M O R P H O L O G Y O F T H E M O U T H O F T H E R I V E R D O U R O (P O R T U G A L)

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ABSTRACT

The river Douro debouches into the Atlantic Ocean near Oporto (Portugal) with a funnel-shaped mouth, partly closed from the ocean with a sand spit. Both the wave-induced longshore sediment transport as the sediment yield of the river are limited by the available quantity of sediment (non-alluvial conditions). The results of some sediment transport measurements are presented. The morphology of the river mouth is discussed in relation to the geology of the area, the river discharge and the wave climate, based upon data from the field survey as well as upon some additional calculations.

INTRODUCTION

The port of Oporto, Leixôes, is the second largest port of Portugal. This port is located in the valley at the mouth of the river Leça and nowadays completely enclosed by hills and urban areas. Expansion is therefore difficult. One of the possibilities of creation of new port areas outside the Leixôes area is a tidal flat in the mouth of the river Douro. Because almost nothing is known on the hydromorphology of the mouth of the river Douro, it was decided to investigate this, before making more concrete plans for harbour development on the tidal flat. In this paper the results of a general explorating study of the Douro mouth are presented. The study consists of a short field survey, some calculations and an interpretation of the observations.

GEOLOGY AND GEOMORPHOLOGY OF THE COAST

The mountains of the western part of the Iberian peninsula were formed during the Hercynian orogenesis. For the greatest part they were not covered with sediments during later geological periods. The area around Oporto and the greatest part of the drainage basin of the river Douro consists of crystalline granite, which can hardly be eroded. Because no faults or other depressions were available, the Douro had to scour its bed in the crystalline material. This has resulted in valleys with steep slopes or even gorges.

Geological studies by Boillot, Depeuble and Musellec (1975) show that the coastline between Póvoa de Varzim and Valadares, 10 km south of the mouth of the Douro coincides with the boundary between the crystalline base material and Cretaceous deposits. These deposits are covered with Tertiary and Quaternary sediments. The normal on this boundary has a direction of 255^{o}. (see fig. 1).

The coast between Valadares and Espinho has the same orientation, but here a narrow strip of recent sediment can be found between the coastline and the boundary of the crystalline base material. More to the south the base material continues in the same direction, but the coastline turns. The normal on the coast has a direction of 280^{o}.

Until the submarine canyon of Nazaré (175 km south of Oporto) the coastline remains in this direction.

North of Póvoa de Varzim the crystalline base material continues under the sea until a fault, approx. 15 km offshore.

The geological structure of the coast is highly related to the sediment budget of the coast. North of Póvoa de Varzim the seabed consists of hard material, and is no source of sediment for the coast. Transport from the north is not possible because of the existance of a submarine canyon near Vigo. Consequently the only source of sediment for the coast north of Póvoa de Varzim are the rivers Lima and Minho, which have a very limited sediment yield.
Between Póvoa de Varzim and Leixôes sediment is available on the seabed and might be transported towards the coast; the quantity of sand supplied to the littoral sediment transport is very small.
The coast itself consists of granite and is no source of sediment.

From the above one may conclude that along the coast north of Leixôes the available quantity of sediment is very limited and thus that in sediment transport calculations a distinction has to be made between transport capacity and effective transport.

Along the coast of northern Portugal tidal currents and ocean drift currents are negligible. Wave action can be rather severe. Waves mainly come from W and NW. In general, due to this wave action a longshore sediment transport capacity can be expected from north to south. As discussed above, the sources of sediment north of Leixôes are very limited, it is to be expected that the transport capacity exceeds the actual transport.

The north breakwater of Leixôes harbour (see fig. 2), build in 1892, extends until a depth of 8 m below ZH (ZH= Zero Hidrografico, approx. 2 m below mean sea level). On the hydrographic survey of 1935 at Leçabeach an accretion of approx. one million m^3 is found. On that survey no siltation can be found in front of the deeper section of the breakwater. This indicates that not very much sand was passing the breakwaters. The next detailed survey is of 1972.

Not very much more sediment had settled at Leça beach in that period but new siltation at the toe of the breakwater indicates that sediment passes the breakwater. At the south side of the harbour moles exists an entrance channel with a depth of 15 metres. Nearly all sediment which passes the harbour moles will settle in this sand trap. Only a small part will go to the beach of Matosinhos. Because this beach is protected from W and NW waves, there is no sand transport from this beach towards the south. In the period between 1935 and 1972 approx. 800,000 m^3 settled on Matosinhos beach, (Pires Castanho et al., 1981).

The approach channel is maintained upon a constant depth by dredging. Between 1953 and 1967 approx. 160,000 m^3/year has been dredged. In the Period between 1968 and 1974 some capital dredging has been done (deepening and widening the channel). From 1975 to 1978 the average quantity was 210,000 m^3/year (Hidrotechnica Portuguesa, 1980). It is to be expected that after deepening and widening the channel more sand is trapped, and less is transported to Matosinhos beach. In fact it is to be expected that accretion stopped overthere after the capital dredging of 1969. This means: before 1968 160,000 m^3/year in the channel and 24,000 m^3/year on the beach, after 1978 210,000 m^3/year in the channel. The dredged material has been dumped at sea on deep water.

Between the Castelo do Queijo and Foz do Douro (see fig. 2) the small beach has disappeared completely during the last 75 years. Nowadays there is found no sand at all along this section of the coast.

From the above one may conclude that the sediment transport from the north is in the order of 200,000 m^3/year, however that all this sediment is trapped near the harbour of Leixões and that near the mouth of the river Douro the effective transport from the north is practically zero.

South of the mouth of the river Douro there is a rocky coast. The transport capacity along this coast is also very big. The real transport is limited by the supply from the river. The supply has decreased in the recent years, as will be discussed lateron. South of Valadares the coast is sandy, and was originally supplied with sand from the Douro. Because this supply has decreased considerably, the beaches south of Valadares are eroding. Especially near Espinho this erosion is substantial. Heavy groins are under construction to prevent further erosion.

THE RIVER DOURO

The river Douro flows from the Urbion mountains in Spain 752 km to reach its mouth at Oporto. The total height difference between the source of the Douro and the sea is 2060 m, resulting in an average slope of $2.73 * 10^{-3}$, which is relatively steep. The last 215 kilometres the river Douro flows completely in Portugal, after being the borderline between Spain and Portugal for 112 kilometres. The river enters Portugal at Barco d'Alva, at a level of 130 m, thus the slope in the last section is still $0.6 * 10^{-3}$. The main type of rock in the river basin is granite, which causes the river to scour narrow gorges. The natural runoff of the river Douro is completely determined by rainfall, because snow occurs only in small quantities in the higher regions. The rainfall is limited to short periods between December and April. Because the hard rocky bottom of the drainage basin is only covered with a thin layer of soil, the runoff reacts rather quickly to rainfall. Only a small quantity of water can be stored in the soil. Rainfall in the 94,500 km^2 of the basin causes an almost immediate increase in river discharge. The yearly average discharge of the river Douro is 700 m^3/s. The average discharge during the month with the highest discharge is 2000 m^3/yr.The average discharge during the month with the lowest discharge is 105 m^3/s. The maximum observed discharge was 15,909 m^3/s (on January 3rd, 1962). Due to this regime the sediment yield of the river was very irregular and, as an average, quite high. During only a few days of the year the velocity was high, but during these days the river had an extremely high sediment yield.

However, in the Douro basin a number of dams has been built (see fig. 3). These dams have been built for the production of electricity, although they also improve the navigability of the river and are used for irrigation purposes. Although the last dam (at Crestuma) is still under construction, the dams have completely changed the hydraulic regime of the river. In order to use the dams to optimum, the dam authorities try to keep the reservoirs behind the dams as full as possible. This means that the discharge in the lower sections of the river is governed by the electricity demand, for the period in which the lakes are not completely full. When the reservoirs are full, the natural discharge will also be the effective discharge. The discharge in excess of electricity demand will be sluiced through the dams.

The effect of this regulation is twofold. Firstly a great part of the high runoff discharge is filtered away and decreases the transport capacity. Secondly, even during extreme high floods the velocity directly upstream of a dam is low, causing sedimentation in the reservoir. The river is not able to adjust completely the sediment yield downstream of the dam by erosion because of the non-alluvial bed. According to calculations by Hidrotechnica Portuguesa (1980) the sediment yield before construction of the dams was $1.8 * 10^6$ m^3/yr. Nowadays it is $1.3 * 10^6$ m^3/yr, and after completion of the dam at Crestuma it will be only $0.25 * 10^6$ m^3/yr. These calculations were based upon theoretical formulae only (Meyer-Peter & Müller, Engelund & Hansen, Dubois) and were not verified by measurements. During a few measurements, performed by the author in November 1982 with a river discharge of approx. 600 m^3/s, no sediment yield, neither as bedload, nor as suspended load could be ascertained (less than 10 m^3/hr). Bed samples and vibrocores from the river section between Ponte Dom Luiz I and the river mouth did not show sand or gravel on the river bottom. All samples were taken during medium or low river discharge. From the fact that no sand was found one may conclude that during normal river discharge the sediment transport capacity is rather small. The small quantity of sand which is able to pass the dams is trapped in the artificial or natural holes in the river bottom. Because of contraction during extreme river runoff the river between the Ponte Dom LuizI and the Ponte Donna Maria Pia (see fig. 4) has scoured until considerable depths. For extraction of sand deep holes are dredged in the river bottom (until 20 m deep). Between Oporto and Crestuma, approx. 15 km, there are 15 of such pits. During high, but not extreme discharge, these pits act like sand traps. During extreme runoff sediment will not settle in these pits, and is transported towards the river mouth.

In the river bed itself it is inconspicious that the sediment transport capacity has decreased during the recent past, also because the river is not navigated at this moment. In the river mouth one can observe that the Cabedelo is moved a few hundreds of metres towards the east, but this change is not very striking. As discussed before the sediment transport capacity along the coast has a southward direction, so changes in the sediment yield of the river influence the coast south of the Douro mouth.

THE RIVER MOUTH

Near the mouth three relatively hard zones can be distinguished in the granite. These zones are more or less parallel to the coastline. The first zone is directly behind the coastline, the second one is near the Ponte de Arrábida and the third one is near the old town of Oporto. These zones are identifiable on the steep slopes of the river. For the locations see figure 4, figure 5 shows these steep slopes near Oporto. At these zones the bottom consists of rocky material. Between these zones fine, cohesive material is found. None of the samples, taken between Cantareira and the Ponte Dom Luiz I proved the existance of coarse sand. According to Carrington da Costa & Teixeira (1957) the bedrock near the Ponte de Arrábida lies at a depth of approx. 50 metres. On the river bottom lies a layer of approx. 5 m of silt, overlaying a number of layers with sand and gravel. The river mouth itself (the section west of the Ponte de Arrábida) is funnel-shaped. The northern shore consists of migmatite, the southern shore consists of porphyric granite. The rocks in the mouth (Felgueiras, Fogamanadas, etc.) consist of alkaline granite, the same granite as under the town of Oporto. Besides, the location of the bed rock rises some questions. Under the Ponte de Arrábida the bed rock lies at a depth of 50 metres. This can be explained by a lower sea level in the past, by which the river could scour until this depth.

However, at Cantareira the river has a rocky bottom at a depth of 6-8 metres. This implies that, in the era that the sea level was considerably lower, the river mouth was not at the present location. Consequently, there has to be a location, somewhere under the Cabedelo, between the Fogamanadas and Seca do Bacalhâo, where the river mouth was located in that past era, and thus the bed rock lies at approx. 50 m deep. For potential harbour construction works in the mouth of the river this might be an important item, because deepening the existing entrance at Cantareira requires rock blasting and is very expensive. Because neither borings nor geophysical investigations are available this hypothesis cannot be verified at this moment.

MEASUREMENTS

During a field survey on approximately ten locations sediment transport measurements have been performed, each during one tidal cycle. In the past not any measurements were done in this area and also no morphological study of the river mouth was made. The measurements made during this survey had therefore the character of a first reconnaissance. The aim was to get a first idea of the magnitude of sediment transport. Both bed load and suspended load were measured.

Bed load transport was measured with a sediment-catcher mounted on a standard Van Essen frame (fig. 6). The catch is callected in a net, which can be changed easily after heaving the instrument out of the water. Although not very accurate, this simple approach allows operation in relatively rough conditions. Suspended load was determined by measuring simultaneously the velocity and the concentration on a number of levels in the water. To achieve this an optical turbidity meter (MEX of Eurcontrol) and a simple current meter (F1 of Seba) were built together in a measuring frame (fig. 7). This equipment was chosen because it allows easy operation in areas were no fully equipped survey vessels are available (these measurements were made from a small wooden fishing boat) and because they can cover a very wide range of transport quantities. The disadvantage is their limited accuracy.

The locations of the measurements are indicated in figure 4.
At sea (stations 6, 7 and 9) measurements were performed in wave-fields (swell) with a visually estimated height up to 2.5 m. In the river mouth the wave-height was up to 0.5 m.
The analysis is split in the results of the data from the sea and data from the river mouth.

In the river mouth grab samples indicated a sandy bottom with a D_{50} of 2500 μ and a D_{90} of 7500 μ. On some points no sand could be found, the grab came up empty. A sounding lead filled with sticky soap showed sand at the locations where the grab cought nothing. At those locations the bottom consists probably of rock with sand-filled crevaces.

It is tried to fit the measured data to a sediment transport formula of the type: $S_{tot} = S_{bed} + S_{sus} + S_{wash}$

in which S_{tot} - total transport
S_{bed} - bed load transport calculated with the Bijker-formula
S_{sus} - suspended load with the Bhattacharya-formula
S_{wash} - wash load transport

The wash load is determined as $S_{wash} = A.v$ in wich A is a constant and v the current velocity. For a detailed description of the formula of Bijker and Bhattacharya can be referred to text-books as Muir Wood and Fleming (1981).

Both formulae are highly non-linear functions of the velocity, the waterdepth, sediment properties, the waves and the bottom roughness. Curve fitting has been performed with a non-linear regression analysis (the SPSS subprogram NONLINEAR). The given variables in this analysis were the vlocity, the waterdepth, the wave height and period and values for D_{50} and D_{90} of the sediment.

The parameters to be found by the program ware B (constant factor in the bed load) R (bottom roughness) and A (wash load constant).
The best-fit lines gave sometimes quite unrealistic values for B and R, for example during outflow at the neck of the entrance, the optimal values were B =0.044 and R = 0.001 (m) (B should be between 1 and 10).
A had a value of 0.00172. The correlation between measurements and calculation is 88%. However, when the sediment transport formula is reduced to $S_{tot} = Av$, then still a correlation of 80% could be obtained.

Transport vs veloctiy is plotted in fig. 8.
The coefficient A varies very much for each station, and also varies for inflow and for outflow.
From the above has to be concluded that for the area around the river mouth sediment transport cannot be described as a function of local environmental parameters, as velocity and waterdepth.

When the concentration is plotted as a function of the tidal phase (see fig. 9), then a relation becomes aparent. The number of observations is too limited to give quantitative relations, but it is clear that the concentration in the neck of the entrance depends on the tidal phase plus a basic concentration, which varies from day to day. The basic concentration depends on the general state of turbulence in the estuary.

Although in the above only the outflow has been discussed, the conclusions are probably also valid for the inflow. But because the transported quantities were only 10-20% of the transport during outflow, which is in the same range as the accuracy of the instruments, the inflow situation is not discussed in detail.

All measurements were made in the deeper sections of the entrance. Visual observations showed that on the sandy slopes of the Cabedelo, south of the throat, a considerable quantity of coarse sand was transported. However, it was not possible to measure the transport on the slopes because of the draught of the measuring ship.

For the measurements at sea the procedure of non-linear regression analysis provided reasonable parameters (A = 0, B = 1, R = 0.1 m). The value for B is low. The correlation between measured and calculated data was only 38%, which means a very low reliability of the found parameters. This is to be explained by the fact that the number of samples was too small for a situation with waves (the sampling interval was half an hour). For example in station 7 are measured the following successive transports: 2.5 3.0 7.0 5.2 1.6 1.9 3.7 ($* 10^{-2}$ kg $s^{-1}m^{-1}$).

During these $3\frac{1}{2}$ hours no significant changes occurred in the environmental conditions (current velocity 0.5 m/s, waves of 1 m and a period of 7 sec, waterdepth 11 m). During the measurements also a number of qualitative observations have been made. One of the most interesting observations was at locations 6 and 7. When the frame with the concentration meter was placed on the bottom (the meter is then 20 cm above the bottom) increases of the concentration were measured during the passage of a wave crest for approx. 3-5 seconds. The increase was considerable, a factor 50 or more was common. This happened only under long waves (periods of more than 12 seconds) with a height of 2 m and more. Under shorter waves with the same height this increase was not observed. Because the orbital movement under the crest in a progressive wave has the same direction as the wave propagation, this observation indicates that sand is transported towards the shore by these long waves. (The bottom was relatively flat, waterdepth was 7-8 metres). With the applied equipment it was not possible to quantify the transport.

Because of refraction the waves approach the coastline of the Cabedelo nearly perpendicular. Observations of waves showed that wave crests broke simultaneously over the whole length of the beach, regardless the original deepwater direction of the waves. The beach slope of the Cabedolo is nearly constant. Because a clear difference in run-up was observed, this implies a difference in wave height along the beach. The wave height at the south side of the Cabedelo was considerably higher than at the north side. Consequently there had also to be a difference in wave set-up along the coast. The magnitude of this set-up is too small to observe without instruments, but big enough to generate currents, as will be discussed lateron.

CALCULATIONS

From the measurements followed that, outside the direct river mouth, the sediment transport due to tidal currents is relatively small. The transport caused by breaking waves and by the longshore current due to these breaking waves could not be measured, because it is not possible to anchor a measuring vessel in the breakerzone. In order to get an indication of the transport and transport capacity in the breakerzone, a number of calculations has been carried out.

The nearshore wave data required for the sediment transport calculations have been calculated with a numerical refraction model for linear waves. The refraction calculations have been executed in two steps. Using an overall model (60 x 30 meshpoints, mesh-size 250 m) the boundary values for the detailed model (80 x 40 points, mesh-size 62.5 m) have been calculated. The refraction calculations had to start in relatively deep water. It proved to be more economic to apply two models, instead of one big, detailed model.

The deepwater wave data applied were based upon observations of the Instituto Hidrografico (1974). These observations cover a period of five years. The observations of wave height and wave periods were made with a submerged [Chatou] pressure cell. The wave directions were mainly radar observations and partly visual estimations. More recent waverider measurements cover only short periods and are therefore less suitable as basis for sediment transport calculations. The results of the Chatou-cell have been compared with the wave-rider measurements. The results of the measurements are in concordance with long-term measurements on other locations off the Portuguese coast (the wave-climate along the Portuguese west coast is rather uniform). Based upon the set of five-year observations a deepwater wave climate for the northern Portuguese coast has been determined, consisting of 34 elements (see table 1). For each of the 34 climate elements a refraction calculation has been made. One of the ray-diagrams of the detailed model is presented in fig. 12. Figure 13 gives an example of a wave height plot. Wave climate 23, which is presented in figures 12 and 13 is not the most frequent wave climate elememt, but it is the element which causes the highest transport rate.

The computer program used for the calculation of sediment transport along the coast neglects the influence of tidal currents and also neglects onshore-offshore transport by waves.
As discussed before tidal currents along the coast are negligible. Onshore-offshore transport will exist, the results of these calculations have therefore to be interpreted with care.

The program calculates the longshore current at various waterdepths, and subsequently calculates the sediment transports at these water depths due to current and wave action. The longshore current is calculated with the radiation stress method. Lateral mixing is neglected, the wave height in the breakerzone is calculated acc. to Battjes (1974, p. 142). The influence of differences in set-up along the coast is included in the equation of the propulsing force. Sediment transport is calculated with the Bijker/Battacharya formula (Swart, 1974) applying a D_{50} of 1000 μ, a D_{90} of 1500 μ, a bed roughness of 10 cm and a B-factor of 5. For all the 34 wave climate elements a calculation has been made for high water, low water and average water level.

The four profiles in which the longshore sediment transport is calculated are given in fig. 14. The given values are net sediment transport capacities in m^3/year per metre. In profiles 2 and 3 there is, near to the shore a transport in southward direction. This is mainly caused by short waves from NW, which do not refract very much, and also cause a small set-up. The longer, and generally, higher waves do refract more and approach the beach of the Cabedelo practically perpendicular. These waves cause a considerable set-up, which initiates a current in a northern direction (in the river mouth itself is nearly no set-up). Because these waves are higher, the zone with northward directed transport lies in some deeper water.

It has to be stressed that the given values are transport capacities. The capacity can only be used if sand is available. This is the case for profiles 2 and 3, but not for the profiles 1 and 4. Especially in profile 1 the bottom is very rocky, and consequently the transport capacity can only be used for a limited part (cf. fig. 2).

INTERPRETATION OF THE RESULTS

Given the predominant wave direction (from NW) and the absence of tidal currents, one should expect a sand spit, pointing towards the south. However, the spit in the mouth of the Douro, the Cabedelo, is directed towards the north. For normal, and even for relatively high river runoff the width of the 'hard mouth' (between the rocky formations of Foz do Douro and Seca do Bacalhao) is too wide for a stable river.

In situations where longshore transport is not dominant and the mouth of the river is limited in width by hard shores, the channel will be formed at that side of the river where the waves come from. In this case the waves come from NW and consequently the channel is on the north side (see fig. 15).
Because of diffraction, and to a lesser extend, also because of refraction the waves at the northern shore of the river are lower than at the southern one. This means less wave set-up at the northern shore, and thus a lower water level. The difference is small but the river water inclines to flow along the northern shore, maintaining a channel overthere.

To retain the channel deep enough a training wall has been built in the middle of the river in the former century (Pedras do Lima). This (partly submerged) dam is already indicated on charts of 1833. In history this dam has indeed taken care of scouring all the sand from the rock bottom between the northern shore and the dam during peak runoff of the river. Without the dam the opening would be much wider and more shallow. Especially in the last stage of the passage of a flood wave a very wide and shallow mouth is formed. In 1962 the discharge had such a high value that all the water could not flow free towards the sea, and the water level inside the estuary rose to a level of more than 7 m above ZH. At that moment the Cabedelo was flooded, and a new river mouth was created. After creation of the new mouth, the training wall was no longer effective, and on charts made after the flood of 1962 (and also after the natural closing of the Cabedelo) the river entrance is very shallow. Instead of the usual depth of 7-8 metres the greatest depth was in that year only 4-5 metres. In the years after 1962 the extra mouth in the Cabedelo was closed by wave-induced transport along the Cabedelo, and the training wall became effective again. The navigation channel at the north side deepened out until its usual depth. To get a good idea on pattern of channels and sand banks, the 4 m contour line is most illustrative. This line is given on fig. 16.

Figure 16 is based on the nautical chart of 1972, what is the most recent complete survey of the area. The river debouches into the sea with a bend. The last section of the river has a SW-direction. Two channels can be distinguished. The measurements indicated that in the northern channel the ebb-current dominates, while the southern channel is a typical flood channel. The northern channel is deeper and narrower than the southern one.

Between the 4 and 5 m contour a substantial sediment transport capacity from north to south exists. North of the ebb-channel hardly any sand is available, consequently the effective transport is almost zero. The ebb-channel transports sand to this location, as indicated by the measurements. The origin of this sand will be discussed later.
The sand is mainly deposited on the western shore of the sandbank, area A. Because of the transport capacity of the waves, breaking on the sandbank, the sand will be transported towards the south along the slope. A small part will be transported onto and over the bank. Because of this transport the sandbank becomes falcated.

Long, shoaling waves have a capacity to transport sediment in the direction of propagation of the waves. So they will transport sediment from the offshore sandbank towards the beach of the Cabedelo. Also the measurements indicated the existance of such a transport.

The flood current, between the offshore bank and the Cabedelo, directed towards the north, does not transport much sand. The quantity of sand being stirred up is small and the current velocity is low, because of the width of the channel. Besides that the measurements indicated that this current (of course only near stations 6 and 7) is only apparent near the water surface.

According to the calculations a relatively strong set-up current occurs along the coast in a northward direction. The visual observations confirmed the difference in set-up. This current transports the sediment, supplied and stirred up by waves, also towards the north. A part of this sand sedimentates directly north of the Fogamanadas; an other part is transported to the head of the Cabedelo.

The sand, sedimentated between the Fogamanadas and the head of the Cabedelo, is transported by waves and by flood current to the eastside of the Cabedelo. The sand settles just east and southeast of the head because both wave influence (by diffraction) and current decrease (by flow expansion). This phenomenon causes a relatively gentle slope in profile B (see fig. 16).

During ebbing tide there is generally no wave influence near the head of the Cabedelo. The strong current keeps the waves out of the river entrance. The ebb-current scours the slope at the head of the Cabedelo. Because of the high velocities on the slope, there is a fast erosion. Steep sandy bluffs are created (see fig. 17). The eroded sand is transported by the ebb-current towards the sea, and settles on the offshore side of the outer bank (A, fig. 16).

The transport mechanism described above implies a circulation of sediment in front of the river mouth. Nowadays this is a nearly closed system. The supply of sand from the river is negligible, and also the conveyance of sand to the southern coast (south of Seca do Bacalhao) is very small.

The shape of the head of the Cabedelo depends on current and wave climate. In periods with high river discharge the head is pointing seaward (fig. 18, type I). After periods with small river discharge (and thus with relatively big wave influence) the head is pointing towards the east (type III). Normally in spring the Cabedelo has a type I shape and in autumn a type III shape, but the differences during one year are small. More clearly are the effects of a serie of dry winters. Then, also in spring there is a type III shape.

CONCLUDING REMARKS

At this moment a balance exists in the morphology of the river mouth. The Cabedelo moved recently somewhat towards the east in order to get a stable position after the decrease of the supply of sediment from the river. The Cabedelo is a stable sand spit, breakthroughs are only to be expected during very extreme river runoff, gaps in the spit will be closed quickly in a natural way. Changes in the river mouth by harbour works should be studied carefully, because they disturb the existing equilibrium, and may cause erosion and siltation in unexpected areas. Extraction of sand from the system should not be recommended, because the naturaly supply of sand is quite limited.

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element number	significant wave height (m)	wave period (sec)	angle of incidence (degrees)	occurrence %
1	1.0	8	315	1.70
2	1.0	8	300	18.53
3	1.0	8	285	0.77
4	1.0	8	270	0.51
5	1.0	8	250	0.24
6	3.0	8	300	0.69
7	3.0	8	285	0.21
8	1.0	10	315	2.25
9	1.0	10	300	23.34
10	1.0	10	285	7.26
11	1.0	10	270	0.64
12	1.0	10	250	0.30
13	3.0	10	315	0.69
14	3.0	10	300	7.55
15	3.0	10	285	2.35
16	3.0	10	270	0.21
17	3.0	10	250	0.10
18	1.0	12	315	0.63
19	1.0	12	300	6.87
20	1.0	12	285	2.14
21	1.0	12	270	0.19
22	3.0	12	315	0.76
23	3.0	12	300	8.23
24	3.0	12	285	2.56
25	3.0	12	270	0.23
26	3.0	12	250	0.11
27	4.5	12	315	0.12
28	4.5	12	300	1.37
29	4.5	12	285	0.43
30	3.0	14	315	0.19
31	3.0	14	300	2.05
32	3.0	14	285	0.64
33	4.5	14	300	0.68
34	4.5	14	285	0.21

Table 1: Wave climate used in the wave penetration model

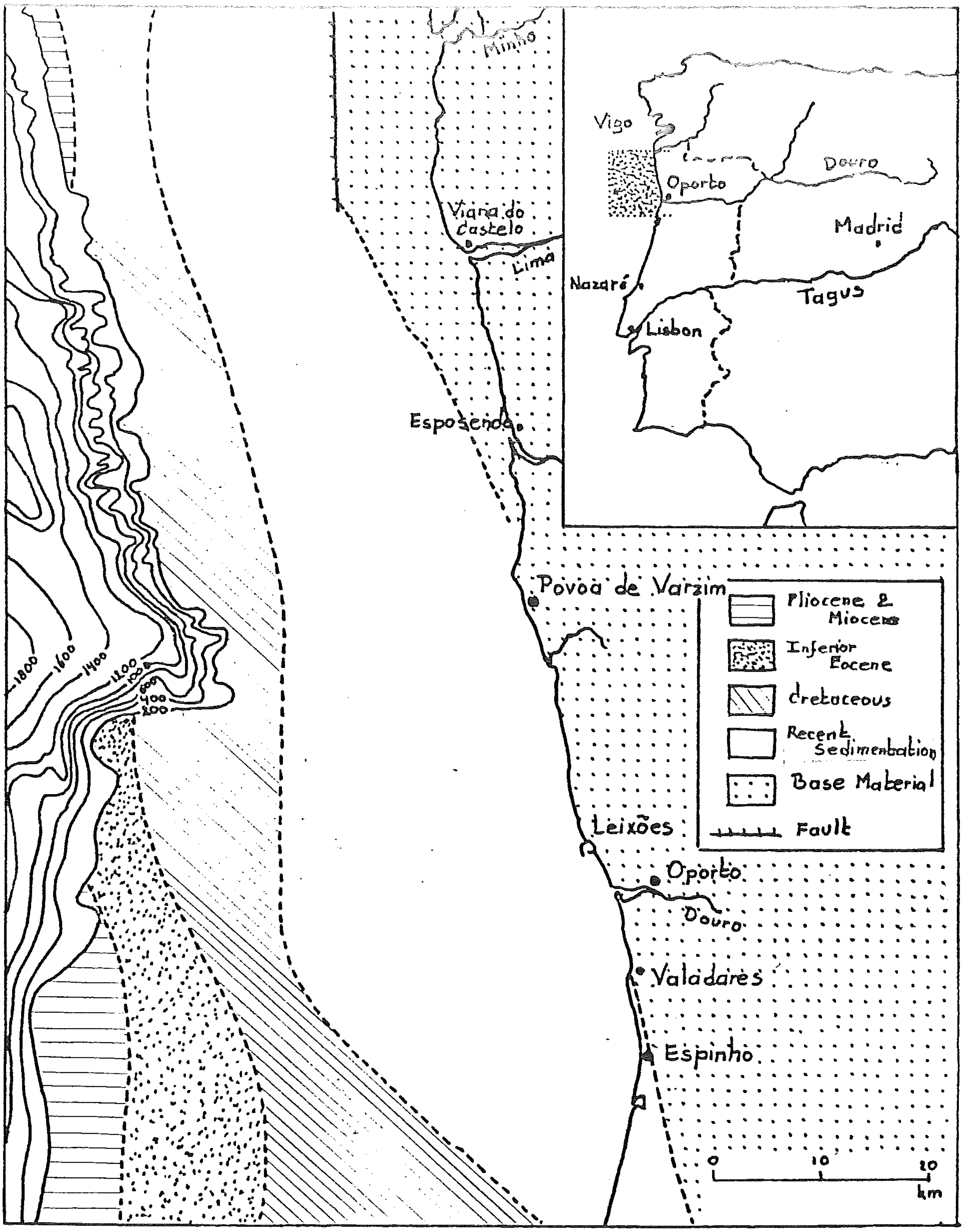


fig. 1. Geological map of the Portuguese coast near Oporto

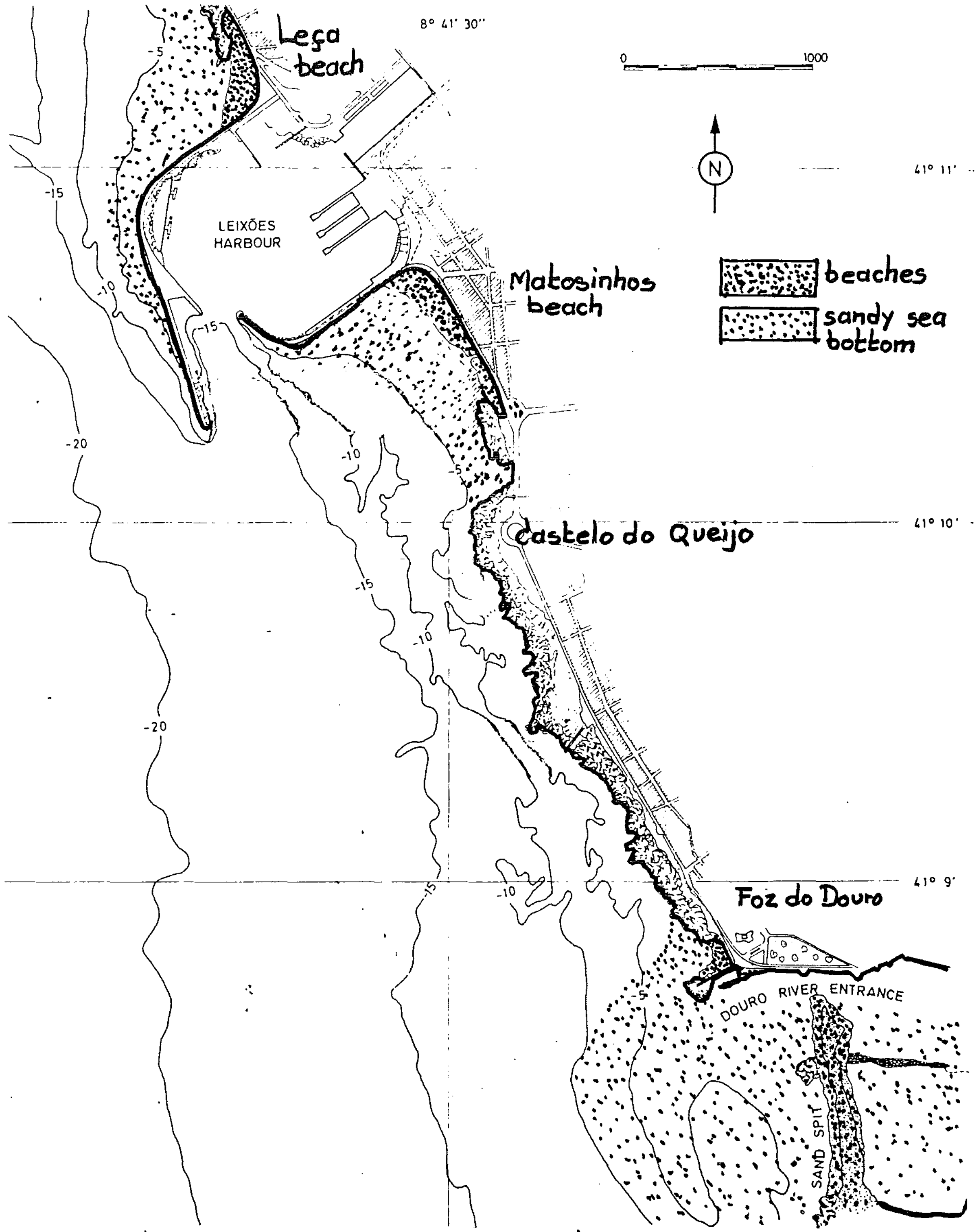


Fig.2. Sediments between Leixões and the mouth of the Douro

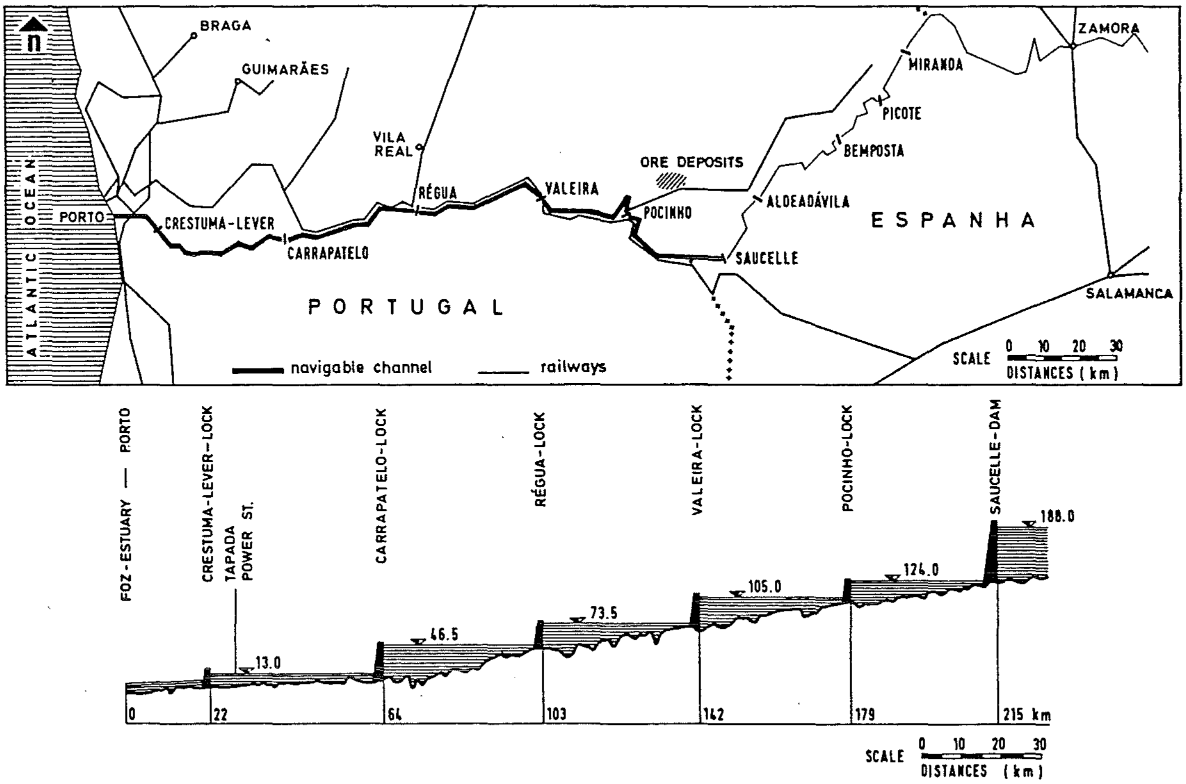


fig 3 Dams in the Portuguese section of the Douro

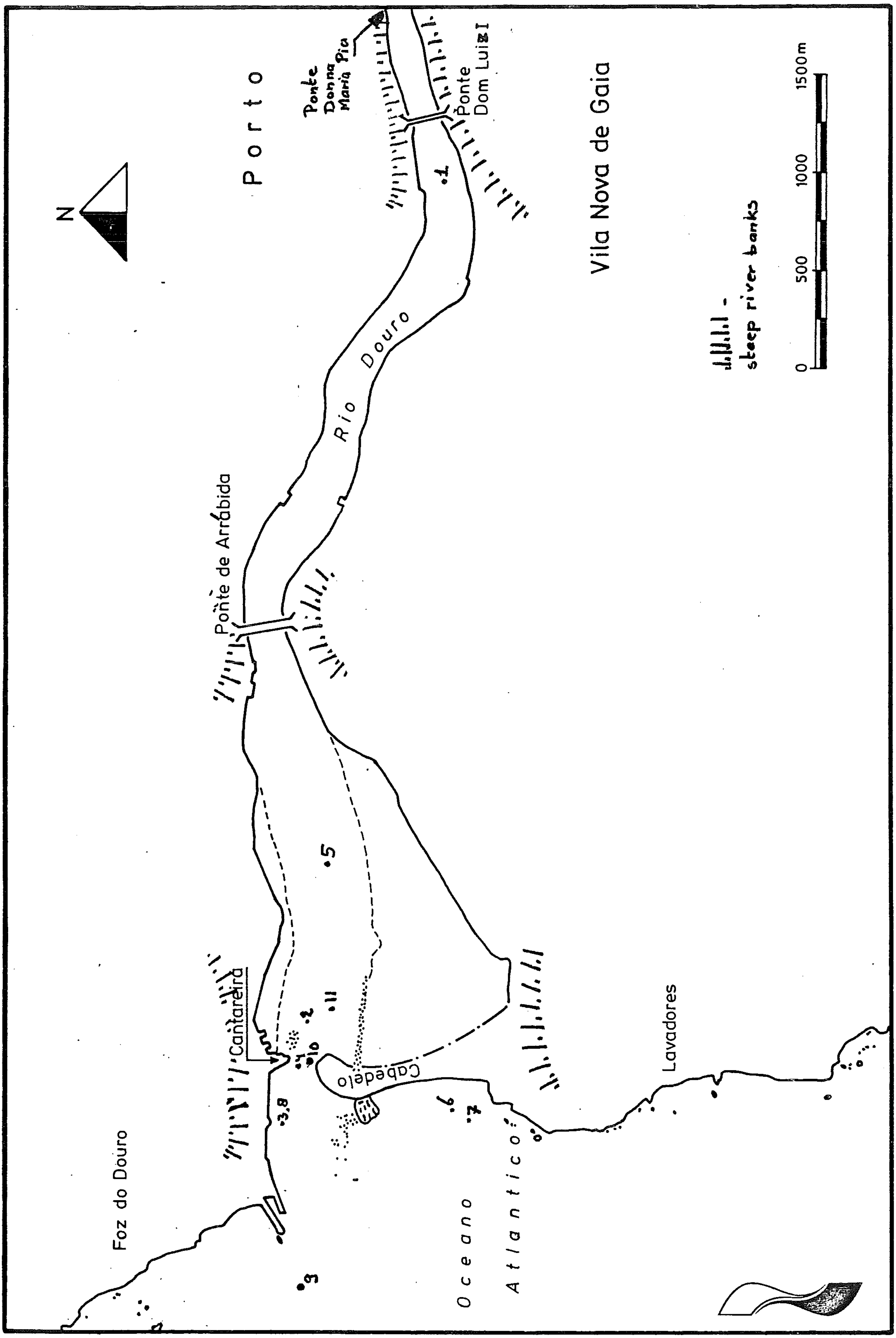


FIGURE 4. The river Douro between Oporto and the coast

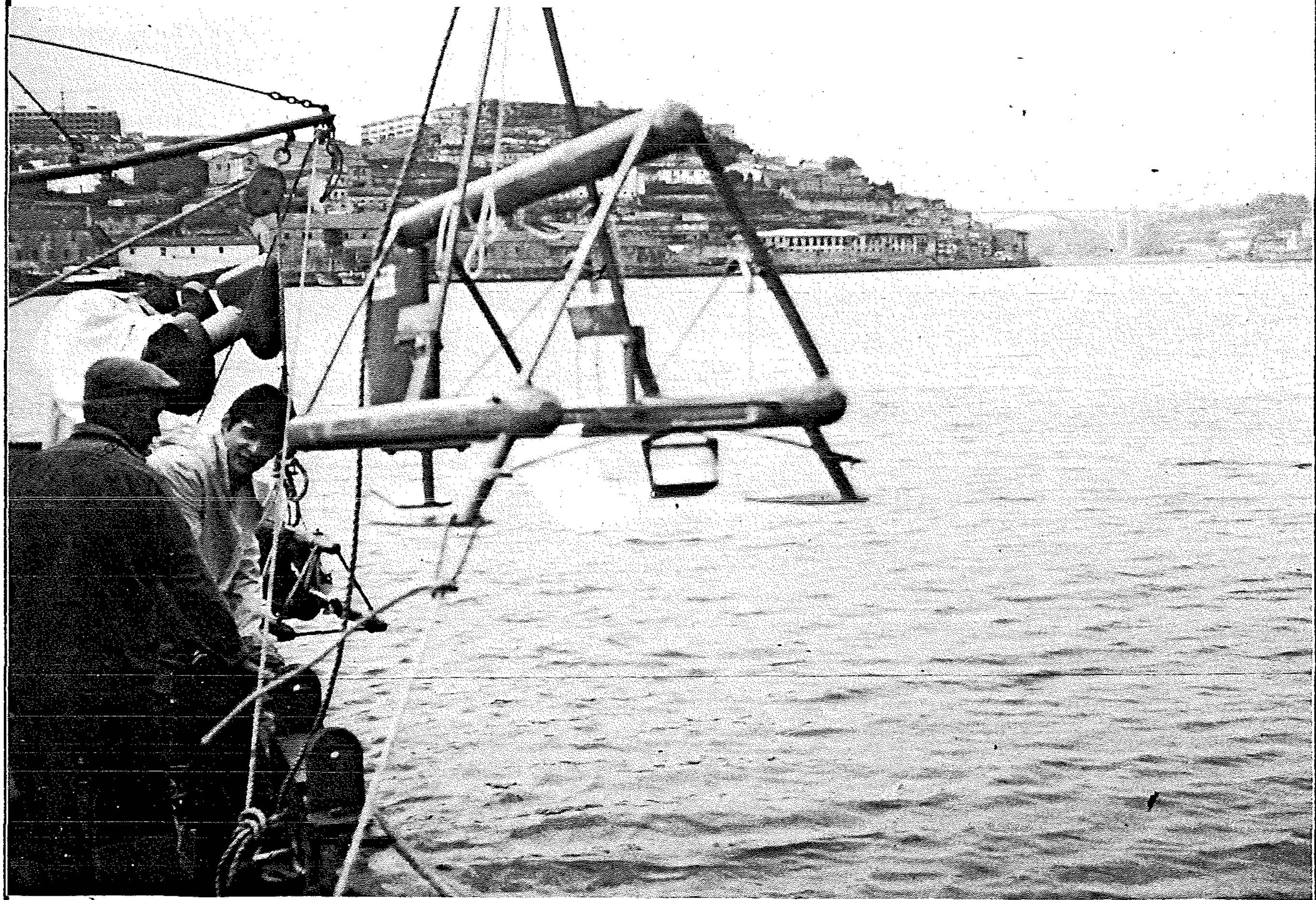


FIGURE 5 *Bed load meter*

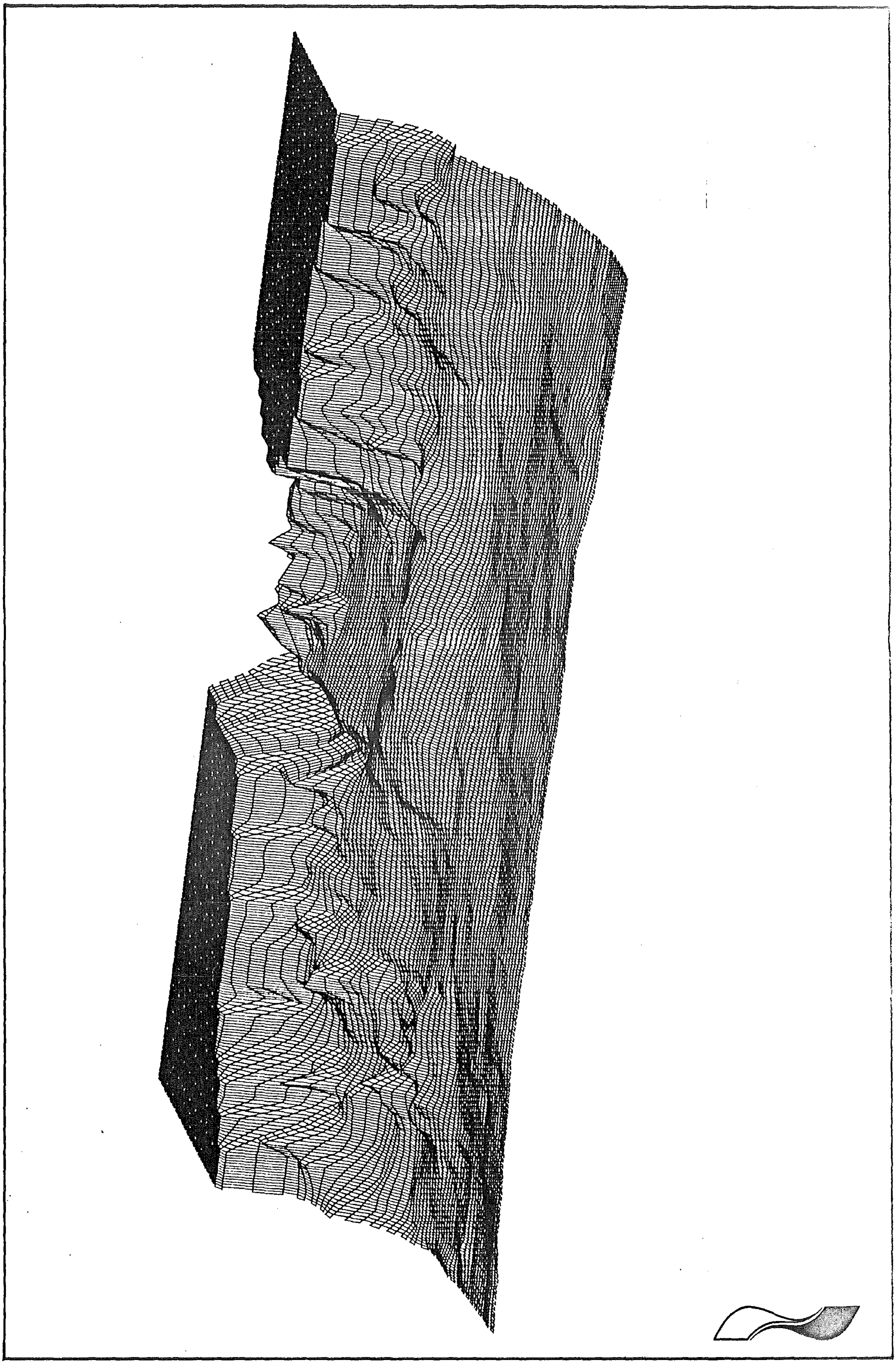


FIGURE 5: *THREE DIMENSIONAL PLOT.*

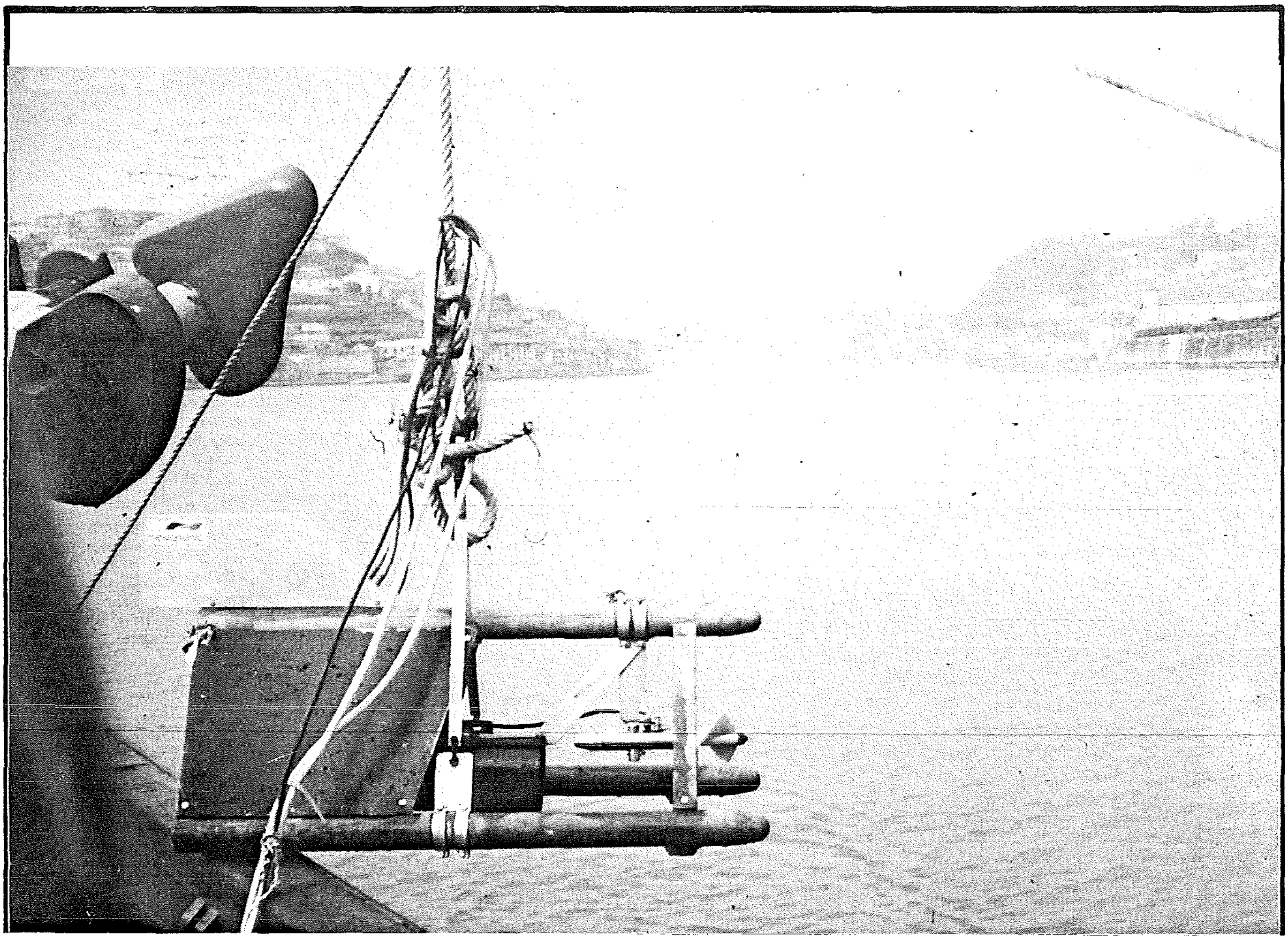


Fig. 6 Suspended load meter

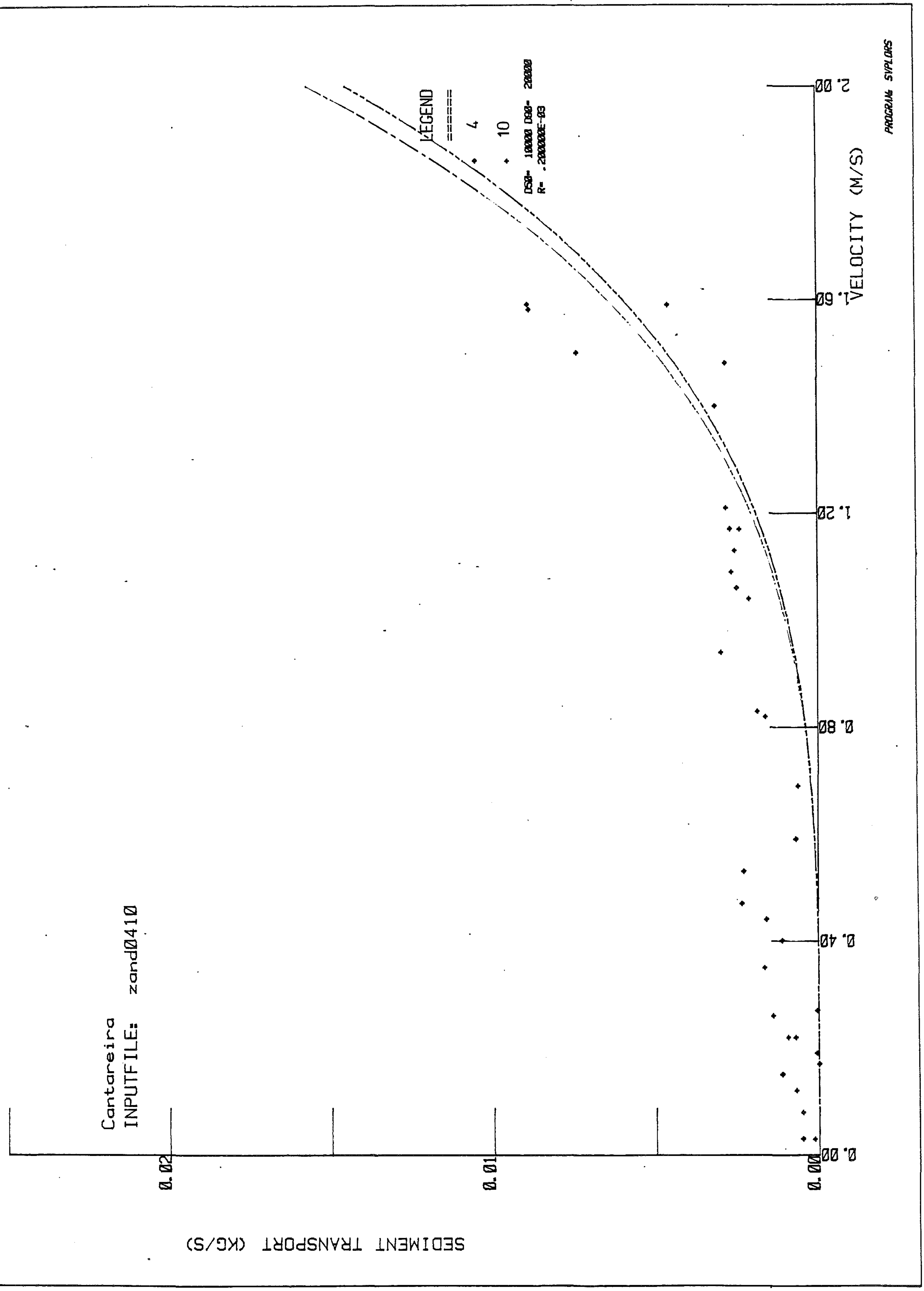


FIGURE *8* *measured transport near Cantareira*

FIGURE 9 Measured transport near Cantareira

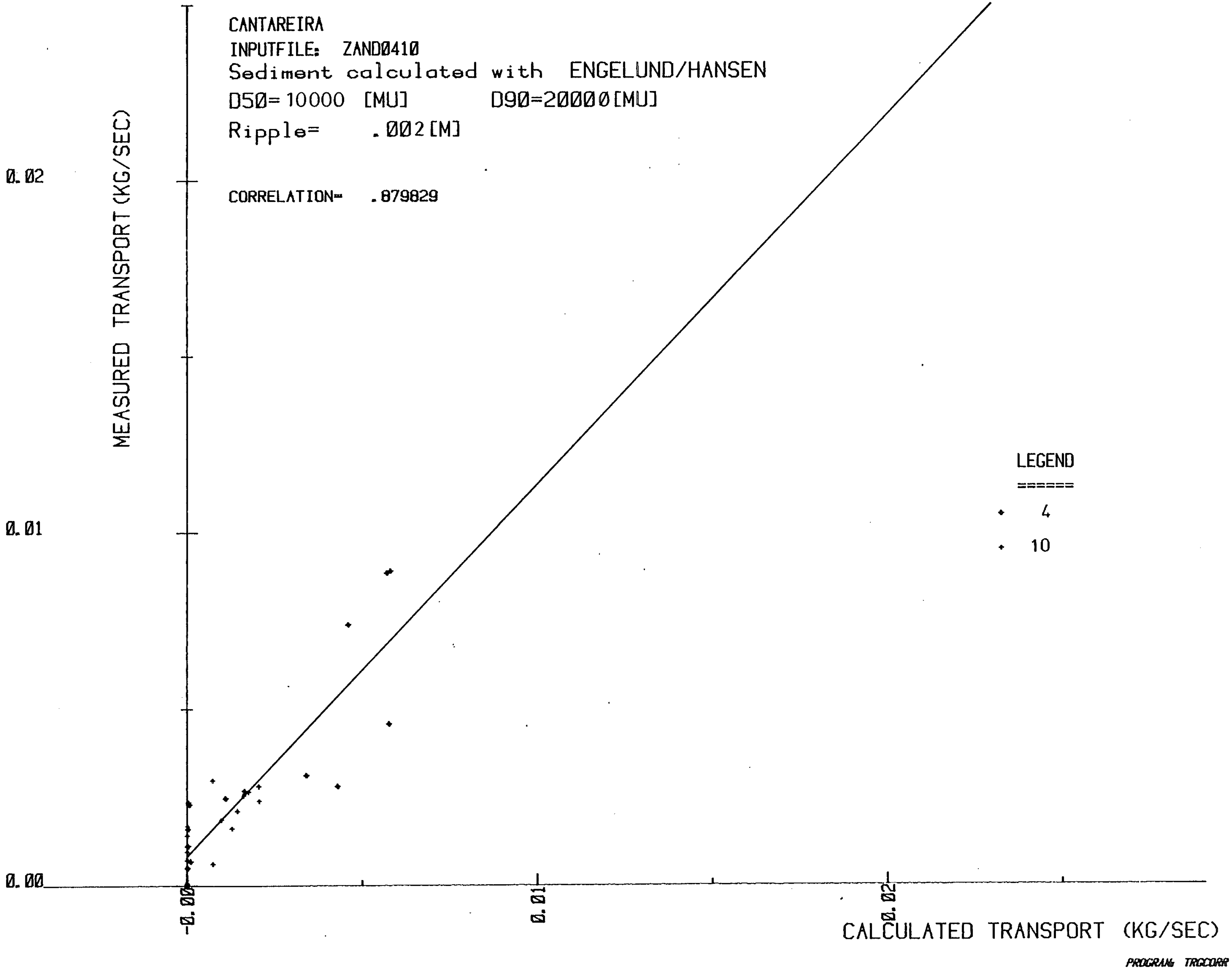
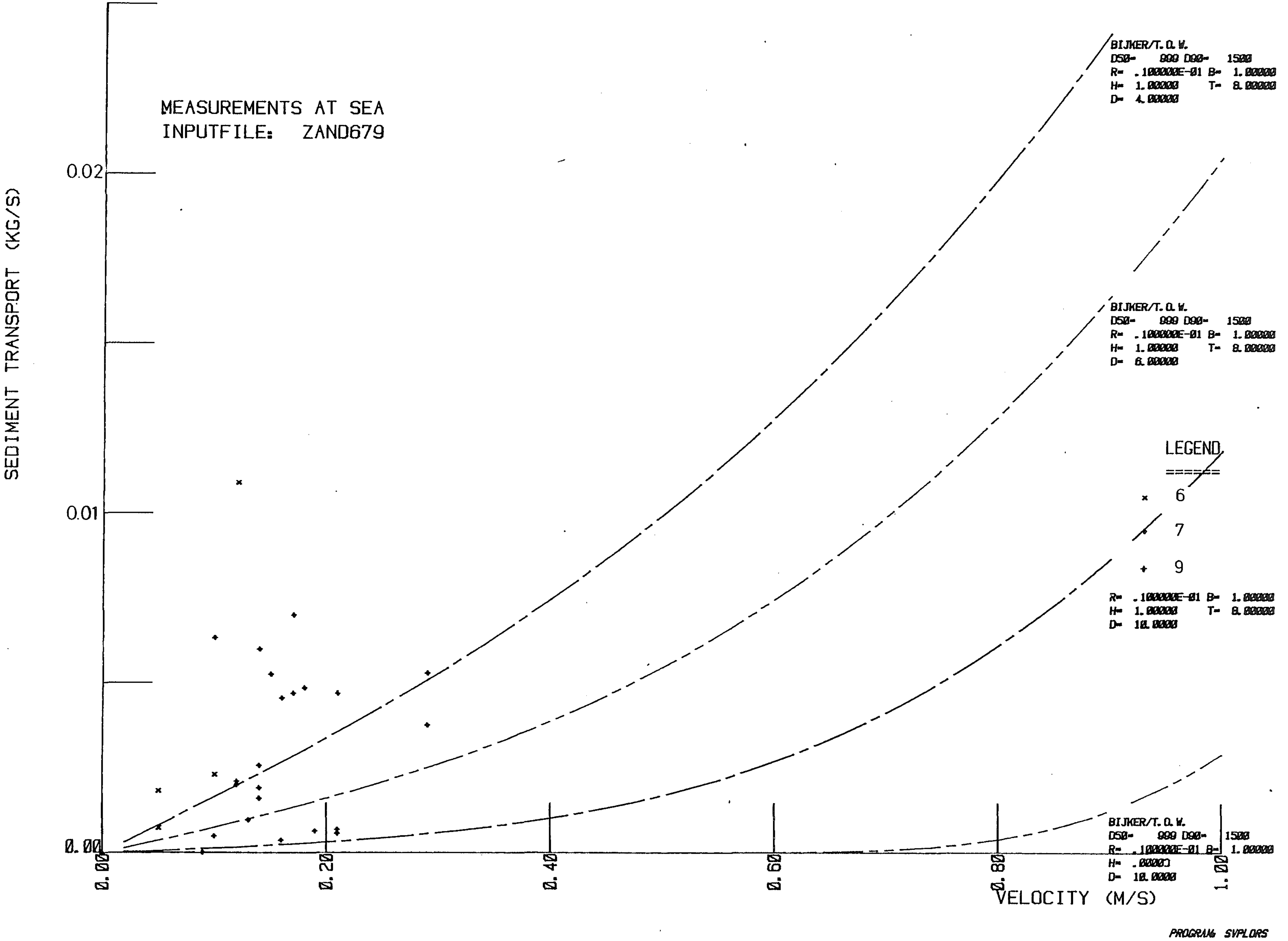
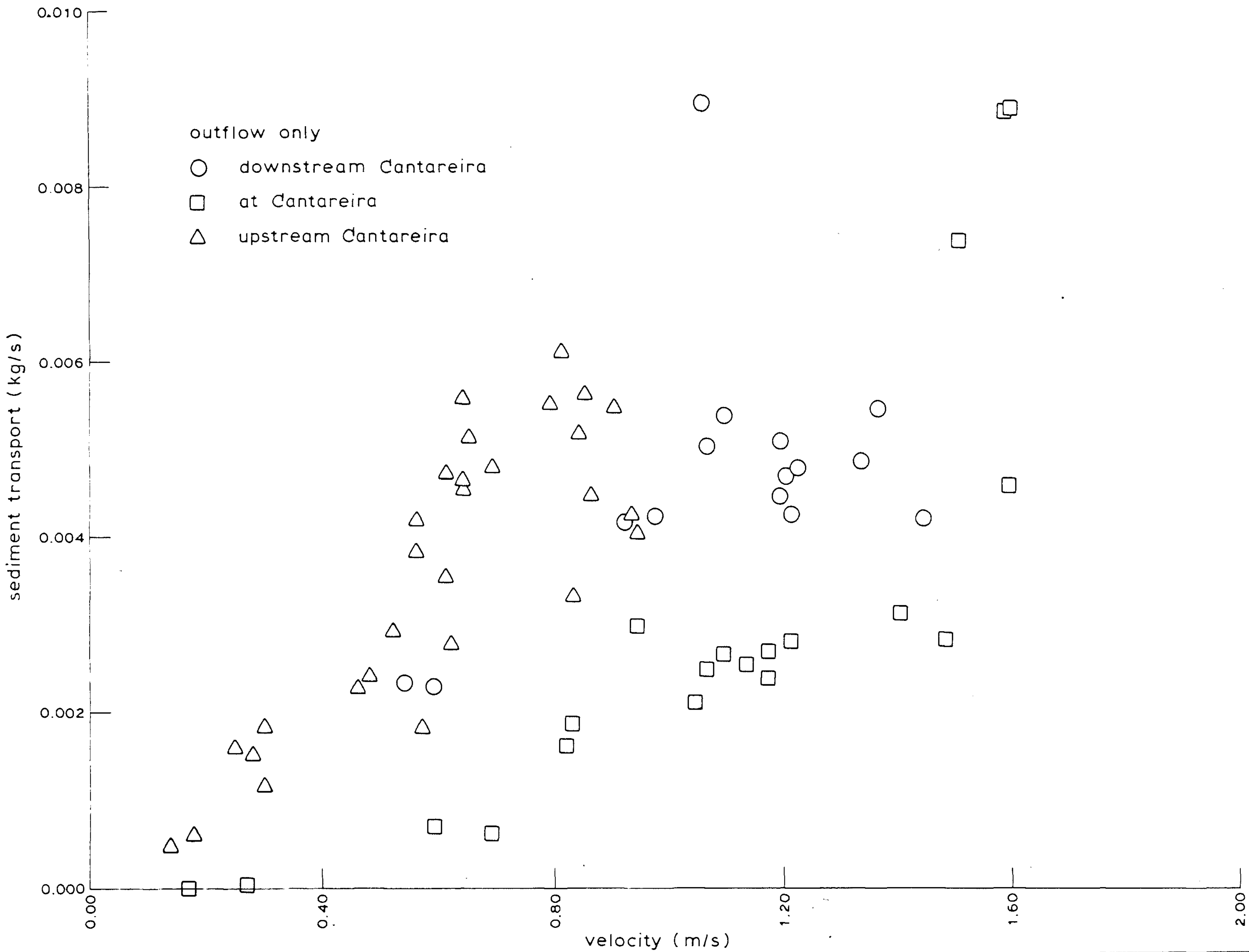


FIGURE 10 *Measured transport at sea*





0.010
0.008
0.006
0.004
0.002
0.000
sediment transport (kg/s)
outflow only
downstream Cantareira
at Cantareira
upstream Cantareira
0.00
0.40
0.80
1.20
1.60
2.00
velocity (m/s)

fig. 8

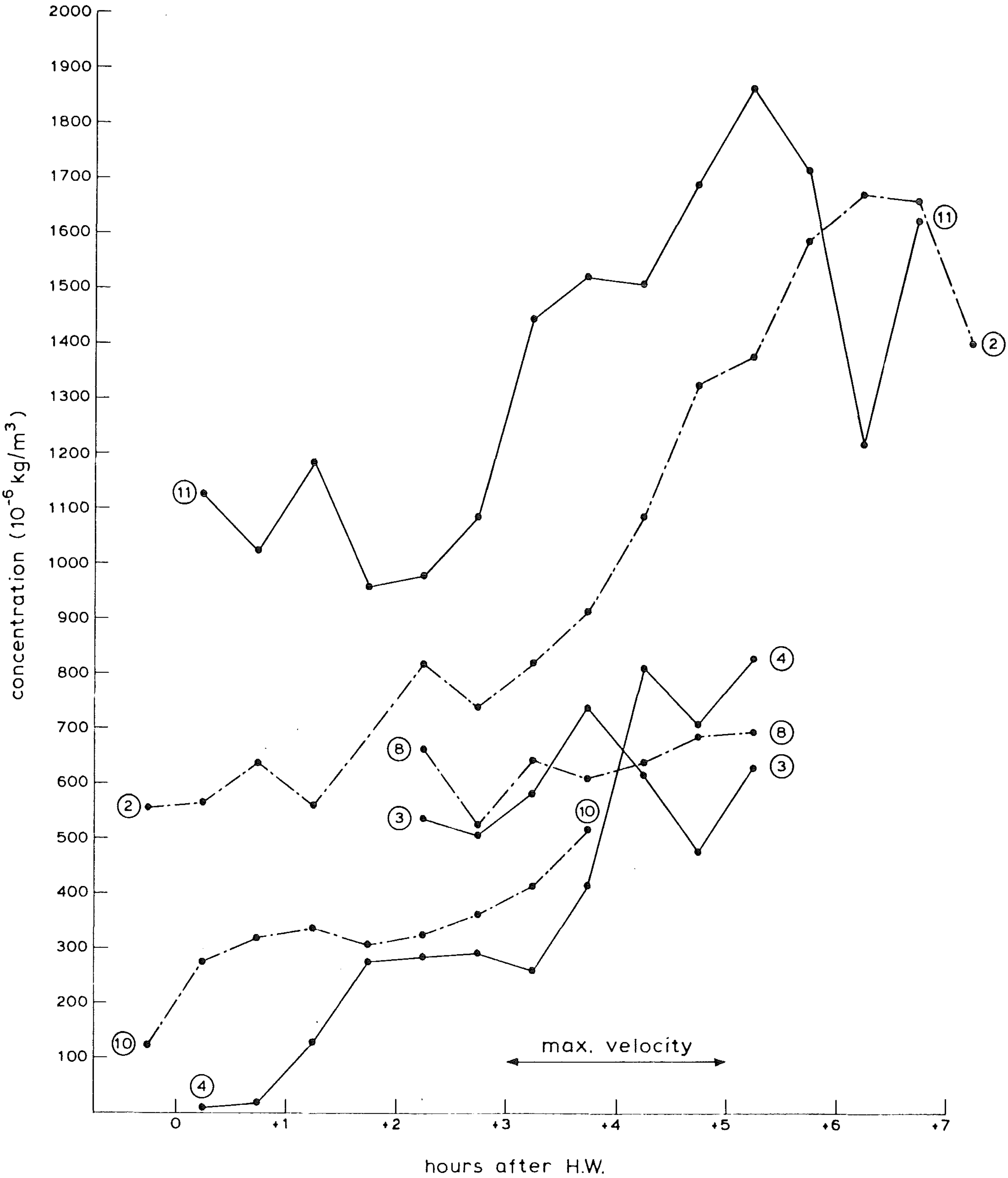
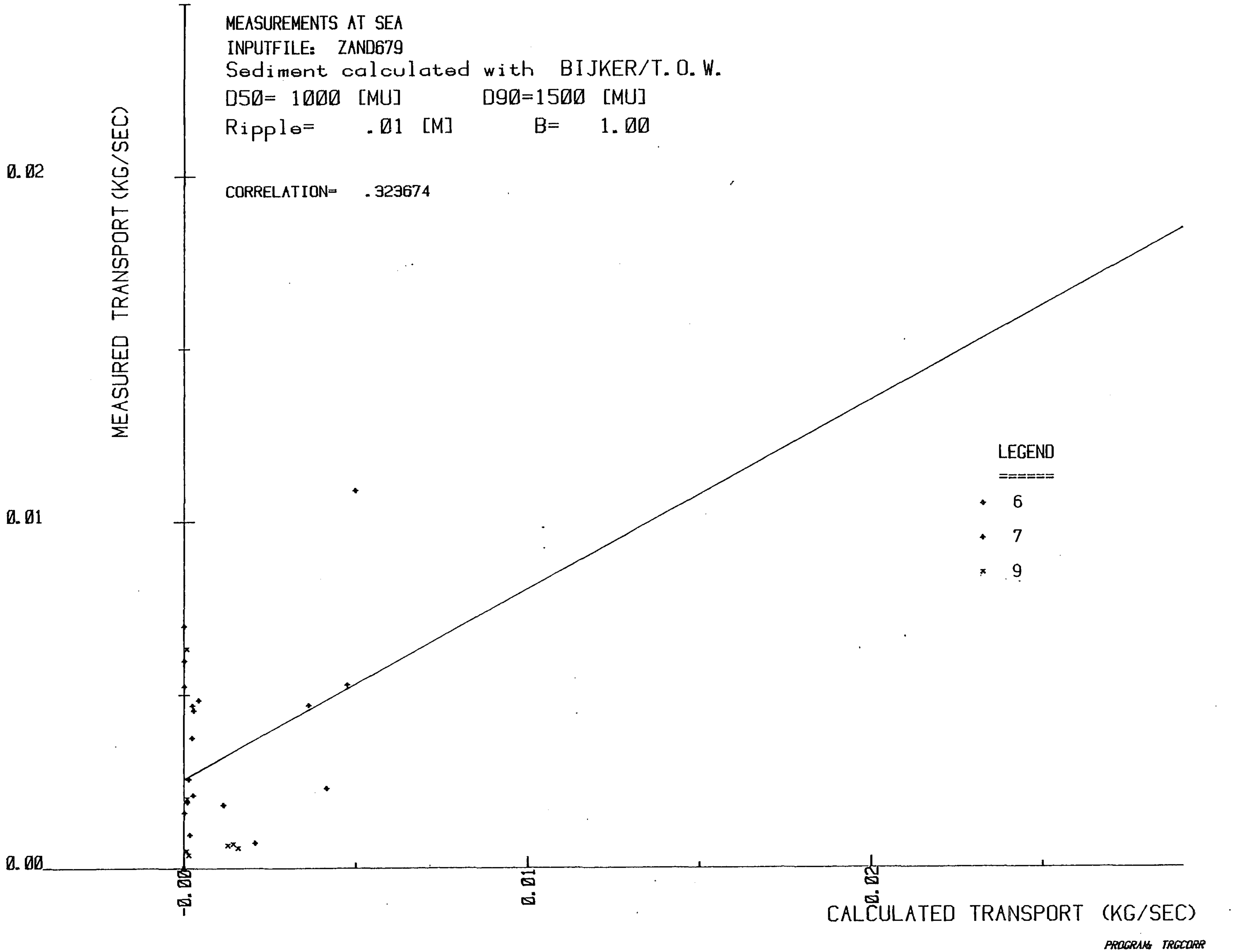

2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
concentration (10^{-6} kg/m^3)
0
+1
+2
+3
+4
+5
+6
+7
hours after H.W.
max. velocity
11
2
4
8
3
10

fig 9

FIGURE 41 Measured transport at sea



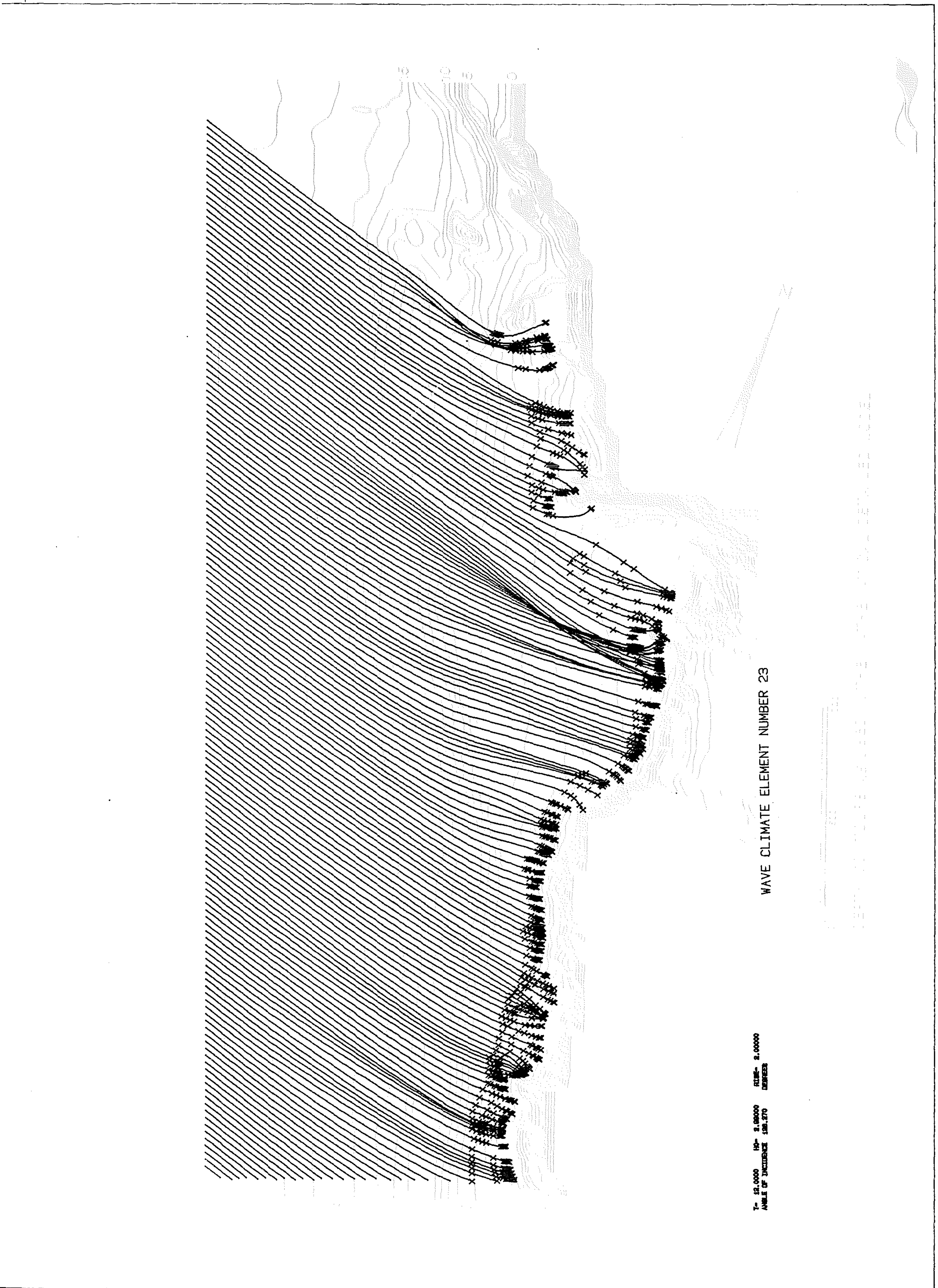


fig 12 example of a wave penetration calculation

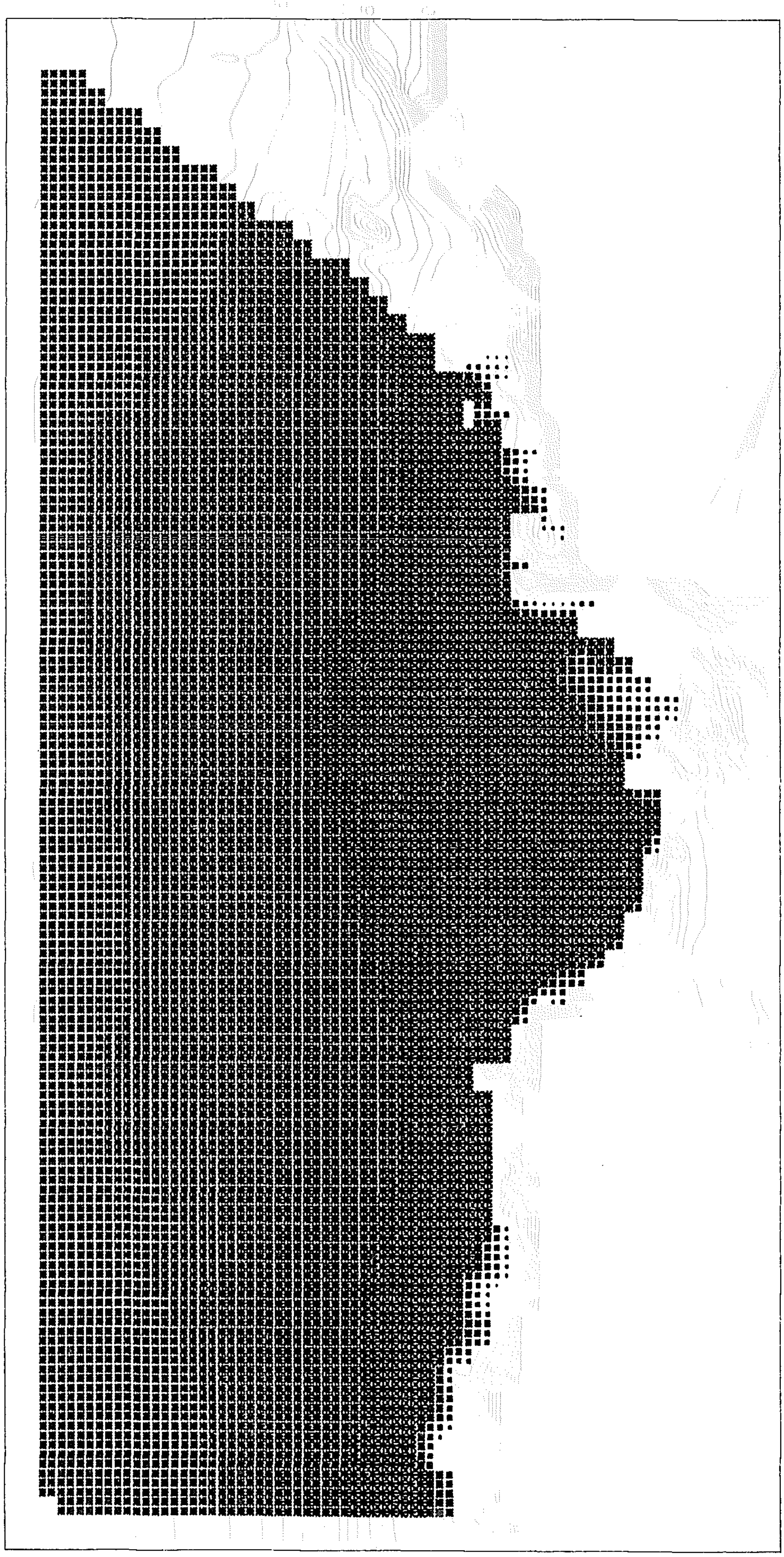


Fig 13. Wave-heigt diagram of wave climate element 23

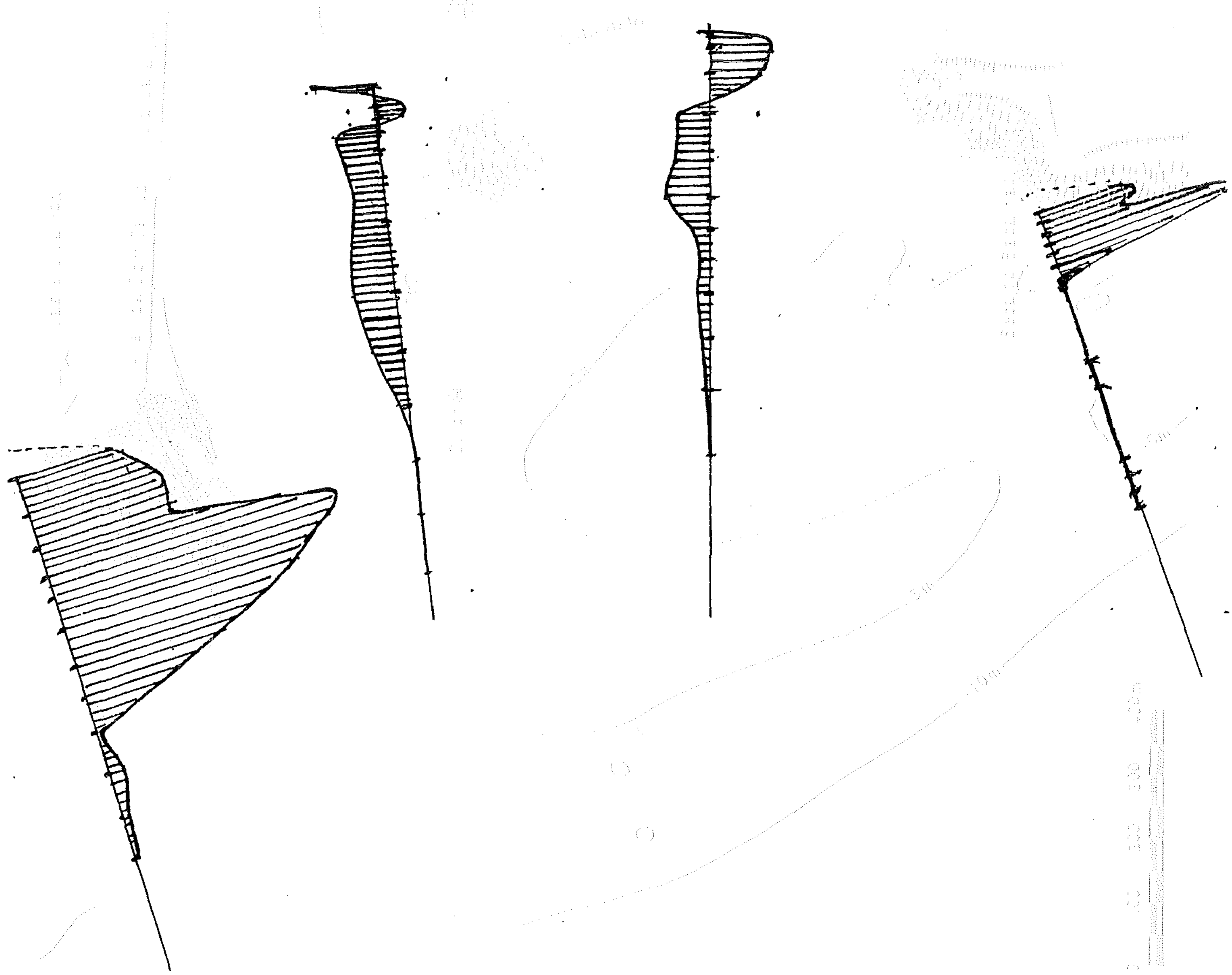


Fig. 14. Sand transport capacity along the coast

fig. 15. Aereal view of the river mouth

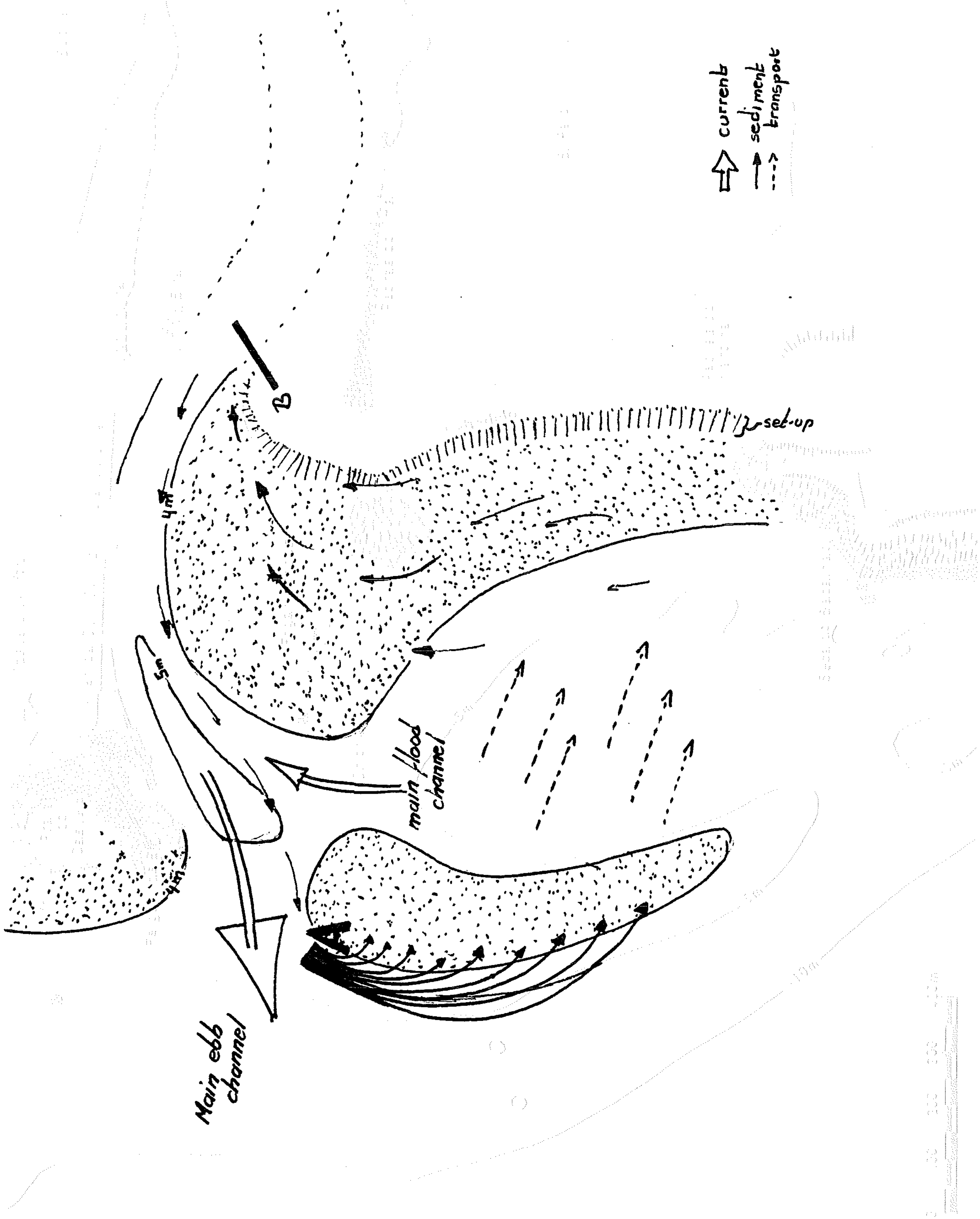


fig. 16. Bathymetry of the river mouth

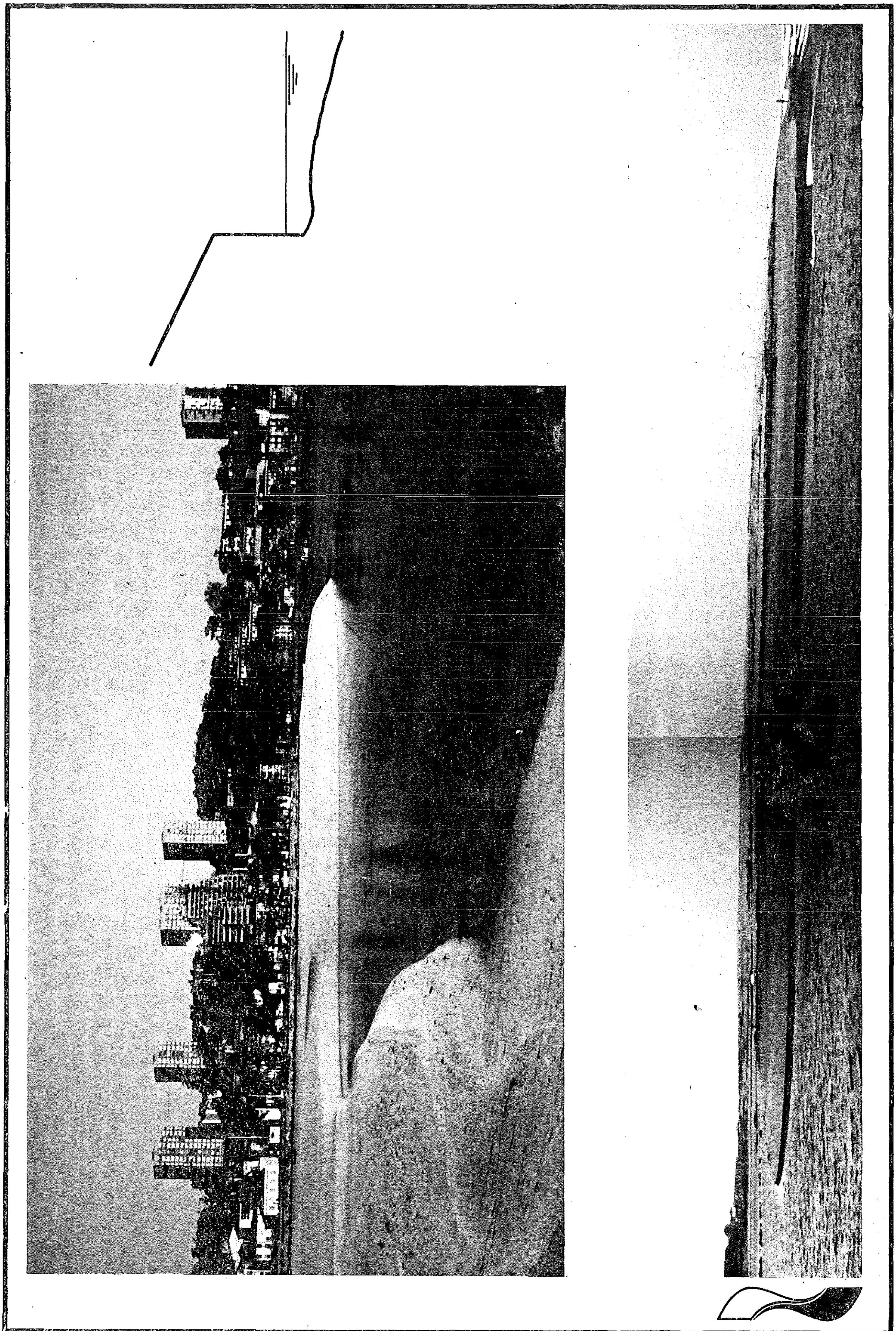


FIGURE 17: *SLOPE OF THE CABEDELO DURING LOW WATER.*

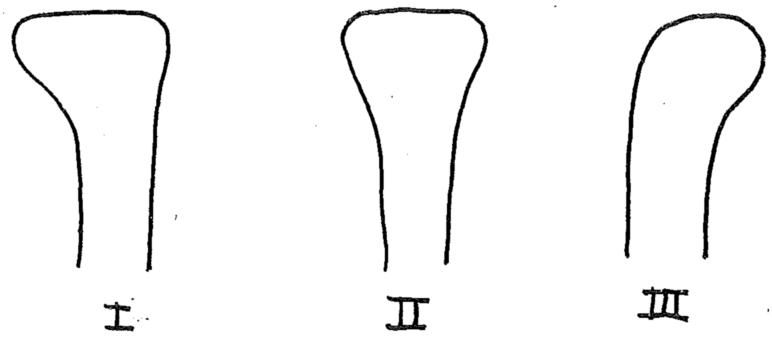


fig. 18 shapes of the dabedelo