Hydro-morphological study Douro Estuary

Part 4
Results of field measurements

january 1983 / P613

PORT AND WATERWAY ENGINEERS

hydronamic bv
sliedrecht holland

TABLE OF CONTENTS

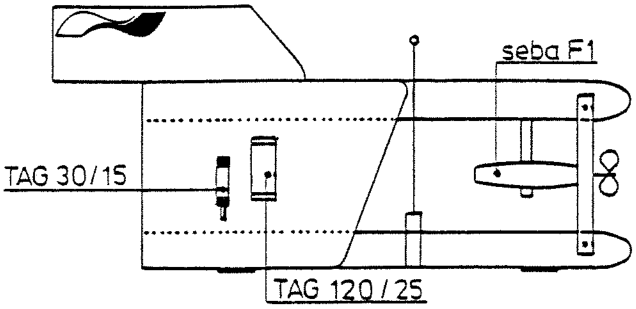
c set-up of the mathematical model

As described in our proposal of January 1982, a report for each phase will be presented to APDL.

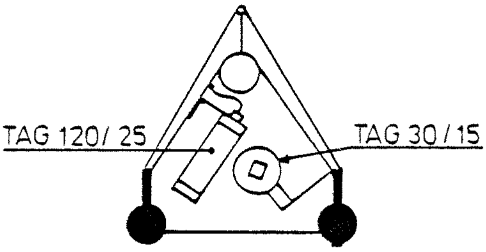
This report gives the results of the field measurements, which are a part of phase b of the study.

The shape of the frame is such that it keeps in a stable position during the whole underwater measuring period. This is caused by the "rudder" and the specially designed bearing system. The frame was designed in co-operation with the manufacturer (van Essen Instruments, Delft, Netherlands).

For operation all over the world, the frame can be dismantled into smaller pieces to allow easy airfreight.



Side view



Back view

Calibration of the turbidity-meter

The turbidity meter gives a value between 0% and 100% turbidity for a certain range. This percentage of turbidity has to be correlated to a concentration. Because this relation depends very much on the type of sediment (grain-size, colour, chemical properties, shape) there is no fixed relation between percentage of turbidity and concentration. This relation has to be found using the samples, which are to be investigated later in a laboratory.

The best way to work is to determine the calibration curve before starting the measurements. Unfortunately, this is usually impossible for measuring campaigns abroad. In that case the calibration curve has to be made after completion of the measurements. This can be done by taking samples from the water-sediment mixture during the

measuring campaign, reading the MEX-value of this sample, and taking a small quantity of the total sample to a well-equipped laboratory for later investigation.
Because the quantity of mixture is generally small (say 0.2 liter) the sediment concentration of the sample has to be determined very accurately, e.g. 0.1 gram accuracy. Because of the required accuracy of these laboratory tests, they should be executed in a well-equipped laboratory with an experienced staff.

The samples to be taken should be equally distributed over the various existing concentrations in the field. These concentrations can be made by taking some mud from the upper layer of the bottom sediment and "dissolving" various quantities of it in a bucket.
From these various concentrations the MEX-value is read and a small quantity is bottled for laboratory investigation later.

Thus, for calibration of the instrument it is unnecessary to use samples with concentrations actually taken from the sea. The concentrations can be made artificially. However, there should be enough samples to draw a complete calibration curve. For the absorption-probes as used by Hydronamic this curve should be almost linear.

Calibration of the current meter

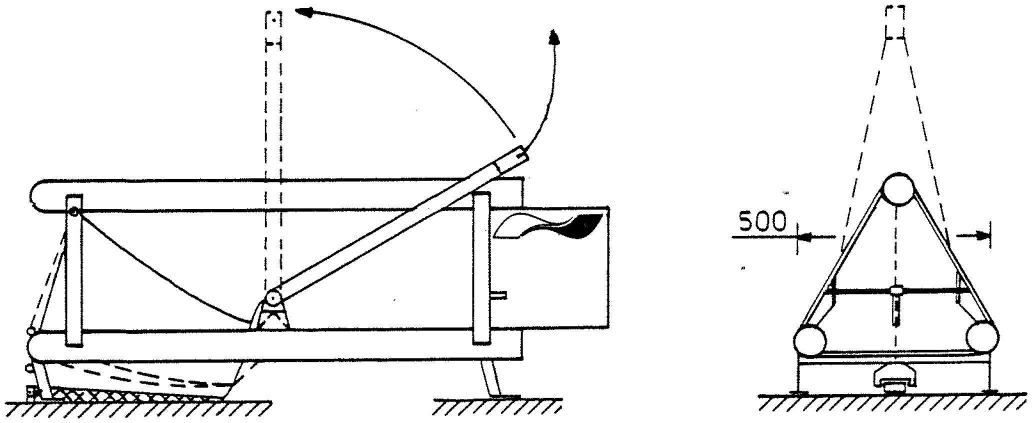
The current meter gives a number of pulses during each revolution of the propeller. The manufacturer of the current meter provides a formula to find the relation between the number of pulses and velocity.

But, because in the Hydronamic Sediment Transport Meter the current meter has been built into a frame, some deviations from the standard calibration curve might occur.

Therefore we have made some calibration tests for this particular velocity meter in our in-house research laboratory.

Measurement of bedload (see fig. 4)

Generally speaking bedload transport is difficult to measure.
One measuring device that is suitable for this is the Bedload Transport Meter Arnhem (BTMA).
An improved version of this instument as used by Hydronamic consists of a sampling body suspended from a triangular frame. The sampling body is a small steel window on which a net with a fine mesh-size has been mounted. The meter is directed towards the current with a rudder or with a drag. The drag is used for measurements in wave conditions in order to filter out the velocities of the orbital movement of the waves. (See sketch below).



For measuring, the frame-mounted sample is slowly pressed on the riverbed or seabed by a leaf spring.

With frequently repeated measurements, the order of magnitude of bedload transport can be established.

Other measurements

The salinity, conductivity and temperature have been measured with the Hidrotop salinometer, type YS133. The probe was mounted on the frame of the suspended load meter. The electronic unit was placed on board. Readings were made simultaneously with those of the velocity-meter and concentration meter.

Bottom samples have been taken with a 0.8 litre Van Veen grab.

Sieve analyses have been made in our laboratory in Holland.

For the simultaneous water-level measurement at three points, the exact level of several points had to be determined.

The levelling work was done by Hidrotop, applying a Wild levelling instrument.

Positioning of the ship was done by sextant.

3. SEDIMENT TRANSPORT MEASUREMENTS

General

Sediment transport measurements have been made at 11 locations. For the exact locations see table 1 and fig. 5.

The measurements have been elaborated by computer and are presented in the annex to this report. On each page the result of one measured profile is given. Profiles are plotted for the velocity, the concentration, the salinity and the temperature. At the bottom information is given on the waves, on the water depth and the tide, on averaged values and on the sediment transport. When instead of a value, the sign is given, it means that that value was not measured for that profile.

In figures 6-16 the water-level, the velocity, the salinity and the bedload are given as function of the time of the day. The values of the velocity, the salinity and the concentration are plotted for the top and for the bottom of the river. In the next sections a short description is given of the findings at the 11 measurements stations. The sieve analysis of the bed-samples is given in fig. 17 and fig. 18.

Station 1. River near Ponte Luiz I (fig. 6/9-11-82)

The bottom consists of hard material, probably rock covered with a thin layer of sand. Grab samples show coarse sand and fine gravel, mixed with muddy material. Bedload transport was only found during bottom velocities of more than 0.15 m/s and only after this current has existed for some time.

The water-level at the top of the figure is not the local water-level, but the water-level at Cantareira, which makes some difference. High water at the measuring station is a few minutes later than at Cantareira.

Between 10.30 and 11.00 a sudden increase of the salinity was observed. This was the front of the salt wedge, which extends approx. to this point during relatively low river runoff (460 m3/s).
The salt water from the sea is much clearer than the river water. This can be seen in the value of the concentration, which is lower between 10.30 and 11.00 hours.

The velocity of bottom currents going out to the sea have only a low value and a very short duration. It was observed that during the period this seaward bottom current of some organic material was caught by the bedload meter but not during river currents going upstream (and also no sand).

Station 2. Just upstream of Cantareira (fig. 7/10-11-82)

At this location the influence of waves is minimal. Measurements were not taken in the deepest part, but somewhat to the north.
At this point the upper layer always has an outward bound direction, while the direction of the lower layer varies with the tide. The salinity of the lower layer is identical to seawater during incoming tide, but is less than seawater for outgoing tide. One can deduce from this that the estuary is partially mixed.

The total quantity of bedload was 63 cm3 during one tide. Assuming a meter efficiency of 50% and a river width of 150 m, this results in a transport of 150.000 m3/year. This is a small quantity for a river the size of Douro.

The material caught was of the same composition as the material which was obtained with the grab, except that the gravel particles with a size of more than 0.5 cm did not occur in the bedload sample.

Fine material (less than 0.1 cm) is hardly transported by the river.

The half hour wave in the bottom recordings of the velocity-meter is a remarkable feature. This is possibly the effect of an internal wave.

A quantity of dirt, mainly organic material is pushed in front of the freshwater "wedge". The specific weight of the organic material has probably a value between 1000 and 1033, and consequently it floats between the two layers.
The river discharge was 637 m3/sec.

Station 3. Meia Laranja (fig. 8/11-11-1982)

At this station the waves have a strong influence. Waves are getting shorter due to high outflow velocity. Big differences in velocity were observed between the upper freshwater layer and the lower seawater layer.
This causes quite big internal waves at the boundary between salt water and freshwater. Current refraction was also observed, as well as reflection against the sea-wall.

The behaviour of the survey vessel was therefore quite unpredictable and it was quite difficult to handle the equipment.

Because of the confused state of the sea, combined with the extremely fast current, it was impossible to do bedload measurements in the afternoon. Measurements performed during the morning indicated that bedload transport occurs only during high bottom velocities.

The average runoff was 640 m3/sec.

Station 4. Cantareira (fig. 9/12-11-1982)

The bottom at this station consists of hard rock. It was impossible to take grab samples. In ten trials to get a sample with the grab, our only "catch" was a big shell.
Using a log with soft soap on it, we found medium coarse sand, probably sand which was transported over the bottom at that moment, or sand in small crevices between the rocks.

The salt wedge is arrested for a long period exactly at this point. At the bottom, seawater was flowing into the river with relatively high velocity. At the surface the velocity was zero.
Floating dirt remained in position (see fig. 19). Also very peculiar short white-capped breaking waves were observed in this zone. This situation remained for 1.5-2 hours.

During maximum inflow over the bottom, the bedload meter only caught some organic material. The quantity of sand, transported into the estuary in the middle of the flow channel seems to be nearly zero.

At the inner side of the Cabedelo a steep bank was (1.5 m high) observed during low water in the sand. During flood tide, waves were observed entering past the head of the Cabedelo, faltteninq the bank and transporting sediment into the estuary.

The river discharge was 597 m3/sec.

Station 5. River near Afurada de Baixo (fig. 10/15-11-1982)

At this station the bottom material looked very muddy, although the sieve-analysis shows a D50 of 2.4 mm. This is probably caused by the high silt content of the bottom material. A boring made by us approx. 15 years ago showed at this location layers of a mixture of sand and silt, separated by thin silt layers.

This is the only location where we measured "normal" estuarine concentration profiles, especially during the passage of the salt-water front from the sea. (see e.g. the profile of 12.15 hours). After the front has passed, the average concentration becomes gradually lower.

The river discharge at station 5 was 625 m3/sec.

Station 6. Sea off Cabedelo (fig. 11/16-11-1982)

At station 6 only 4 measurements were made. It was not the intention to make a complete measurement, but to test all the equipment for use in sea conditions.

The tests showed that all equipment could be used, even during relatively high waves (3 m, 12 sec). The main problem was to keep the boat in the appropriate position.

The measured concentrations were quite high, because of the stirring of the waves. In the afternoon, the state of the sea was a combination of sea and swell, which resulted in a rather rough surface.

Station 7. Sea off Cabedelo (fig. 12/17-11-1982)

At station 7, a whole day of measurements at sea were completed. The swell had a height of 1-2 m with periods between 8-10 sec. Because there were hardly any wind waves there were no problems, and the ship could follow the waves easily. It was observed that during the passage of wave-crests, the concentration near the bottom suddenly increased.
This was observed when the waves were very long (12 sec.). With waves of the same height, but with a shorter period this was not observed.

The increase in concentration is caused by the sediment transport under the crest of solitary waves, which are transformed long waves in shallow water.

The bottom consists mainly of sand, somewhat finer than the sand of the Cabedelo, and considerably less sorted (D90/D10 is 13.7). The bedload samples from the morning mainly consisted of organic material, while in the afternoon large quantities of sand were caught.
At 15.10 (approx. half an hour before high water) the boundary between fresh water and seawater passed this point. The velocity of the front was approx. 17 cm/sec. It was quite simple to distinguish the front because of the floating dirt.

The water in the front consisted of only a very thin layer of fresh water. After passage of the front no freshwater could be demonstrated with the salinometer.

Station 8. Meia Laranja (see fig. 13/19-11-1982)

It would have been irresponsible because of very high swell (more than 3 m) to measure the bar, so it was decided to measure once more at Meia Laranja, but now during rising tide (measurement 3 was during falling tide). Until some time after low water, the whole vertical remains freshwater.

The penetration of the salt wedge occurs quite suddenly.

The whole profile, to a few meters under the surface becomes salt water in a period shorter than 30 minutes (the interval of the measurements). Because of the reasonably high runoff (648 m3/s), the current at the surface has always a seaward direction. In the salt wedge there is a current into the estuary. The maximum velocity of the penetrating current lies a few meters below the surface.

Grab samples showed some coarse sand at the south side of the ship. (D50 = 2.4 mm). At the north side of the ship it was impossible to take a sample because of the rock bottom.

Station 19. Sea west of Felgueiras (see fig. 14/22-11-1982)

The state of the sea was quite rough, although the wave height was not more than 1.5 m. This was caused by the fact that there were many shoaling wind waves which were very steep.

At the beginning of the morning the salinity near the surface varied very much, probably caused by fresh water streaming into the sea, but not yet fully mixed. Also at this location, the sandtransport near the bottom occurred during the passage of long waves.

Station 10. Cantareira (see fig. 15/23-11-1982)

A second measurement was made at Cantareira, now with simultaneous water-level measurements at two points on the shore. The water-level measurements will be discussed in the next chapters. The wave climate at sea was extremely rough, long swell from NW and wind waves from S-SW. Wave-heights were somewhat more than 3 m. In the evening they reached, approx. 4 m. There were heavy breakers at the bar and the few fishermen who tried to enter the river had serious problems. No fishermen left the river in the afternoon.

Much spray was whipped from the waves by the strong wind.

It was notified that there were no banks in the sand of the Cabedelo. This was probably caused by a smaller river discharge (523 m3/s), a heavy wave attack and the fact that there was a neap-tide condition.

On this date als the border between salt water and fresh water was arrested at Cantareira for a couple of hours. The separation zone was not wider than 25 m, and could be clearly recognised by floating dirt and short white capped waves.

Station 11. Upstream from Cantareira (see fig 16/25-11-1982)

The last measurement was made just upstream from Cantareira, in the middle of the river. The data are comparable with station 2. Only a somewhat different part of the tidal curve was measured. No special observations were made at this station.

4. OTHER MEASUREMENTS

Salinity profiles

On November 18th, in the afternoon, a number of salinity profiles were measured in order to get an impression of the movement of the salt wedge in the mouth of the river.
The locations can be found in fig. 20. In fig. 21, 7 velocity profiles and 7 salinity profiles are drawn.

Even after a longer period, no saltwater was measured at stations F and G. This is probably caused by the fact that the freshwater river discharge is quite high, and consequently the discharge by the layer of saltwater in upriver direction is low. When the salt wedge reaches the deep section under the Ponto da Arrabida, the saltwater has to fill the complete volume of this section before penetration into the river can continue.

Topography of the head of the Cabedelo

Because no detailed information was available about the shape of the head of the Cabedelo, it was measured. The results of this measurement are used on the maps in this and subsequent reports the results of this measurement are used.
Also two profiles of the slope of the Cabedelo have been measured. These profiles are presented in fig. 22.

Water-level measurements

On November 23rd a combined measurement of waterlevels and velocity in the area of Cantareira was made. The velocity was measured between Cantareira and the head of the Cabedelo.

Water-levels have been measured at two locations, one upstream from Cantareira, (station a) and at the Praia dos Pastores (station b).

Water-levels from the maregraphs at Cantareira and Leixoes have also been included (see fig. 23; for location of station a and

b see fig. 19). For the water-levels at stations a and b, the exact height level of the quay-wall had to be determined. This was done with normal topographic equipment (levelling instruments and gauges). The level from the maregraph at Cantareira was used as a basis. (see figure 24).

In fig. 23 the water-levels are plotted as well as the velocity. It can be seen that the water-level at the Praia dos Pastores is much lower than those at Cantareira and at Station a.

There is even a remarkable phase difference between the moment of high water and the moment of low water (high-water difference 30 minutes, low-water difference approx. 90 minutes).

The velocity in a narrow gap can be calculated with the formula V = A*sqrt (h2-h1) in which the coefficient A represents some constants and the contraction losses. The coefficient A has been calculated for the differences between station a and Cantareira and for the differences between station a and station b.

The results are printed in table 3.

From the measurements and calculations, one may conclude that the water-level at Cantareira is strongly influenced by the river and cannot be used as a "sea-boundary" in the mathematical model. The

curve for Leixoes is more fitted for this purpose, although it is not completely correct.
The fact that low water at station b was approx. 35 cm lower than at Leixoes cannot be explained. Thorough checks of the calculations and the levelling work indicated that no systematic mistakes have been made.

Although it is not directly related to this study, it is advisable to instal a temporary maregraph at the Felgueiras lighthouse in order to investigate this difference and be able to make better tidal predictions for the Barra do Douro.

5. CALIBRATION OF SEDIMENT TRANSPORT METER

General

Knowledge about the bedload and suspended load is inevitably needed for description and prediction of siltation and erosion.

There are many sediment transport formulae, even for situations where both waves and currents occur.

Sometimes these were determined by field tests, but the most work is done in the laboratory. The coefficients involved in the formulae vary considerably for different locations.

Hydronamic has developed a quick method to determine the coefficients, so that correct and valid formulae are used in the numerical models regarding the prediction of the morphology.

The sediment transport formulae can be divided into two groups:

- formulae for transport caused by currents only
- formulae for transport caused by both currents and waves

Disregarding the wave influence, nearly all formulae for sediment transport can be simplified as

$$S = a\,V^{b}$$

where: S sediment transport [kg/s/m]

V depth averaged flow velocity [m/s]

a,b coefficients

The coefficients a and b depend on many factors, such as water depth, bottom roughness, grain-size etc.

It has been proved in practice that the coefficients largely depend on unknown local parameters which cannot be calculated.
The results of the various theoretical formulae can vary as much as a factor 10 in actual practice. It is for this reason that Hydronamic has developed a method to find a calibrated sediment transport formula.

Either the value of a and b are defined directly from measurements, or the coefficients from theoretical formulae are defined in this way.
With this method it is also possible to know the reliability of the formulae used, by calculating the correlation between measurements and formulae.

There is no direct method for measuring sediment transport. Measurements must be made of the concentration and velocity at various levels in the water. The velocity is measured in m/sec the concentration in kg/cum. The product thus is kg/s/sqm. If this value is integrated over the water depth the transport in kg/s per m width is known. The total suspended sediment transport is found by measuring simultaneously the velocity and concentration at the same level in the water. Various levels are used, spaced at regular intervals (see the computer output in the annex). The transport over the bottom (bedload) cannot be measured with the concentration meter. For measuring bedload a separate meter is used. The same method can be applied to find the depth-averaged current velocity.

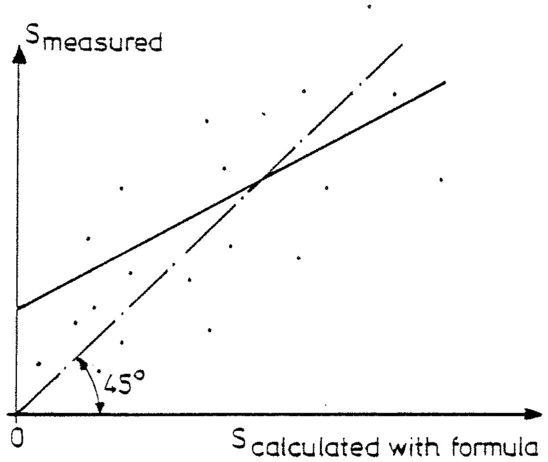
The depth-averaged current velocity V and a total sediment transport S can be found for every location and later on correlated.
By repeating this whole procedure several times during one tidal cycle, a whole set of relations between S and V can be obtained for that location.

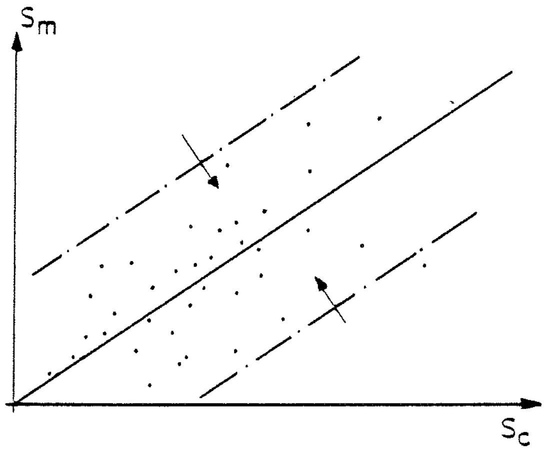
The water depth can be measured easily with an echo-sounder or even more simply with a rope and weight.
If the wave action becomes predominant, the wave heights and periods have to be measured.

Calibration method

A large number of points can be found if the method, as described in the previous section, is repeated at various locations. The sediment transport is then known at each point for different current velocities, water depths, wave heights and wave periods.
With sufficient information, statistical correlations can be carried out.
The sediment transport is calculated using a certain sediment transport formula. The other data such as current velocity , water depth and possibly wave height and period are measured. These calculations are applied to all the measurements. The other parameters used in the formula, such as grainsizes, bottom roughness and other formula-constants, also have to be fixed. If certain values are assumed for this, the sediment transport calculated with the formula can be compared, for the whole set of records, with the transport using measured data (see sketch).

The statistical regression line indicating the agreement between measured and calculated transport must pass at an angle of 45. through the origin. This can be obtained by varying the coefficients used in the sediment transport formula. This is a trial and error process.





As soon as the line is at 45. through the origin, the result is satisfactory. After that the correlation between measured and calculated transport must be improved, that is to say that the deviation between the line and the different points must be as small as possible.

The formulae used by Hydronamic in the above procedure are:

- combined theoretical/empirical formulae:

  * Bijker
  * Ackers/White
  * Swart/Lemhoff
  * Engelund/Hansen
  * Meyer-Peter/Muller

* Yalin

- completely empirical formulae:

  * polynomials : $S = a.V + b.V^2 + c.V^3 + d.V^4 + ...$

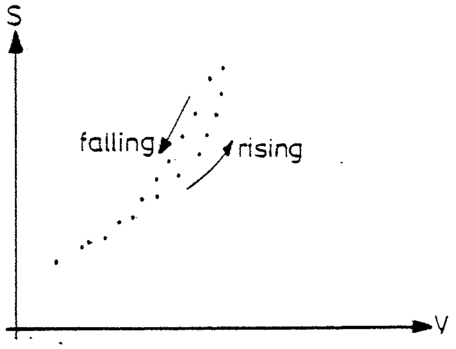
  * power function : $S = a.V^b$

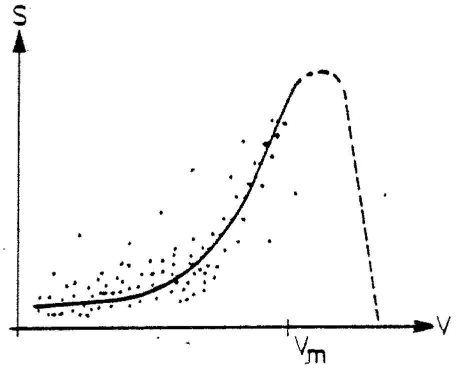
In the latter two formulae water depth is of no account.
It must be stressed that the various formulae often give completely different correlation. Which formulae are most suitable can vary from situation to situation.

The above measurements should preferably be done where there is sufficient spread over a large interval of current velocities, and, if possible, water depths. The calibrated formulae are more reliable if enough points are available and sufficiently spread in the whole field of current velocities that require to be calculated later on. If, for example, only one or two points are available with relatively large current, the chances are high that these points reflect occasional deviations from the regular sediment transports. Such points can distort the whole set of measuring data.

In tidal areas the velocities and water depths usually increase and decrease with time. This has the advantage that the measurements are spread -already by nature- over a wide field. On the other hand, in such cases, there are relatively few points available with higher current velocities.

A distinction should also be made in tidal areas between the coefficient for rising and for falling water, because sometimes a so called hysteresis loop may be seen (see sketch below, left). If it is proven that there is not such a hysteris loop, all the values can be used together to find the functions for example of a and b.





The coefficients a and b can be found by mathematical curve fitting. This means that, the best fit polynominal exponential function can be found using the least square method. It is better, however, to use one of the theoretically derived formulae, because then extrapolations are more safely allowed. As an example the above (right) figure a typical set of data from one of our measurements in Zeebrugge (Belgium) is reproduced. The best fit was a higher-order polynomial. But as can be seen in the figure, as soon as V gets a value higher than the maximum measured velocity Vm, the curve gives a totally wrong value of S.

There was one single point of very high velocity, deviating from the general tendency, and this polynomial gave a completely wrong impression for the sediment transport at high current velocities. It is thus clear that such formulae should be checked carefully for the whole area where they will later be used.

It is usually better to use formulae, which also have a physical background, in order to prevent this kind of problem.

If waves are also important, it is better to measure during periods of different wave heights.
Water depth can be chosen by going to an appropriate location, but the wave height cannot be determined beforehand. One has to wait for the right weather. Usually the weather will vary enough to get some range in wave climate, and so have some idea of the effect of waves on transport.

Waves do not effect the transport velocity, but there is usually a higher concentration of suspended material, so that more sediment is transported. Of course sediment will only be stirred up into suspension if the waves are high enough to cause sufficient orbital movement along the bottom. Transport is effected by the tidal current. If the waves are high enough to create suspended material but there is no tidal current, then there will be no clear sediment transport.

The direction of the waves does not affect the stirring ability and therefore does not have to be included in calculations for sediment transport. It is quite possible for sediment transport and wave direction to be completely opposed.

Results of the calibration

From the computer analysis followed that it is not possible to apply only one formula for the whole river, the estuary and the offshore

zone. It proved that 3 different formulae had to be applied, viz. a polynomial, the modified Engelund-Hansen formula and the Bijker-T.O.W formula. They will be discussed below.
For each measuring station, or group of stations two diagrams are presented. In the first diagram the measured transport is plotted vs. the velocity. In this diagram also one of more lines are drawn for a given specific waterdepth and wave condition. In the second diagram the measured transport is plotted vs. the calculated transport. The correlation between calculation and measurement is given, as well as the least-square fit. The perfect formula gives a correlation of 1.0, and a line at 45. through, but such a perfect formula is hardly found.

The transport in the river near Ponte Dom Luis I is only washload so transport is a linear function of the velocity (s = 0.08 v). The correlation is 99%, which is extremely high (see fig. 25 and 26).

For the river near Afurada de Baixo the best formula is the modified Engelund Hansen formula. The parameters are D50 = 2000 mu, D90 = 4000 mu and R = 0.004 m, which are directly related to the bed-propertied of the river. The correlation (82%) is good.

A plot of all the data, measured near Cantareira (see fig. 29) shows a lot of variation. It is not possible to draw a simple line through the cloud of dots with a reasonable correlation. But one can distinguish clearly groups of points from the various locations. Therefore three separate sets of coefficients are determined, one for the sites upstream Cantareira, one for Cantareira and one for Meia Laranja.

Upstream Cantareira the analysis with the Engelund-Hansen formula gives D 50= 5000 mu, D90 = 10000 mu and R = 0.01 m.
A correlation of 69% is reasonable.
At Canteira D50 = 10.000 mu, D90 = 20000 mu and R= 0.002 m.
The correlation is 88%, which is rather good.
At Meia Laranja D50 = 10000 mu, D90 = 10000 mu and R = 0.001 m.
The correlation is 50%, which is not perfect.

From the above figures one may conclude that at Cantareira and at Meia Laranja the influence of very course material (gravel of 1-2 cm) plays an important role in the determination of sand transport. In fact this is caused by the fact that the bottom is not completely covered with sand, but that locations with rocks are present.

The measurements at sea show that the best formula is the Bijker-T.O.W. formula, with parameters D50 = 1000 mu, D90 = 1500 mu, R = 0.1 m and B = 5. These parameters are the parameters of the local bed. The ripple is 10 cm, which is higher than in the river. This is caused by the influence of waves.
The low correlation is caused by one extreme transport value, measured at station 6 (0.0011 kg/s). It is expected that the correlation will become lower is long term measurements are made.
Because of the costs of measurements is it not advised to do long term measurements of sediment transport at sea. In a later stage of the development of the Douro Estuary Project this might be considered.

Conclusions

Sediment transport in the Douro mouth can be calculated rather trustworthy. However, it is not possible to apply one single formula for the whole area. For the offshore area the Bijker T.O.W. formula is recommended, for the rivermouth the modified Engelund Hansen formula is recommended.

The theoretical backgrounds of these formula are not discussed in this report. For detailed theoretical information is referred to Dr. Ir. D.H. Swart, Compution of longshore transport. T.O.W. report R968, september 1976, DHL, Delft, Holland.

6. GENERAL OBSERVATIONS

In this chapter some general observations are discussed. These observations are related to the measurements, but do not give quantitative values. First some observations on various points of the estuary are discussed, followed by observations on the locations of the measurements.

During a trip along the river Douro as far as the dam at Carapatello, the most remarkable point was the excavation of big quantities of river sand for construction purposes. Due to this excavation, many deep holes are dug in the river bed, causing a change in the average equilibrium depth. The bed consists of very coarse material. Fig. 38 shows the grain-size distribution of samples taken at various locations between Porto and Crestuma.
The structure of the river bed clearly indicated that sediment transport would only occur during extreme discharges of the river.
Records of water-level measurements taken along the river showed that tidal influence can still be observed at the gauging station of Rio Mau (16 km upstream of Crestuma). After closing the dam at Crestuma, this will, of course, change.

A trip from Porto to Espinho resulted in the following remarks.
The seaward profile of the Cabedelo has a typical parabolical shape. The top is a nearly vertical bank. The sediment is very coarse. The coarsest particles are found in the fans at the end of the locations of maximum wave runup. At some locations, gravel with a diameter of 1-2 cm can be found. At the trunk of the spit, (near

the Guardia Fiscal) much gravel is found on the slope of the beach. (see fig. 39).

On the spit two sandridges with a height of approx. 7 m +ZH can be found, one at the seaward side, one at the river side. Between these ridges a shallow valley exists, ensuring drainage of the spit from rainwater.

Sand samples were taken at points 1-4. See fig. 40 for a sediment analysis.

In the valley and on the ridge at the side of the river, some vegetation (grasses) can be found. The high-water runup line is on top of the sand ridge. This line is marked very clearly by shells and empty plastic bottles.

A breakerline can be found directly south of the Felgueiras lighthouse. Here the higher waves break on the offshore bank.

On the section of the spit between the Fogamanadas and the Guardia Fiscal, the wave-crests are parallel to the shorelines.

At the head of the breakwater between 2 and 1 the wavecrests are nearly perpendicular to the coastline.

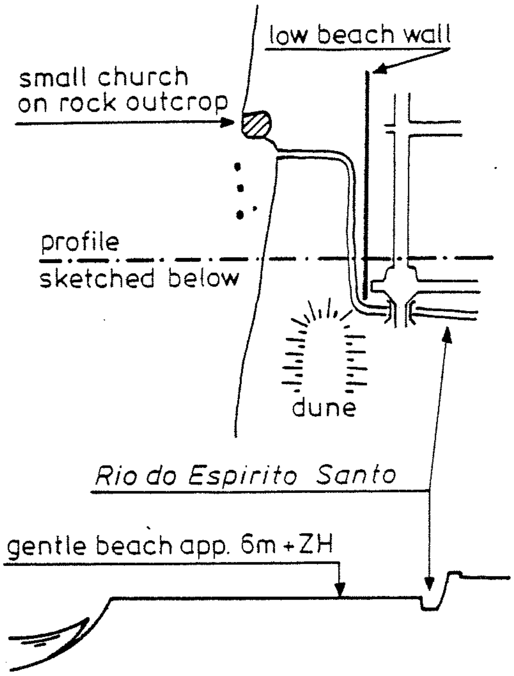
At the inner side of the head of the Cabedelo (near 1) a low, but very steep erosion-bank can be observed.

Behind the Fogamanadas, one can observe a tombolo-effect. This means that the coastline is moved more to the west at this point. Also behind the Fogamanadas one observes that the waves are lower.

South of Seca do Balcalhao the waves approach the coastline at approx. 20.. Praia de Lavadores is rather wide, protected by rocky-outcrops. This beach is less steep than the beach of the Cabedelo, but still quite steep (see fig. 41).

A little bit more to the south, at Praia de Salgueras, the beach overthere has a more southward direction. Because of refraction, the waves still reach the coast parallel to the beach line (although the original direction was from the N.W.). A sample of the beach has been analysed (see fig. 42).
Generally the coast is very rocky; a typical eroding coastline with pocket beaches.

At Praia da Madalena the beach is wider. The coastline is less rocky. The Rio de Valadares is a very small river, but shows that even small rivers can resist the closing forces of the longshore transport. This river has made a "canyon" in the beach, 20 m wide and 3 m deep
More to the south, at Praia de Francelos the beach is still relatively wide. Some very low dunes can be observed here.
Near Senhor da Pedra, the Rio do Espiroto Santo flows into the sea. One can observe here, on a small scale, the same as at the mouth of the Douro, viz that a river flows into the sea in the lee of a fixed point. The brooklet has moved its mouth a few 100 meters towards the north, in order to flow into the sea just in the lee the rock on which the curch stands,
Sediment sample 6 comes from this beach. South of the church some higher dunes may be observed.



At Granjo, the coastline.s direction is a little bit different. The waves are reaching the coastline with a relatively high angle of incidance, causing a large sediment transport. Considerable erosion can be observed in front of the seawall.

The erosion at Espinho is notorious and much work is being done to prevent further erosion. Sample no. 7 is taken from the beach just north of the first groin. Because Espinho is far out of the area of interest of APDL, and because many studies on the erosion at Espinho are available, this item will not be discussed here.

no.	date	position		location
		x	y	
1	9-11-82	463367	159540	river near Ponte Luiz
2	10-11-82	464215	155360	upstream Cantareira
3	11-11-82	464335	154848	Meia Laranja
4	12-11-82	464200	155200	Cantareira
5	15-11-82	464250	157750	River near Afurada de Baixo
6	16-11-82	463485	154700	Sea off Cabedelo
7	17-11-82	463439	154664	Sea off Cabedelo
8	19-11-82	464335	154848	Meia Laranja
9	22-11-82	463980	153755	Sea west of Felgueiras
10	23-11-82	464200	155200	Cantareira
11	25-11-82	464121	155365	upstream Cantareira

Table 1.: Measuring stations

Day	river discharge	measurements at
1	129.1	
2	191.2	
3	299.7	
4	253.0	
5	246.6	
6	122.9	
7	204.7	
8	527.3	
9	459.4	station 1
10	637.2	station 2
11	640.3	station 3
12	597.1	station 4
13	905.0	
14	752.5	
15	625.8	station 5
16	579.5	station 6
17	681.2	station 7
18	658.2	
19	648.4	station 8
20	530.1	
21	347.8	
22	473.8	station 9
23	515.0	station 10
24	611.2	
25	618.4	station 11
26	587.9	
27	581.8	
28	609.5	
29	461.6	
30	542.5	

Table 2.: Discharge of the river Douro in November 1982

time	station a	station b	Cantareira	Leixoes	velocity m/s	A_1	A_2
7.75	2.84	2.55	2.82	2.60	.00	.00	.00
8.00	2.84	2.40	2.84	2.59	.00	.00	.00
8.25	2.84	2.35	2.82	2.57	-.69	-.99	-1.01
8.50	2.84	2.45	2.80	2.55	.00	.00	.00
8.75	2.80	2.50	2.76	2.51	-.82	-.62	-.67
9.00	2.74	2.45	2.74	2.48	.00	.00	.00
9.25	2.68	2.34	2.70	2.42	-.83	-.72	-.70
9.50	2.64	2.39	2.64	2.36	.00	.00	.00
9.75	2.54	2.14	2.58	2.30	-1.09	-.61	-.58
10.00	2.44	2.00	2.54	2.24	.00	.00	.00
10.25	2.37	1.97	2.48	2.18	-1.17	-.61	-.54
10.50	2.32	1.84	2.40	2.10	.00	.00	.00
10.75	2.24	1.86	2.34	2.06	-1.04	-.67	-.59
11.00	2.16	1.80	2.28	2.00	.00	.00	.00
11.25	2.15	1.61	2.18	1.92	-1.13	-.67	-.65
11.50	2.02	1.52	2.12	1.84	.00	.00	.00
11.75	1.99	1.39	2.06	1.77	-1.21	-.68	-.64
12.00	1.94	1.29	2.00	1.72	.00	.00	.00
12.25	1.88	1.20	1.96	1.66	-.94	-.93	-.86
12.50	1.83	1.15	1.90	1.60	.00	.00	.00
12.75	1.79	1.00	1.84	1.54	.00	.00	.00
13.00	1.75	1.11	1.80	1.48	.00	.00	.00
13.25	1.75	1.03	1.76	1.44	.00	.00	.00
13.50	1.69	1.08	1.72	1.40	.00	.00	.00
13.75	1.64	1.00	1.71	1.36	.00	.00	.00
14.00	1.64	1.25	1.69	1.35	.00	.00	.00
14.25	1.64	1.33	1.68	1.34	.22	2.69	2.53
14.50	1.61	1.22	1.66	1.35	.00	.00	.00
14.75	1.69	1.50	1.68	1.36	.22	1.93	1.98
15.00	1.72	1.30	1.70	1.38	.00	.00	.00
15.25	1.72	1.40	1.72	1.42	-.35	-1.62	-1.62
15.50	1.97	1.45	1.74	1.48	.00	.00	.00
15.75	2.04	1.50	1.76	1.52	.08	6.37	9.19
16.00	2.10	1.60	1.80	1.58	.00	.00	.00
16.25	2.17	1.65	1.84	1.63	.26	1.68	2.77
16.50	2.24	1.75	1.90	1.68	.00	.00	.00
16.75	2.24	1.90	1.96	1.72	.03	8.16	19.44
17.00	2.26	1.98	2.00	1.78	.00	.00	.00
17.25	2.26	2.05	2.08	1.86	.12	1.44	3.82
17.50	2.34	1.85	2.14	1.92	.00	.00	.00
17.75	.00	1.95	2.20	1.98	.00	.00	.00
18.00	.00	2.00	2.26	2.02	.00	.00	.00
18.25	.00	2.00	2.30	2.08	.00	.00	.00
18.50	.00	2.08	2.36	2.12	.00	.00	.00
18.75	.00	2.15	2.40	2.16	.00	.00	.00
19.00	.00	2.20	2.46	2.20	.00	.00	.00
19.25	.00	2.35	2.50	2.24	.00	.00	.00
19.50	.00	2.45	2.54	2.27	.00	.00	.00
19.75	.00	2.50	2.58	2.30	.00	.00	.00
20.00	.00	2.50	2.60	2.32	.00	.00	.00
20.25	.00	2.45	2.62	2.34	.00	.00	.00
20.50	.00	2.45	2.64	2.36	.00	.00	.00
20.75	.00	2.35	2.62	2.34	.00	.00	.00
21.00	.00	2.30	2.60	2.32	.00	.00	.00

$A_1 = \sqrt{h_a - h_c}/v$ $\overline{A_1} = .88$ $\sigma_{A_1} = 2.8$

$A_2 = \sqrt{h_a - h_b}/v$ $\overline{A_2} = 1.99$ $\sigma_{A_2} = 5.4$

Table 3: waterlevels and velocities near Cantareira

FIGURE 1

FIGURE 2

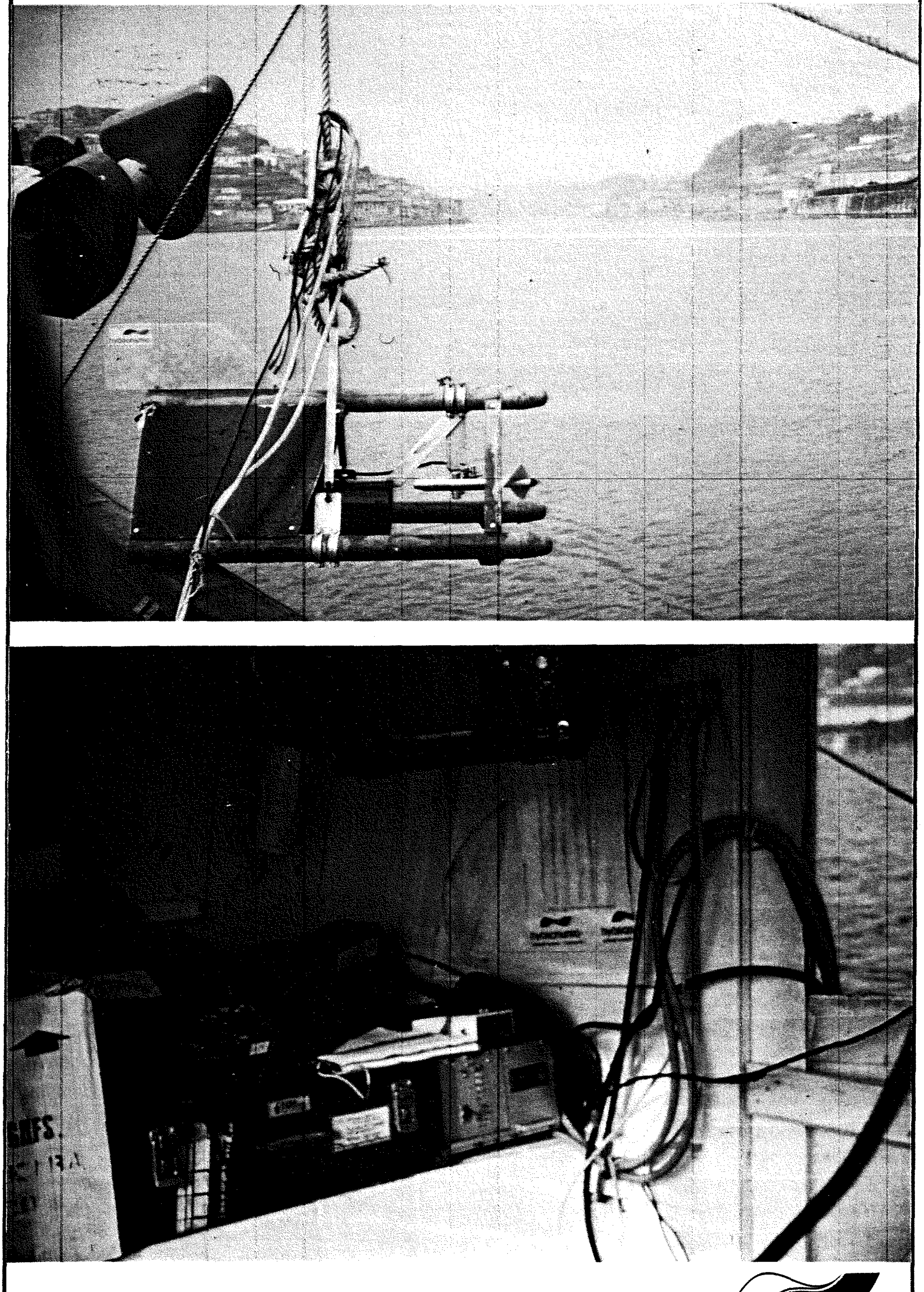


FIGURE 3

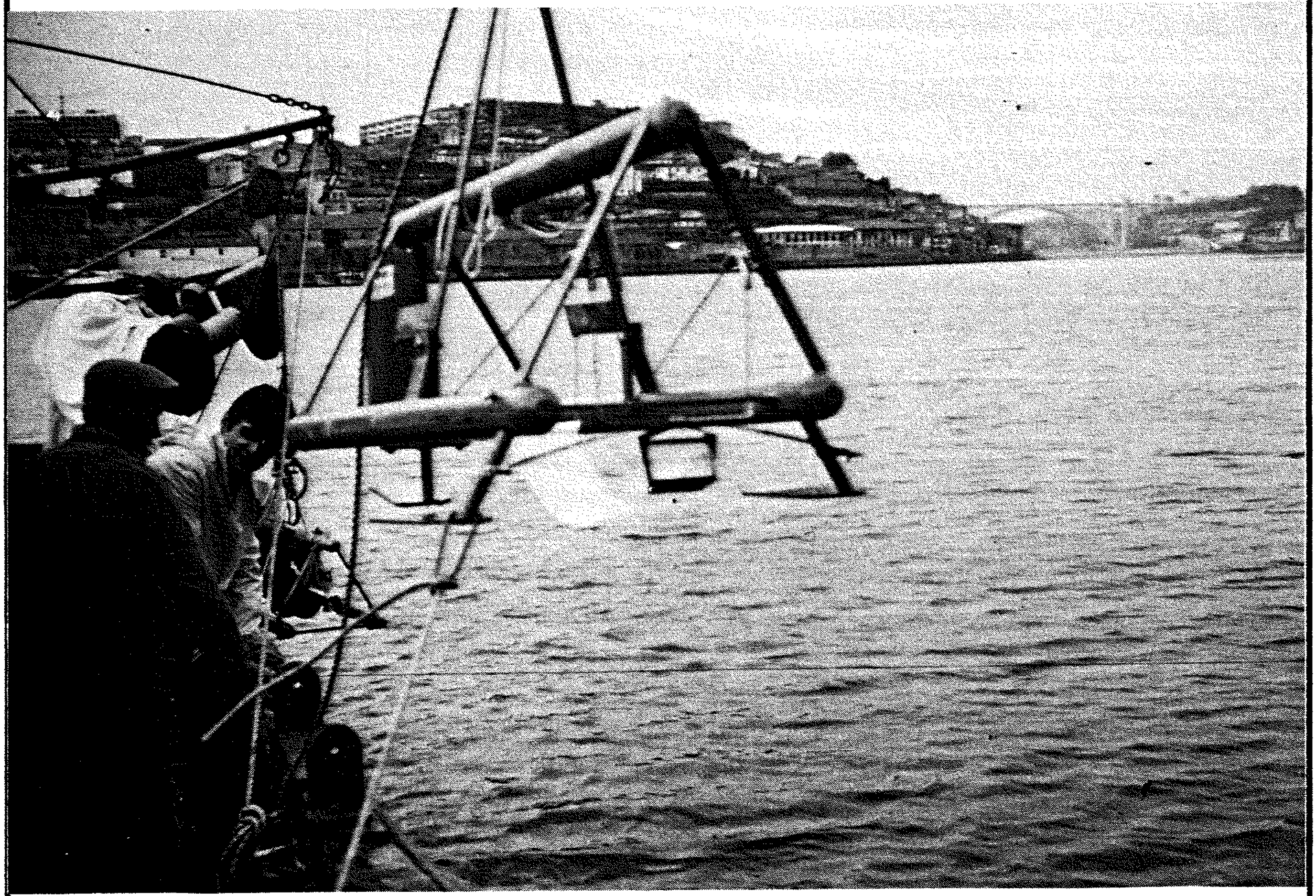


FIGURE 4

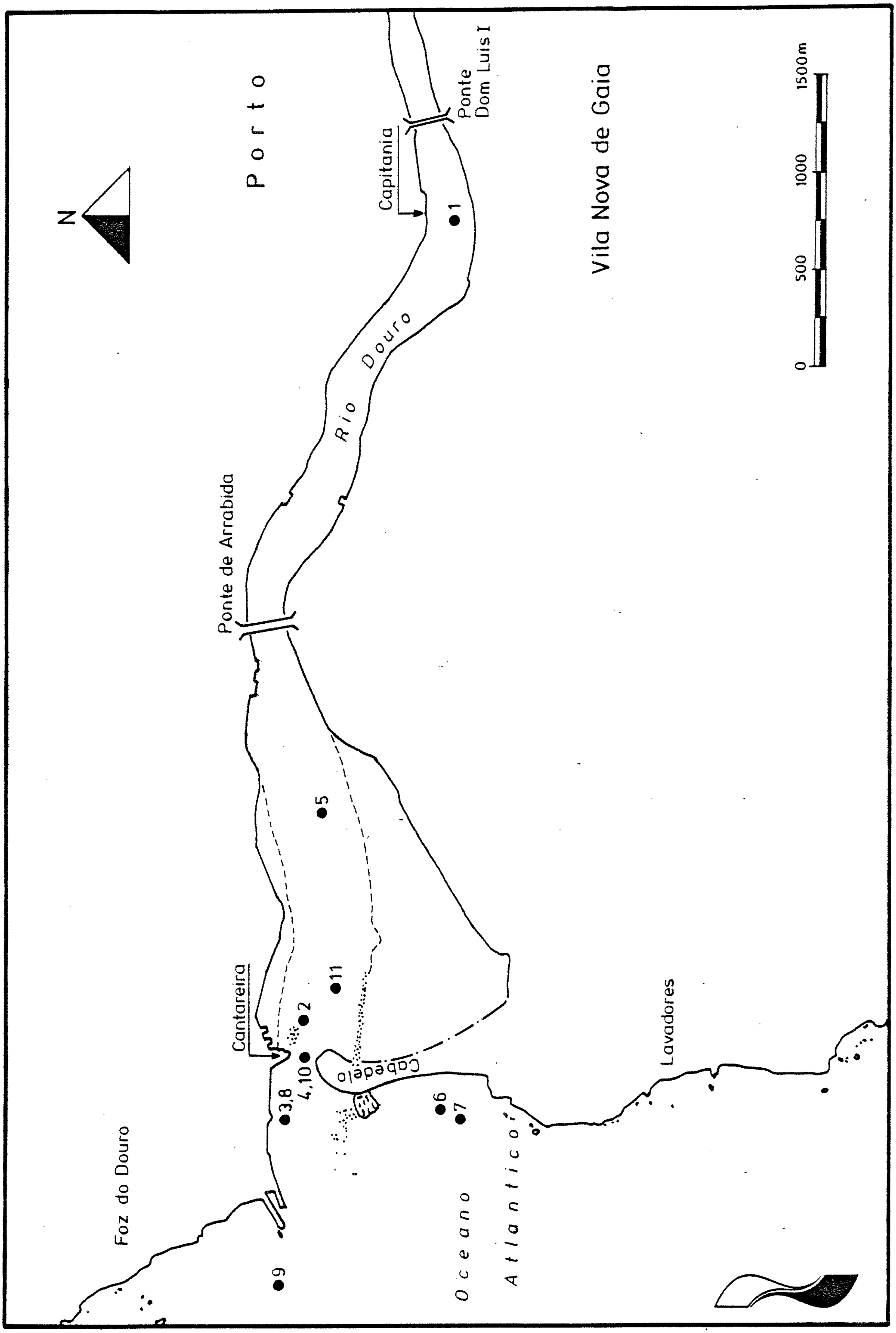
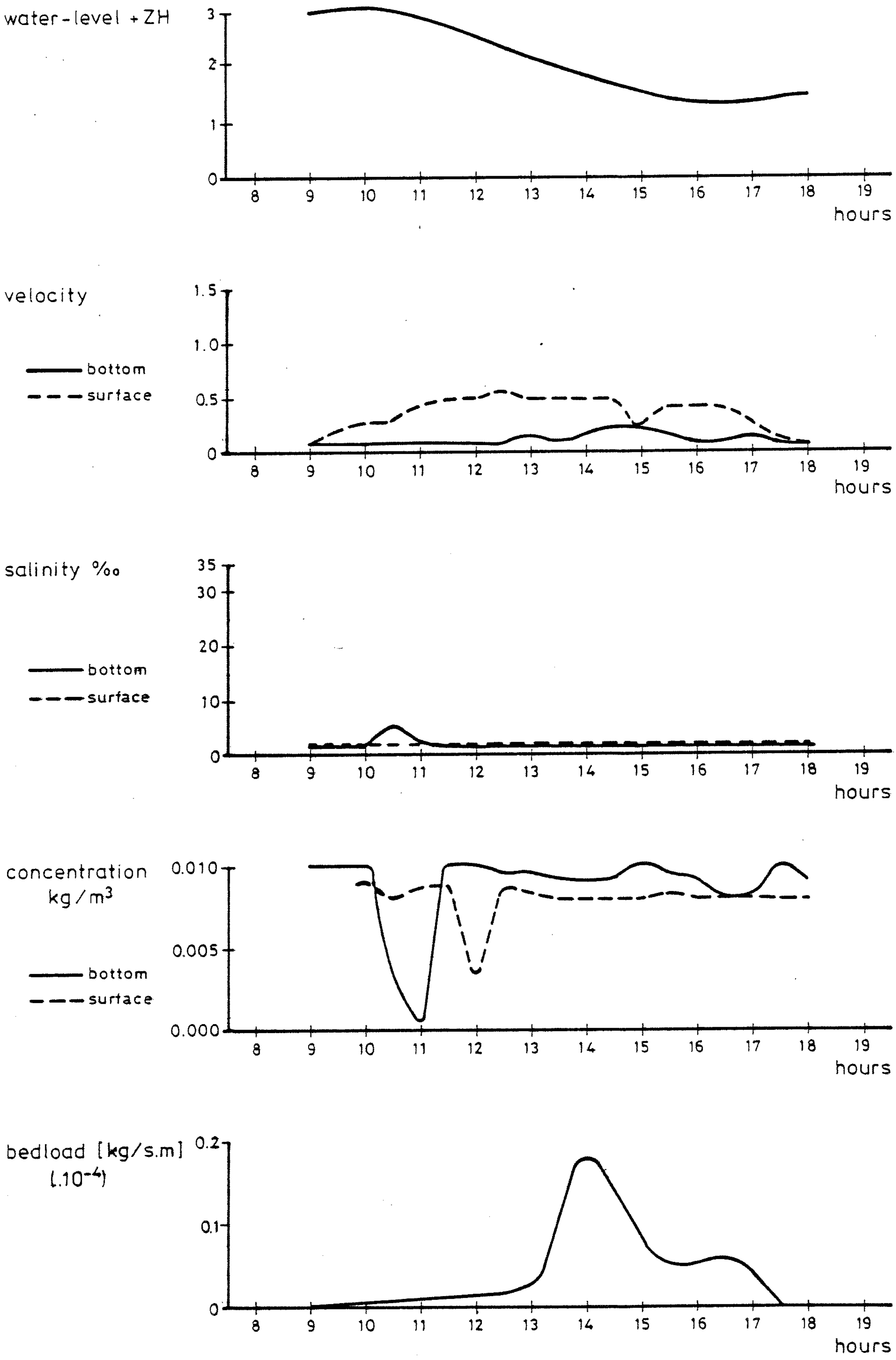
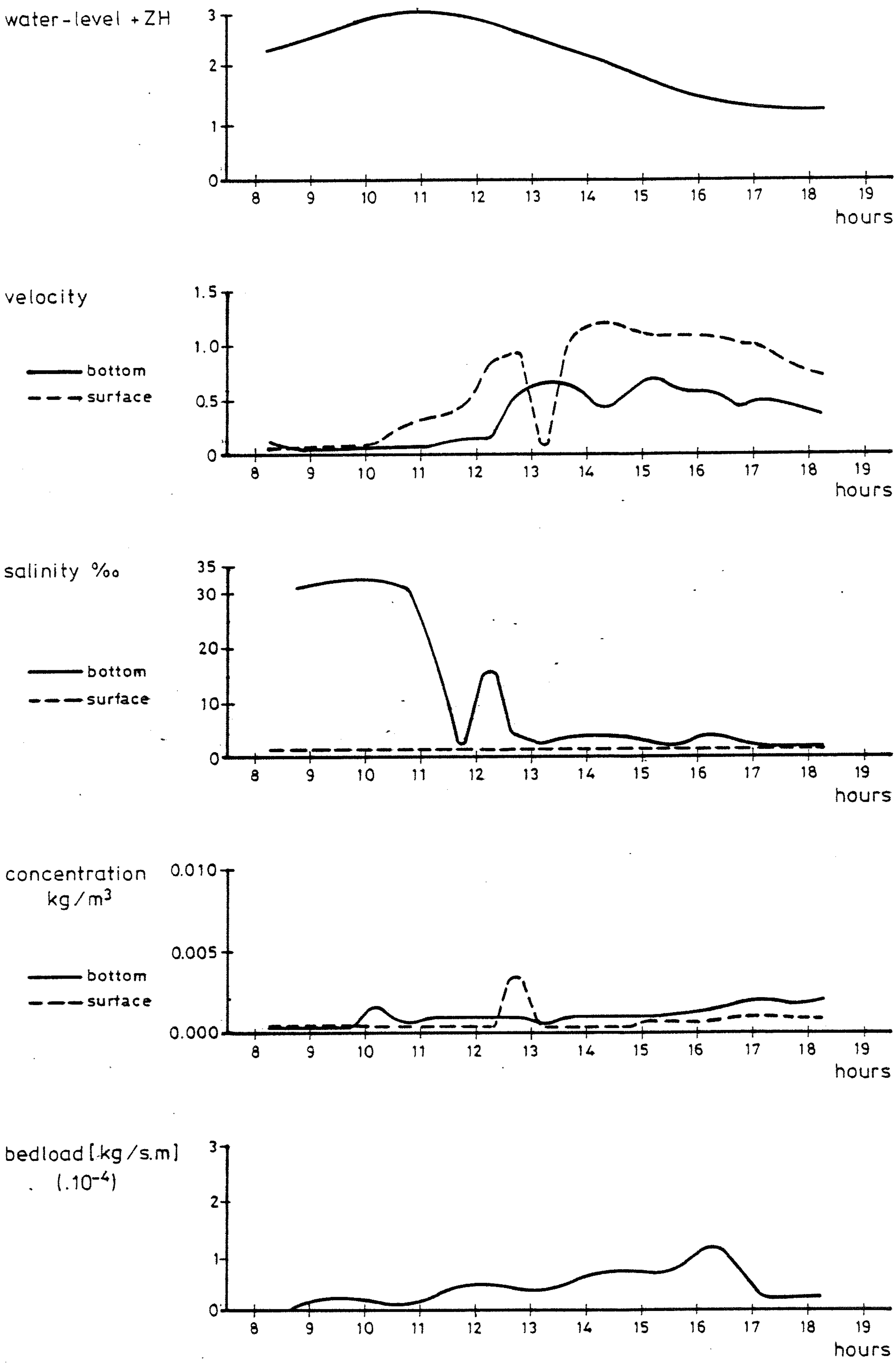


FIGURE 5 : *LOCATIONS OF THE MEASUREMENTS.*



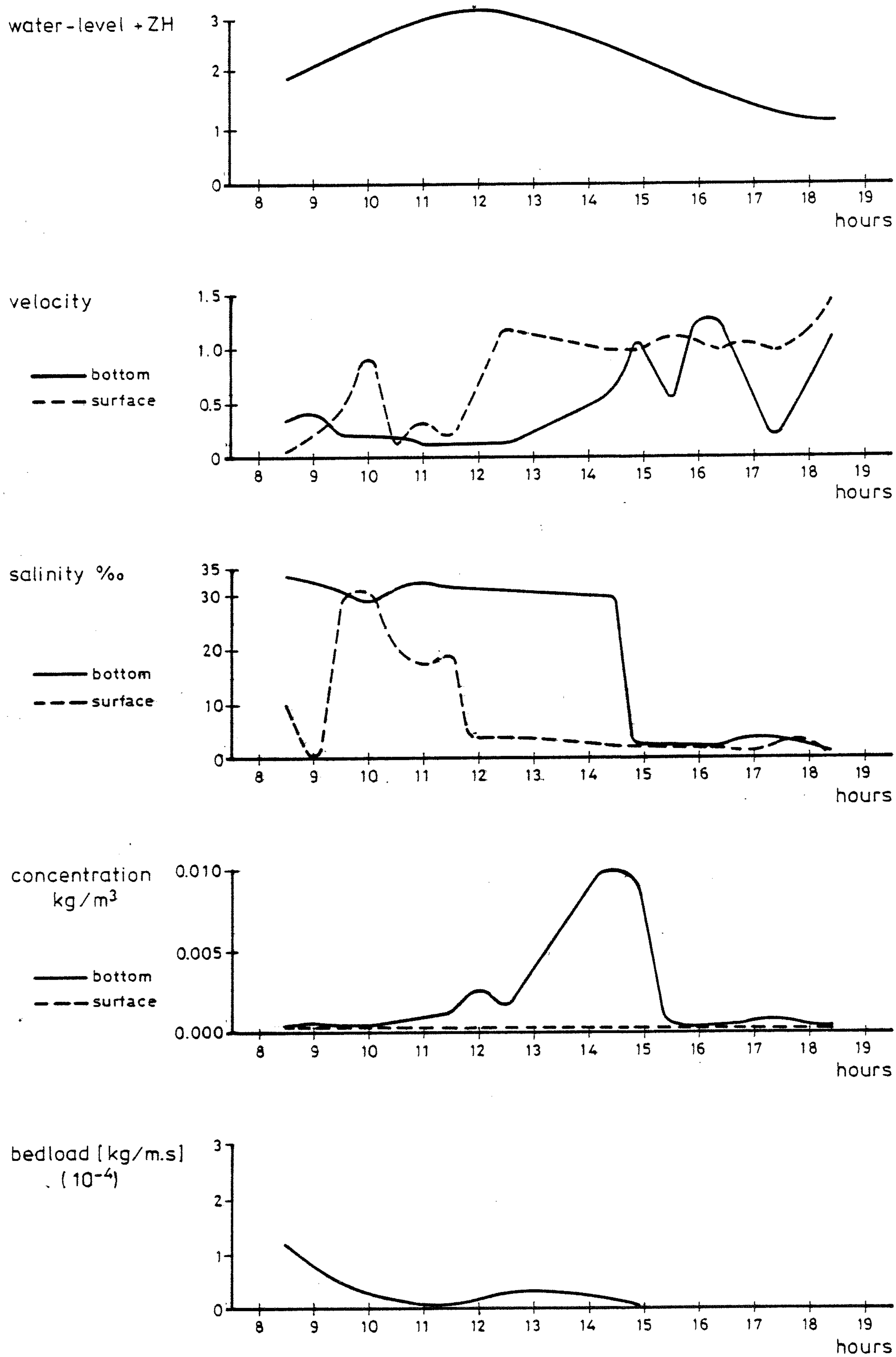
location: 0601
date: 09 - 11 - 1982

FIGURE 6



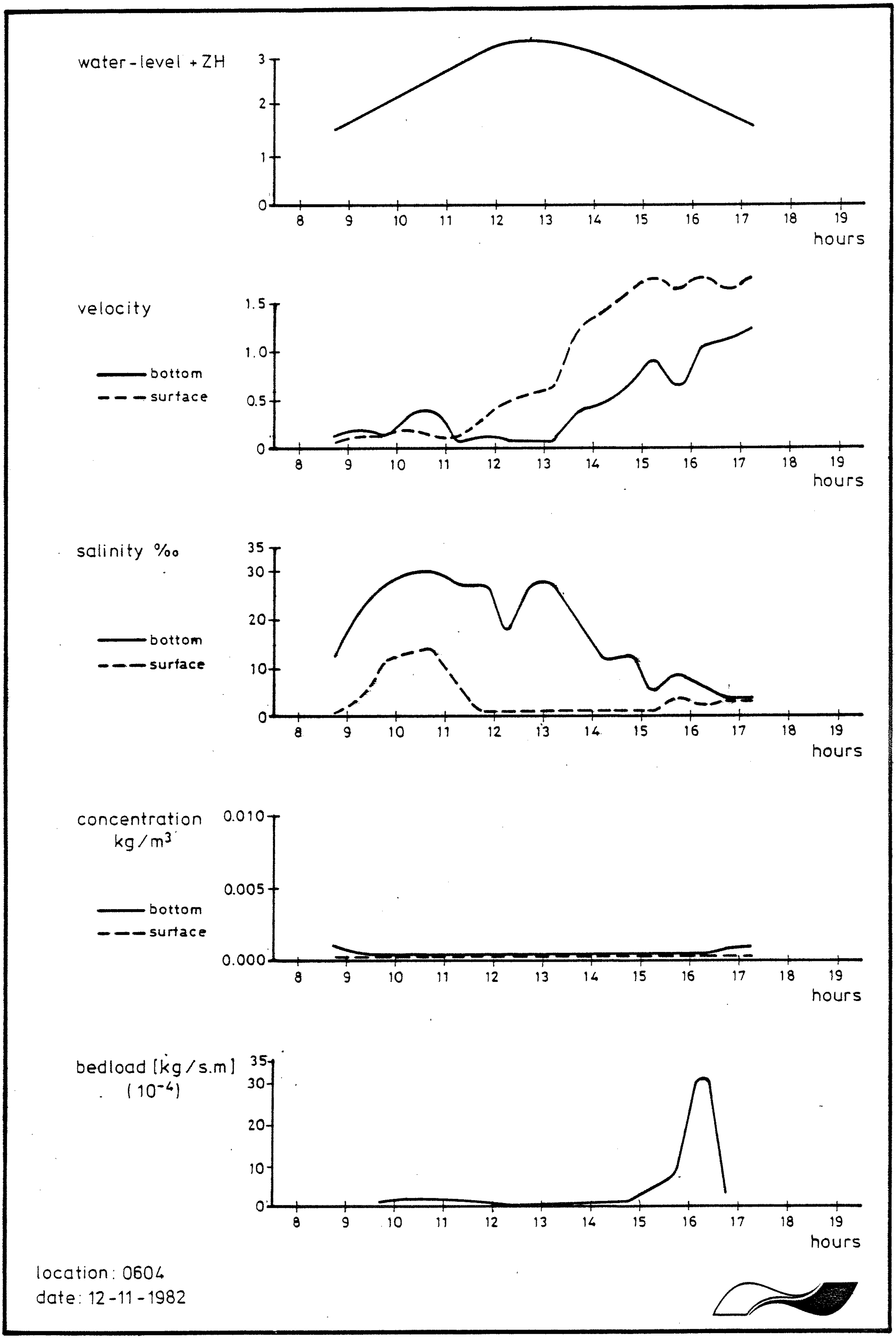
location: 0602
date: 10-11-1982

FIGURE 7



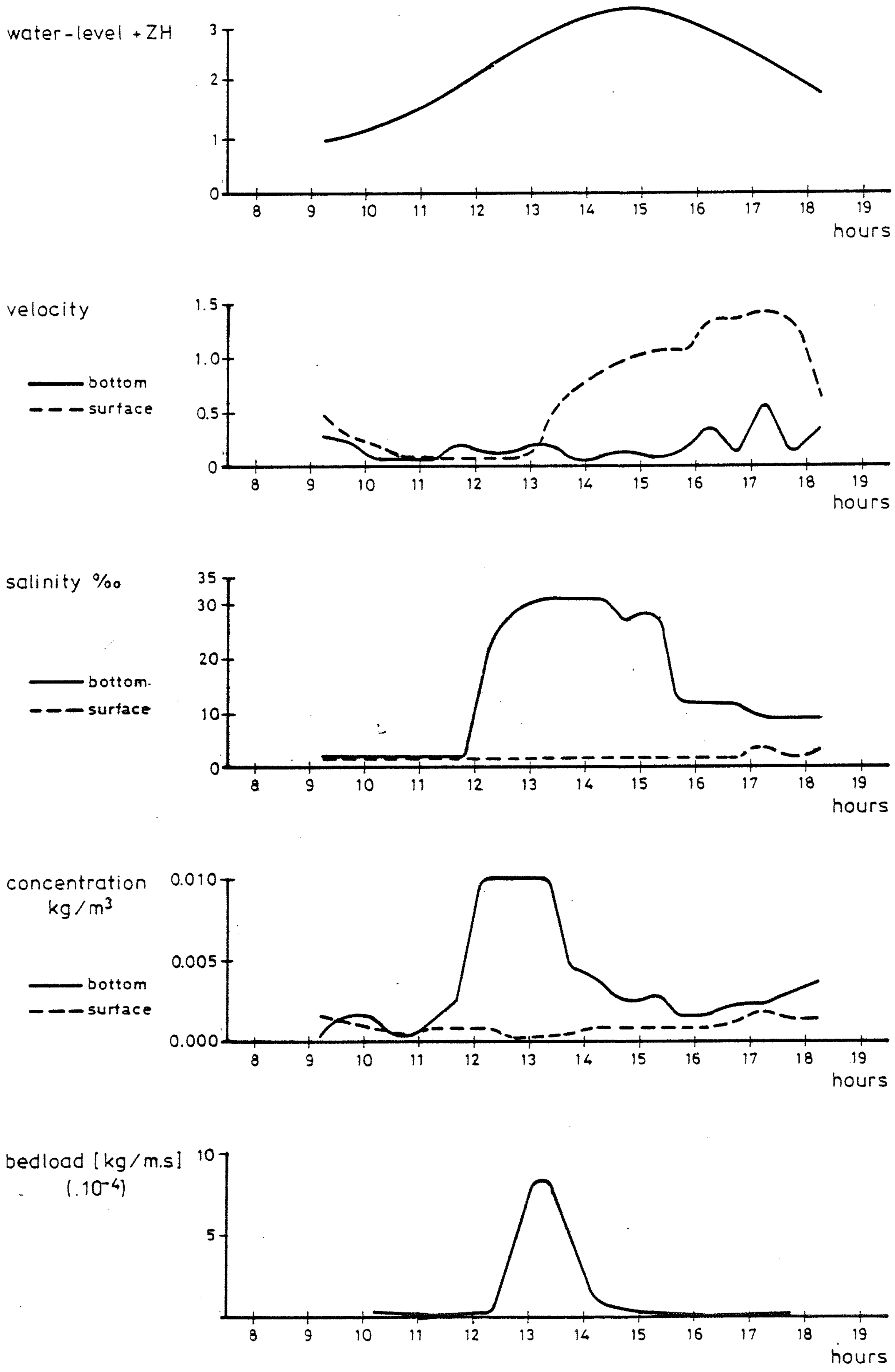
location: 0603
date: 11-11-1982

FIGURE 8



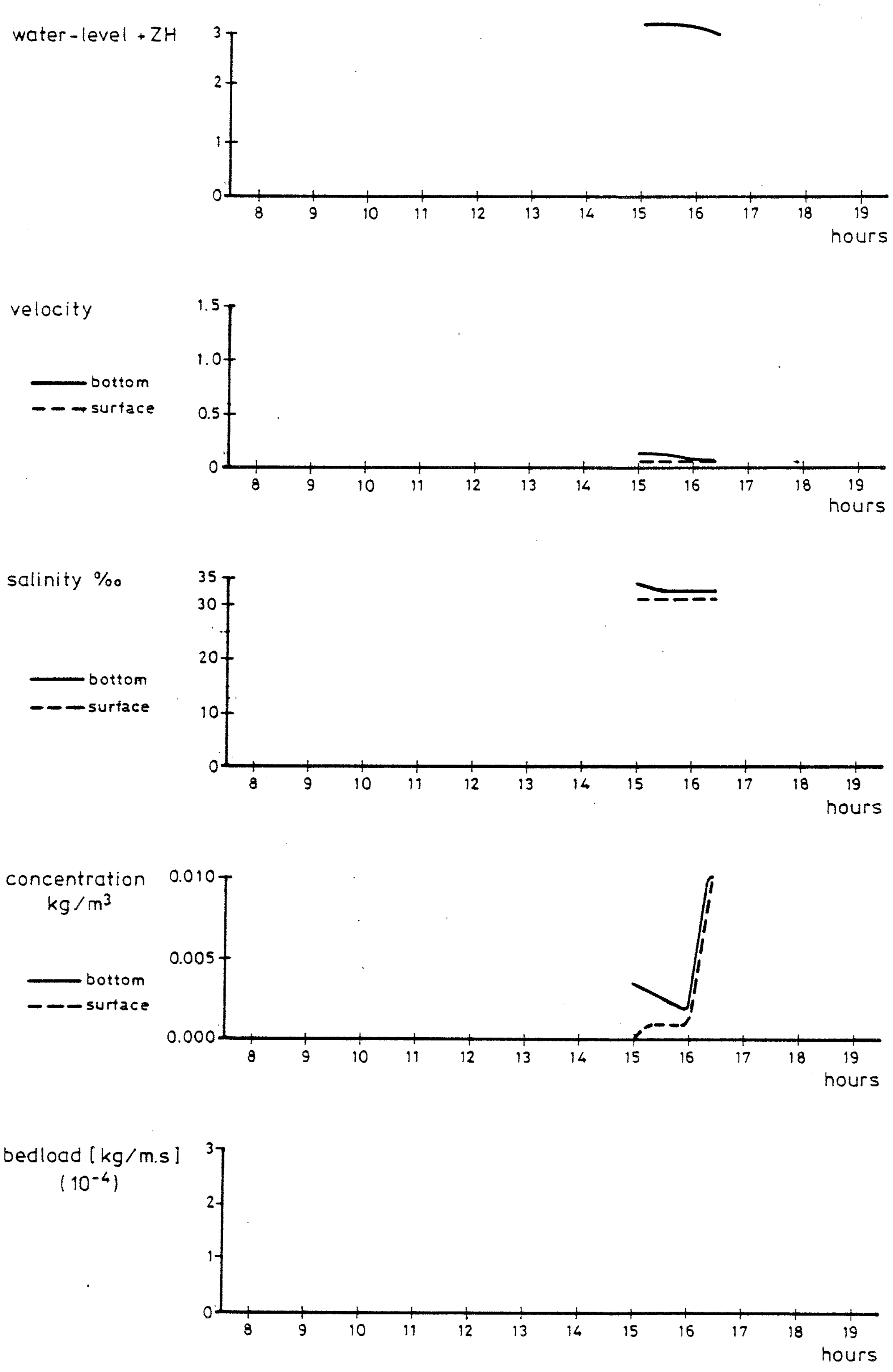
location: 0604
date: 12-11-1982

FIGURE 9



location: 0605
date: 15-11-1982

FIGURE 10



location: 0606
date: 16 - 11 - 1982

FIGURE 11

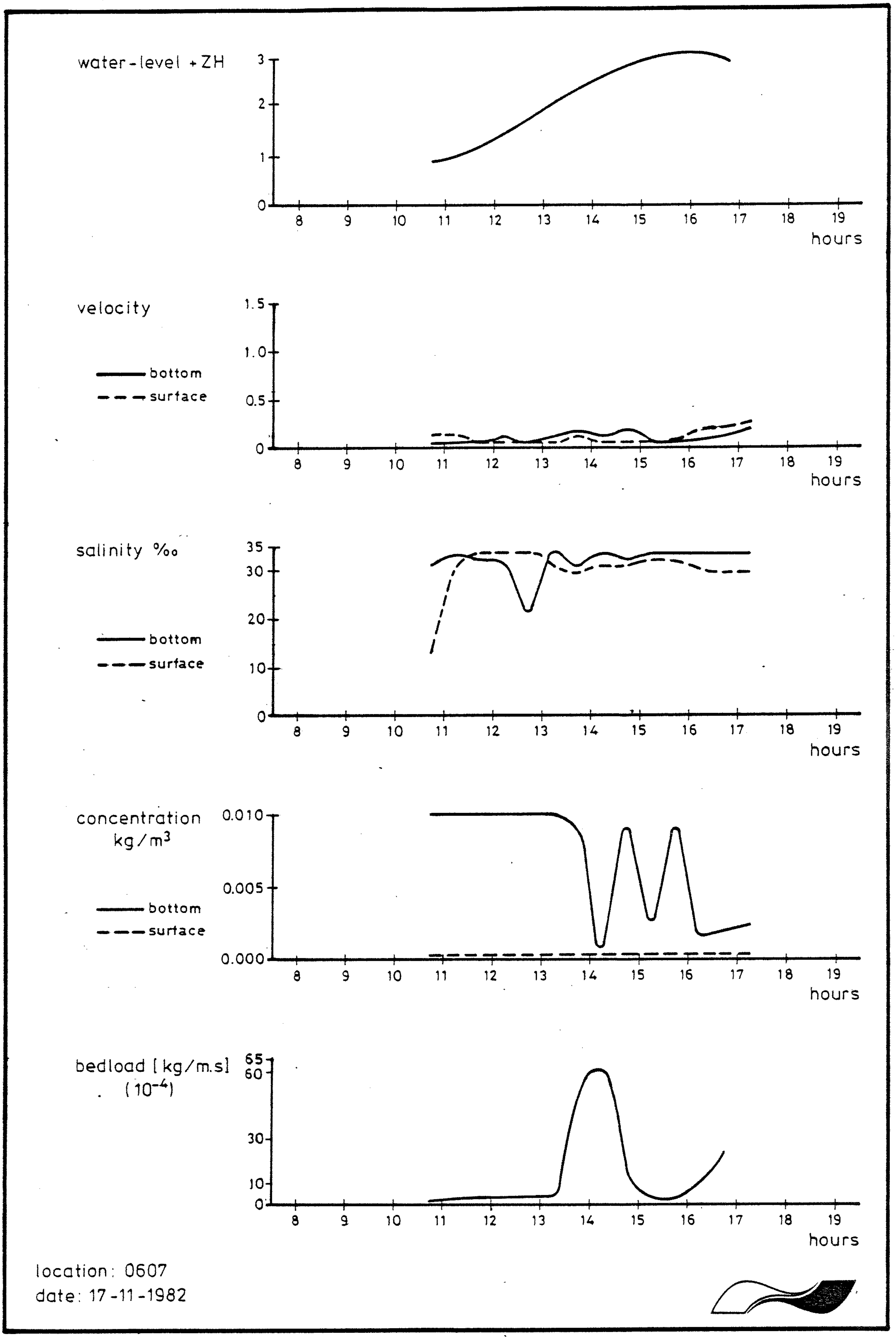
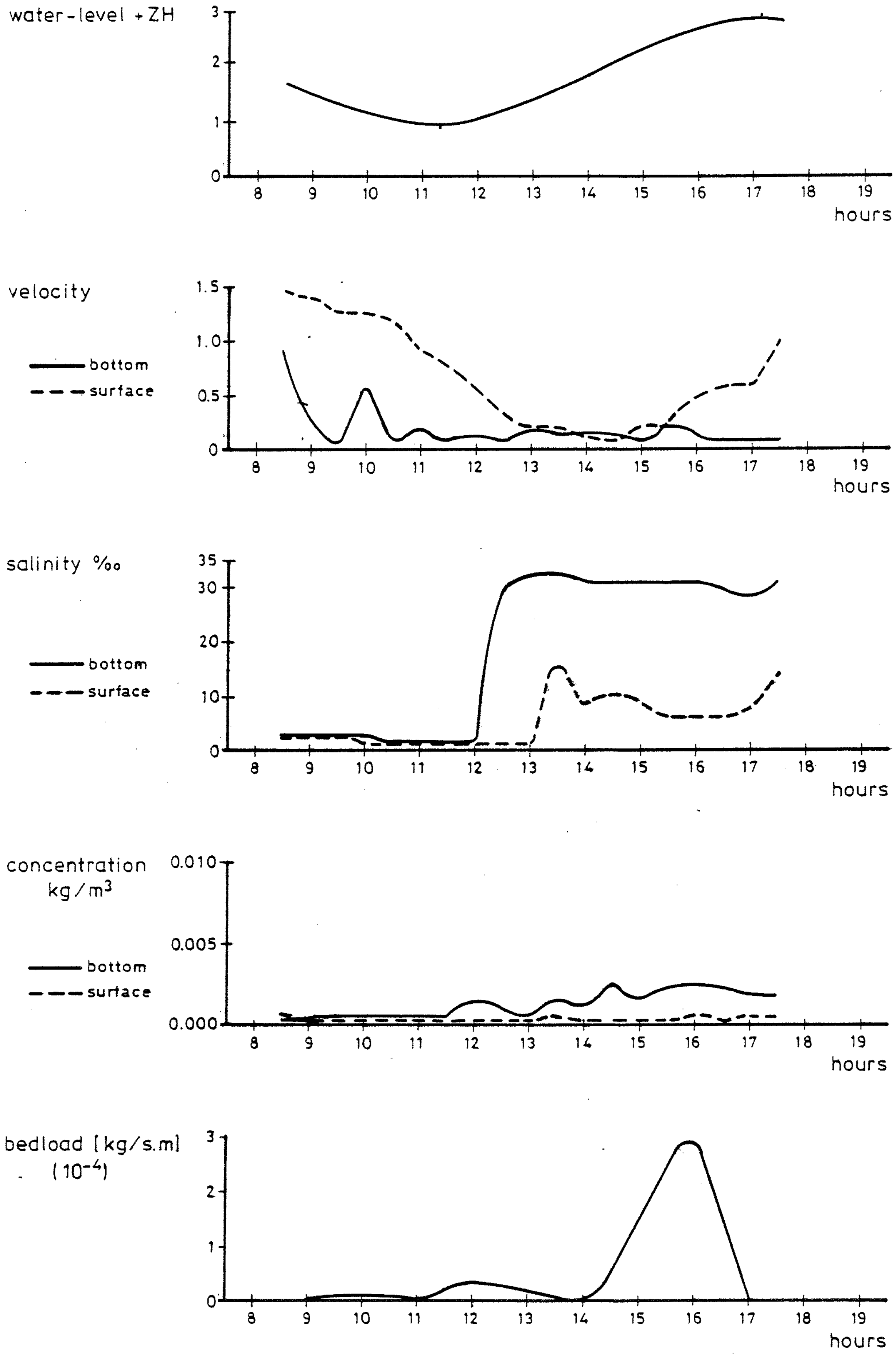
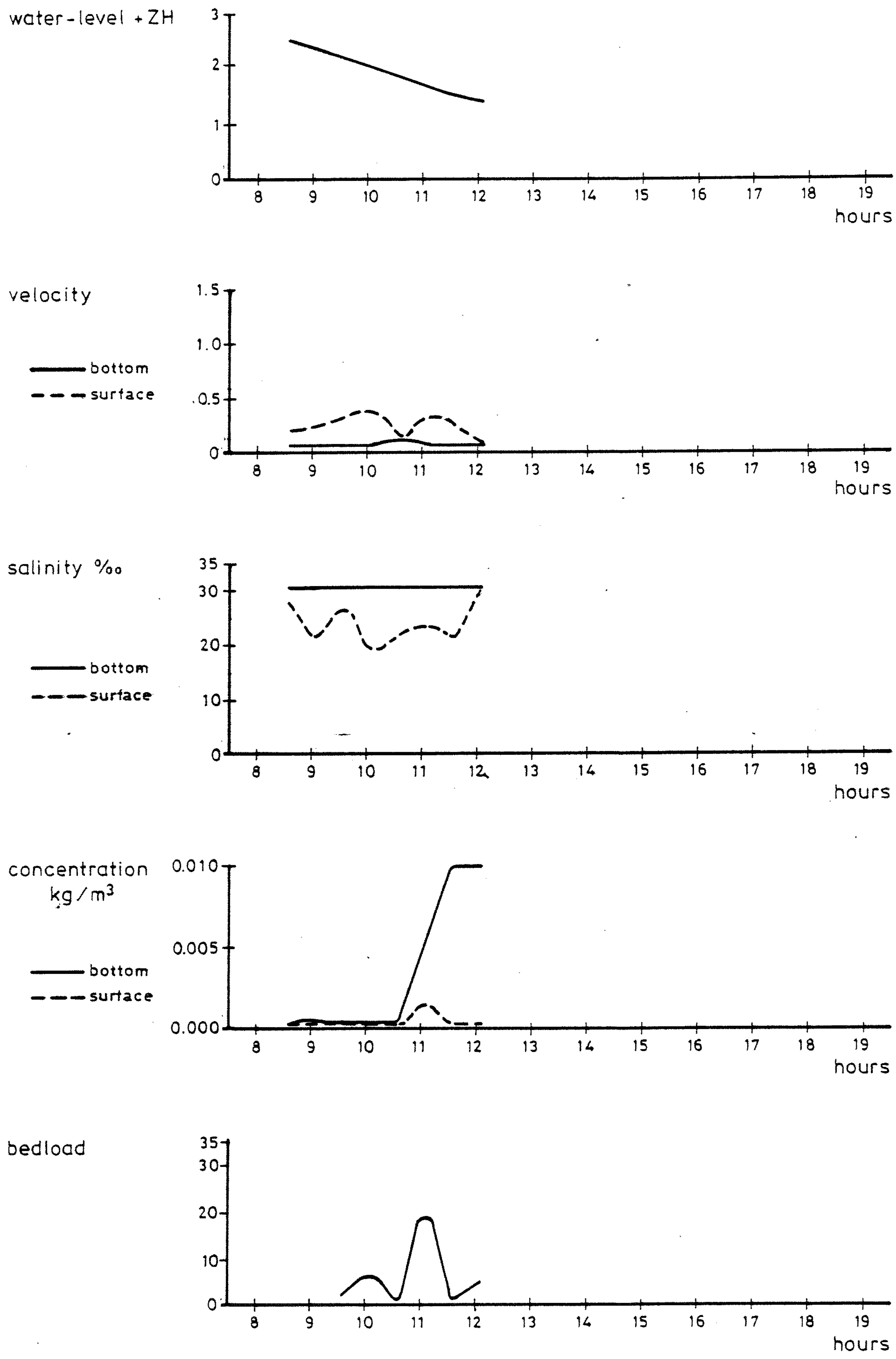

water-level +ZH
3
2
1
0
8
9
10
11
12
13
14
15
16
17
18
19
hours
velocity
bottom
surface
1.5
1.0
0.5
0
8
9
10
11
12
13
14
15
16
17
18
19
hours
salinity ‰
bottom
surface
35
30
20
10
0
8
9
10
11
12
13
14
15
16
17
18
19
hours
concentration
kg/m³
bottom
surface
0.010
0.005
0.000
8
9
10
11
12
13
14
15
16
17
18
19
hours
bedload [kg/m.s]
(10⁻⁴)
65
60
30
10
0
8
9
10
11
12
13
14
15
16
17
18
19
hours
location: 0607
date: 17-11-1982

FIGURE 12



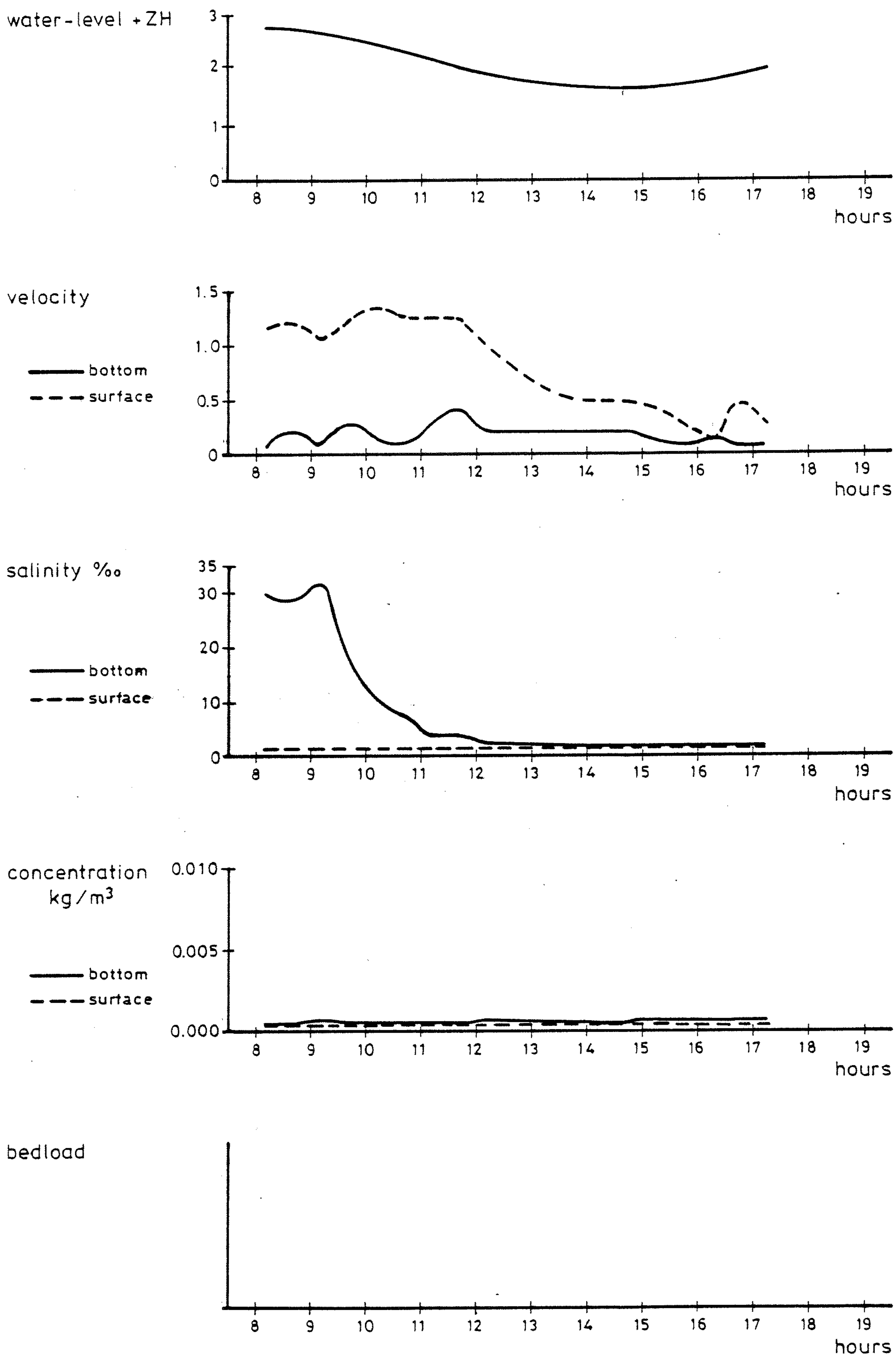
location: 0608
date: 19-11-1982

FIGURE 13



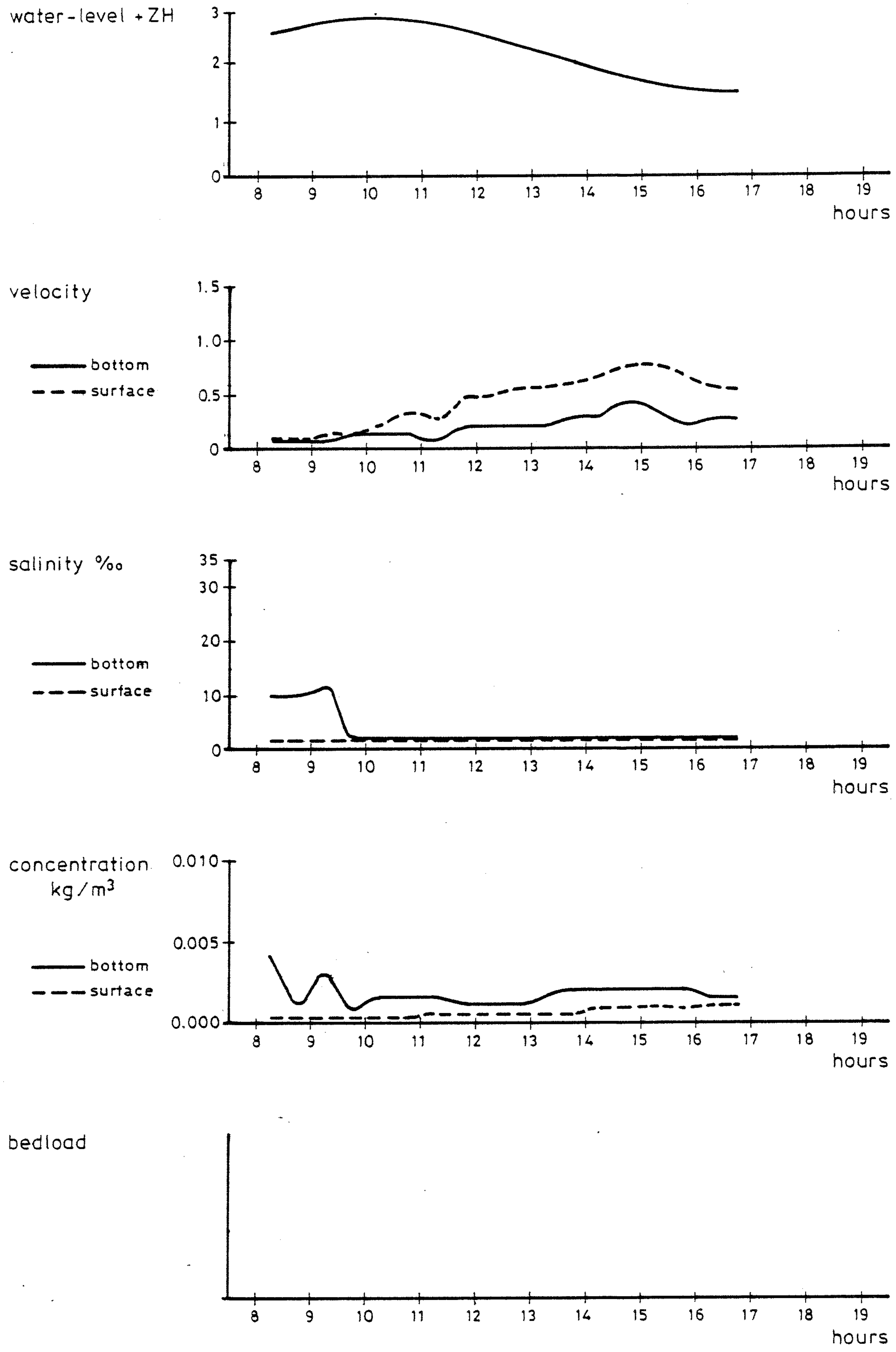
location: 0609
date: 22-11-1982

FIGURE 14



location: 0610
date: 23-11-1982

FIGURE 15



location: 0611
date: 25-11-1982

FIGURE 16

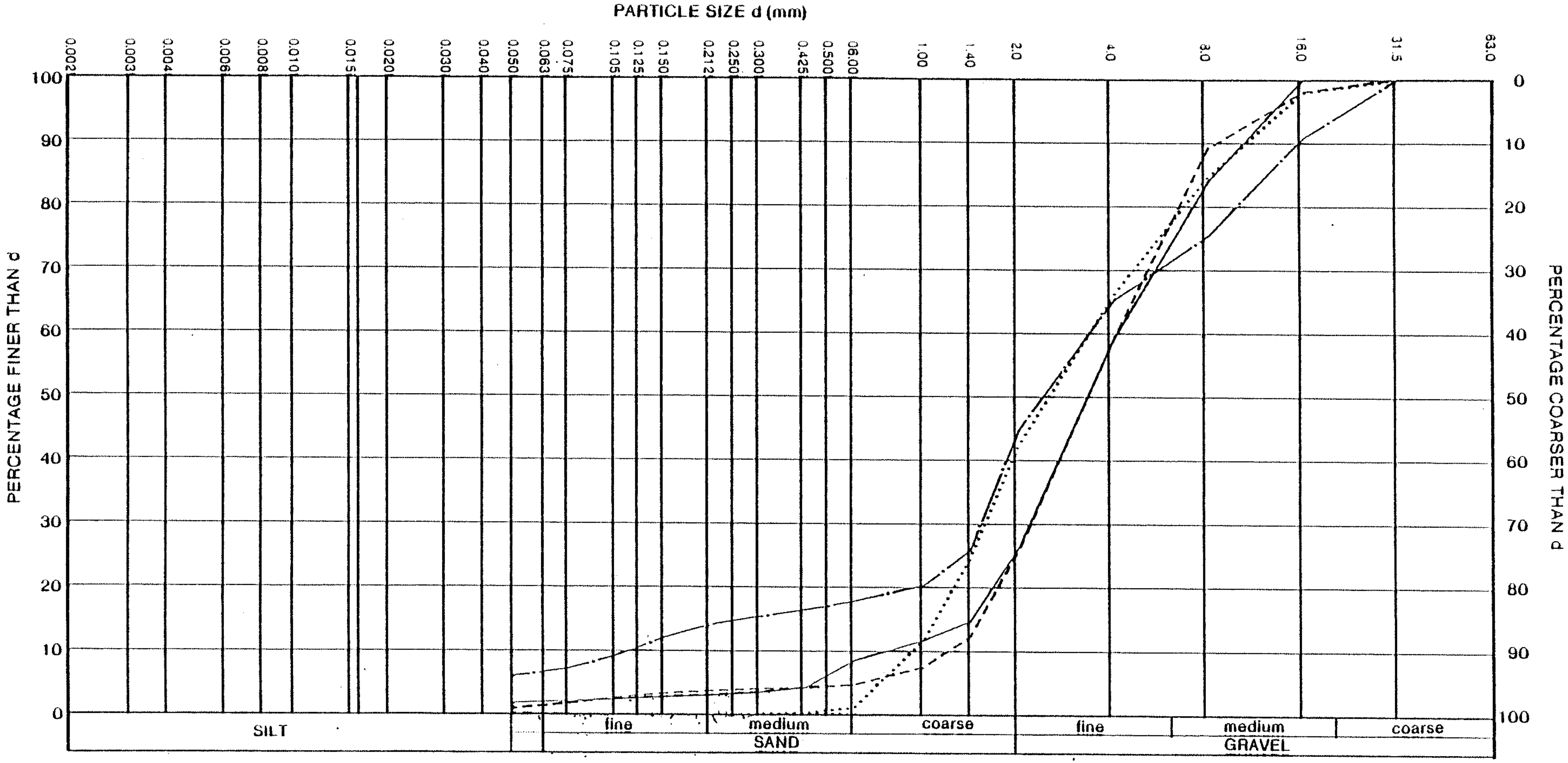
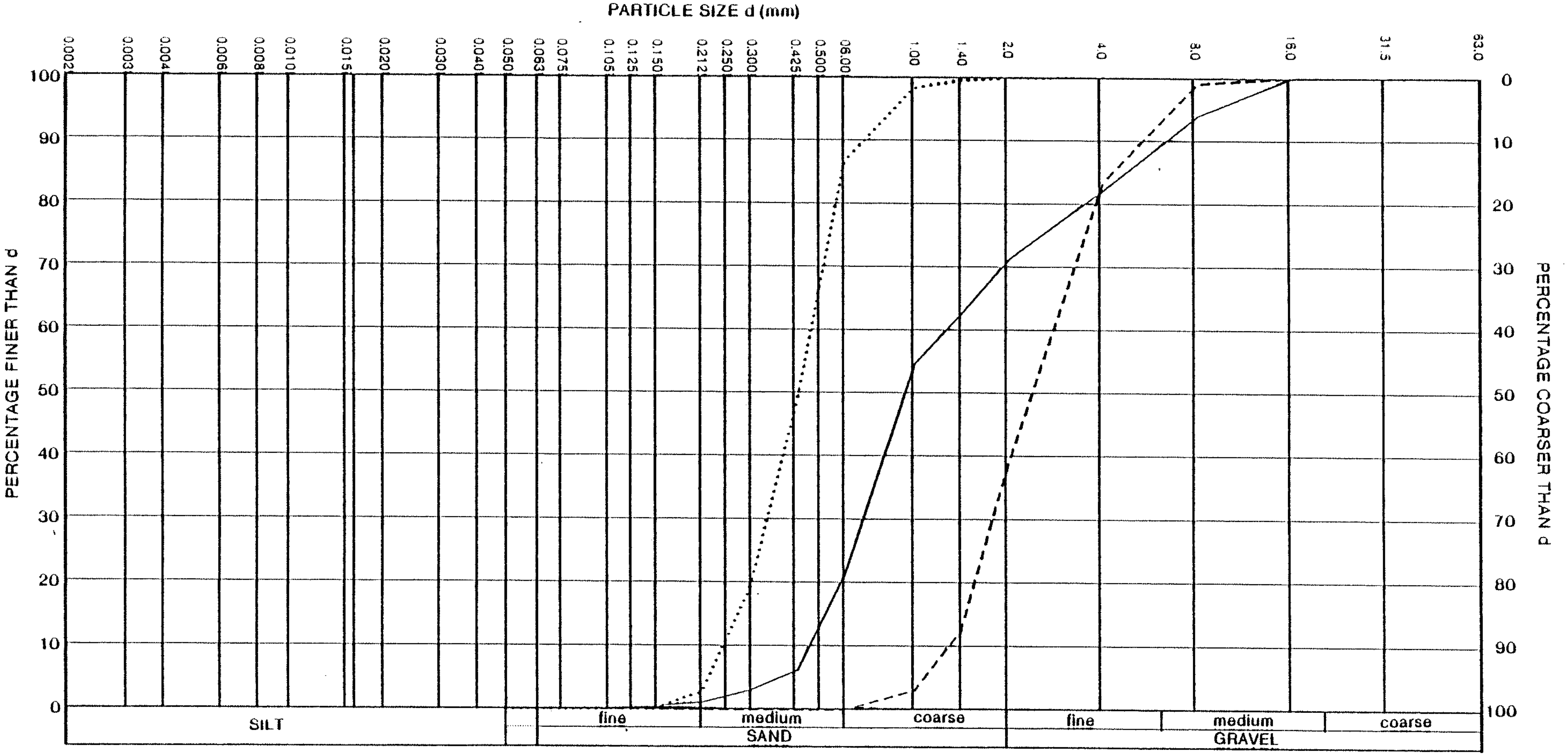


FIGURE 17: SIEVE ANALYSIS FROM MEASURING STATIONS 1-2-3 AND 5.

INDICATION	BOR. NO.	SAMPLE NO. /DEPTH [m]	D10 um.	D20 um.	D30 um.	D40 um.	D50 um.	D60 um.	D70 um.	D80 um.	D90 um.	D90/D10 --	D60/D10 --	DMF um.	U- NO.	WGT. % < 50um	16um	2um
————		1 /	780	1654	2166	2678	3310	4122	5447	7199	10435	13.4	5.3	4199	16	1.6	--	--
- - - - - - -		2 /	1196	1715	2181	2689	3316	4097	5154	6485	8551	7.1	3.4	3932	20	0.9	--	--
....		3 /	923	1245	1564	1911	2508	3359	4646	6741	10579	11.5	3.6	3719	9	--	--	--
——·——		5 /	118	942	1514	1828	2389	3356	5559	9857	15443	130.9	28.5	4556	27	5.9	--	--

FIGURE 18: *SIEVE ANALYSIS FROM MEASURING STATIONS 6,8 AND 9.*



INDICATION	BOR. NO.	SAMPLE NO. /DEPTH [m]	D10 um	D20 um	D30 um	D40 um	D50 um	D60 um	D70 um	D80 um	D90 um	D90/D10 --	D60/D10 --	DMF um	U-NO.	WGT.% < 50um	16um	2um
————		6 /	464	582	685	799	931	1262	1908	3500	6357	13.7	2.7	1832	15	--	--	--
- - - - - -		8 /	1280	1540	1770	2028	2372	2774	3243	3793	5358	4.2	2.2	2685	7	--	--	--
…………		9 /	247	304	341	383	430	471	516	565	697	2.8	1.9	439	26	--	--	--

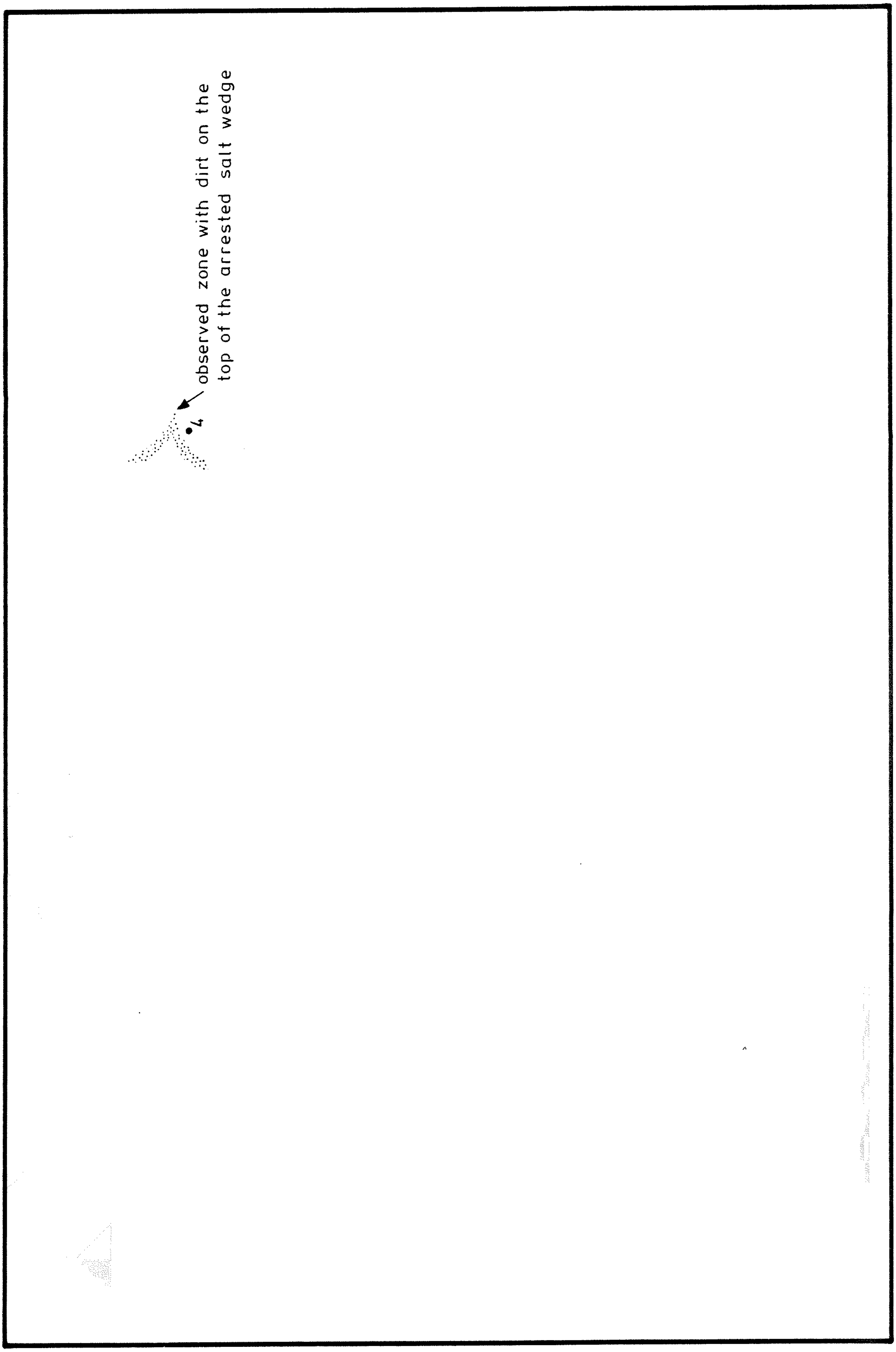


FIGURE 19 : *LOCATION OF THE SALT WEDGE.*

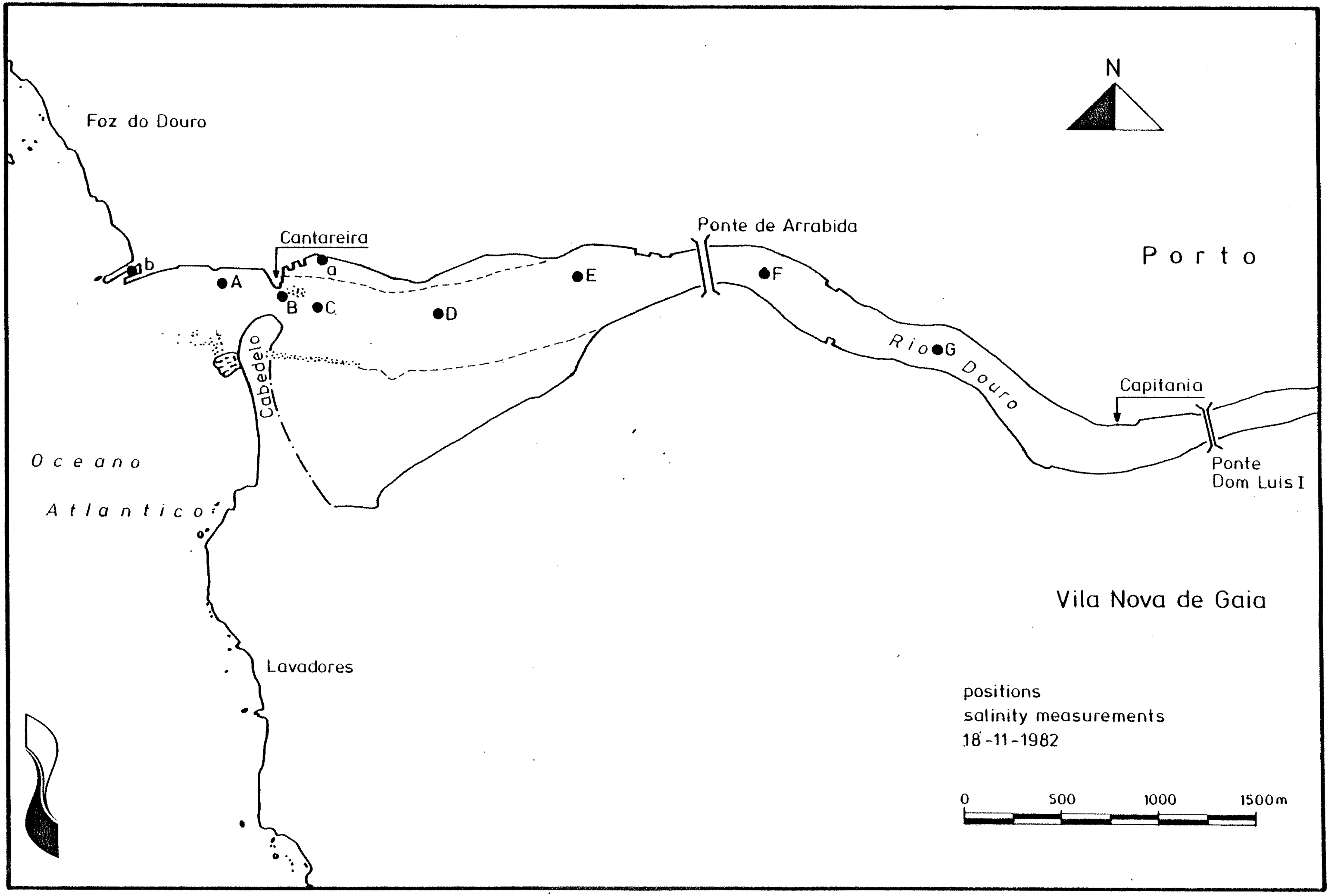
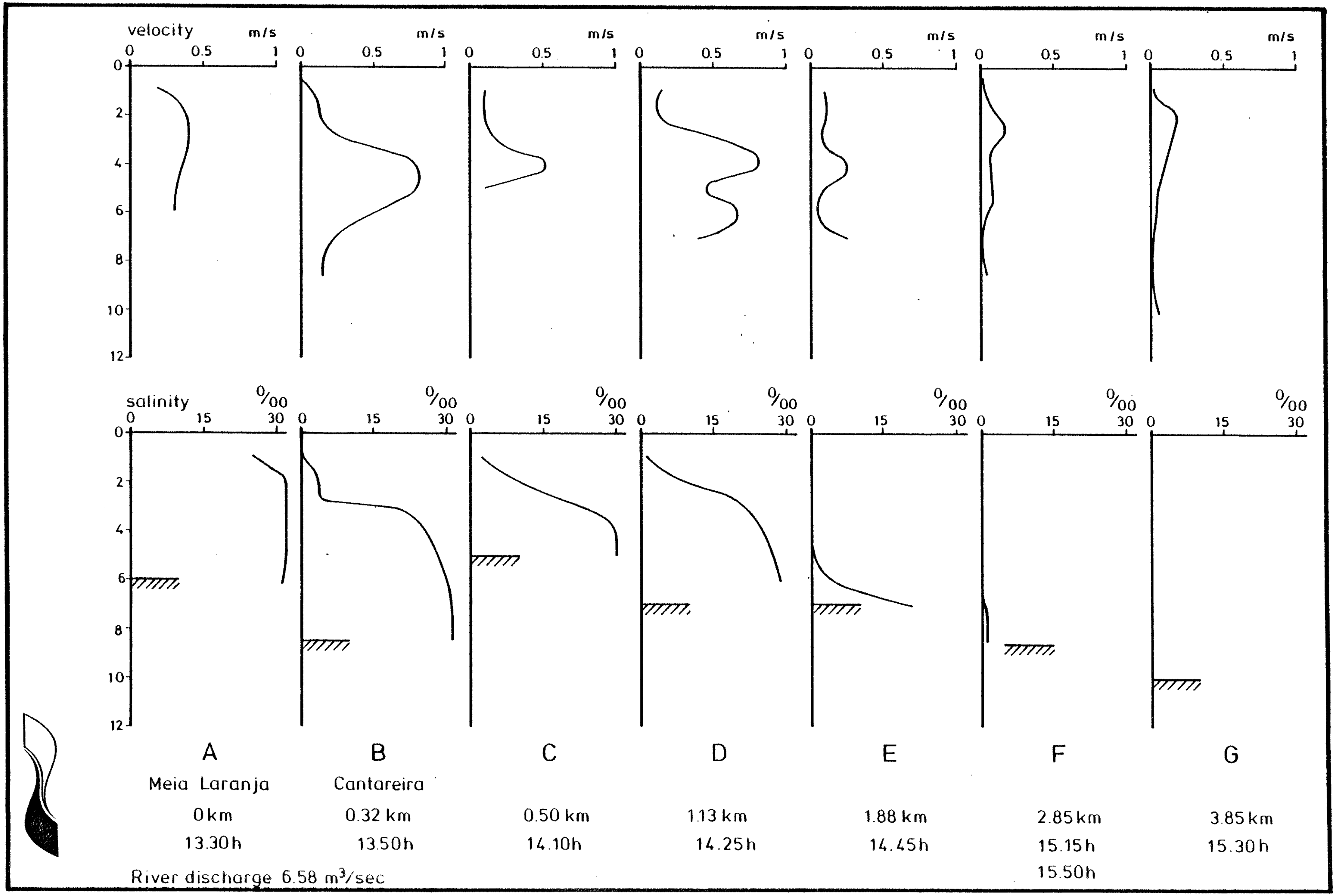


FIGURE 20: *POSITIONS OF SALINITY PROFILES, MEASUREMENTS ON 18-11-1981.*

FIGURE 21 : VELOCITY AND SALINITY PROFILES ON 18 NOVEMBER 1982.



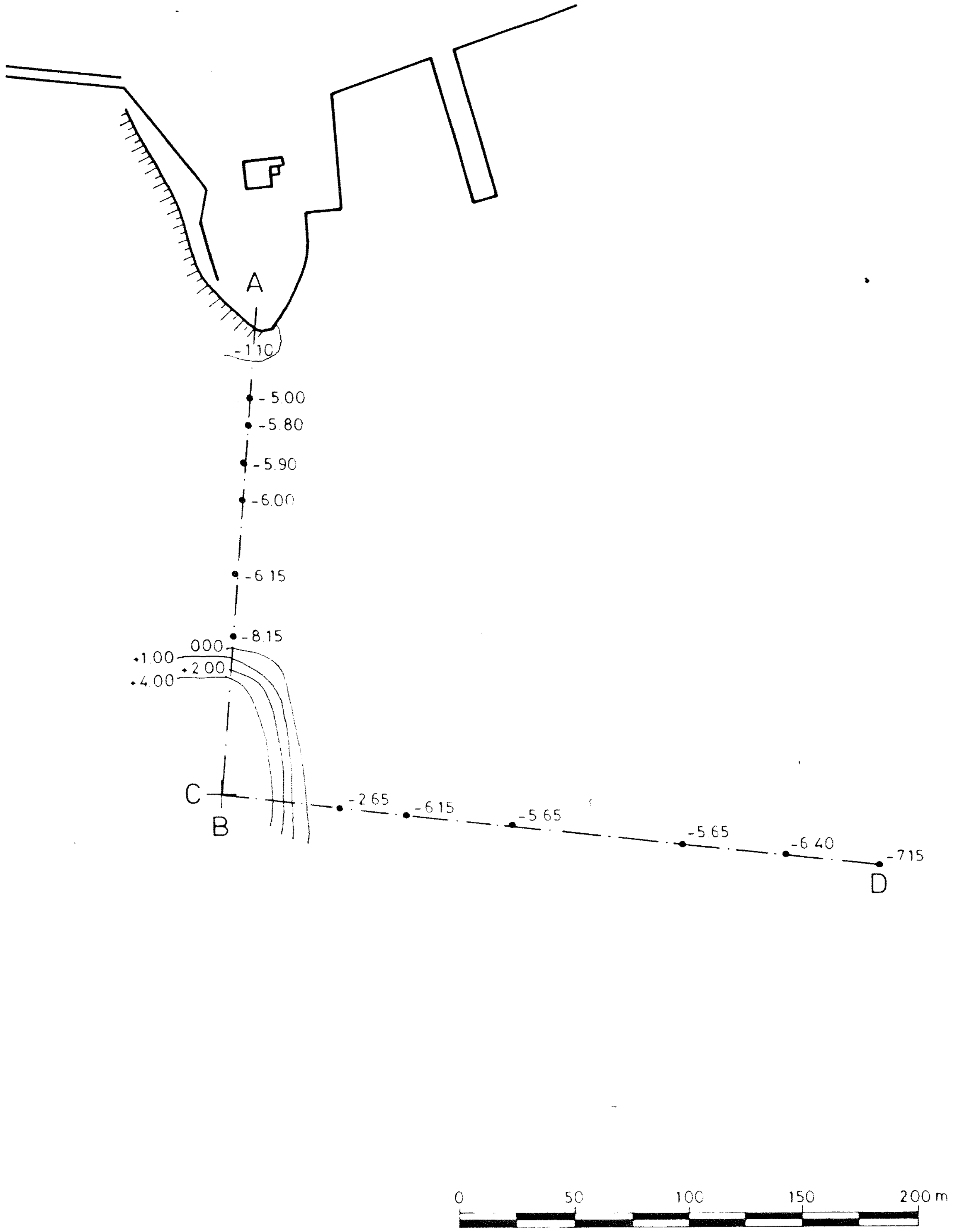


FIGURE 22 *CROSS-SECTIONS AT THE HEAD OF THE CABEDELO*

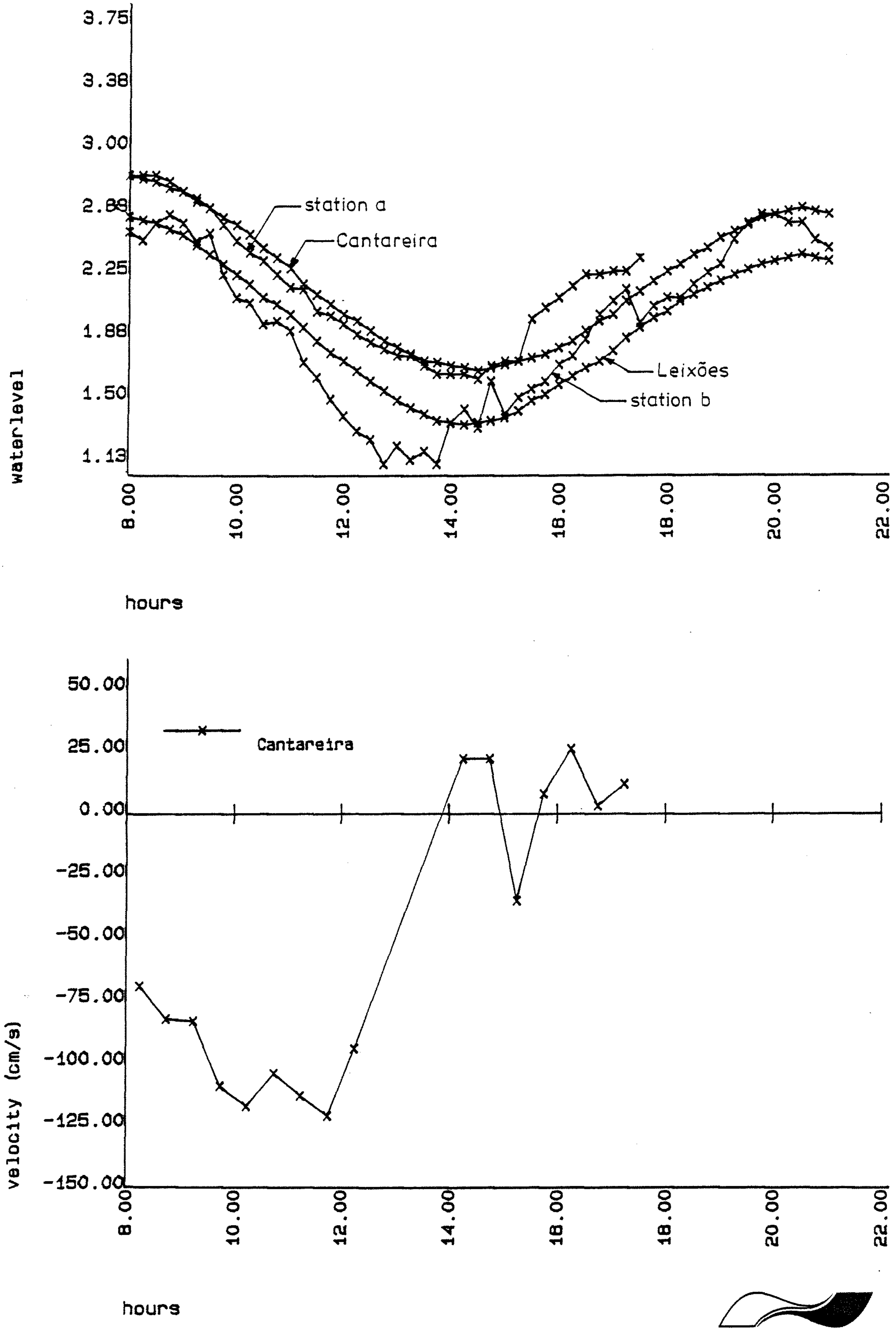


FIGURE 23: *WATERLEVELS AND VELOCITIES ON NOVEMBER 23rd, 1982.*

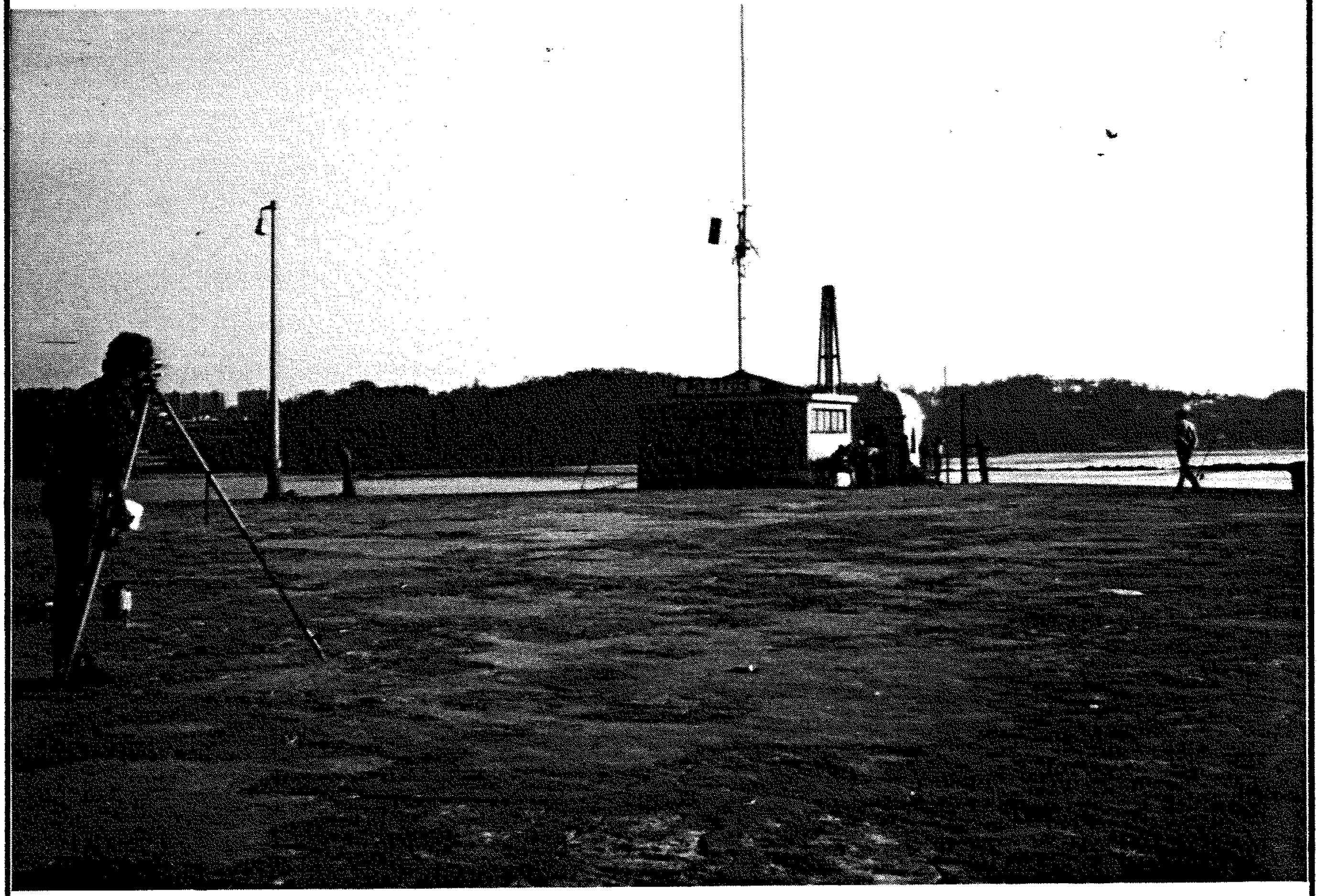
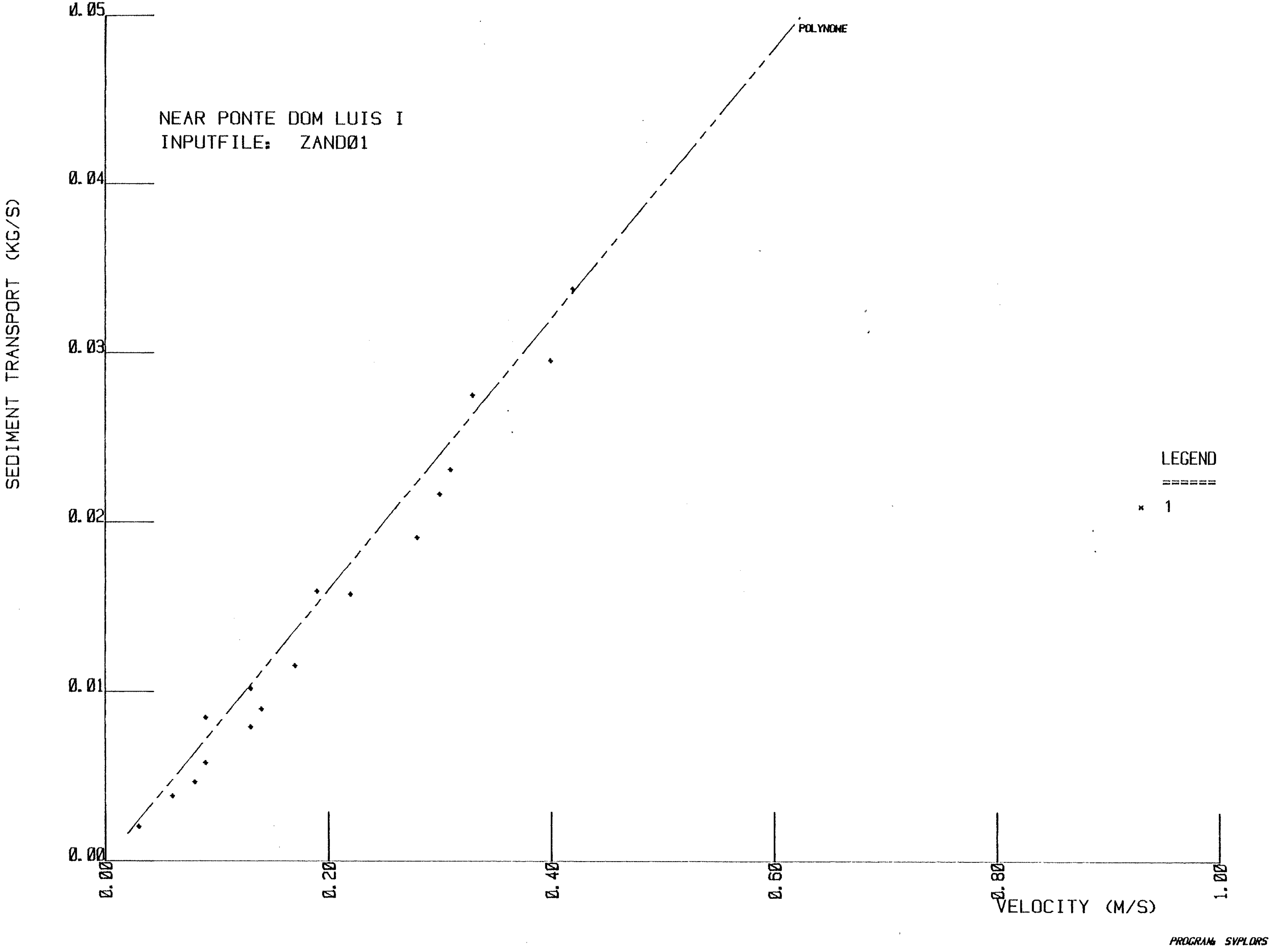


FIGURE 24

FIGURE 25


NEAR PONTE DOM LUIS I
INPUTFILE: ZAND01
POLYNOME
SEDIMENT TRANSPORT (KG/S)
0.05
0.04
0.03
0.02
0.01
0.00
0.00
0.20
0.40
0.60
0.80
1.00
VELOCITY (M/S)
LEGEND
======
× 1
PROGRAM: SVPLORS

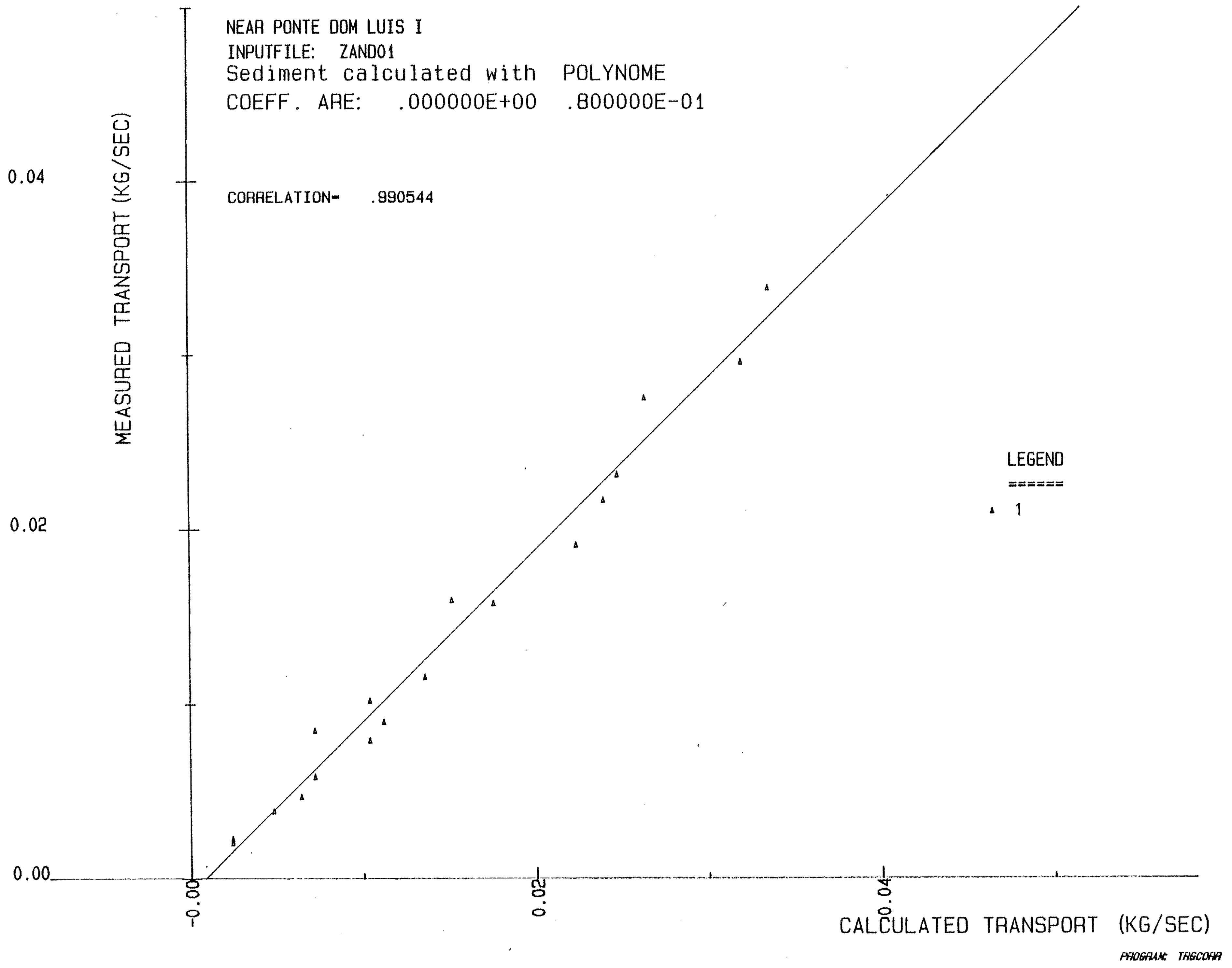

NEAR PONTE DOM LUIS I
INPUTFILE: ZAND01
Sediment calculated with POLYNOME
COEFF. ARE: .000000E+00 .800000E-01
CORRELATION= .990544
MEASURED TRANSPORT (KG/SEC)
0.04
0.02
0.00
-0.00
0.02
0.04
CALCULATED TRANSPORT (KG/SEC)
LEGEND
======
1
PROGRAM: TRGCORR

FIGURE 26

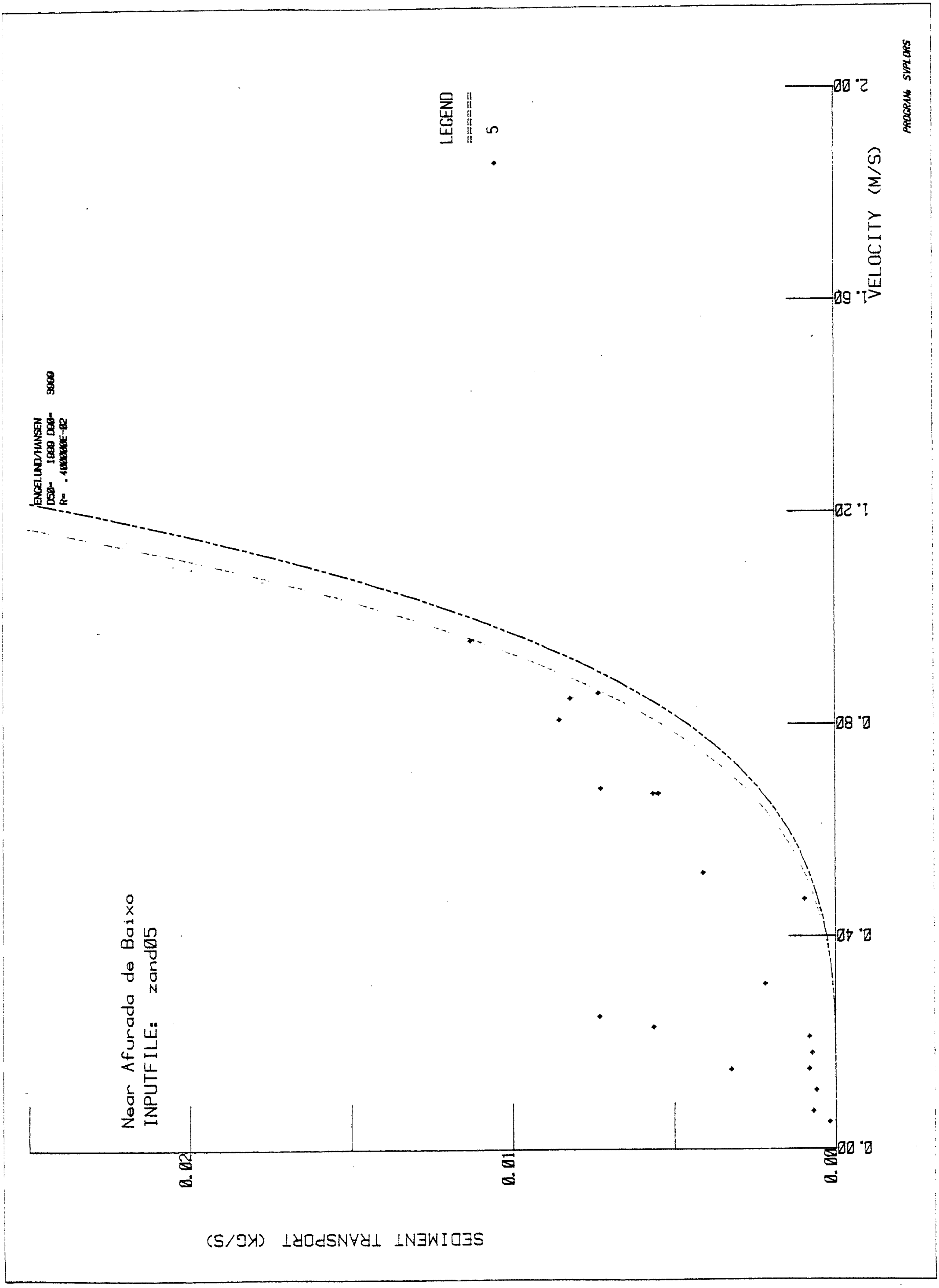
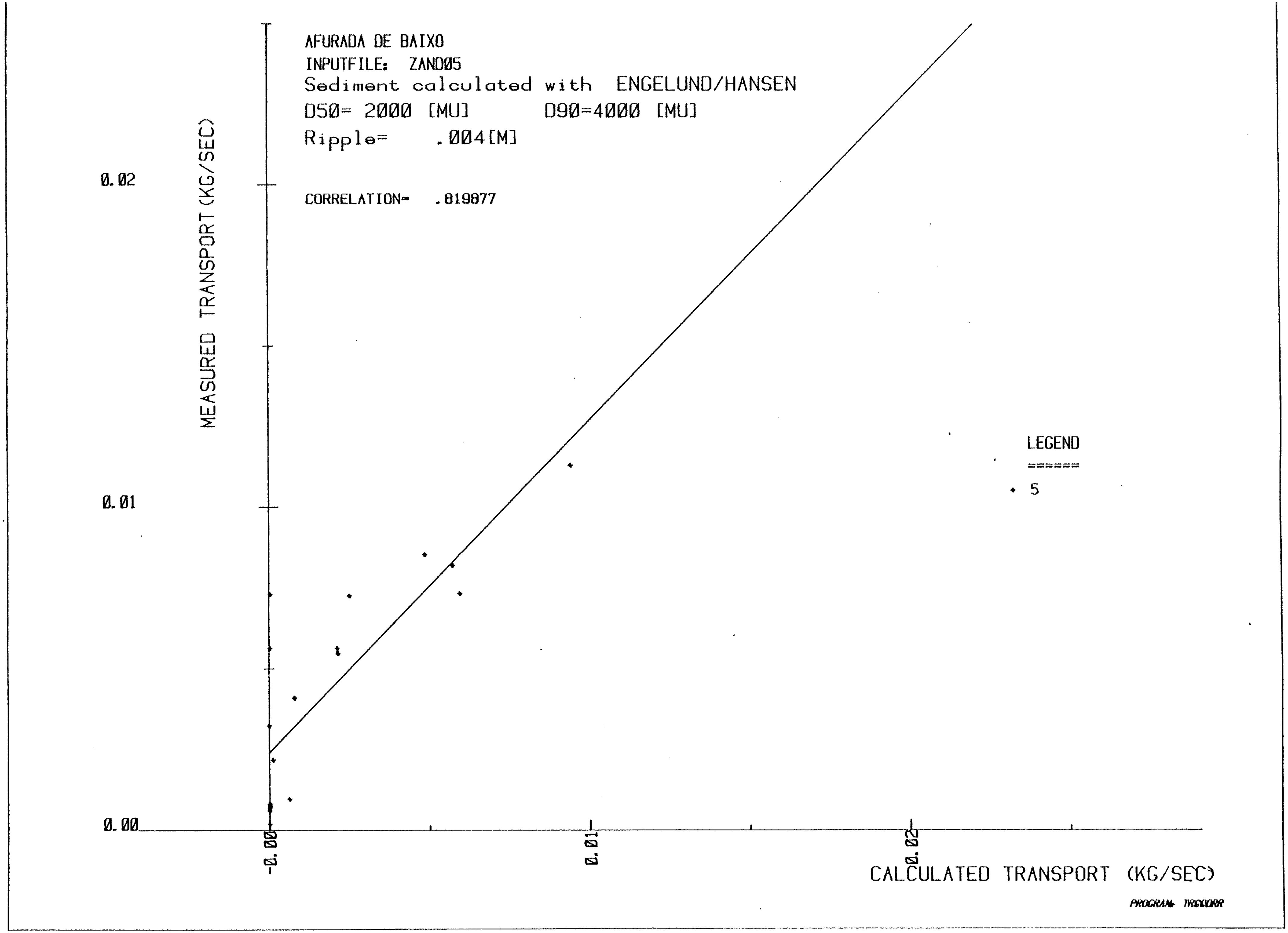

Near Afurada de Baixo
INPUTFILE: zand05
ENGELUND/HANSEN
D50= 1000 D90= 3000
R= .400000E-02
LEGEND
======
5
VELOCITY (M/S)
0.00
0.40
0.80
1.20
1.60
2.00
SEDIMENT TRANSPORT (KG/S)
0.00
0.01
0.02
PROGRAM: SVPLOTS

FIGURE 27

FIGURE 28


AFURADA DE BAIXO
INPUTFILE: ZAND05
Sediment calculated with ENGELUND/HANSEN
D50= 2000 [MU] D90=4000 [MU]
Ripple= .004[M]
CORRELATION= .819877
MEASURED TRANSPORT (KG/SEC)
0.02
0.01
0.00
-0.00
0.01
0.02
CALCULATED TRANSPORT (KG/SEC)
LEGEND
======
◆ 5
PROGRAM: TRGCORR

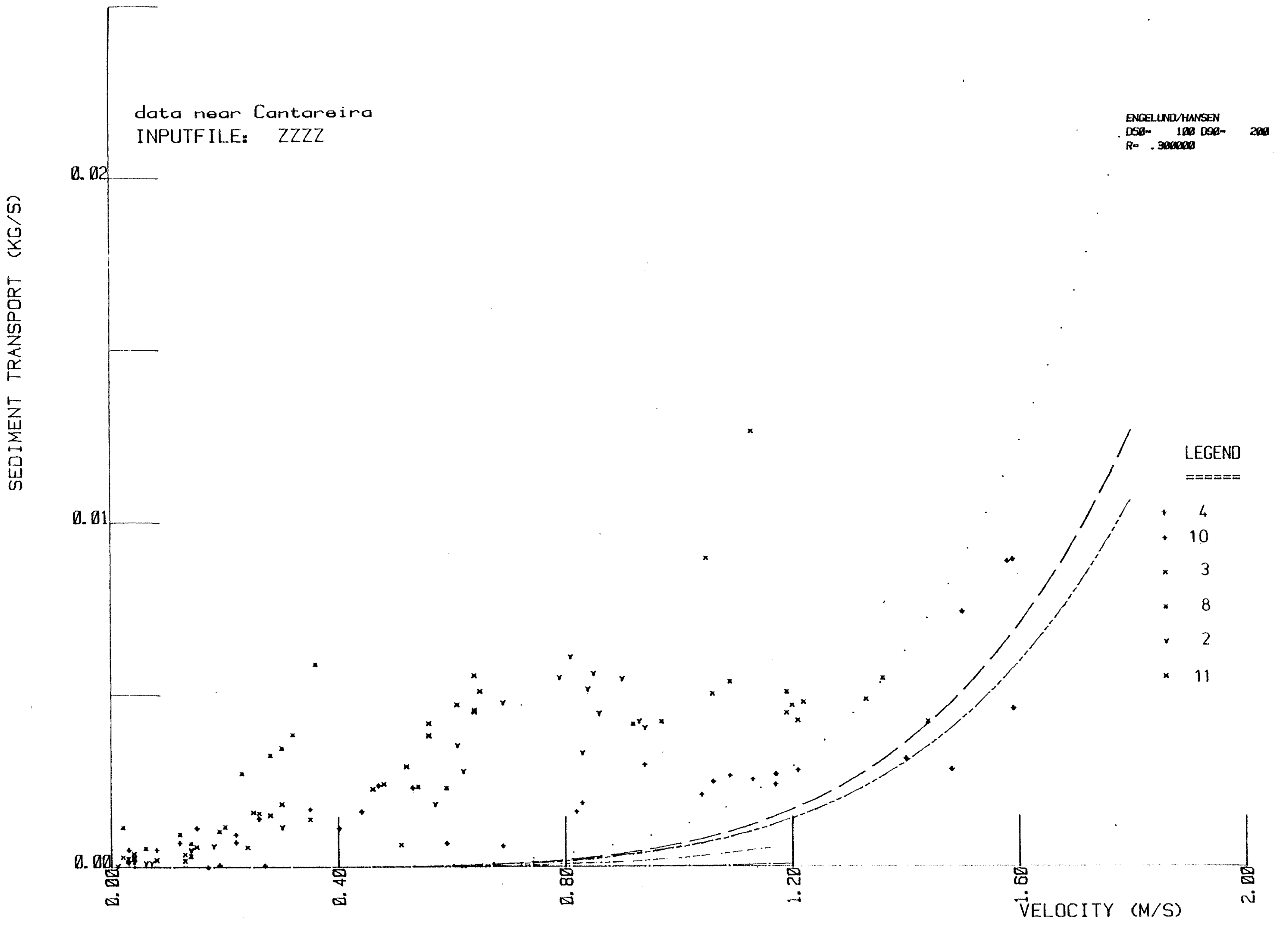

data near Cantareira
INPUTFILE: ZZZZ
ENGELUND/HANSEN
D50= 100 D90= 200
R= .300000
SEDIMENT TRANSPORT (KG/S)
0.02
0.01
0.00
0.00
0.40
0.80
1.20
1.60
2.00
VELOCITY (M/S)
LEGEND
======
+ 4
◆ 10
x 3
x 8
Y 2
x 11

FIGURE 29

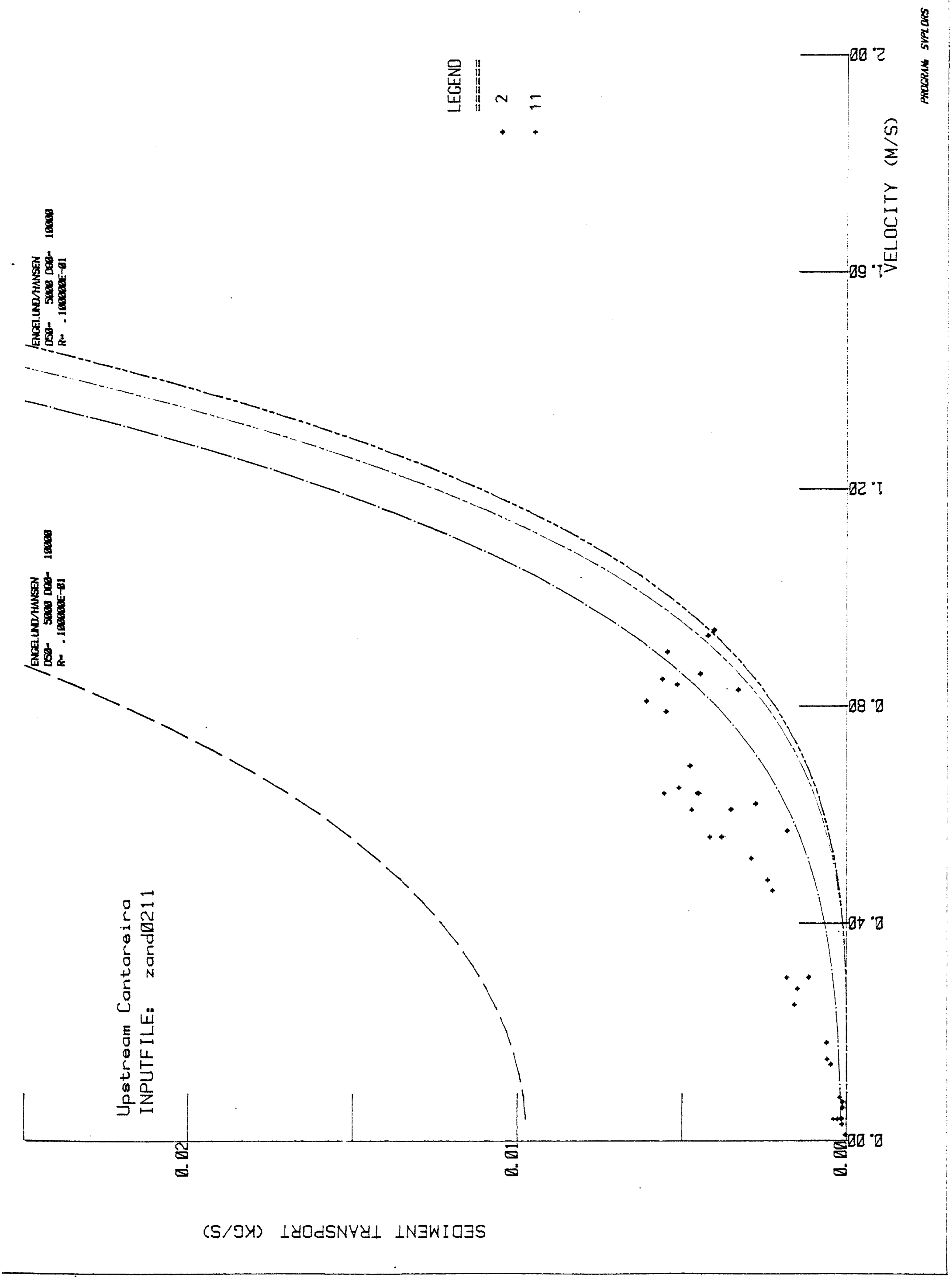

Upstream Cantareira
INPUTFILE: zand0211
ENGELUND/HANSEN
D50= .5000 D90= .10000
R= .100000E-01
ENGELUND/HANSEN
D50= .5000 D90= .10000
R= .100000E-01
LEGEND
======
2
11
SEDIMENT TRANSPORT (KG/S)
0.00
0.01
0.02
VELOCITY (M/S)
0.00
0.40
0.80
1.20
1.60
2.00
PROGRAM: SYPLORS

FIGURE 30

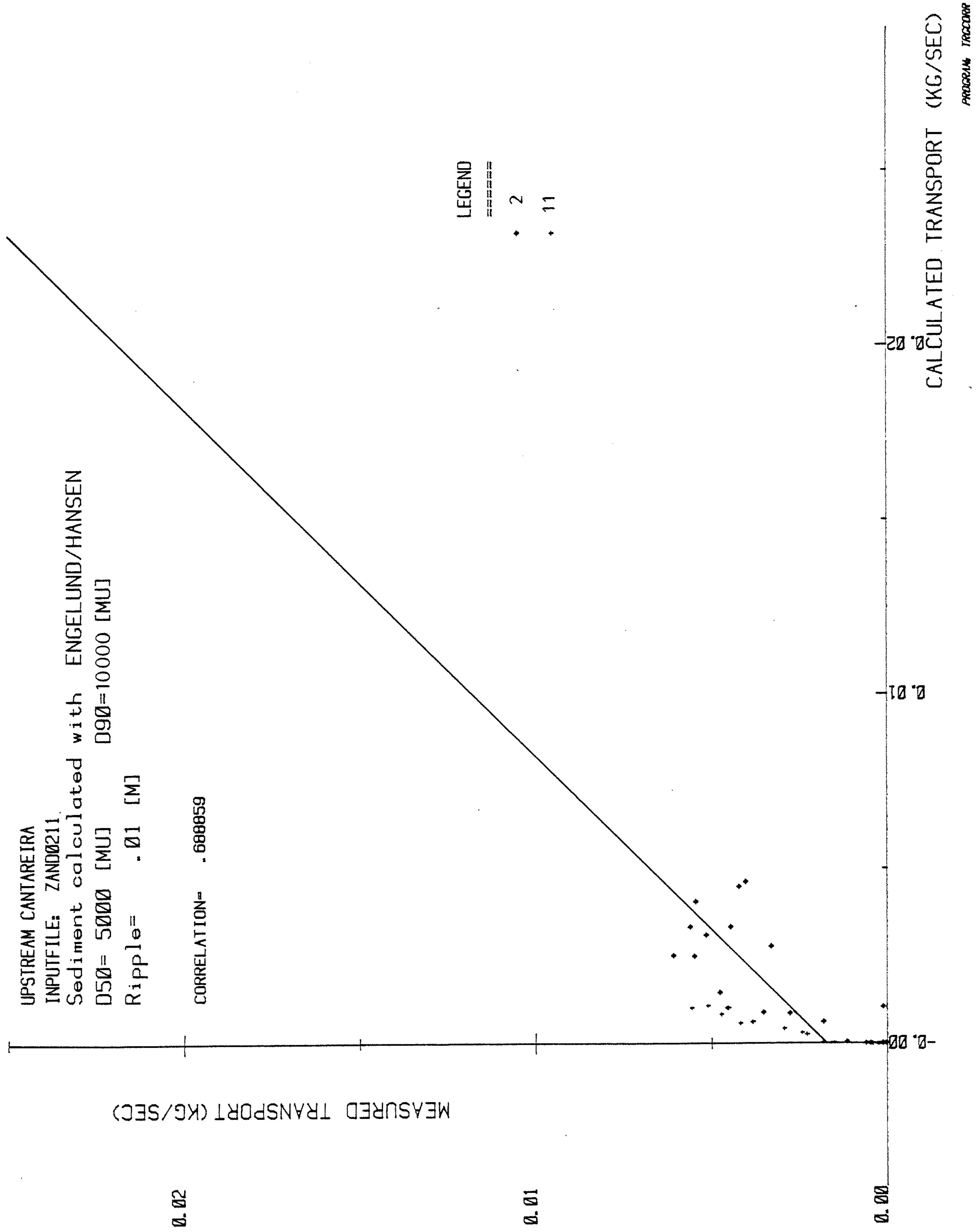

UPSTREAM CANTAREIRA
INPUTFILE: ZAND0211
Sediment calculated with ENGELUND/HANSEN
D50= 5000 [MU] D90=10000 [MU]
Ripple= .01 [M]
CORRELATION= .688859
LEGEND
======
2
11
CALCULATED TRANSPORT (KG/SEC)
MEASURED TRANSPORT (KG/SEC)
0.00
0.01
0.02
0.00
0.01
0.02
PROGRAM TRCORR

FIGURE 31

FIGURE 32

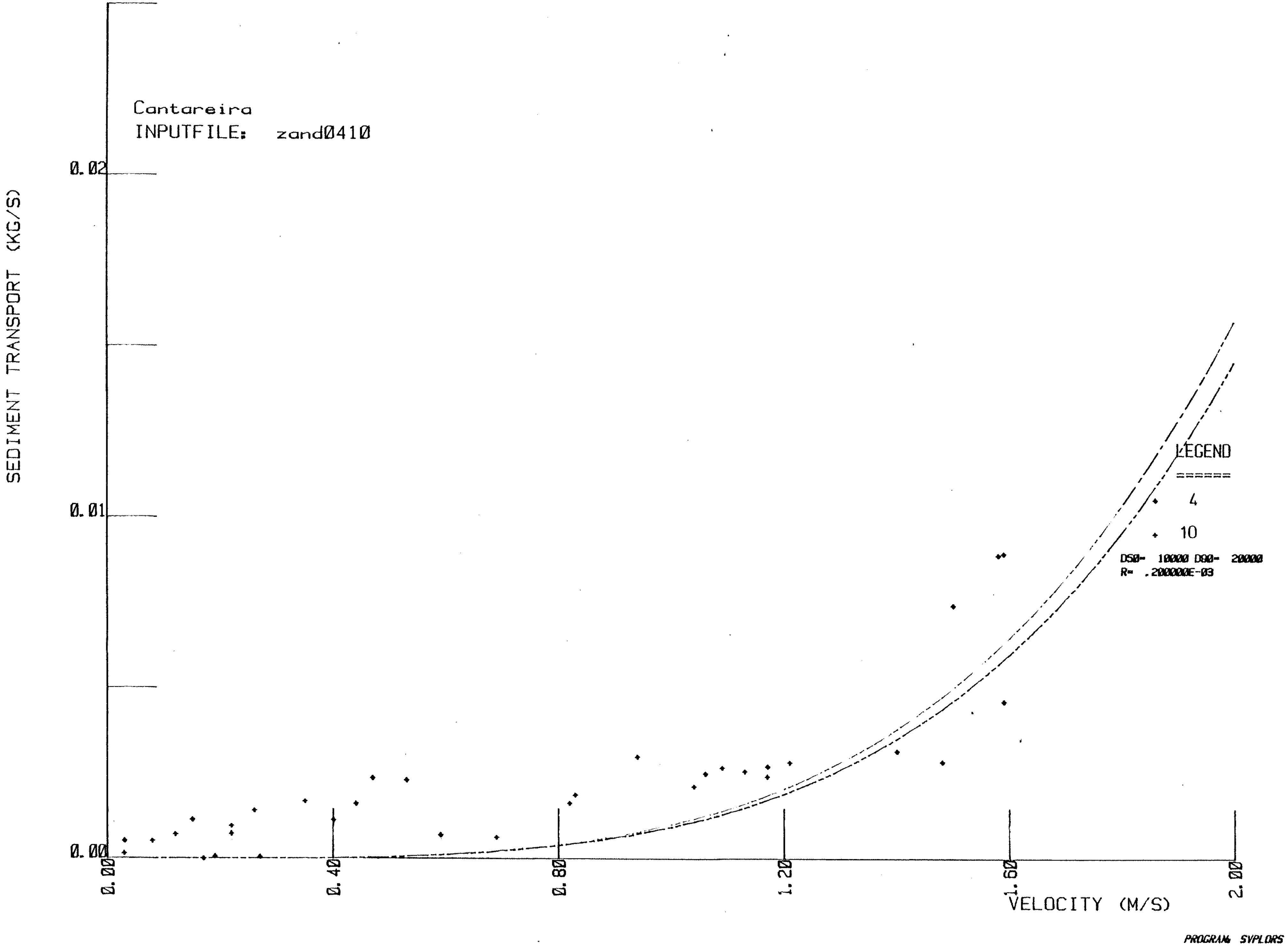

Cantareira
INPUTFILE: zand0410
SEDIMENT TRANSPORT (KG/S)
0.02
0.01
0.00
0.00
0.40
0.80
1.20
1.60
2.00
VELOCITY (M/S)
LEGEND
======
4
10
D50= 10000 D90= 20000
R= .200000E-03
PROGRAM: SVPLORS

FIGURE 33

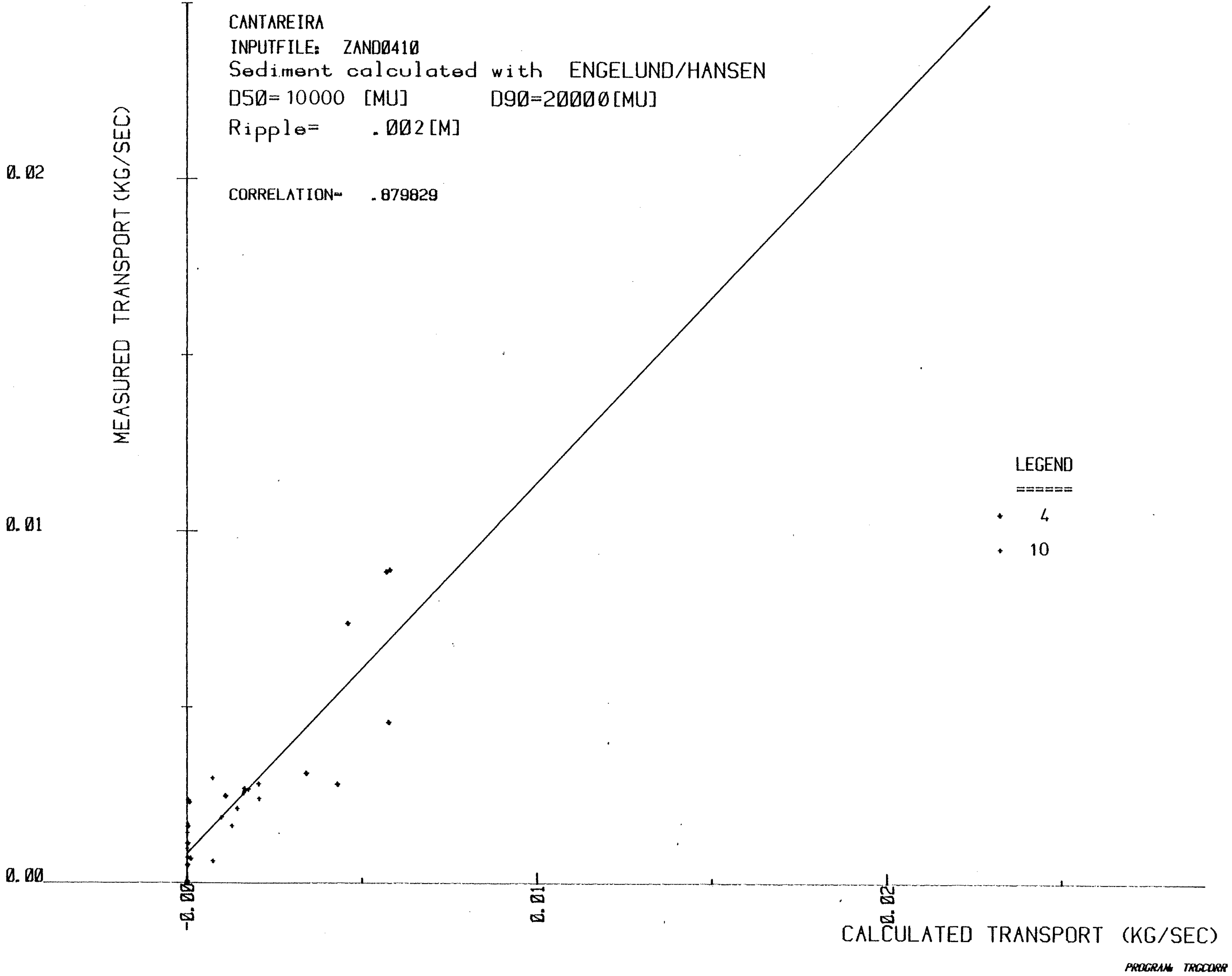
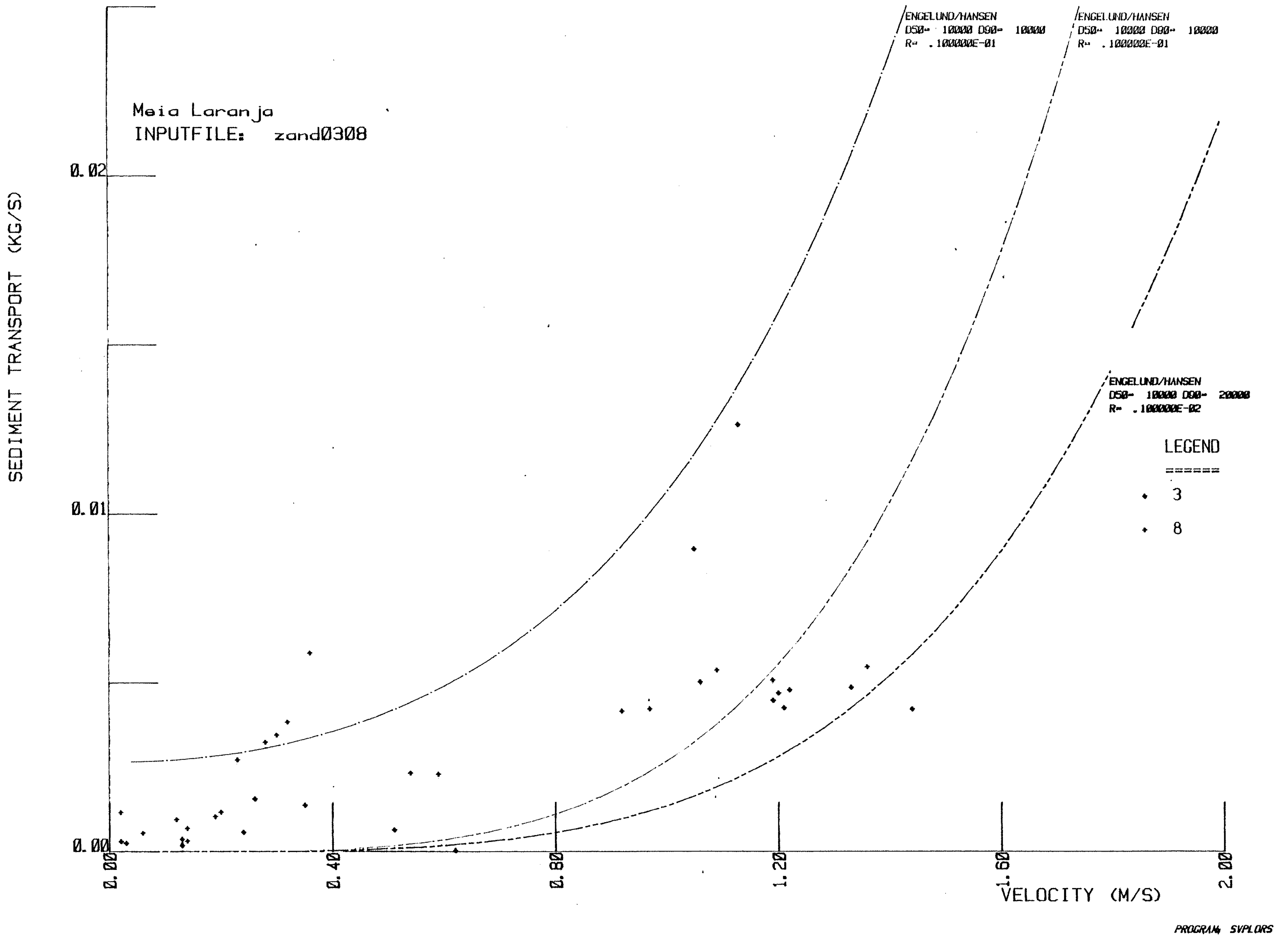

CANTAREIRA
INPUTFILE: ZAND0410
Sediment calculated with ENGELUND/HANSEN
D50= 10000 [MU] D90=20000 [MU]
Ripple= .002 [M]
CORRELATION= .879829
MEASURED TRANSPORT (KG/SEC)
0.02
0.01
0.00
-0.00
0.01
0.02
CALCULATED TRANSPORT (KG/SEC)
LEGEND
======
+ 4
+ 10
PROGRAM: TRGCORR

FIGURE 34


Meia Laranja
INPUTFILE: zand0308
SEDIMENT TRANSPORT (KG/S)
0.02
0.01
0.00
0.00
0.40
0.80
1.20
1.60
2.00
VELOCITY (M/S)
ENGELUND/HANSEN
D50= 10000 D90= 10000
R= .100000E-01
ENGELUND/HANSEN
D50= 10000 D90= 10000
R= .100000E-01
ENGELUND/HANSEN
D50= 10000 D90= 20000
R= .100000E-02
LEGEND
======
3
8
PROGRAM: SVPLORS

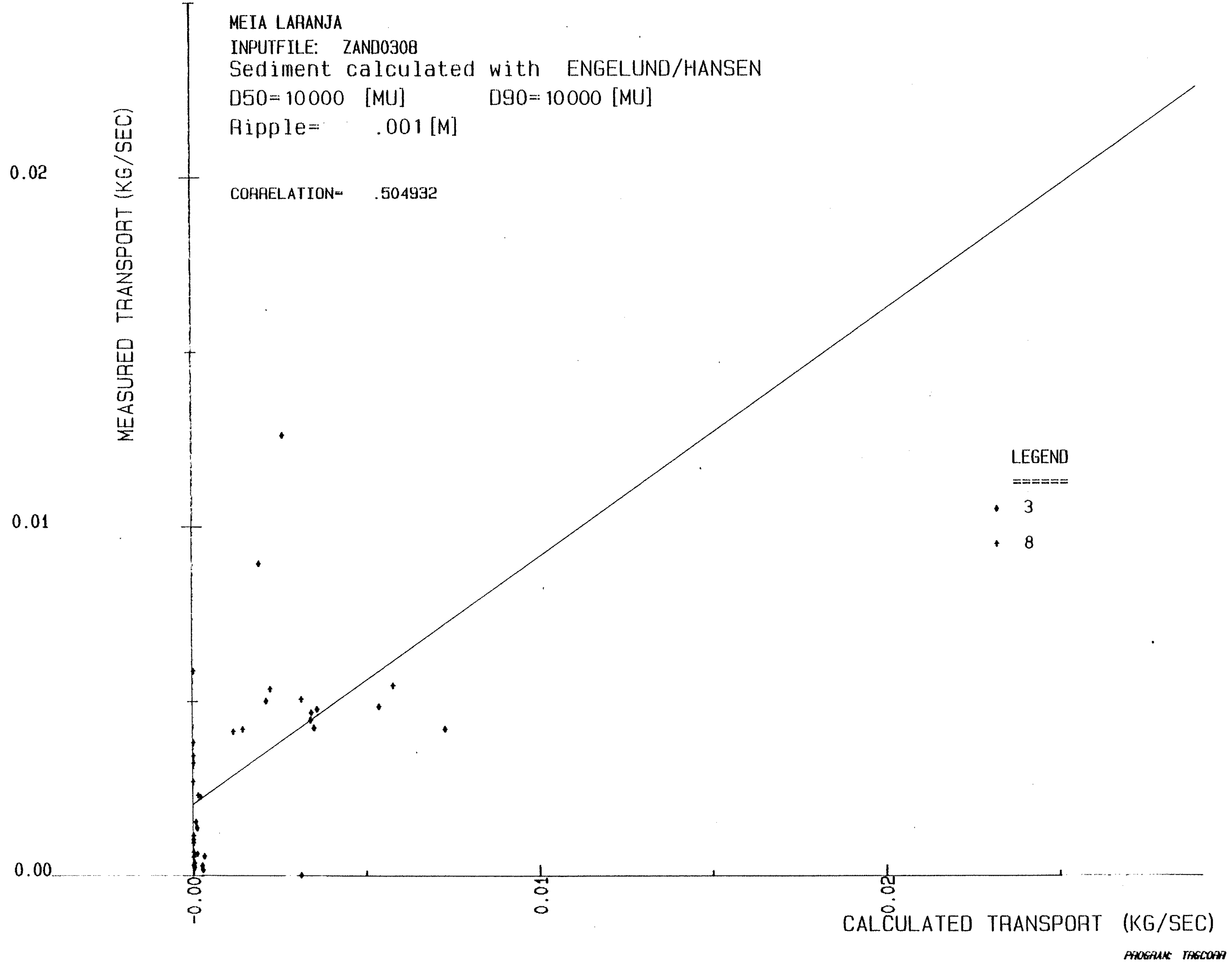

MEIA LARANJA
INPUTFILE: ZAND0308
Sediment calculated with ENGELUND/HANSEN
D50=10000 [MU]
D90=10000 [MU]
Ripple= .001 [M]
CORRELATION= .504932
MEASURED TRANSPORT (KG/SEC)
0.02
0.01
0.00
-0.00
0.01
0.02
CALCULATED TRANSPORT (KG/SEC)
LEGEND
======
3
8
PROGRAM: TRGCORR

FIGURE 35

FIGURE 36

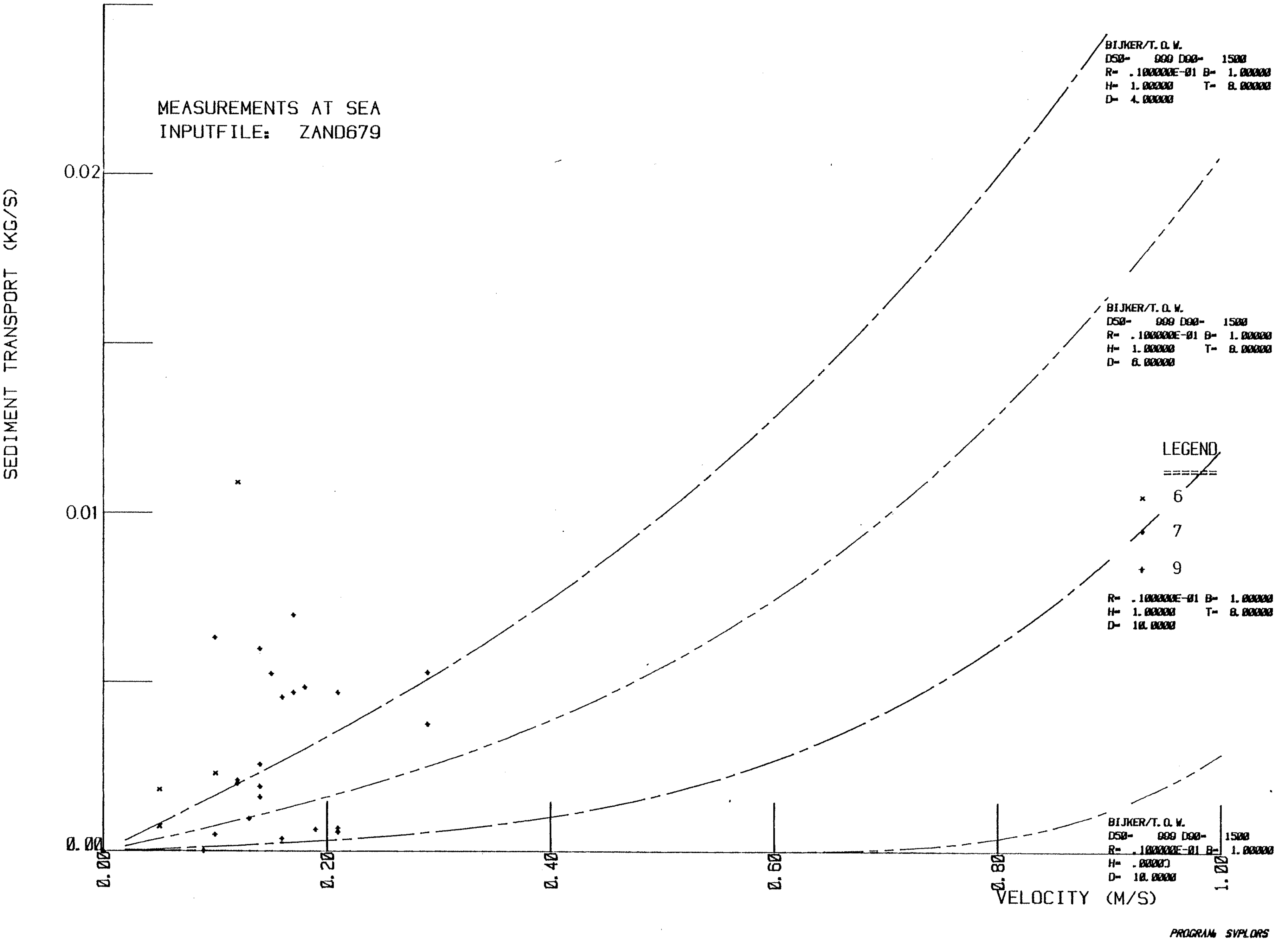
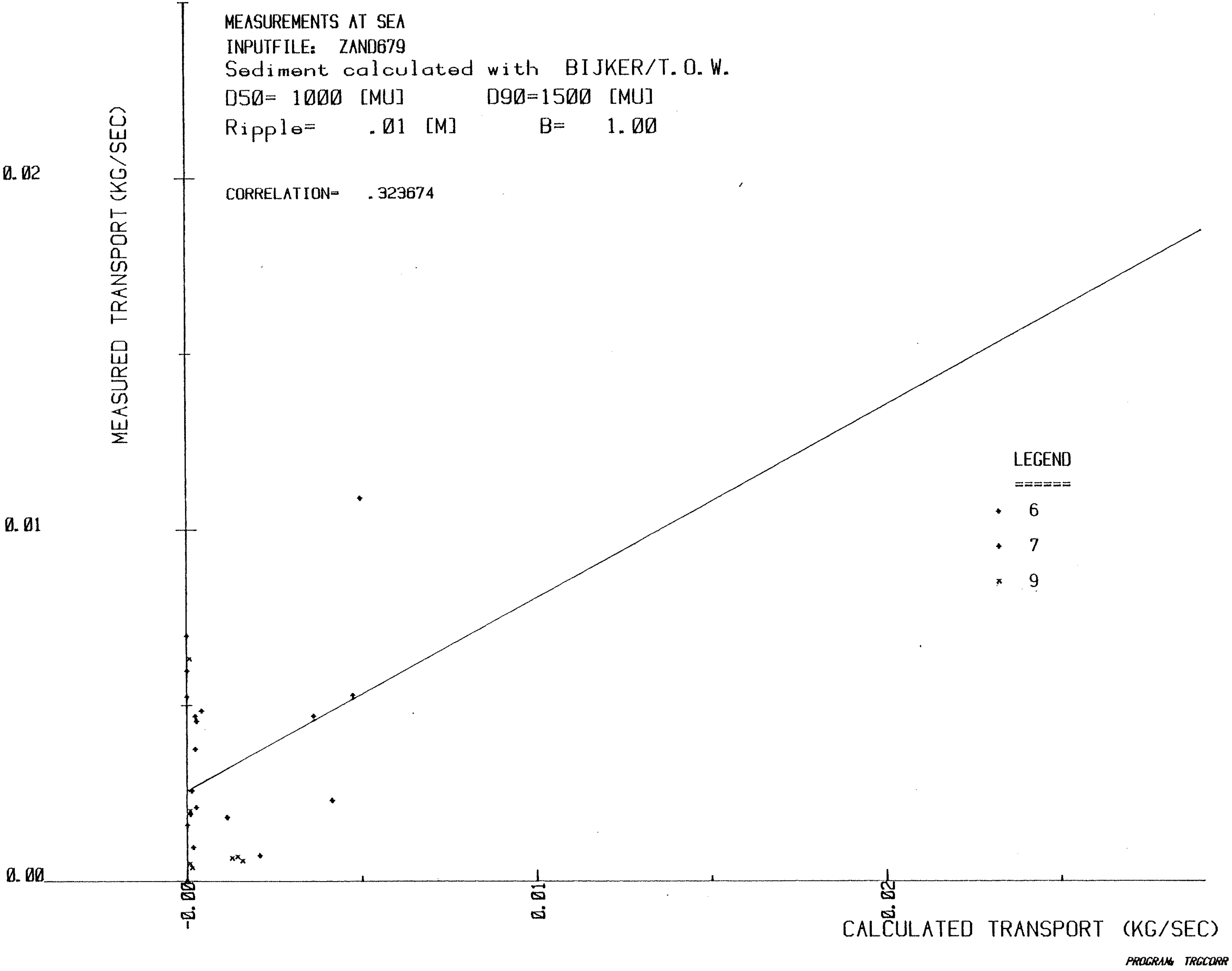

MEASUREMENTS AT SEA
INPUTFILE: ZAND679
SEDIMENT TRANSPORT (KG/S)
0.02
0.01
0.00
0.00
0.20
0.40
0.60
0.80
1.00
VELOCITY (M/S)
BIJKER/T.O.W.
D50= 999 D90= 1500
R= .100000E-01 B= 1.00000
H= 1.00000 T= 8.00000
D= 4.00000
BIJKER/T.O.W.
D50= 999 D90= 1500
R= .100000E-01 B= 1.00000
H= 1.00000 T= 8.00000
D= 6.00000
LEGEND
======
× 6
♦ 7
+ 9
R= .100000E-01 B= 1.00000
H= 1.00000 T= 8.00000
D= 10.0000
BIJKER/T.O.W.
D50= 999 D90= 1500
R= .100000E-01 B= 1.00000
H= .00000
D= 10.0000
PROGRAM: SVPLORS

FIGURE 37


MEASUREMENTS AT SEA
INPUTFILE: ZAND679
Sediment calculated with BIJKER/T.O.W.
D50= 1000 [MU] D90=1500 [MU]
Ripple= .01 [M] B= 1.00
CORRELATION= .323674
MEASURED TRANSPORT (KG/SEC)
0.02
0.01
0.00
-0.00
0.01
0.02
CALCULATED TRANSPORT (KG/SEC)
LEGEND
======
6
7
9
PROGRAM: TRGCORR

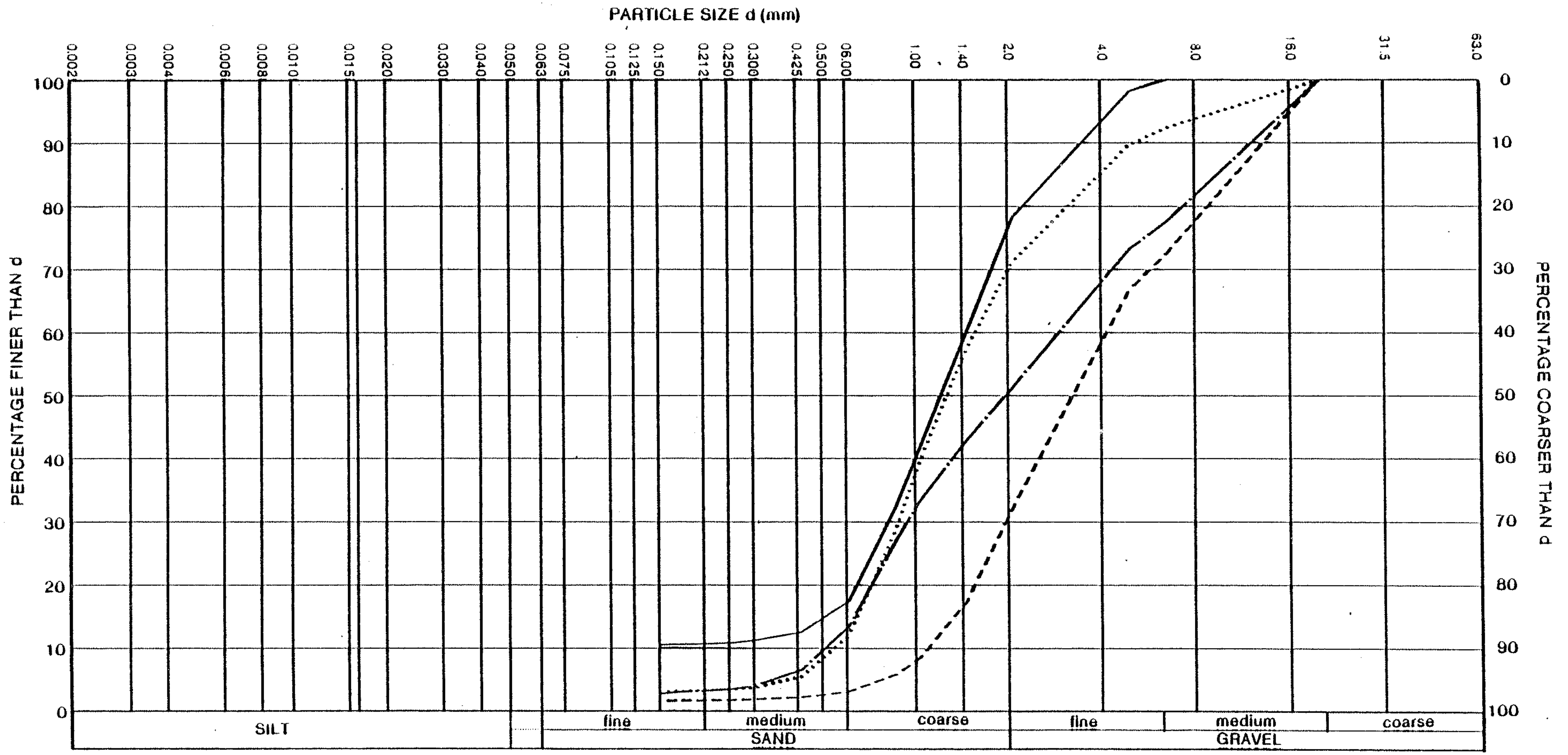


FIGURE 38: SIEVE ANALYSIS FROM DOURO (BETWEEN PORTO AND CRESTUMA)

INDICATION	BOR. NO.	SAMPLE NO. /DEPTH [m]	D10 um.	D20 um.	D30 um.	D40 um.	D50 um.	D60 um.	D70 um.	D80 um.	D90 um.	D90/D10 --	D60/D10 --	DMF um.	U- NO.	WGT. % < 50um	16um	2um
————		1/	---	632	796	972	1174	1418	1713	2162	3332	--	--	---	11	10.5	--	--
- - - - - -		2/	1064	1501	1892	2420	3109	3995	5500	8420	12665	11.9	3.8	4507	9	1.6	--	--
···········		3/	535	702	858	1014	1231	1518	1942	3011	4848	9.1	2.8	1740	12	3.2	--	--
—·—·—		4/	501	704	915	1276	1896	2811	4158	6980	11531	23.0	5.6	3419	14	2.8	--	--

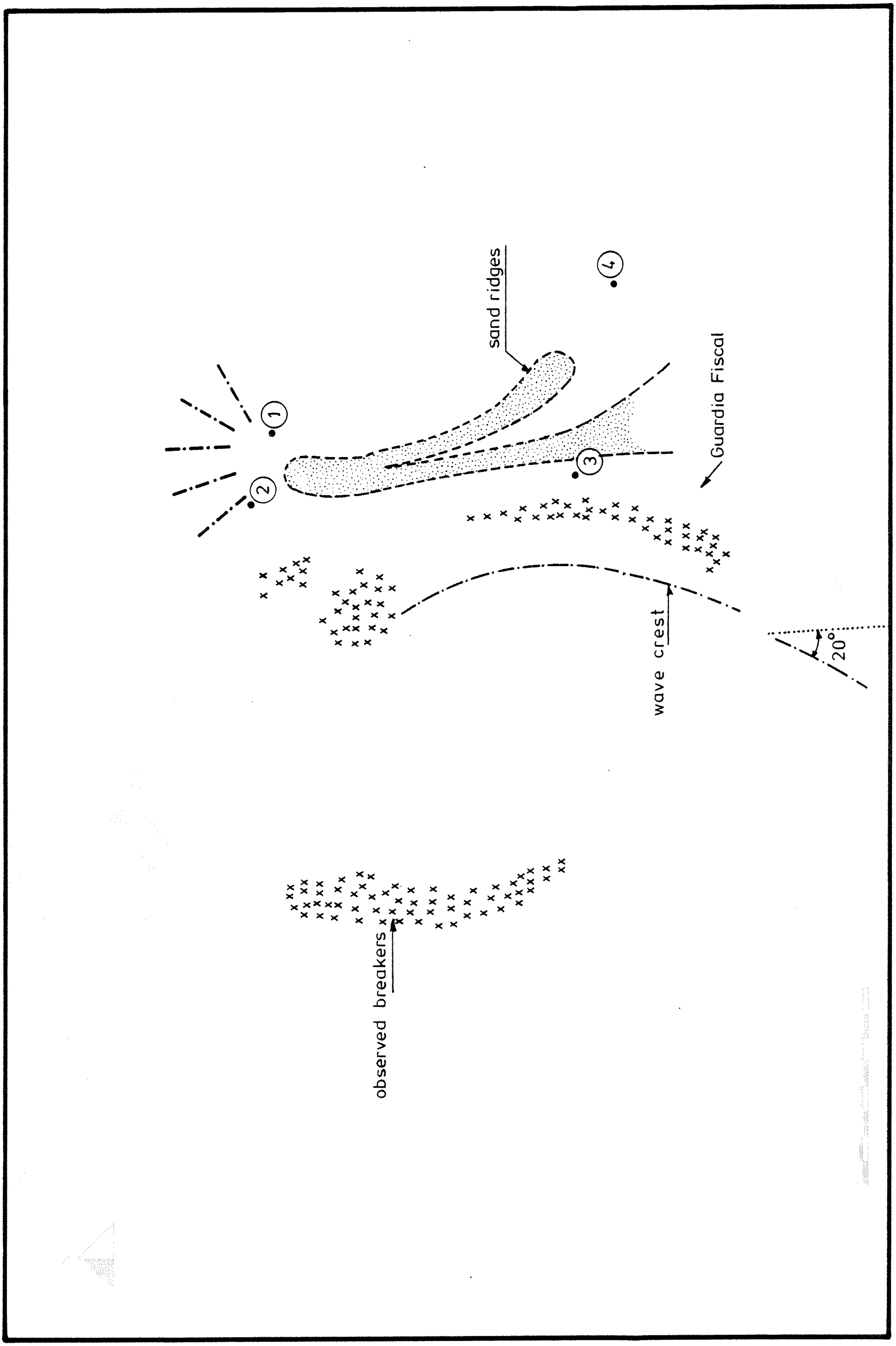


FIGURE 39 : *VISUAL OBSERVATIONS.*

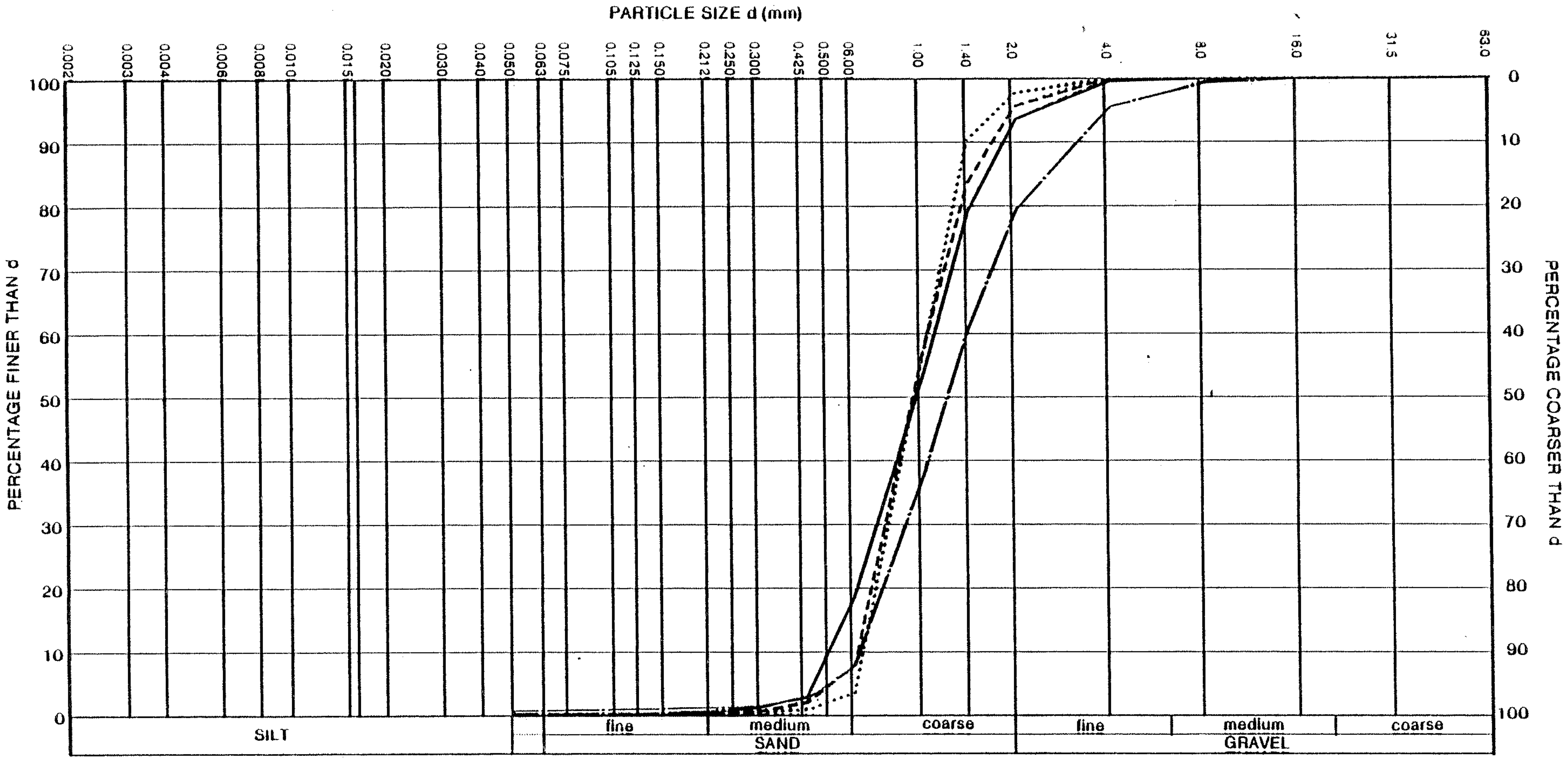


FIGURE 4.0: SIEVE ANALYSIS FROM SEVERAL POINTS ALONG THE CABEDELO.

INDICATION	BOR. NO.	SAMPLE NO. /DEPTH [m]	D10 um.	D20 um.	D30 um.	D40 um.	D50 um.	D60 um.	D70 um.	D80 um.	D90 um.	D90/D10 --	D60/D10 --	DMF um.	U- NO.	WGT.% < 50um	16um	2um
———————		1/	496	613	710	823	953	1091	1243	1430	1832	3.7	2.2	1021	13	--	--	--
- - - - - - -		2/	614	681	756	839	930	1040	1180	1340	1696	2.8	1.7	1008	12	--	--	--
···········		3/	639	704	775	854	941	1037	1145	1264	1396	2.2	1.6	973	11	--	--	--
——·——		4/	624	740	878	1036	1196	1382	1669	2054	3156	5.1	2.2	1415	11	0.8	--	--

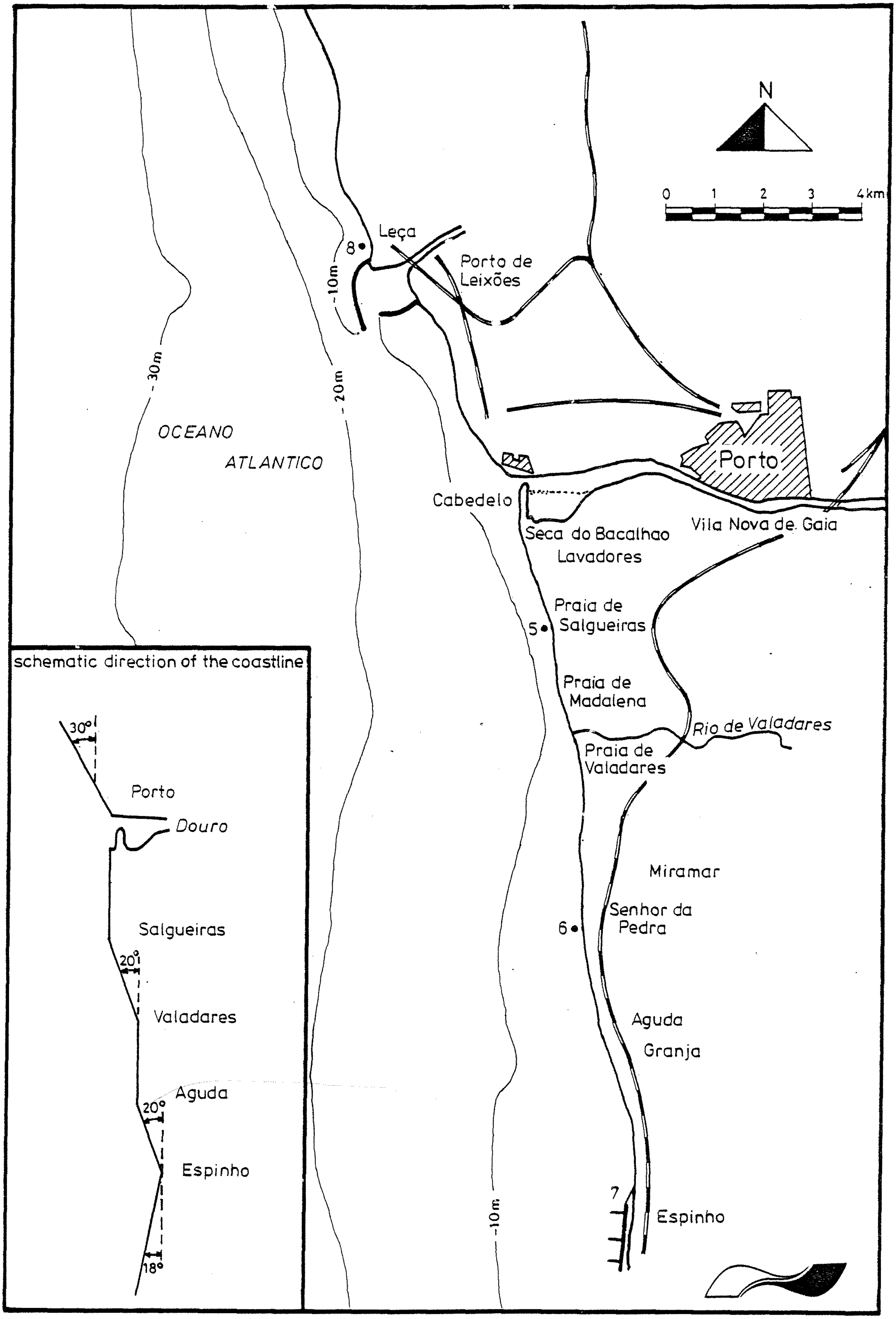


FIGURE 41: *THE COAST SOUTH OF PORTO.*