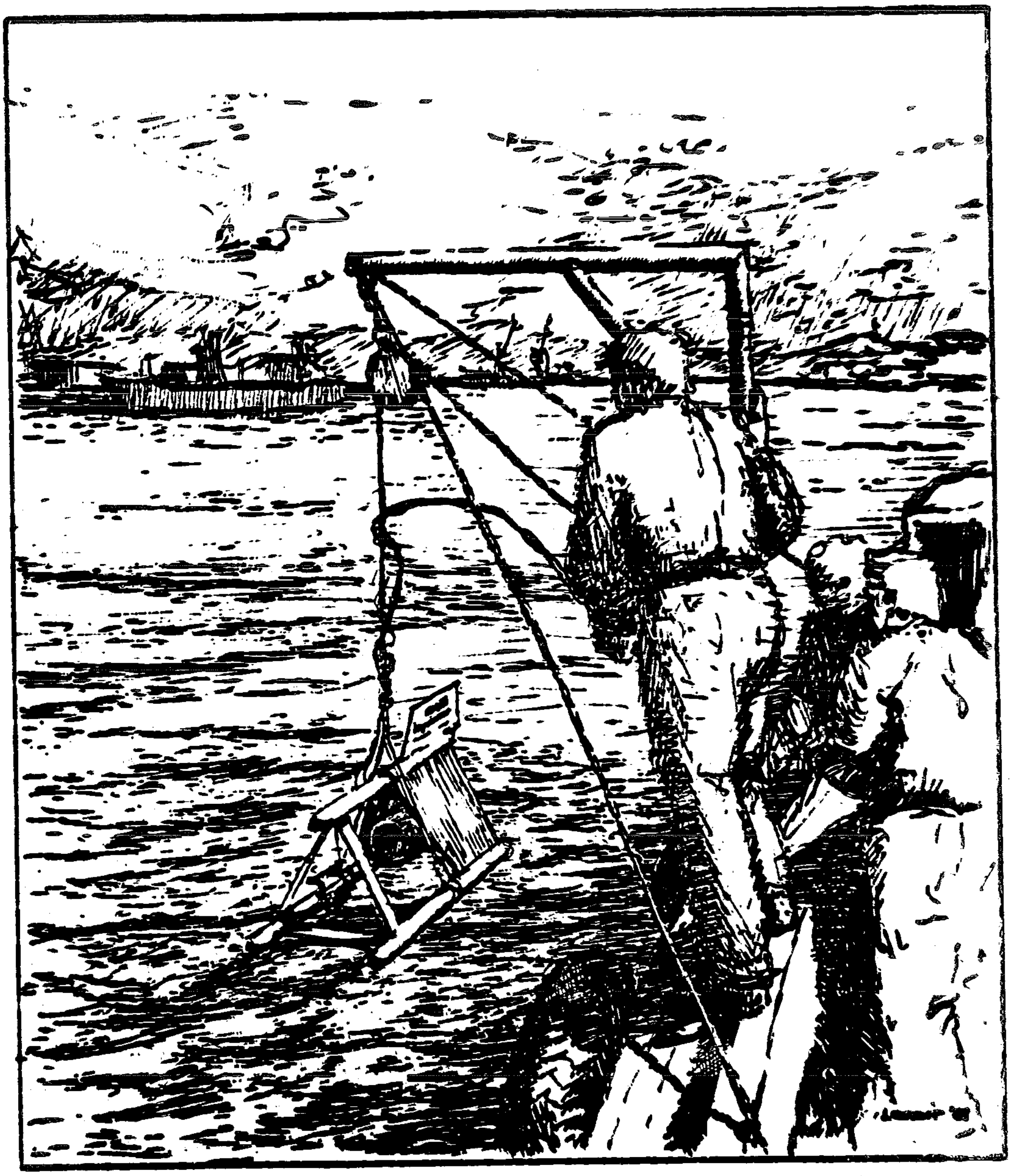
Verhagen

QUIMIGAL, QUIMICA DE PORTUGAL

Hydro - morphological study part I Results of measurements



November 1981 / P 405

PORT AND WATERWAY ENGINEERS

hydronamic bv
sliedrecht holland

QUIMIGAL, QUIMICA DE PORTUGAL

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hydronamic bv

1. INTRODUCTION

The access channel to the newly build liquid terminal of Quimigal, Portugal is expected to be deepened in the near future. Quimical invited Hydronamic B.V. to study the erosion and sedimentation behaviour along the access channel and prospect the changes thereof in case the channel will be deepened.

This report deals with the calibration of existing morphological formulae for the area concerned in the Tagus Estuary. The calibration is based on field measurements in the Estuary which were executed in the period from November 9th until November 14th, 1981.

For these measurements the Hydronamic Sediment Transport Meter has been used. The other equipment, the survey-vessel and the crew were supplied by Hidrotop Lta, Lisbon, Portugal. The operation was supervised by Mr. A.C. Starink from Hydronamic B.V.

The present report gives a short description of the equipment used and the measuring campaign. The results are analysed and discussed in chapter 4 and 5. Conclusions of this report are given in chapter 6. In the annex to this report the registrations are presented.

In a succeeding report the siltation aspects will be discussed.

2. CALIBRATION OF SEDIMENT TRANSPORT FORMULAE

2.1. Introduction

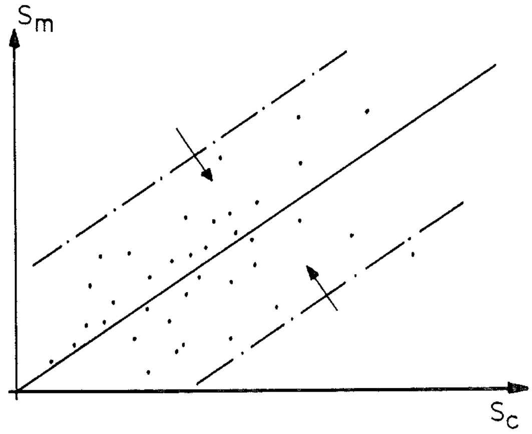
The main function of the Hydronamic mathematical morphological model is the calculation of sediment transport. It predicts changes in waterdepth by calculating the total quantity of sediment which is coming into, and going out of a given square in the modeled area, and this during a certain time. Many different formulae have been developed for sediment transport. These can be divided into two groups: formulae for transport caused by currents only, and formulae for transport caused by both currents and waves.
If we disregard the wave-influence for the time being, nearly all formulae for sediment transport can be simplified as

$$s=A\ v^{B}$$

in which s= sediment and v= velocity. The coefficients A and B depend on many factors, such as waterdepth, bottom-irregularities (roughness), grain-size etc.
Every scientist has his own methods for calculating the coefficients (A + B) and they tend to vary considerably. There seems to be no uniform method for calculating A and B at the moment.

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.

As soon as the line is at 45° through the origin, the result is satisfactory. After that be 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:

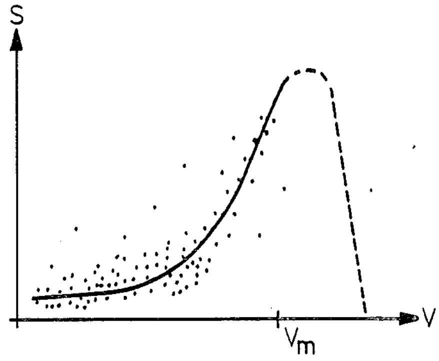
  * Bijker
  * Ackers/White
  * Engelund/Hansen
  * Meyer-Peter/Müller
  * Yalin

- completely empirical formulae:

  * polynomials : $S = a.v + b+v + c+v^2 + d.v^3 + \dots\dots\dots$
  * power function: $S = a.v^b$

In the latter two formulae waterdepth 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 coefficients A and B can be found by mathematical curve fitting. This means that, the best fit polynomial 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 in adjacent 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 v_m, 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 better to use formulae, which also have a physical background, in order in order to prevent this kind of problem.

If waves are also important, it is better to measure during periods of different wave-heights. This is however, not so simple.
Waterdepth 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 affect the transport velocity, but there is usually a higher concentration of suspended material, so that more sediment is transported. Of course only if the waves are high enough to cause orbital movement along the bottom will sediment be stirred up into suspension.
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 sediment transport.

The direction of the waves does not affect their 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.

The mathematical morphological model uses as input data:

- waterlevels } derived from a hydraulic (current) model,
- velocities } either mathematical or physical.
- wave data - derived from measurements and/or a wave model
- a correct transport formulae, calibrated as described above.

Water levels and velocity data from the current model were calibrated in the current model. These results may therefore be regarded as correct. The same is valid for the wave data. Calibration of the transport-formulae is described above. It is very important to note that the sediment transport measurements are not carried out for calibration of the mathematical morphological model as a whole.

This method of calibrating needs fewer measurements which is a district advantage. A large number of transport measurements are needed to calibrate the whole morphological model. Five or six measurements are certainly not enough.

More attention would also have to be paid to seasonal influences, meaning measurements would have to be taken regularly throughout the year.

3. DESCRIPTION OF MEASUREMENTS

In the period from November 9th until November 14th, 1981, the following measurements have been carried out:

	location number	coordinates	number of registrated profiles
1. November 9th, 1981	no. 2	115.880 E 190.350 N	18
2. November 10th, 1981	no. 4	117.420 E 189.850 N	18
3. November 11th, 1981	no. 3	117.450 E 191.420 N	18
4. November 12th, 1981	no. 6	122.360 E 191.780 N 122.320 E** 191.800 N	18
5. November 13th, 1981	no. 5	114.280 E 191.180 N	18

* The locations are plotted on fig. 1

** On November 12th, the survey-vessel shifted approx. 50 m from her original position. In this case two positions are recorded.

In total 90 profiles were registrated. The results of these measurements are presented in the Annex of this report.
The locations were all chosen in such a way that a representive picture of the sediment movement could be obtained. The measurements of the profiles were carried out every half hour during 9-10 hours of the day. The measurements on all five locations cover nearly one tidal cycle.

Originally one location, location no. 1, was planned in front of liquid terminal (see fig. 1). During the measuring campaign a bucket dredge was dredging on this location. As the measurement should be useless in this disturbed water, a new location was selected approx. 2 km east of the original location.

The shifting of location number 4 will not have any repercussions on the calibration of the formulae. So all data are taken into account.

During the measuring period only small waves occured so it was not possible to get a good impression of the influence of wave-action on the sediment transport.

Further more it should be noted that the campaign was executed in one of the most dry summers of the past 20 years.

For calibration one watersample has been taken at a depth of 2.5 m from the watersurface at all five locations. On location no. 2 and no. 3 an additional bottom sample have been taken.

4. ELABORATION OF THE RESULTS

4.1. General

With use of the labortory-results of the watersamples it was possible to determine the relation between the data gathered in the field and the real concentration. It proved that there is a significant difference in the sediment for point 2 and 5, comparing them with sediment from the points 3, 4 and 6. This difference is probably not a difference in grainsize, but in color, shape and texture. All data were processed on one of our HP3000-computers and in the Annex to this report the results of the processing are presented. Each page represents one half-hour measurement. In this Annex, three histograms are given. The measured velocity, the measured concentration and the product of velocity and concentration, being the sediment-transport, are given as a function of depth. At the bottom of each page, information regarding the waves and the tide is given. Also the average waterdepth, velocity and concentration is presented. Finally the total sediment transport in kg/m^3 per m is given.

In this way 90 values of measured transport have been determined. A statistical analysis has been done on this 90 values. The measured data are compared with the results of calculations with widely used transport formulae, such as Bijker/Einstein, Ackers/White, Engelund/Hansen and Meyer-Peter/Müller. Also a fully empirical formula (polynome) using the least-square method, has been determined.

Initial tests showed that only the Bijker-Einstein formula gives reasonable results. The correlation between measured transport and calculated transport is for the other three semi-theoretical formulae less than 60%. This is conform our experience with similar tests in this area.

4.2. Bijker/Einstein formula

The computer program for the determination of the coefficients indicated that a fictive D50 and D90 of 5 μ, 25 μ, together with a B-factor of 5 and a ripple of 0.075 m results in the best correlation. In table I the correlation-calculations are presented. Besides the already mentioned Bijker/Einstein formula, also some calculations were made with the Bijker/T.O.W. formula. It seems that this second formula gives approx. the same results as the Bijker/Eistein formula. Also in table I the results of a calculation in which the wave-height is set to zero is presented, as well as a comparison of the new data with previous measurements. In fig. 2 a plot of all the measured data is presented as a function of the velocity. Also 3 lines are drawn, these lines give the calculated transport for three different waterdepths, also as function of the velocity. In fig. 3 the measured data are plotted as a function of the calculated data. The ideal relation is that all points are placed on a line which goes at an angle of 45° through the origin. As can be seen the best-fit line through all points is quite reasonable, and also a correlation coefficient of 71% is sufficiently high.

4.3. Polynome

Two least-square optimizations, one for a straight line and one for a parabolic function. This resulted in

$$s = -0.052 + 0.28\ v \qquad \text{(correlation 37\%)}$$

and $$s = -0.26 + 1.81\ v - 1.64\ v^2 \qquad \text{(correlation 37\%)}$$

See also fig. 4,5 and 6. In these calculations the highest values of velocity and measured transport were omitted in order to improve the results. But as can be seen the results are still quite unsatisfactory.

4.4. Conclusions

It is clear that the Bijker/Einstein formula gives results with a sufficiently high correlation-coefficient. The polynome-method is unsatisfactory. The reason that the Bijker formula gives good results is that the influence of fine sediment is handled in a better-way. The Bijker formula will be discussed in more detail in the next chapter.

In the case of fine sediments, which is the case in the Tagus estuary the concentration is rather constant over the depth. In other words, the concentration of suspended material at a depth of two meters below the surface is nearly equal to the concentration at 4 meters below the surface. This can be seen very clearly in the results of the measurements.

The above implies that the total quantity of suspended material over one square meter of bottom is linear proportional to the waterdepth: for a waterdepth of 10 m, there is twice as much sediment as there is a waterdepth of 5 m.

Because sediment transport is the product of suspended mass and current velocity it means that at the same velocity, the sediment transport for a depth of 10 m is twice that for a depth of 5 m.
In fig. 2 this effect can be seen. For a velocity of 1 m/sec the transport in water of 5 m deep is 42 kg/sec, while in water of 10 m deep it is 84 kg/sec.

5. THE BIJKER/EISTEIN METHOD

With this method first the bottom transport is calculated. Then, in a second step the suspended transport is calculated as a function of the bottom transport.

The bottom transport is calculated by a formula developed by Bijker (1967) from the existing formula of Kalinske. Suspended transport is calculated with the so-called Eistein integration (Eistein, 1950).

First bottom transport is calculated according to Bijker:

$$s = b\ D_{50}\ \frac{v}{c}\sqrt{g}\ \exp\left[\frac{-0.27\ \Delta D_{50}\ C^2}{\mu v^2\ \{1 + \frac{1}{2}\ (\xi\frac{u}{v})^2\}}\right]$$

in which:

b	- Bijker parameter	Δ	- relative density of sediment
D_{50}	- median grainsize	u	- orbital velocity near the bottom
μ	- ripple factor	v	- current velocity
C	- Chézy-value	ξ	- stirring parameter

The value of S can be used as boundary value in the equation of Eistein to calculate suspended load.

$$S_s = \frac{0.73\ S}{K}\left[\text{Int1}\ \ln\left(\frac{33D_{50}}{r}\right) + \text{Int2}\right]$$

$$\text{Int1} = 0.216\ \frac{A^{(z_* - 1)}}{(1 - A)^{z_*}} \int_A^1 \left(\frac{1 - y}{y}\right)^{z_*} dy$$

$$\text{Int2} = 0.216 \frac{A^{(z_* - 1)}}{(1 - A)^{z_*}} \int_A^1 \left(\frac{1 - y}{y}\right)^{z_*} \ln y \, dy$$

in which:

$A = {}^{r}/_{D50}$

$z_* = \frac{W}{K} \frac{\tau}{\rho}$

W - fall velocity of particles

K - constant of Von Karman

The computer solves the integration with a special designed procedure, because normal numerical integration techniques give rather untrustworthy results for these types of intergrals. Two aspects of the Bijker-formula will be discussed more in detail, viz. the effect of waves and the effect of the grainsize.

In fig 7 and fig 8 a plot is given of the formula for various waves. It can be seen clearly that an increase of wave-height will also increase the transport, but only to a certain maximum. For water with a depth of 5 m one can see that waves of 1 m and more give always the same concentration. It is not possible to stir-up more material. The water is fully "saturated" with sediment. When the water is deeper, this "saturation-wave-height" is higher. Fig 8 shows that at 10 m depth the water is "saturated" at a wave-height of 1.5 m.

Fig 9 shows a plot of the Bijker-formula for different grainsizes. From this figure follows that with fine material the sediment transport is rather linear with the velocity. Also follows from fig 9 that, for fine material transport will never reach very high values.

To give some more insight a few computer calculations have been made which produce the same type of output as the elaboration of the measured data, viz. the vertical distribution of velocity, sediment concentration and sediment transport, all calculated with the theoretical formulae. The prints are presented at the end of this report (between the figures and the appendix).
In example 1 the distribution is given for sediment with a grainsize $d_{50}=100\mu$, for transport caused by current only.
In example 2 the same diagrams are given for waves of 2 m and 2 sec. As can be seen the influence of the waves is for both cases the same. because waves of 2 seconds cannot reach the bottom.
In example 3 the influence of a wave of 6 seconds is shown.
In example 3 there is a big wave influence since a 6 second wave has an influence on the bottom. One can see that the bedload transport is nearly the same, but the total load is thirty times as big as the transport is without waves. In examples 4 and 5 the same calculations have been made for very fine sediment of $d_{50}= 5\ \mu$. All other parameters used in this calculation are also equal to those giving the best results in the calibrated transport-formula. One can see that the concentration is very constant over the depth, the water is fully "saturated". But the total mass of sediment is very small. The total transport is now only 25% of the transport in case of course material. Comparison between examples 4 and 5 reveals that the presence of a wave hardly any influence on the vertical distribution of the concentration: due to the small grain size the water is already fully saturated without waves.

Also some measured situations have been recalculated according to the theory. One may compare them with the results of the measurements, as presented in the annex.

6. CONCLUSIONS AND RECOMMENDATIONS

From the measurements follows that sediment transport calculations should be carried out with the Bijker/Einstein (or Bijker/T.O.W.) method. The fictive grain size should be 5 μ and a bottom-roughness of 0.075 m has to be used. The correlation between calculated and measured transport is 71%.

The results found in this campaign can be used for sediment transport in morphological models.

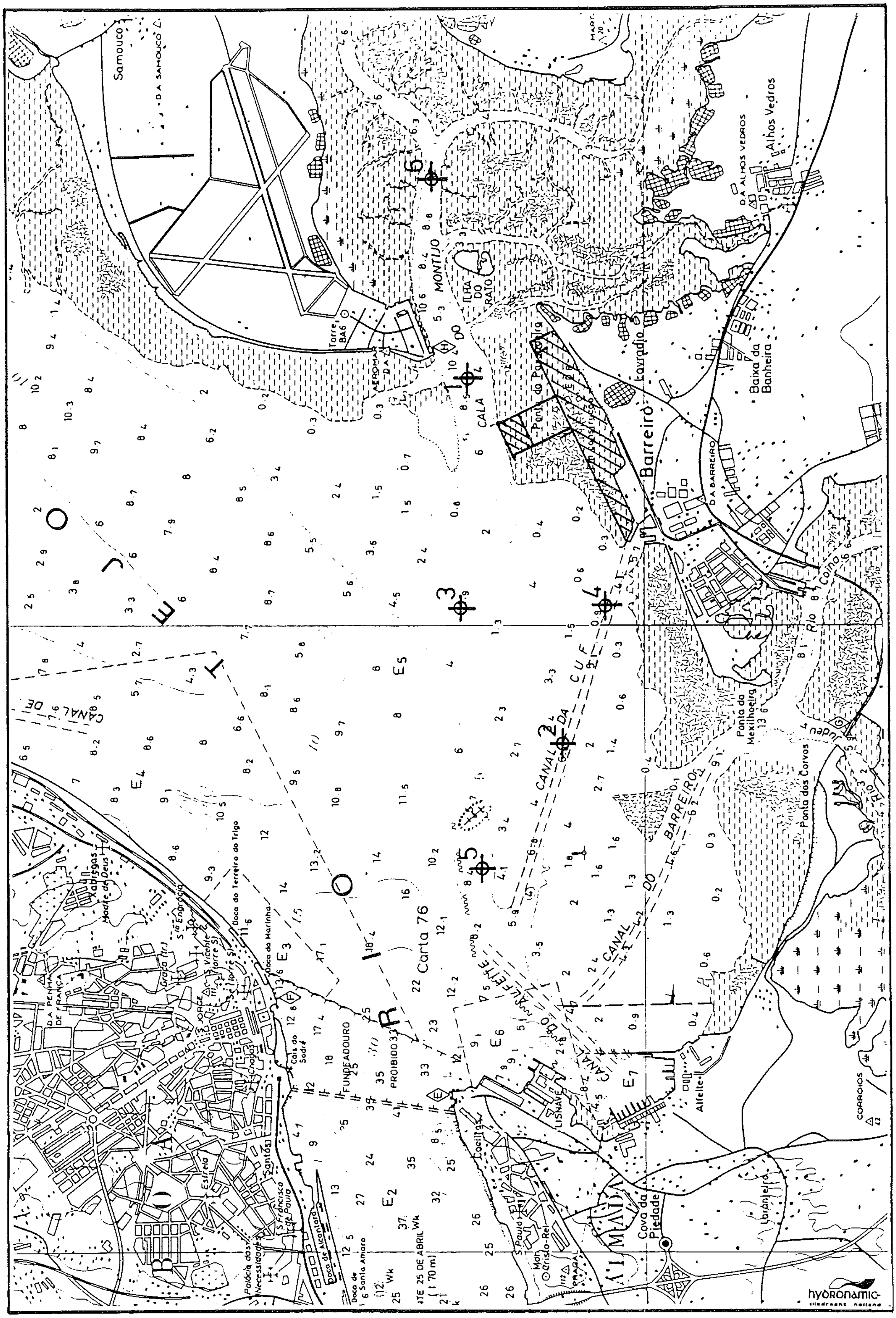

Samouco
Alhos Vedros
Baixa da Banheira
Barreiro
Lavradio
Ilha do Rato
Montijo
Carta 76
Canal da CUF
Canal do Barreiro
Ponta dos Corvos
Ponta da Mexilhoeira
Alfeite
Cova da Piedade
Cacilhas
Lisnave
Fundeadouro proibido
Ponte 25 de Abril
Doca de Alcântara
Doca do Terreiro do Trigo
Doca da Marinha
Cais do Sodré
Santos
Estrela
hydronamic

Figure 1.

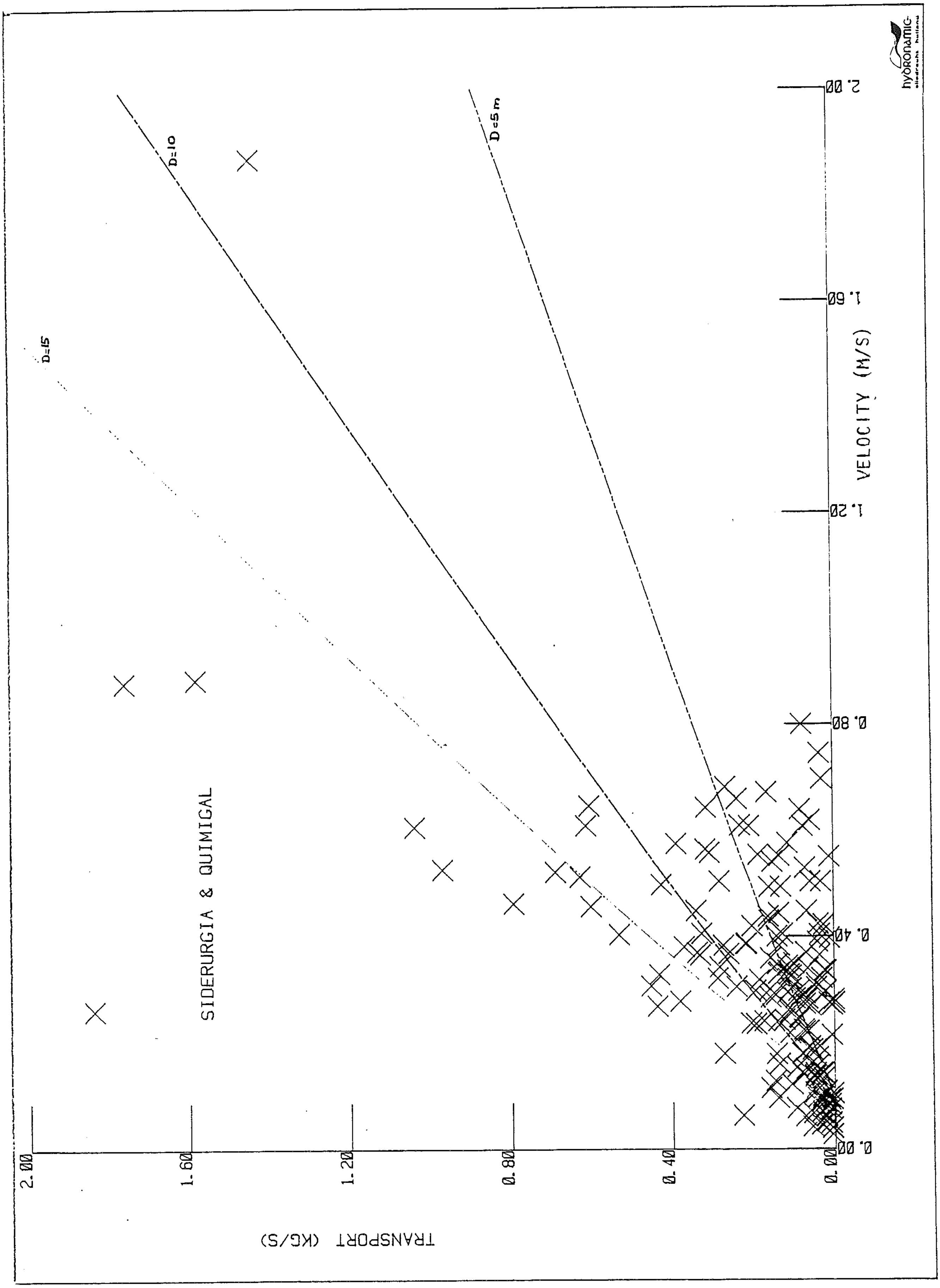

SIDERURGIA & QUIMIGAL
TRANSPORT (KG/S)
VELOCITY (M/S)
0.00
0.40
0.80
1.20
1.60
2.00
D=5m
D=10
D=15
hydronamic

Figure 2.

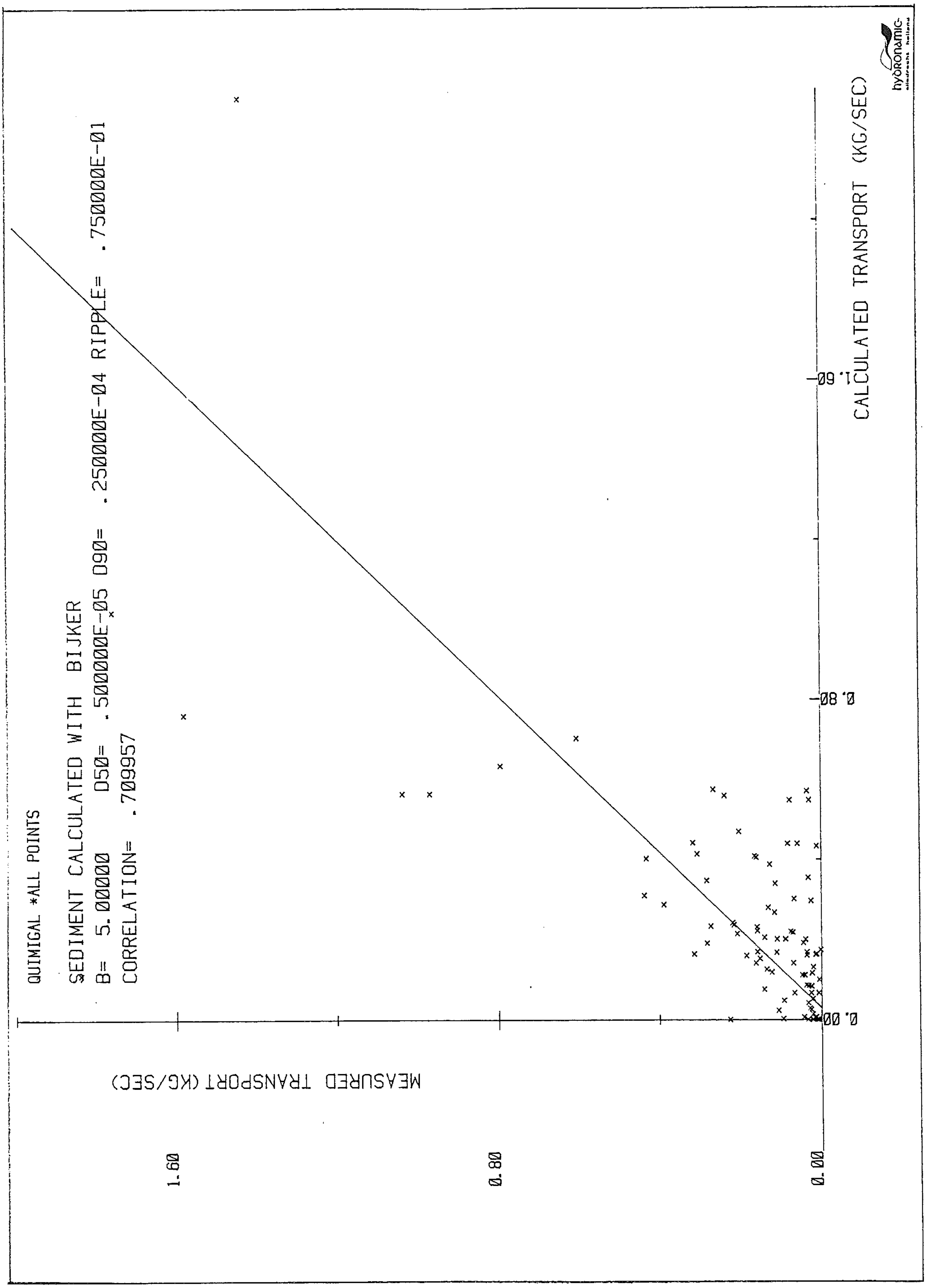

QUIMIGAL *ALL POINTS
SEDIMENT CALCULATED WITH BIJKER
B= 5.00000 D50= .500000E-05 D90= .250000E-04 RIPPLE= .750000E-01
CORRELATION= .709957
CALCULATED TRANSPORT (KG/SEC)
MEASURED TRANSPORT(KG/SEC)
0.00
0.80
1.60

Figure 3.

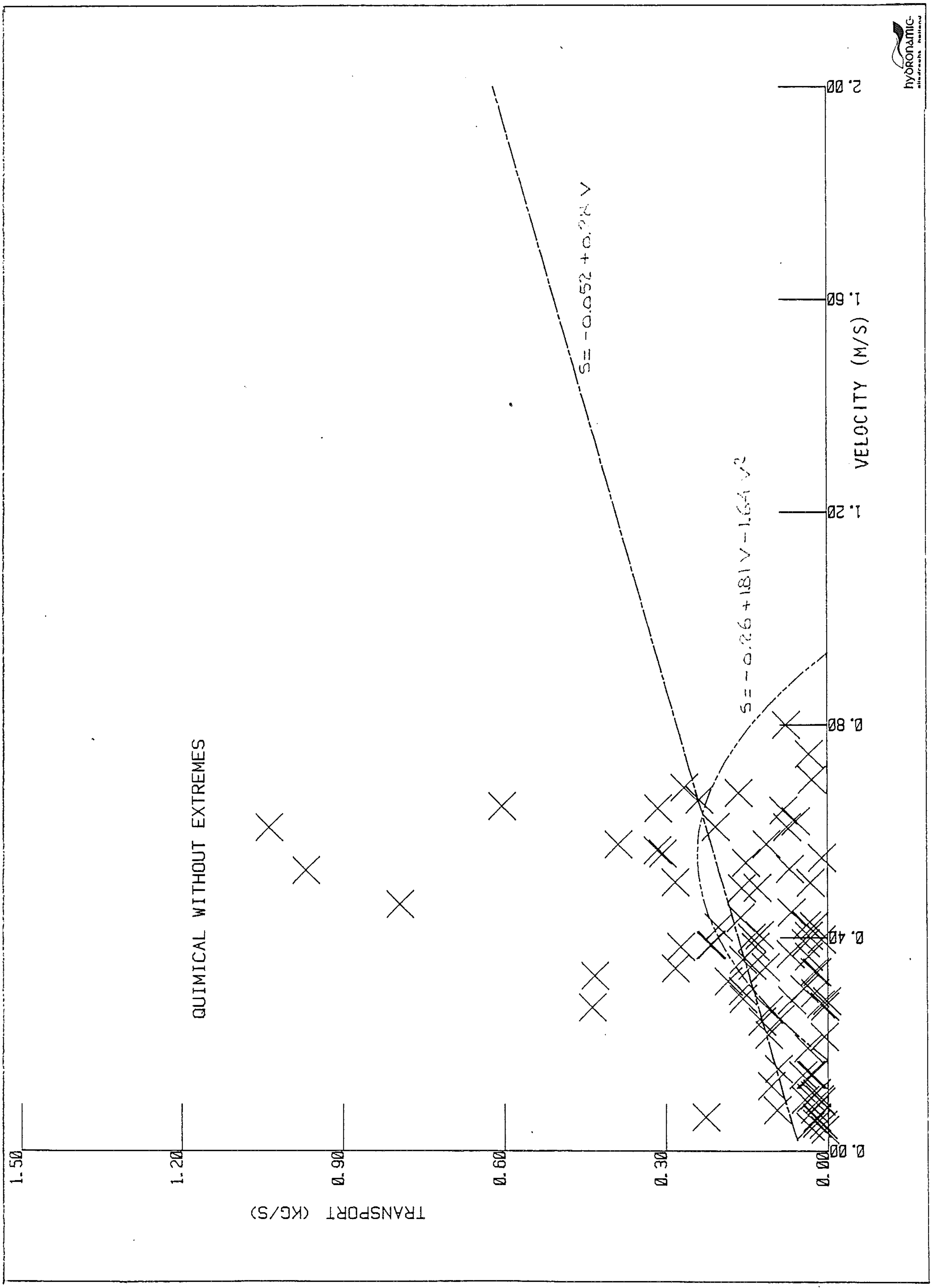
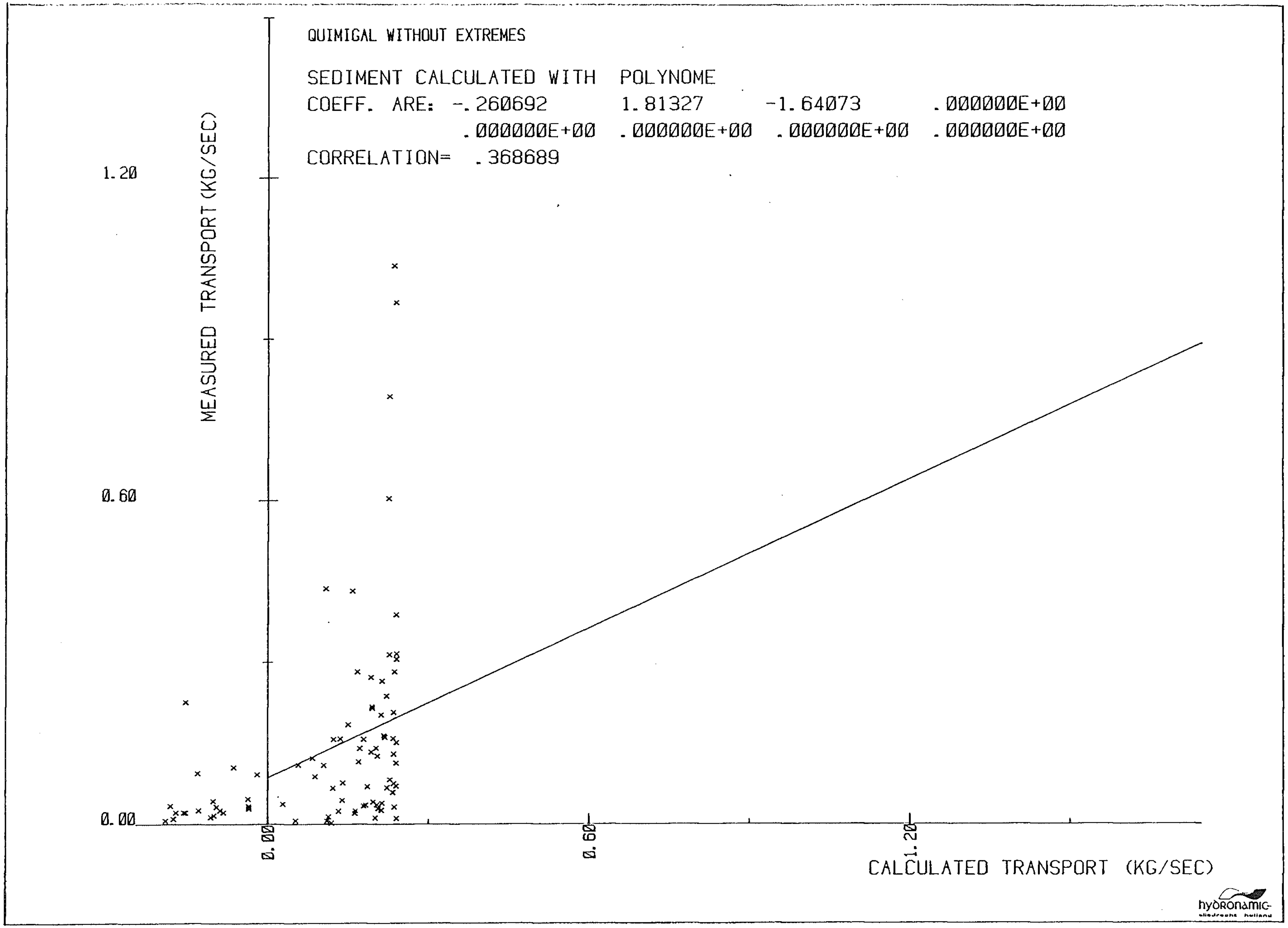

QUIMICAL WITHOUT EXTREMES
VELOCITY (M/S)
TRANSPORT (KG/S)
0.00
0.30
0.60
0.90
1.20
1.50
0.40
0.80
1.20
1.60
2.00
hydronamic

Figure 4.

Figure 5.


QUIMIGAL WITHOUT EXTREMES
SEDIMENT CALCULATED WITH POLYNOME
COEFF. ARE: -.260692 1.81327 -1.64073 .000000E+00
.000000E+00 .000000E+00 .000000E+00 .000000E+00
CORRELATION= .368689
MEASURED TRANSPORT (KG/SEC)
1.20
0.60
0.00
0.00
0.60
1.20
CALCULATED TRANSPORT (KG/SEC)
hydronamic

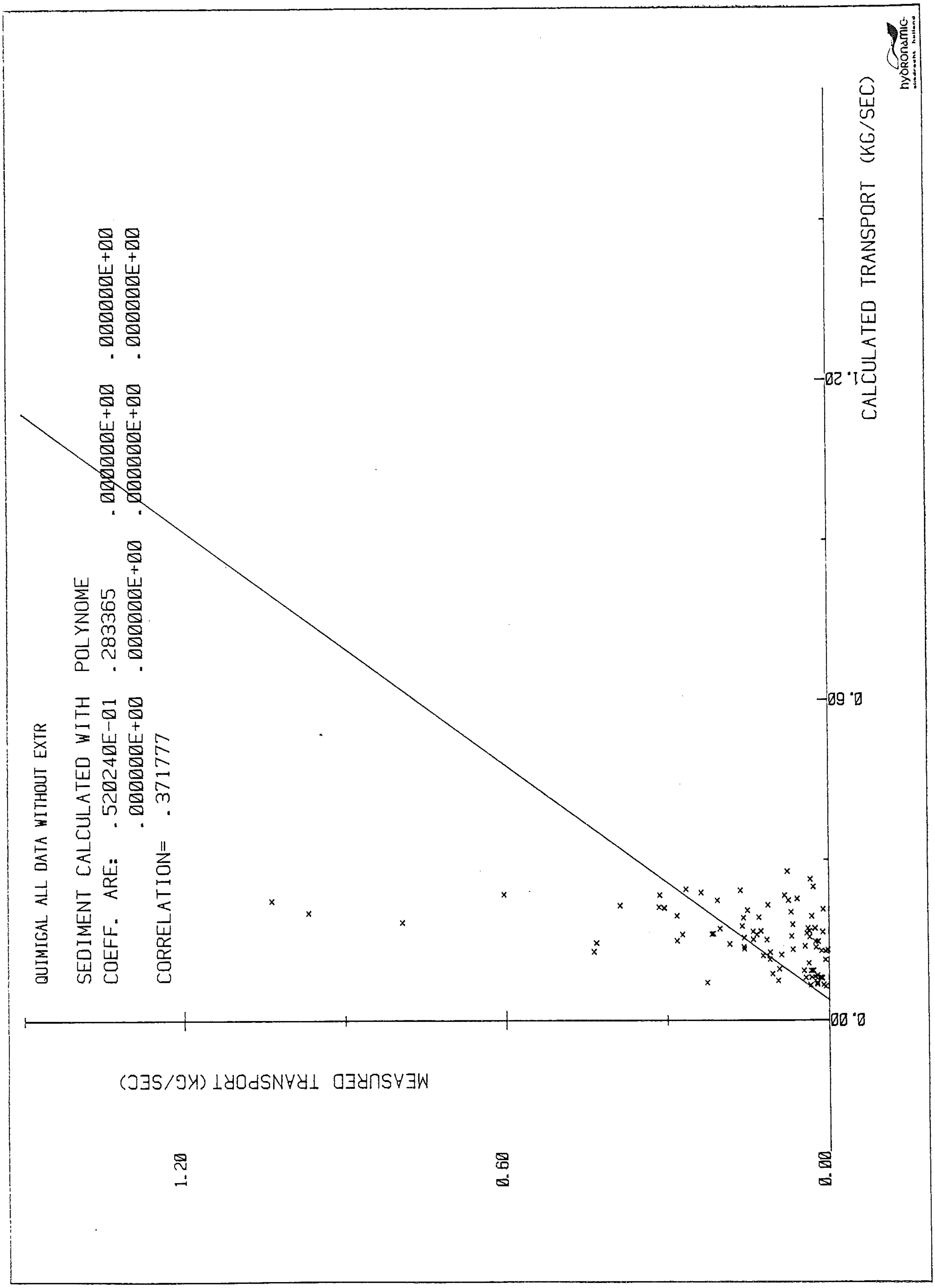

QUIMIGAL ALL DATA WITHOUT EXTR
SEDIMENT CALCULATED WITH POLYNOME
COEFF. ARE: .520240E-01 .283365 .000000E+00 .000000E+00
.000000E+00 .000000E+00 .000000E+00 .000000E+00
CORRELATION= .371777
MEASURED TRANSPORT (KG/SEC)
CALCULATED TRANSPORT (KG/SEC)
0.00
0.60
1.20
hydronamic

Figure 6.

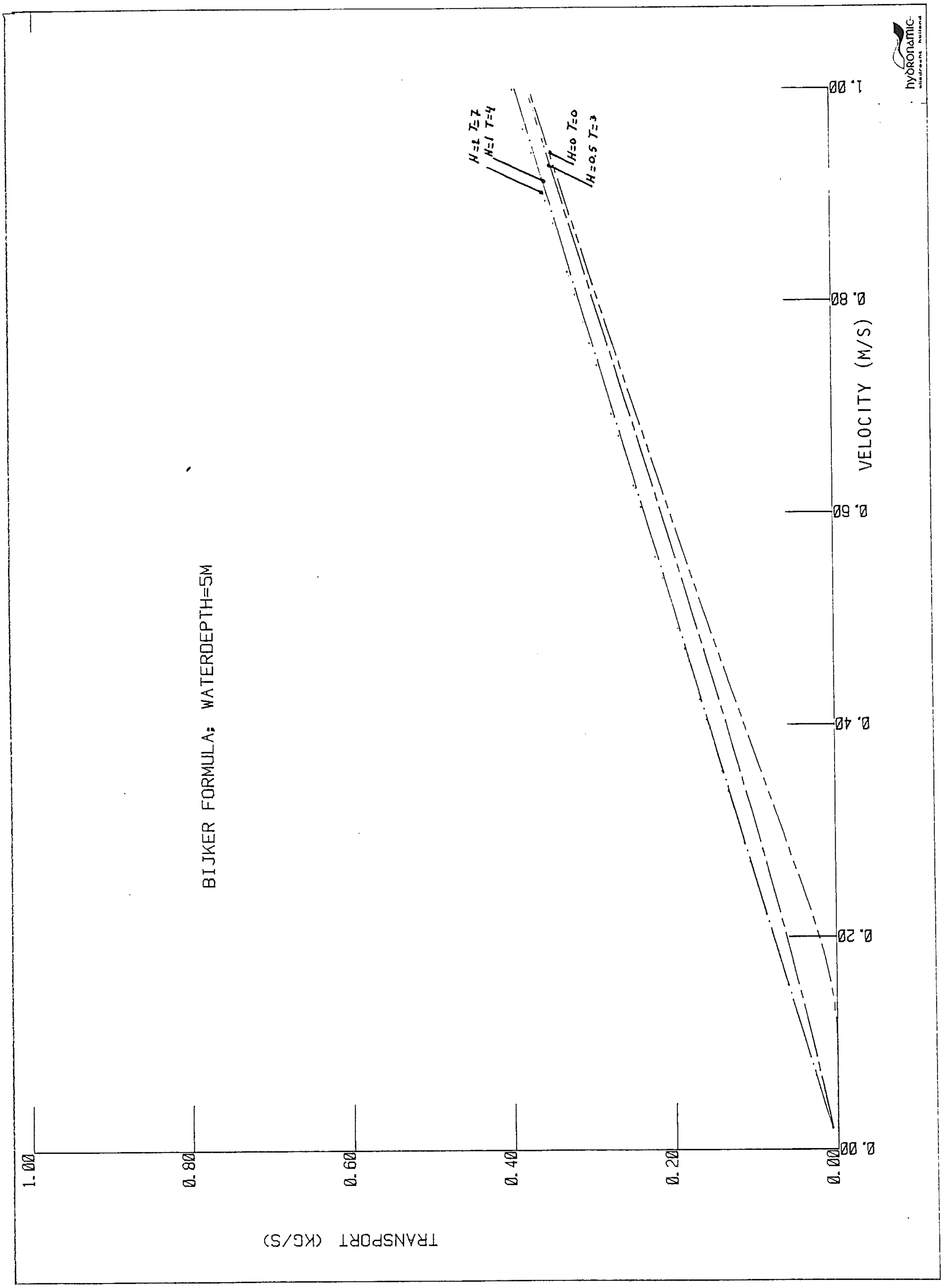

BIJKER FORMULA; WATERDEPTH=5M
VELOCITY (M/S)
TRANSPORT (KG/S)
0.00
0.20
0.40
0.60
0.80
1.00
H=1 T=7
H=1 T=4
H=0 T=0
H=0.5 T=3
hydronamic

Figure 7.

Figure 8.

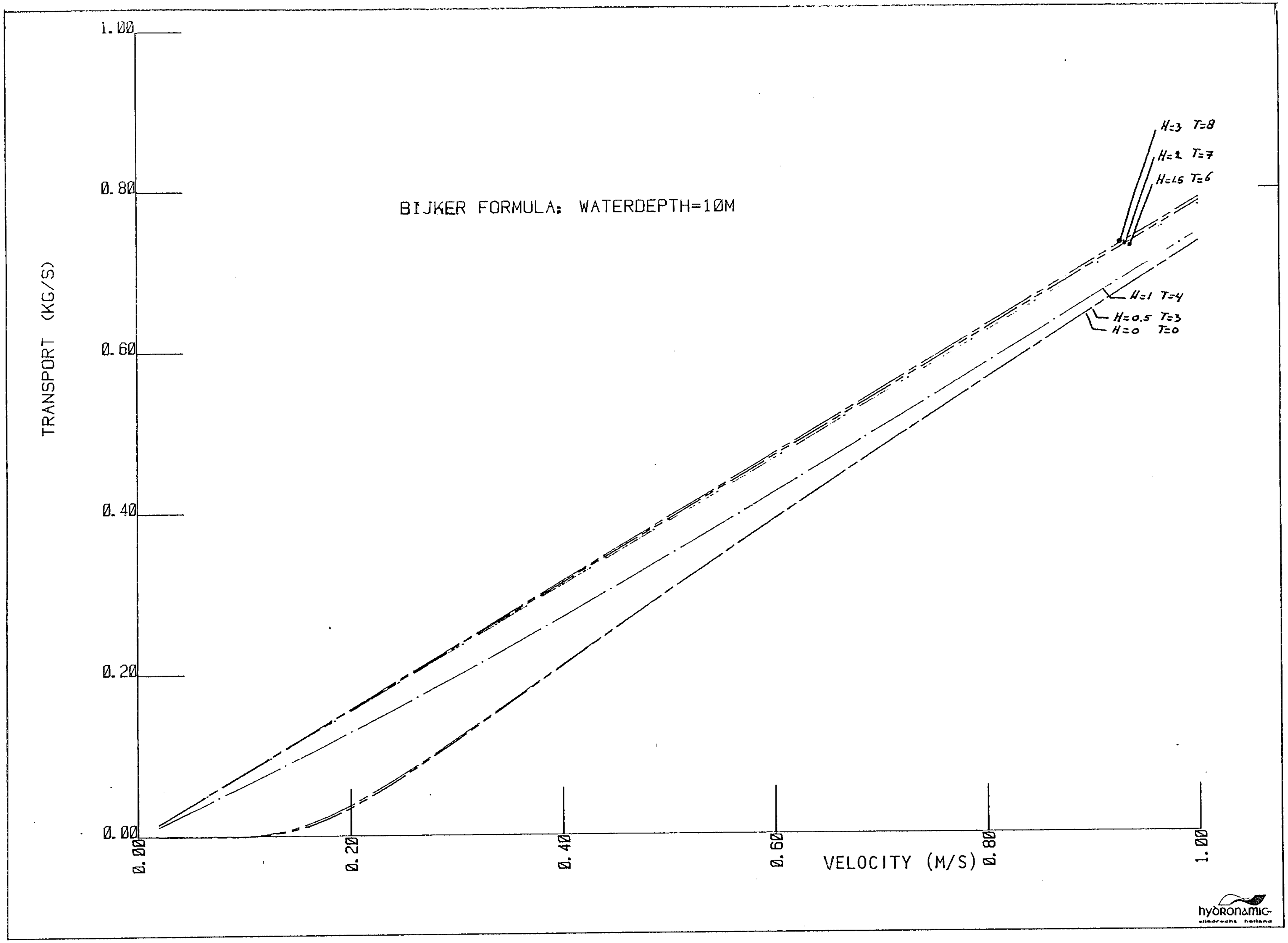
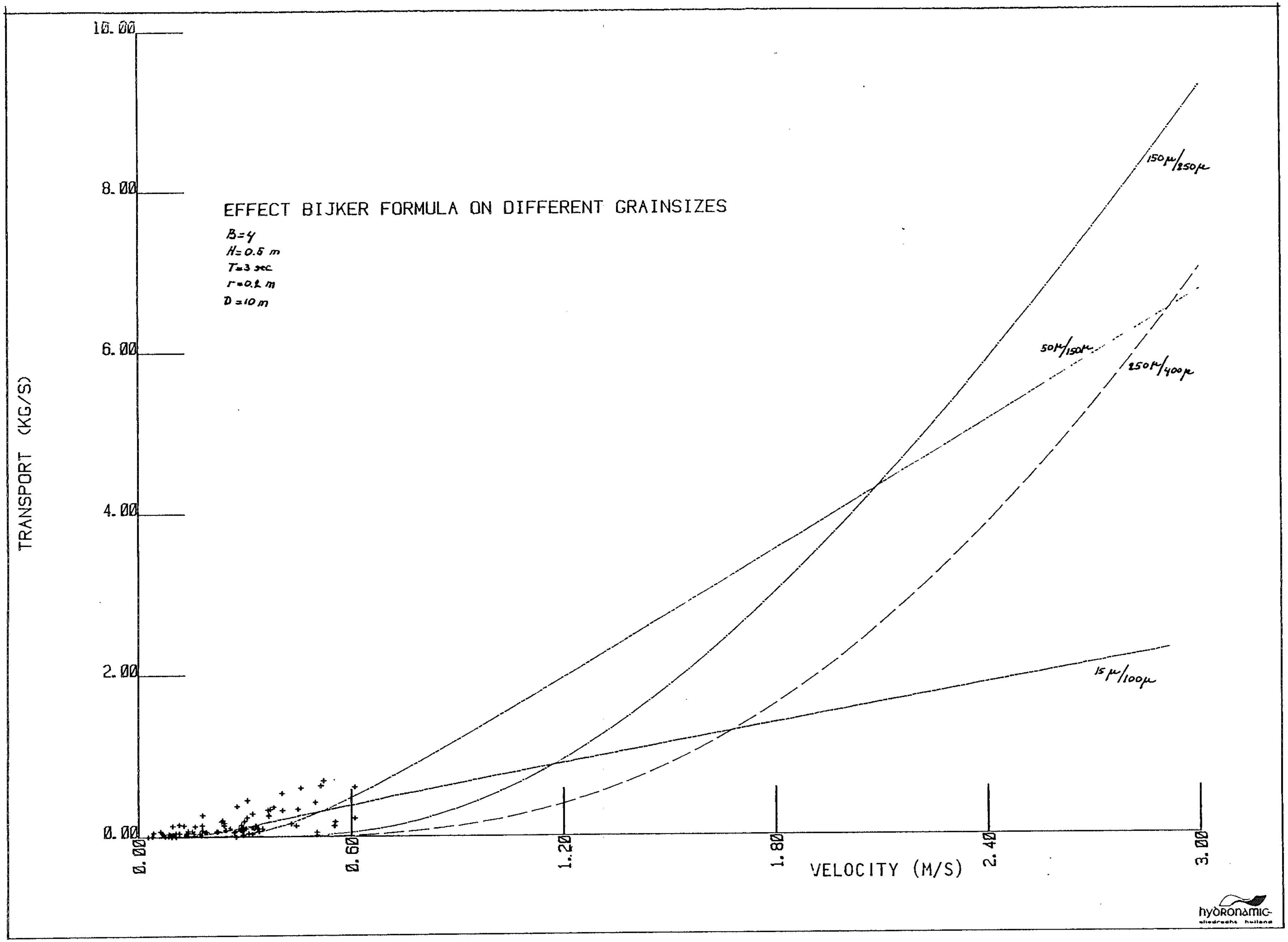

BIJKER FORMULA; WATERDEPTH=10M
TRANSPORT (KG/S)
VELOCITY (M/S)
0.00
0.20
0.40
0.60
0.80
1.00
H=3 T=8
H=2 T=7
H=1.5 T=6
H=1 T=4
H=0.5 T=3
H=0 T=0
hydronamic

Figure 9.


EFFECT BIJKER FORMULA ON DIFFERENT GRAINSIZES
B=4
H=0.5 m
T=3 sec
r=0.2 m
D=10 m
150μ/250μ
50μ/150μ
250μ/400μ
15μ/100μ
TRANSPORT (KG/S)
VELOCITY (M/S)
0.00
2.00
4.00
6.00
8.00
10.00
0.60
1.20
1.80
2.40
3.00

all data Quimigal

```
[illegible]
[illegible]
ENTER [illegible]
CORREL[illegible]ON= .7[illegible]
S(measu[illegible])=M*S(calc[illegible]lated)+0
M= 1.[illegible]
Q= -.2[illegible]E-01
CALCULATED WITH BIJKER-T.O.W.
=====================================================
ENTER GRAINSIZE (D50,D90) IN MU ?25 25
ENTER RIPPLE (m) ?.075
ENTER B ?5
CORRELATION= .709[illegible]57
S(measured)=M*S(calculated)+0
M= .9[illegible]2727
Q= -.2[illegible]8890E-01
CALCULATED WITH BIJKER-EINSTEIN
=====================================================
```

all data Quimigal H=0

```
ENTER GRAINSIZE (D50,D90) IN MU ?25 25
ENTER RIPPLE (m) ?.075
ENTER B ?5
CORRELATION= .710149
S(measured)=M*S(calculated)+0
M= [illegible].01003
Q= -.2[illegible]1903E-01
CALCULATED WITH BIJKER-T.O.W.
=====================================================
ENTER GRAINSIZE (D50,D90) IN MU ?25 25
ENTER RIPPLE (m) ?0.075
ENTER B ?5
CORRELATION= .710099
S(measured)=M*S(calculated)+0
M= .985485
Q= -.235079E-01
CALCULATED WITH BIJKER-EINSTEIN
=====================================================
```

all data Siderurgia

```
NAME OF DATAFILE [illegible]
ENTER GRAINSIZE (D50,D90) IN MU ?5 [illegible]
ENTER [illegible]
ENTER B [illegible]
CORRELATION= .804686
S(measured)=M*S(calculated)+0
M= [illegible]
Q= [illegible]
CALCULATED WITH BIJKER-T.O.W.
=====================================================
```

all data Siderurgia & Quimigal

```
NAME [illegible]AFILE [illegible]
ENTER [illegible]
ENTER [illegible]
ENTER [illegible]
CORRE[illegible]
S(me[illegible])=M*S(calc[illegible])+0
M= [illegible]
Q= -.[illegible]E-01
CALCULATED WITH BI[illegible]
=====================================================
```

TABLE 1

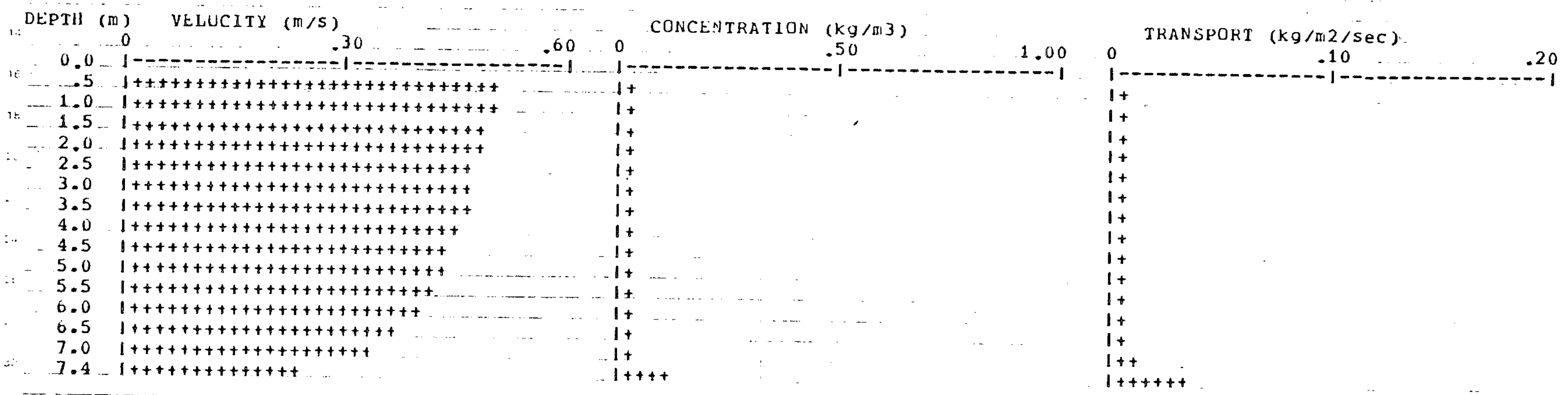
```
Hydronamic BV                                                                                              project: QUIMIGAL
Port & Waterway Engineers
Sliedrecht = Holland

                                           ***********************************
                                           * SEDIMENT TRANSPORT CALCULATION *
                                           ***********************************

DEPTH (m)   VELOCITY (m/s)                     CONCENTRATION (kg/m3)                  TRANSPORT (kg/m2/sec)
         0                .30                .60  0                .50                1.00  0                .10                .20
   0.0   |-----------------|-----------------|    |-----------------|-----------------|     |-----------------|-----------------|
    .5   |+++++++++++++++++++++++++++++             |+                                        |+
   1.0   |+++++++++++++++++++++++++++++             |+                                        |+
   1.5   |++++++++++++++++++++++++++++              |+                                        |+
   2.0   |++++++++++++++++++++++++++++              |+                                        |+
   2.5   |+++++++++++++++++++++++++++               |+                                        |+
   3.0   |+++++++++++++++++++++++++++               |+                                        |+
   3.5   |+++++++++++++++++++++++++++               |+                                        |+
   4.0   |++++++++++++++++++++++++++                |+                                        |+
   4.5   |+++++++++++++++++++++++++                 |+                                        |+
   5.0   |+++++++++++++++++++++++++                 |+                                        |+
   5.5   |++++++++++++++++++++++++                  |+                                        |+
   6.0   |+++++++++++++++++++++++                   |+                                        |+
   6.5   |+++++++++++++++++++++                     |+                                        |+
   7.0   |+++++++++++++++++++                       |+                                        |++
   7.4   |++++++++++++++                            |++++                                     |++++++

INPUT VALUES: VELOCITY     .45 M/SEC                  BEDLOAD TRANSPORT  .0049 KG/SEC
              WAVE HEIGHT  .00 M                    SUSPENDED TRANSPORT  .0421 KG/SEC
              WAVE PERIOD  .00 SEC                      TOTAL TRANSPORT  .0470 KG/SEC
              WATERDEPTH  7.65 M
              RIPPLE       .20 M                    SUSPENDED TRANSPORT IS   90 % OF TOTAL TRANSPORT
              GRAINSIZES   100  200   MU (D50/D90)
```

example 1

Hydronamic BV
Port & Waterway Engineers
Sliedrecht - Holland

project: QUIMIGAL

```
**********************************
* SEDIMENT TRANSPORT CALCULATION *
**********************************
```




```
INPUT VALUES: VELOCITY     .45 M/SEC
              WAVE HEIGHT  2.00 M
              WAVE PERIOD  2.00 SEC
              WATERDEPTH   7.65 M
              RIPPLE        .20 M
              GRAINSIZES   100  200   MU (D50/D90)
```

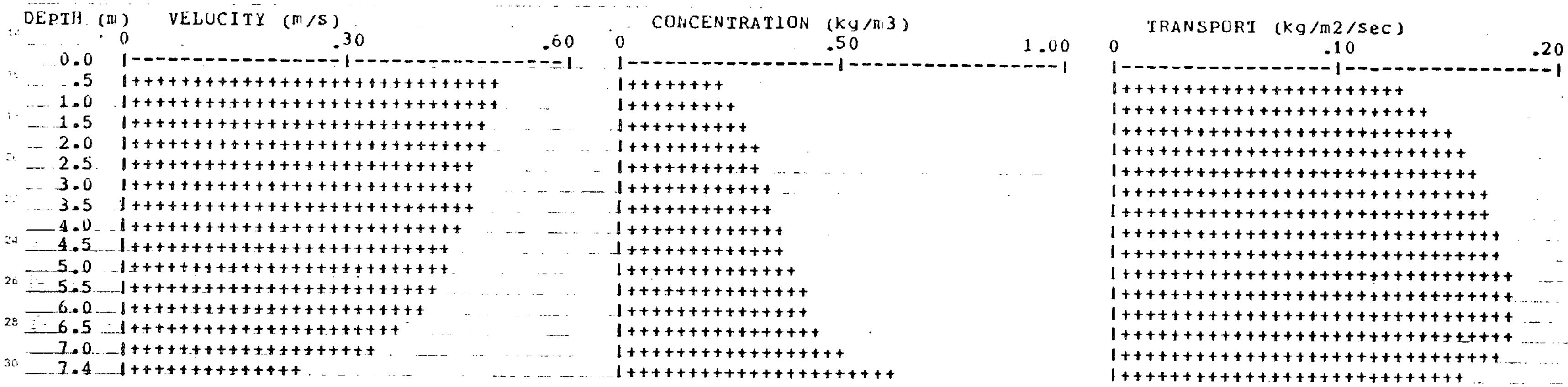
```
   BEDLOAD TRANSPORT   .0049 KG/SEC
 SUSPENDED TRANSPORT   .0422 KG/SEC
     TOTAL TRANSPORT   .0471 KG/SEC

SUSPENDED TRANSPORT IS   90 % OF TOTAL TRANSPORT
```

example 2

Hydronamic BV.
Port & Waterway Engineers
Sliedrecht - Holland

project: QUIMIGAL

```
***********************************
* SEDIMENT TRANSPORT CALCULATION *
***********************************
```




```
INPUT VALUES: VELOCITY      .45 M/SEC          BEDLOAD TRANSPORT   .0225 KG/SEC
              WAVE HEIGHT  2.00 M            SUSPENDED TRANSPORT 1.3006 KG/SEC
              WAVE PERIOD  6.00 SEC              TOTAL TRANSPORT 1.3231 KG/SEC
              WATERDEPTH   7.65 M
              RIPPLE        .20 M            SUSPENDED TRANSPORT IS   98 % OF TOTAL TRANSPORT
              GRAINSIZES    100  200   MU (D50/D90)
```

example 3

Hydronamic BV
Port & Waterway Engineers
Sliedrecht - Holland

Project: QUIMIGAL

4.

```
***********************************
* SEDIMENT TRANSPORT CALCULATION *
***********************************

DEPTH (m)  VELOCITY (m/s)                       CONCENTRATION (kg/m3)                  TRANSPORT (kg/m2/sec)
           0                 .50        1.00    0              .10           .20      0                .10            .20
   0.0     |-----------------|-----------------|  |--------------|--------------|     |----------------|----------------|
    .5     |+++++++++++++++++                     |+++++++++++++                     |+++++++
   1.0     |+++++++++++++++++                     |+++++++++++++                     |++++++
   1.5     |+++++++++++++++++                     |+++++++++++++                     |++++++
   2.0     |+++++++++++++++++                     |+++++++++++++                     |++++++
   2.5     |+++++++++++++++++                     |+++++++++++++                     |++++++
   3.0     |++++++++++++++++                      |+++++++++++++                     |++++++
   3.5     |++++++++++++++++                      |+++++++++++++                     |++++++
   4.0     |++++++++++++++++                      |+++++++++++++                     |++++++
   4.5     |++++++++++++++++                      |+++++++++++++                     |++++++
   5.0     |+++++++++++++++                       |+++++++++++++                     |++++++
   5.5     |+++++++++++++++                       |+++++++++++++                     |++++++
   6.0     |++++++++++++++                        |+++++++++++++                     |++++++
   6.5     |+++++++++++++                         |+++++++++++++                     |+++++
   7.0     |++++++++++++                          |+++++++++++++                     |+++++
   7.5     |+++++++++                             |+++++++++++++                     |++++
   7.6     |+++++++                               |+++++++++++++                     |+++
                                                                                      |+++

INPUT VALUES: VELOCITY     .45 M/SEC                  BEDLOAD TRANSPORT   .0009 KG/SEC
              WAVE HEIGHT  .00 M                    SUSPENDED TRANSPORT   .2728 KG/SEC
              WAVE PERIOD  .00 SEC                      TOTAL TRANSPORT   .2737 KG/SEC
              WATERDEPTH  7.65 M
              RIPPLE       .08 M                    SUSPENDED TRANSPORT IS  100 % OF TOTAL TRANSPORT
              GRAINSIZES     5   25   MU (D50/D90)
```

example 4

5.

```
Hydronamic BV                                                                               project: QUIMIGAL
Port & Waterway Engineers
Sliedrecht - Holland

                                                     ***********************************
                                                     * SEDIMENT TRANSPORT CALCULATION *
                                                     ***********************************

DEPTH (m)  VELOCITY (m/s)                            CONCENTRATION (kg/m3)                          TRANSPORT (kg/m2/sec)
           0                .50               1.00   0                .10               .20     0                .10               .20
    0.0    |----------------|-----------------|      |----------------|-----------------|       |----------------|-----------------|
     .5    |+++++++++++++++++                        |+++++++++++++++                           |+++++++
    1.0    |+++++++++++++++++                        |+++++++++++++++                           |+++++++
    1.5    |+++++++++++++++++                        |+++++++++++++++                           |+++++++
    2.0    |+++++++++++++++++                        |+++++++++++++++                           |+++++++
    2.5    |+++++++++++++++++                        |+++++++++++++++                           |+++++++
    3.0    |++++++++++++++++                         |+++++++++++++++                           |+++++++
    3.5    |++++++++++++++++                         |+++++++++++++++                           |+++++++
    4.0    |++++++++++++++++                         |+++++++++++++++                           |+++++++
    4.5    |++++++++++++++++                         |+++++++++++++++                           |+++++++
    5.0    |+++++++++++++++                          |+++++++++++++++                           |++++++
    5.5    |+++++++++++++++                          |+++++++++++++++                           |++++++
    6.0    |++++++++++++++                           |+++++++++++++++                           |++++++
    6.5    |+++++++++++++                            |+++++++++++++++                           |++++++
    7.0    |++++++++++++                             |+++++++++++++++                           |+++++
    7.5    |+++++++++                                |+++++++++++++++                           |++++
    7.6    |+++++++                                  |+++++++++++++++                           |+++

INPUT VALUES: VELOCITY      .45 M/SEC                   BEDLOAD TRANSPORT   .0010 KG/SEC
              WAVE HEIGHT  2.00 M                     SUSPENDED TRANSPORT   .3032 KG/SEC
              WAVE PERIOD  6.00 SEC                       TOTAL TRANSPORT   .3043 KG/SEC
              WATERDEPTH   7.65 M
              RIPPLE        .08 M                     SUSPENDED TRANSPORT IS  100 % OF TOTAL TRANSPORT
              GRAINSIZES      5    25   MU (D50/D90)
```

example 5

Hydronamic BV
Port & Waterway Engineers
Sliedrecht - Holland

project: QUIMIGAL

6.

```
**********************************
* SEDIMENT TRANSPORT CALCULATION *
**********************************

DEPTH (m)   VELOCITY (m/s)                   CONCENTRATION (kg/m3)                TRANSPORT (kg/m2/sec)
         0                 .50         1.00  0              .10              .20  0              .10              .20
  0.0   |-----------------|-----------------|  |-----------------|-----------------|  |-----------------|-----------------|
   .5   |+++++++++++++                          |+++++++++++++                        |+++++
  1.0   |+++++++++++++                          |+++++++++++++                        |++++
  1.5   |+++++++++++++                          |+++++++++++++                        |++++
  2.0   |+++++++++++++                          |+++++++++++++                        |++++
  2.5   |+++++++++++++                          |+++++++++++++                        |++++
  3.0   |++++++++++++                           |+++++++++++++                        |++++
  3.5   |++++++++++++                           |+++++++++++++                        |++++
  4.0   |++++++++++++                           |+++++++++++++                        |++++
  4.5   |++++++++++++                           |+++++++++++++                        |++++
  5.0   |++++++++++++                           |+++++++++++++                        |++++
  5.5   |++++++++++++                           |+++++++++++++                        |++++
  6.0   |++++++++++++                           |+++++++++++++                        |++++
  6.5   |+++++++++++                            |+++++++++++++                        |++++
  7.0   |+++++++++++                            |+++++++++++++                        |++++
  7.5   |+++++++++++                            |+++++++++++++                        |++++
  8.0   |+++++++++++                            |+++++++++++++                        |++++
  8.5   |++++++++++                             |+++++++++++++                        |+++
  9.0   |++++++++++                             |+++++++++++++                        |+++
  9.5   |+++++++++                              |+++++++++++++                        |+++
 10.0   |+++++++                                |+++++++++++++                        |++
 10.1   |+++++                                  |+++++++++++++                        |++

INPUT VALUES: VELOCITY     .34 M/SEC               BEDLOAD TRANSPORT  .0006 KG/SEC
              WAVE HEIGHT  .25 M                 SUSPENDED TRANSPORT  .2593 KG/SEC
              WAVE PERIOD 4.00 SEC                   TOTAL TRANSPORT  .2600 KG/SEC
              WATERDEPTH 10.20 M
              RIPPLE       .08 M                 SUSPENDED TRANSPORT IS  100 % OF TOTAL TRANSPORT
              GRAINSIZES    5.  25   MU (D50/D90)
```

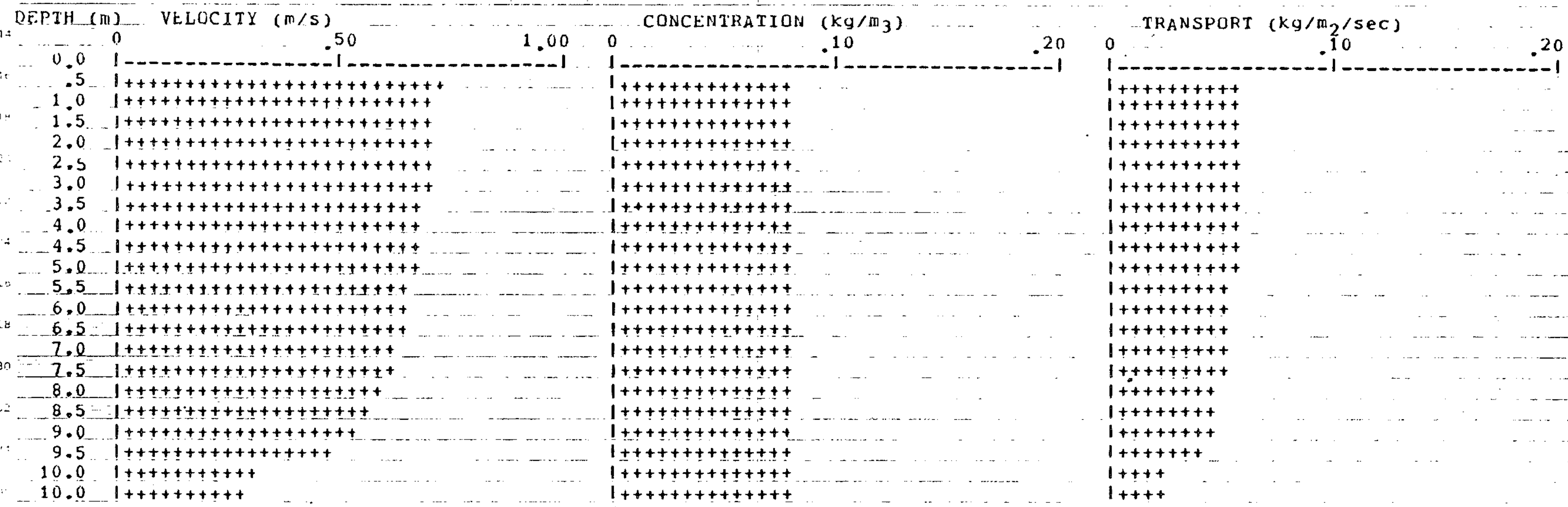
cf datafile QUI20207

Hydronamic BV
Port & Waterway Engineers
Sliedrecht - Holland

project: QUIMIGAL

7.

```
***********************************
* SEDIMENT TRANSPORT CALCULATION *
***********************************
```




```
INPUT VALUES: VELOCITY      .66 M/SEC          BEDLOAD TRANSPORT   .0014 KG/SEC
              WAVE HEIGHT   .00 M            SUSPENDED TRANSPORT   .5589 KG/SEC
              WAVE PERIOD   .00 SEC              TOTAL TRANSPORT   .5603 KG/SEC
              WATERDEPTH  10.10 M
              RIPPLE        .08 M            SUSPENDED TRANSPORT IS  100 % OF TOTAL TRANSPORT
              GRAINSIZES      5   25   MU (D50/D90)
```

cf. Datafile QUI20209

```
Hydronamic BV                                                                                  project: QUIMIGAL
Port & Waterway Engineers
Sliedrecht - Holland

                                                ***********************************
                                                * SEDIMENT TRANSPORT CALCULATION *
                                                ***********************************

DEPTH (m)   VELOCITY (m/s)                           CONCENTRATION (kg/m3)                    TRANSPORT (kg/m2/sec)
         0                 .50                1.00   0                 .10               .20   0                 .10               .20
   0.0  |-----------------|-----------------|        |-----------------|-----------------|    |-----------------|-----------------|
    .5  |++++++++++++++++                            |++++++++++++++                          |+++++
   1.0  |++++++++++++++                              |++++++++++++++                          |+++++
   1.5  |++++++++++++++                              |++++++++++++++                          |+++++
   2.0  |++++++++++++++                              |++++++++++++++                          |+++++
   2.5  |+++++++++++++                               |++++++++++++++                          |+++++
   3.0  |++++++++++++                                |++++++++++++++                          |++++
   3.5  |++++++++++++                                |++++++++++++++                          |++++
   4.0  |++++++++++                                  |++++++++++++++                          |+++
   4.1  |+++++++                                     |++++++++++++++                          |++

INPUT VALUES: VELOCITY     .38 M/SEC                     BEDLOAD TRANSPORT   .0008 KG/SEC
              WAVE HEIGHT   .30 M                      SUSPENDED TRANSPORT   .1231 KG/SEC
              WAVE PERIOD  2.00 SEC                        TOTAL TRANSPORT   .1239 KG/SEC
              WATERDEPTH   4.20 M
              RIPPLE        .08 M                      SUSPENDED TRANSPORT IS   99 % OF TOTAL TRANSPORT
              GRAINSIZES     5   25   MU (D50/D90)
```

cf. Datafile QU120305

```
Hydronamic BV                                                                project: QUIMIGAL                       10.
Port & Waterway Engineers
Sliedrecht - Holland

                                                  **********************************
                                                  * SEDIMENT TRANSPORT CALCULATION *
                                                  **********************************

DEPTH (m)    VELOCITY (m/s)                          CONCENTRATION (kg/m3)                      TRANSPORT (kg/m2/sec)
             0                .50              1.00  0                 .10                .20   0                 .10                .20
   0.0       |-----------------|-----------------|   |-----------------|-----------------|      |-----------------|-----------------|
    .5       |++++++++++++++++++                     |++++++++++++++                            |+++++++
   1.0       |++++++++++++++++++                     |++++++++++++++                            |++++++
   1.5       |++++++++++++++++++                     |++++++++++++++                            |++++++
   2.0       |++++++++++++++++++                     |++++++++++++++                            |++++++
   2.5       |++++++++++++++++++                     |++++++++++++++                            |++++++
   3.0       |++++++++++++++++++                     |++++++++++++++                            |++++++
   3.5       |+++++++++++++++++                      |++++++++++++++                            |++++++
   4.0       |+++++++++++++++++                      |++++++++++++++                            |++++++
   4.5       |+++++++++++++++++                      |++++++++++++++                            |++++++
   5.0       |+++++++++++++++++                      |++++++++++++++                            |++++++
   5.5       |++++++++++++++++                       |++++++++++++++                            |++++++
   6.0       |++++++++++++++++                       |++++++++++++++                            |++++++
   6.5       |+++++++++++++++                        |++++++++++++++                            |+++++
   7.0       |+++++++++++++++                        |++++++++++++++                            |+++++
   7.5       |++++++++++++++                         |++++++++++++++                            |+++++
   8.0       |++++++++++++                           |++++++++++++++                            |++++
   8.4       |+++++++                                |++++++++++++++                            |+++

INPUT VALUES: VELOCITY     .45 M/SEC                  BEDLOAD TRANSPORT   .0009 KG/SEC
              WAVE HEIGHT  .00 M                    SUSPENDED TRANSPORT   .3026 KG/SEC
              WAVE PERIOD  .00 SEC                      TOTAL TRANSPORT   .3035 KG/SEC
              WATERDEPTH  8.50 M
              RIPPLE       .08 M                    SUSPENDED TRANSPORT IS  100 % OF TOTAL TRANSPORT
              GRAINSIZES    5   25   MU (D50/D90)
```

cf. datafile QUI20410

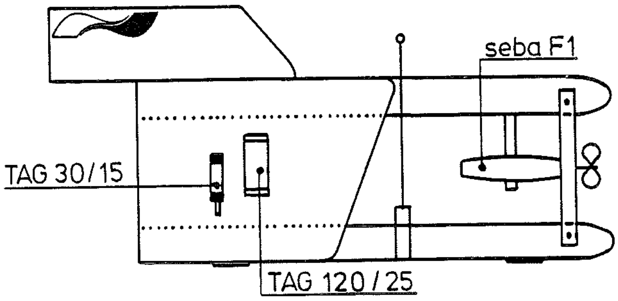
Hydronamic BV
Port & Waterway Engineers
Sliedrecht - Holland

project: QUIMIGAL

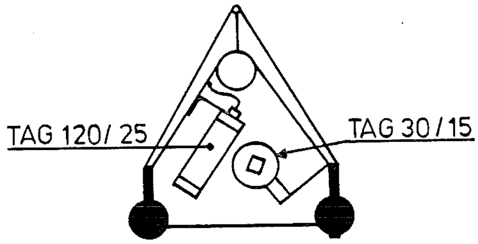
```
**********************************
* SEDIMENT TRANSPORT CALCULATION *
**********************************

DEPTH (m)  VELOCITY (m/s)                     CONCENTRATION (kg/m3)               TRANSPORT (kg/m2/sec)
           0                .50          1.00 0               .10           .20  0              .10             .20
   0.0     |----------------|----------------|  |--------------|--------------|  |----------------|----------------|
    .5     |+++++++++++++                       |+++++++++++++                    |++++
   1.0     |+++++++++++++                       |+++++++++++++                    |++++
   1.5     |+++++++++++++                       |+++++++++++++                    |++++
   2.0     |+++++++++++++                       |+++++++++++++                    |++++
   2.5     |+++++++++++++                       |+++++++++++++                    |++++
   3.0     |+++++++++++++                       |+++++++++++++                    |++++
   3.5     |+++++++++++++                       |+++++++++++++                    |++++
   4.0     |+++++++++++++                       |+++++++++++++                    |++++
   4.5     |+++++++++++++                       |+++++++++++++                    |++++
   5.0     |+++++++++++++                       |+++++++++++++                    |++++
   5.5     |+++++++++++++                       |+++++++++++++                    |++++
   6.0     |+++++++++++++                       |+++++++++++++                    |++++
   6.5     |+++++++++++++                       |+++++++++++++                    |++++
   7.0     |+++++++++++++                       |+++++++++++++                    |++++
   7.5     |+++++++++++++                       |+++++++++++++                    |++++
   8.0     |+++++++++++++                       |+++++++++++++                    |++++
   8.5     |+++++++++++++                       |+++++++++++++                    |++++
   9.0     |++++++++++++                        |+++++++++++++                    |++++
   9.5     |++++++++++++                        |+++++++++++++                    |++++
  10.0     |++++++++++++                        |+++++++++++++                    |++++
  10.5     |++++++++++++                        |+++++++++++++                    |++++
  11.0     |++++++++++++                        |+++++++++++++                    |++++
  11.5     |++++++++++++                        |+++++++++++++                    |++++
  12.0     |++++++++++++                        |+++++++++++++                    |+++
  12.5     |++++++++++++                        |+++++++++++++                    |+++
  13.0     |++++++++++++                        |+++++++++++++                    |+++
  13.5     |+++++++++++                         |+++++++++++++                    |+++
  14.0     |+++++++++++                         |+++++++++++++                    |+++
  14.5     |+++++++++++                         |+++++++++++++                    |+++
  15.0     |+++++++++++                         |+++++++++++++                    |+++
  15.5     |++++++++++                          |+++++++++++++                    |+++
  16.0     |++++++++++                          |+++++++++++++                    |+++
  16.5     |+++++++++                           |+++++++++++++                    |+++
  17.0     |++++++++                            |+++++++++++++                    |++
  17.4     |+++++                               |+++++++++++++                    |+

INPUT VALUES: VELOCITY    .33 M/SEC                 BEDLOAD TRANSPORT   .0005 KG/SEC
              WAVE HEIGHT  .00 M                 SUSPENDED TRANSPORT   .4052 KG/SEC
              WAVE PERIOD  .00 SEC                   TOTAL TRANSPORT   .4057 KG/SEC
              WATERDEPTH 17.50 M
              RIPPLE       .08 M                 SUSPENDED TRANSPORT IS  100 % OF TOTAL TRANSPORT
              GRAINSIZES     5   25   MU (D50/D90)
```

cf. Datafile QU120609

The Hydronamic Sediment Transport Meter



Side view



Back view

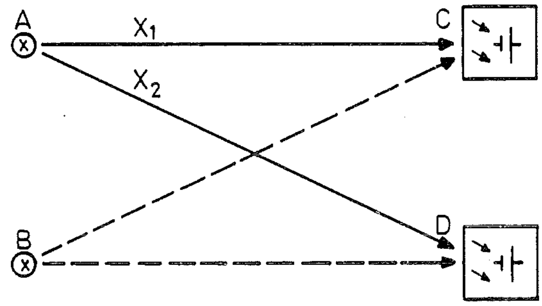
The sediment transport meter is, a triangular frame containing two concentration sensors and a current meter. The current-meter is built into the front of the frame. It is a commercially available seba F1 current meter. The concentration meters are the TAG 30/15 and the TAG 120/25 from Eurcontrol. The TAG 30/15 is for high concentrations, the TAG 120/25 is for low concentrations. The sensors are shielded from direct light by two black plates on each side of the frame. They are connected to an electronic unit on board, the MEX 2.
The frame itself weights approx. 80 kilograms. This weight is required for measurements in water with relatively high velocities. The shape of the frame enables it to stay stable during the whole underwater measuring period. The stability is caused by the "rudder" and the specially designed bearing system. The frame was designed in coöperation with the manufacturer (van Essen instruments, Delft, Netherlands).
For world wide operations the frame can be dismantled for easy transportation by air.

Calibration of the current-meter

The current-meter gives a number of pulses during each revolution of the propellor. The manufacturer of the current meter provide a formula to find the relation between 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 of the velocity meter placed in the frame in our in-house research laboratory.

The optical system of the concentration meter

The continous and in-line measurement of turbidity is carried out by a four-beam alternating light process photometer. The measuring probes are equiped with two light emitters and two receiving photocells. Lamps and photocells face each other across a space that is filled with the sediment-water mixture which is to be measured. Two different probes are available for different concentrations.



The transmitter part consists basically of a supply and a computing circuit.
The supply circuit provides the lamps of the probe with the required voltage and monitors the alternating lighting of the lamps.
The computing unit receives the current signals emitted by the photocells and carries out the processing of the signals. The probe is connected to the transmitter by a splash-proof multiple-pin plug.

For measurement by the four-beam alternating light system the two lamps A and B are alternatingly switched on and oft, while the photocells C and D are operating continuously. If lamp A is on, the two photocells receive two signals, which are different to each other due to the two light paths x_1 and x_2 that are of different length. The same happens when lamp B is switched on.

Accordingly, the following computations are carried out by computing circuit. The intensity of current given by each photocell is given as

$$I_{ca} = I_a \; G_{ca} \; K_c \; \exp\,(-ax_1)$$

$$I_{da} = I_a \; G_{da} \; K_d \; \exp\,(-ax_2)$$

in which:

I_{ca} - current produced by photocell C, lighted with lamp A

I_a - light intensity of lamp A

G_{ca} - geometrical constant of the path CA

K_c - constant of photocell C

a - extinction modulus of the water-sediment mixture

X_1 - length of the path X_1

Both the received intensities I_{ca} and I_{da} are devided, the quotient is stored in memory

$$\frac{I_{ca}}{I_{da}} = \frac{I_a\, G_{ca}\, K_c}{I_a\, G_{da}\, K_d} \exp\,(-a(X_2 - X_1))$$

In stage 2 is calculated:

$$\frac{I_{cb}}{I_{db}} = \frac{I_b\, G_{cb}\, K_c}{I_b\, G_{db}\, K_d} \exp\,(-a(X_2 - X_1))$$

This quotient is also stored in memory.

In stage 3 of the computational process, the stored quotients are devided:

$$\frac{I_{ca}\, I_{db}}{I_{da}\, I_{cb}} = \frac{G_{ca}\, K_c\, G_{db}\, K_c}{G_{da}\, K_d\, G_{cb}\, K_c} \exp\,(2a\,(X_2 - X_1))$$

$$= \frac{G_{ca}\, G_{db}}{G_{da}\, G_{cb}} \exp\,(2a\,(X_2 - X_1))$$

$$= G \exp\,(2a\,(X_2 - X_1)) = V$$

The value V, computed in this way is only a function of the geometry of the probe and the extinctionmodules a, which is a measure for the turbidity. The value a can be written as:

$$a = \frac{1}{2(X_2 - X_1)} \ln\left(\frac{V}{G}\right)$$

It is clear that the variation in the light intensity, produced by the lamps, and the constants of the photocells K do not influence the final result. Thus the instrument is not sensitive to dirt on the lamps, variations in electrical power, dirt on photocells etc.

The four-beam alternating light-beam system is a patented system by the manufacturer of the probes, Eurcontrol.
The value indicated on the analog display of the MEX 2 is proportional with ln V, and should therefore be a linear function of the concentration. But because light is not only absorbed by the medium, but also scattered by the particles, the photocells do also receive this scattered light. This scattering causes an inlinearity in the calibration curve.