. |
| Gao & Collins | The application of the significance test to transport vectors allowed the recognition of the fortuitous influence of local topography on sediment circulation. In general, the deduced sediment transport direction agrees with the near bottom water circulation. The transport directions show that the area represents an important sink for materials. The location of detected depocenter coincides with sector that has been frequently dredged. Sediment transport patterns seem to represent the mesoscale sediment circulation of the study area. |
| Le Roux | Sediment transport path is compatible with near-bottom current pattern observed in summer. Southeasterly sediment transport trend detected along the western border of the area reflects the influence of the strong northerly winds on sediment circulation. A depocenter was identified around the pilings of jetty 1. The sediment transport patterns are likely to be more representative of the mesoscale sediment circulation existing in Lirquén Harbor. |

Table 5 - Correlation coefficients between sediment transport trends.

| | GAO-COLLINS | LE ROUX | MCLAREN-BOWLES |
|----------------|-------------|---------|----------------|
| Gao-Collins | 1 | 0,53 | -0,34 |
| Le Roux | 0,53 | 1 | -0,01 |
| McLaren-Bowles | -0,34 | -0,01 | 1 |

Gao-Collins Methodology

The general trend of the untested transport vectors of following the depth contours would initially suggest a strong influence of bottom topography on sediment circulation. Nevertheless, the adjustment of transport vectors to topography is no longer evident after application of the significance test to the transport vectors, indicating that the influence of topography is only apparent. This observation, in turn, casts doubt on the results of other studies (Gao *et al.*, 1994b; Pedreros *et al.*, 1996), which identified sediment transport pathways without implementing the significance test. Their patterns may also be reflecting trends that do not actually exist in their particular areas. The detected sediment transport from the southeast quadrant is in good agreement with the residual near bottom water circulation recorded by both moorings during winter. However, the bottom current measurements recorded by mooring A in summer also suggest a southeasterly flow, which perfectly matches the southeastward sediment transport direction detected in the western sector. This suggests that the sediment transport patterns obtained after the application of the statistical test reflect well the influence of bottom currents in Lirquén Harbor, which were dominantly southwesterly in winter and southeast-

erly in summer. Thus, according to this model, the spatial mesoscale (as defined by Larson and Kraus, 1995) near-bed sediment circulation seems to be mainly regulated by bottom currents. It is therefore suggested that the Gao-Collins methodology is capable of detecting the mesoscale sediment circulation of Lirquén Harbor at a higher resolution than the McLarens-Bowles method, as long as the appropriate statistical test is applied.

The significant transport directions detected by the test show that the area represents an important sink for materials. A depocenter, which is identified by transport vectors that tend to converge around the southern sector of Jetty 1, is clearly discerned.

Aerial photographs of the study area for different years and seasons reveal a sediment plume from the Lirquén Stream that is carried towards the southern sector of Jetty 1, probably by the longshore current, thus supplying material to the depocenters located here. The supply of material from the Lirquén Stream would not destroy the general residual pattern, since the trends in the Gao-Collins methodology are defined by comparing “neighboring” samples, as opposed to the trends established by the McLaren-Bowles procedure. Consequently, the implementation of this methodology allow for a better definition of local transport components,

identifying significant transport directions and emphasizing the effect of bottom currents on sediment circulation.

Le Roux Methodology

The Le Roux approach distinguishes transport patterns with a generally east-southeasterly trend especially along the western border of the study area. These patterns are similar to those detected by the McLaren-Bowles methodology. Despite the high magnitude of the Type 4 trend, we decided to select the transport path obtained by the use of trend Type 2, because this corresponds more or less to the near-bottom current pattern observed in the study area. The southeasterly sediment transport direction, also detected by the other two methodologies, besides being in accordance with the southeasterly flow recorded by mooring A in summer, may also be attributed to the influence of strong northerly winds during winter, generating waves directed towards the southeast (EULA, 1993). This southeasterly flow may persist throughout the year, probably flowing very close to the bottom and transporting sediments in this direction. As the current meter deployed close to the bottom was lost during the recovery operations, it was not possible to verify the existence of this flow in winter, however. Thus, the Le Roux methodology, based on an approach and statistical test very different from that of Gao and Collins, also gives results compatible with near-bottom current measurements.

To avoid confusing the space scale of the grain-size trends, both the Gao-Collins and Le Roux methodologies use a characteristic distance (maximum sampling spacing) to define neighboring stations. Only the grain-size parameters of the sampling stations located within this distance are compared, which would allow the identification of the mesoscale sediment transport circulation existing in Lirquén Harbor. This condition makes both models *suiBox* for determining sediment transport pathways in coastal environments with multiple sediment sources. Therefore, the combined application of both procedures allows a better understanding of the sediment transport process existing in Lirquén Harbor, where sediment is supplied by different sources. The Le Roux methodology also allows for the identification of depocenters by using vector magnitudes as an indication of energy conditions, so that sectors with low vector magnitudes are interpreted to be undergoing siltation. Thus on both sides

of Jetty 1, low vector magnitudes and clashing transport trends may indicate areas undergoing siltation.

Spatial Correlation Between Transport Trends

The moderate correlation (Hernández *et al.*, 1988), between the sediment transport directions obtained through the Gao-Collins and the Le Roux methodologies supports the idea that both transport patterns may represent sediment transport process on the same spatial scale, whereas the weak correlation (Gao-Collins vs. McLaren-Bowles) and the lack of correlation (Le Roux vs. McLaren-Bowles) reinforces our thesis that the transport pattern obtained through the McLaren-Bowles approach represents sediment circulation on a larger spatial scale.

Discrepancies Between Directions of Residual Current and Predicted Sediment Movement

As pointed out by Vincent *et al.* (1981) current meter data is important in the examination of sediment transport, but only provides part of the overall picture. The sediment transport patterns obtained for Lirquén Harbor in some sectors are in good agreement with the residual direction of the mean current, while in other sectors they are not. Sediments are transported by a combination of advective and non-linear dispersive mechanisms and it is therefore reasonable to expect some sort of deviation between the transport of sediments and the mean flow direction (Su and Wang, 1986). It is also possible that the different time scales represented by the actual measured currents and the 10 cm depth grab samples could cause these discrepancies. In this sense, a precise estimation of the depositional rate in the study area could have provided the required information for determining the time scale represented by the results of the grain-size trend analysis.

Sediment Transport Regime

The three grain-size trend methodologies agree in predicting a sediment input from the west-northwest probably derived from the interior of Concepción Bay and the Andalien River. Input of material from the northeast coast is recognized by the methodologies of Gao-Collins and Le Roux, from where it is transported southwards by the longshore current produced by the refraction of northwesterly waves around Lirquén Point. This

longshore transport has also been recognized by Pineda *et al.* (1988). These transport directions show that the study area represents an important sink for materials. The Lirquén Stream could be an important source of sediments, however as no sediments were collected in the vicinity of the river mouth, this input was not detected by the methodologies.

Using the Yalin entrainment curve (Yalin, 1972), threshold velocities for the sediments present in Lirquén Harbor should range from 13-36 cm/s. Under both summer and winter conditions, current speeds greater than 20 cm/s occurred less than 1% of the time at both moorings, thus resuspension of fine non-cohesive bottom sediments would occur only sporadically and over short time spans.

An estimation of wave conditions based on wind data observed during the survey period, using the shallow-water equations described in the Shore Protection Manual (CERC, 1984) indicates that waves generated during high-wind events (i.e., >10 m/s) are capable of resuspending sediments in water depths of less than 10 m. However, winds records from 1969 to 1978, obtained from the meteorological station at the Carriel Sur Airport, show that such winds occurred less than 6% of the time throughout the 9-year period (CICLO, 1992). In this way, the prevailing low water current regime and the fact that the harbor is a wave-protected environment, allows decopenters to continue to grow throughout the year.

Thus, the grain-size trends, the wind and current data indicate that a combination of forcing parameters (tides, winds and possibly oscillatory motions) mainly control the local sediment transport regime, and it is concluded that the status of this transport regime is characterized by net accretion. Under these conditions, the fine fraction tends to be deposited preferentially around Jetty N° 1.

The detected tidal asymmetry, which is expected to result in a net southwestward residual sediment transport for Concepción Bay, aggravates the siltation problem of Lirquén Harbor. In order to have a better understanding of the local sediment transport process, a future study should determine the long-term average annual net sediment budget of Lirquén Harbor by estimating the volumes of sediment contributed by each of the principal sediment sources and transport mechanisms. Such a study

should confirm whether the detected tidal asymmetry plays an important role in transporting fine sediments into this harbor.

Acknowledgements - We are grateful to Prof. Michael B. Collins and Dr Yo-Ho Chang for providing the GSTA and GSTAST programs. Thanks to Marthe Raymond for correcting the English version of the manuscript.

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