A Feasibility Study of Measurements on the Organic Matter Transfer between the Eastern Scheldt ("Oosterschelde") and the North Sea

Nota DDMI-78.21

Middelburg, The Netherlands, June 1978
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rijkswaterstaat

deltadienst

nota DDMI-78.21

titel: A Feasibility Study of Measurements on the Organic Matter Transfer between the Eastern Scheldt ("Oosterschelde") and the North Sea

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datum: June 28, 1978

bijlagen: 3

samenvatting: In dit rapport worden een aantal mogelijkheden besproken voor het meten van de in- of uitvoer van organische stof naar of vanuit de Oosterschelde. Een dergelijke in- of uitvoer vertegenwoordigt een nutriëntenstroom die van groot belang kan zijn voor een estuarium en het kwantificeren daarvan zou het inzicht in een dergelijk ecosysteem verbeteren (Perkins 1974, p. 152; Bigelow et al. 1977, pp. 201-215). Dit geldt in het bijzonder voor de Oosterschelde waar de toekomstige in- of uitvoer van organische stof gewijzigd kan worden door een stormvloedkering (Bigelow et al. 1977, pp. 201-215).

In tweede instantie, kan een dergelijke meting gebruikt worden voor het ijken van het Polano model, een ecologisch model van de Oosterschelde ontwikkeld door de "Rand Corporation" en de Deltadienst (Bigelow et al. 1977). Een van de modeluitkomsten, gebaseerd op de voedselbehoefte van bodemdieren en de voedselproduktie binnen de Oosterschelde, is een gemiddelde invoer van 700 ton organische stof per 24 uur. Een onafhankelijke meting van de werkelijke invoer kan dus gebruikt worden om het model te kalibreren.

Een van de mogelijke meetmethoden wordt verder onderzocht en geëvalueerd aan de hand van een aantal verkennende veldmetingen. De resultaten hiervan suggereren dat het wellicht mogelijk zal zijn een invoer te meten van de orde grootte voorspeld door het Polano model m.b.v. de gebruikte methode.

Een aantal praktische problemen, zoals het tijdstip van de metingen in relatie tot het getij, monstername bij slecht weer, en het aantal beschikbare schepen zouden nader onderzocht moeten worden voordat een uitgebreider serie van metingen ondernomen kan worden.

Summary

The purpose of this paper is to examine the feasibility of measuring an import or export of organic matter into or from the Eastern Scheldt. The nutrient load represented by an in or outflow of organic matter can be of great significance for an estuarine system and its measurement should contribute to the understanding of such a system (Perkins 1974, p. 152; Bigelow et al. 1977, pp. 201-215). This is especially true for the Eastern Scheldt where a projected storm surge barrier in the tidal entrance will modify the future in or outflow of organic matter (Bigelow et al. 1977, pp. 201-215).

Such a measurement would, in addition, serve as a check on the Polano model, an ecological model for the Eastern Scheldt recently developed as a result of cooperation between the Rand Corporation and the Delta-department of "Rijkswaterstaat" (Bigelow et al. 1977). One of the model outputs, based on the food requirements of the benthic community (mainly cockles and mussels) and the food production in the estuary is a mean net import of organic matter equal to ca 700 metric tons per 24 hours. An independent measurement of this import would serve as a check on the model.
In this report a number of approaches in the literature are reviewed which might be used to measure the net transfer of organic matter. One approach is treated in more detail and serves as the basis for an initial series of field measurements carried out to test the feasibility of the approach. The results of these field measurements suggest that it is probably feasible to measure an import of the order of magnitude predicted by the Polano model using the method outlined. Some practical problems, such as timing of the measurements, rough weather, the number of available ships and equipment would have to be considered in more detail before a series of measurements could be carried out.

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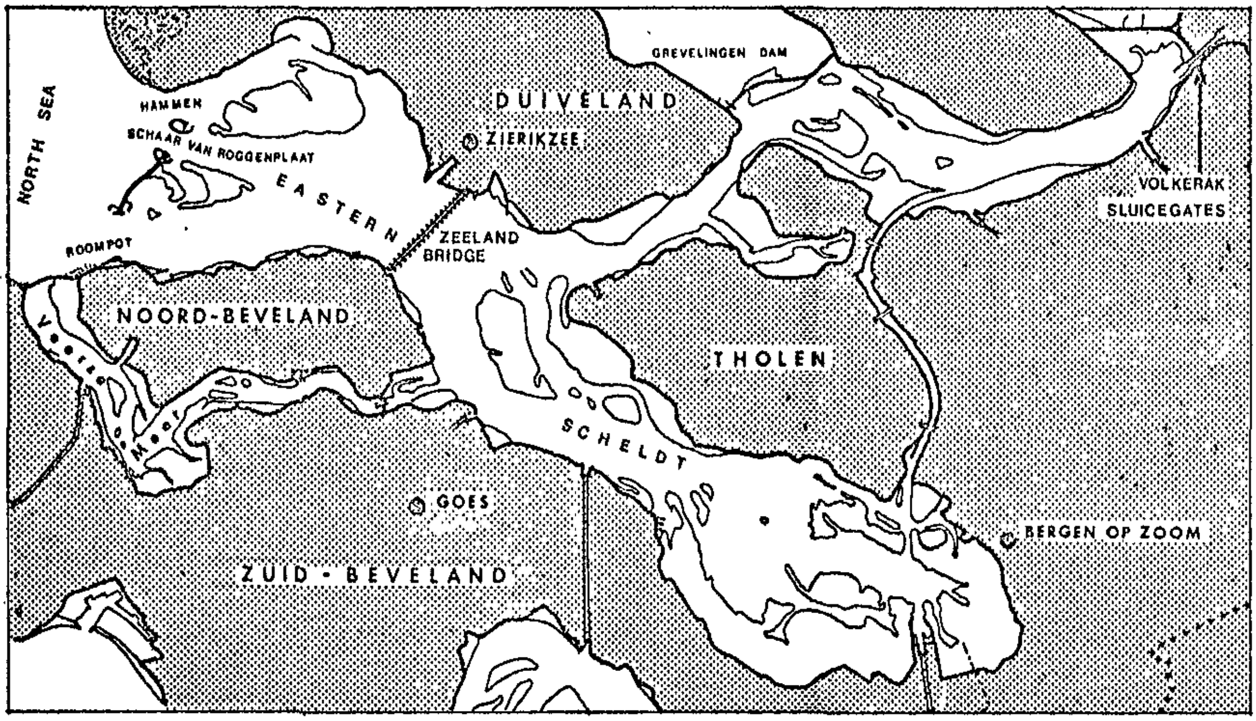
1. Definition of the system

The Eastern Scheldt is a well mixed estuary with an average depth of 8 m and an area of 480 km^2 in the southwestern region of the Netherlands (see Fig. 1).

Fig. 1. *Eastern Scheldt region*



Ca 1.1 x 10^9 m^3 of water move in and out of the estuary per mean tidal cycle. Since construction of the Volkerak dam was completed in 1969 the influence of river water discharged by the Rhine and the Meuse has been greatly reduced (average present inflow of river water through the Volkerak sluice gates is 15-40 m^3/s). The total salinity varies between 18 and 34 grams per liter, the lower values being found only in the vicinity of the Volkerak sluices.

The flows of organic matter into and out of the estuary are outlined in Fig. 2. Flows resulting from rainfall, sewage discharge, and discharge of water through the Volkerak dam are considered too small to be significant and are not represented.

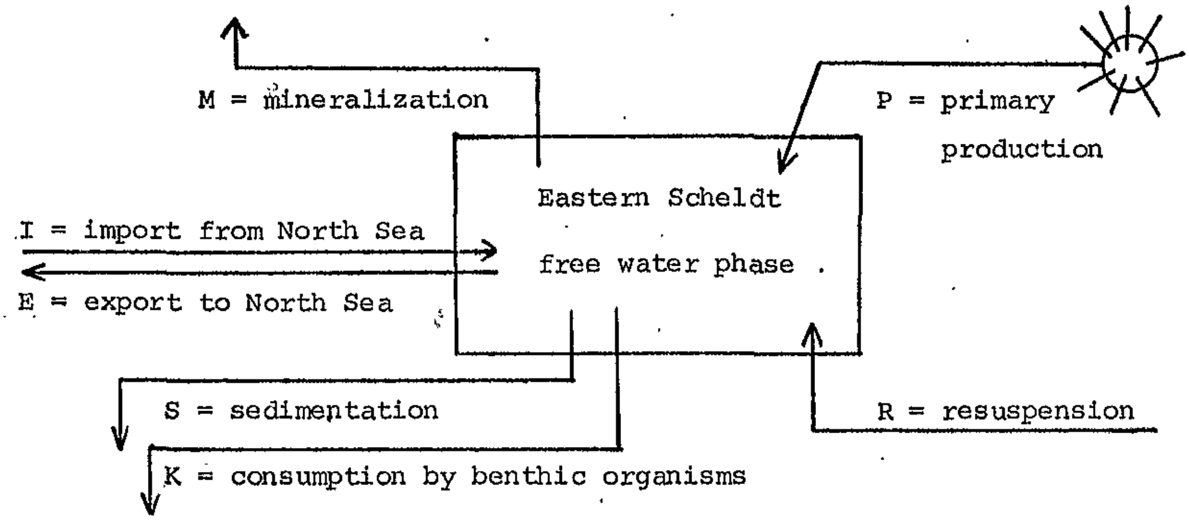


Fig. 2. Flows of organic matter to and from the estuary

Let O = concentration of organic matter, particulate as well as dissolved, in the water of the estuary

V = volume of estuary

t = time

I = import of organic matter into the estuary from sea via tidal exchange

E = export of organic matter from the estuary to sea via tidal exchange

M = mineralization of organic matter by organisms in estuary

P = primary production of organic matter in estuary

K = consumption of organic matter by benthic organisms in estuary

R = input of organic matter due to resuspension of bottom material in estuary

S = loss of organic matter due to sedimentation in estuary

A mass balance for organic matter can be written as follows:

$$(1) \quad \frac{dO}{dt} \times V = I - E + P + R - M - K - S$$

For the sake of simplicity the various forms of organic matter (particular, dissolved, colloidal) have been lumped together. The terms P and K can be roughly estimated from presently available data. The terms M and R - S, though difficult to measure, can be important and deserve attention. This report concerns itself with the measurement of I and E.

2. Alternative methods of measurement

2.1. Indirect measurements

Postma (1961) postulates a tidal mechanism for the transport of suspended matter from the mouth of a tidal inlet towards the interior and presents field measurements in support of this mechanism. The tidal inlet considered, the "Dantzig Gat" in the "Wadden Zee", is, like the Eastern Scheldt, well mixed and not subject to any significant influence from river water. According to Postma, this mechanism is responsible for maintaining the much higher concentrations of suspended matter found within the "Dantzig Gat" in comparison to the open sea outside. He uses measured values for the average concentration of suspended matter over a number of sampling points within the estuary as well as outside the inlet together with values for the average tidal water exchange to calculate the mean loss of suspended matter from the inlet due to tidal exchange. Suspended matter is also removed from the estuary by deposition on the mud flats. In order to maintain the higher concentrations inside the inlet, active transport would have to counterbalance these losses. A summary of his results is given in Table 1.

Table 1. *Summary of Postma's results for the "Dantzig Gat"*

Loss of suspended matter (smaller than 64 microns) from the estuary due to tidal exchange = $E \times (C_1 - C_2)$

$= 5.6 \times 10^7\ m^3 \times (75 - 30)\ mg/l =$ $\underline{\underline{25 \times 10^5 \text{ kg per tide}}}$ *

where E = average tidal exchange

C_1 = average content of suspended matter ($< 64\mu$) in estuary

C_2 = " " " " " " outside estuary

Loss of suspended matter ($< 64\mu$) due to deposition on mud flats near the shore = $\underline{2 \times 10^5 \text{ kg per tide}}$ *

Gain of suspended matter ($< 64\mu$) due to active transport of silt in the direction of the shore = sum of the losses

$= \underline{\underline{27 \times 10^5 \text{ kg per tide}}}$ *

In effect, Postma uses a simplified version of the mass balance presented in equation (1). dO/dt is assumed to be zero over the long

* To roughly convert these figures to equivalent amounts of organic matter, multiply by 0.10.

run; S - R is estimated as well as I and E; P, M and K are not taken into account.

Wolff (1975) uses Postma's method to calculate the import of particulate organic carbon from the North Sea to the Grevelingen estuary. He uses measured values for the average concentration of dissolved phosphorus at three points well within the estuary and at two points in the mouth, and values for the average tidal exchange to calculate the average loss of dissolved phosphorus from the estuary to the sea per tidal cycle. He assumes that an equal amount of particulate phosphorus must enter the estuary from the North Sea to counterbalance the losses of dissolved phosphorus from the estuary. Use of a conversion factor for P and C enables him to calculate the import of particulate carbon as 31 to 45 metric tons per tide (this is equivalent to 62 to 90 tons of organic matter per tide).

A great advantage to this type of approach is that the necessary field measurements can be made at regular intervals and are easily combined with other programs. The accuracy and reliability of the method are rather difficult to estimate.

An approach similar to that of Postma (1961) may be used to estimate the net import, I - E, of organic matter for the Eastern Scheldt. The average concentration of organic matter (to simplify the discussion we will limit ourselves to particulate matter $>0.5\mu$; the method described applies equally well to colloidal and dissolved matter) over a large number of points within the estuary, which we call $\overline{C}_i$, as well as the average concentration just outside the inlet, which we call $\overline{C}_o$, have to be determined. If G = mean tidal exchange, then $G \times (\overline{C}_o - \overline{C}_i) = I - E$ or the net import per mean tidal exchange. For the Eastern Scheldt $G = ca\ 2.2 \times 10^7\ m^3$ or 2% (this is a rough estimate for the estuary as a whole). If I - E is equal to 350 tons per tidal exchange, as predicted by the Polano model, then $\overline{C}_o - \overline{C}_i$ should be ca 16 mg/l as organic matter, or 160 mg/l as total suspended matter (assuming 10% of suspended matter to be organic; see Manuels and Postma 1974). In "Slib in de Deltawateren" (1976) the values for $\overline{C}_o$ and $\overline{C}_i$ are estimated at ca 60 and ca 30 mg/l suspended matter ($< 50\mu$). $\overline{C}_o - \overline{C}_i$ is then ca 30 mg/l suspended matter, or ca 3 mg/l organic matter, which results in a net import of only ca 140 tons organic matter per 24 hours for the Eastern Scheldt. If, however, we assume that 50% of the suspended matter is organic, as reported in "Slib in de Deltawateren" (1976), then $\overline{C}_o - \overline{C}_i$ is ca 15 mg/l with as result a net import of ca 700 tons organic matter per 24 hours. This agrees well with the prediction of the Polano model.

One of the difficulties in this approach is that the mean tidal exchange differs for different parts of the Eastern Scheldt. Also, the values of $\overline{C}_o$ and $\overline{C}_i$ mentioned above are based on measurements during fairly calm weather and not during storms. The accuracy of the calculations is therefore likely to be rather poor.

2.2. Direct measurements

Terwindt (1967) estimates the transport of suspended matter in a rather direct fashion. He states that "Mud discharge across an imaginary line equals the product of the volume of water flowing across the line and the mud content of the water. There is a definite mud discharge if the product is larger for one tidal current direction than it is for the opposite". In this manner he estimated the net amount of mud (suspended matter with an equivalent diameter of less than 50 microns) transported annually into the "Zak van Bergen op Zoom" (easternmost region of the Eastern Scheldt) from the rest of the estuary to be ca 300 metric tons per tidal cycle. Assuming 10% of the mud to be organic material gives a net transport of ca 30 tons of organic matter per tidal cycle. In the same way the net transport from the Eastern Scheldt through the "Keeten" was estimated at ca 3000 metric tons of mud or ca 300 tons of organic matter per tidal cycle.

Using the same approach it should be possible to estimate the net transport of organic matter from the North Sea into the Eastern Scheldt. The only data required are the average tidal flows and the average concentration of organic matter in the flood and ebb waters in the entrance to the estuary. An example of such a series of measurements is reported by Kleinjan (1934). He conducted measurements during a period of 15 days along a transect from Breskens to Flushing in the entrance of the Western Scheldt and determined the average content of suspended matter at flood and ebb tide.

Although the approach is the most direct one, there are a number of practical difficulties involved. Water from the North Sea enters the Eastern Scheldt through three tidal channels. Measurements would thus have to be made in at least three places during the course of a tidal cycle. At least three ships will be necessary for more than 13 hours for each series of measurements. The concentration of organic matter will most likely vary with depth (see Postma 1961), making it necessary to take samples from several depths. The flow of water will also vary with depth, further complicating the calculations. During rough weather it will be difficult or impossible to remain at anchor in one place while taking samples during the tidal cycle. The estimation of flood and ebb volumes in the tidal entrance may also present difficulties.

An obvious question is whether the expected difference in organic matter content between ebb and flood water is of a magnitude which can be measured. The mean ebb and flood volume for the Eastern Scheldt is 1.1×10^9 m^3 per tide. In order to arrive at a net import of 700 tons of organic matter per 24 hours, the difference in organic matter concentration between flood and ebb water would have to be ca 0.30 mg/l (or ca 0.15 mg/l expressed as organic carbon). The average concentration of total suspended matter in the tidal entrance is ca 40 mg/l ("Slib in de Deltawateren" 1976), which is equivalent to roughly 4 mg/l as organic carbon (manuels and Postma 1974).

In order to judge whether it is feasible to measure the organic matter concentration in flood and ebb water with the necessary degree of accuracy, a preliminary series of measurements was carried out on August 11, 1976, in the tidal entrance to the Eastern Scheldt.

3. Initial series of field measurements

3.1. Methods and materials

On August 11, 1976, the concentration of particulate carbon was determined for ebb and flood water in the three channels of the Eastern Scheldt entrance. Prior to the measurements an estimate was obtained of the expected flow through the channels over the period from low water at 10:15 until low water at 22:30 (see appendix 1). With the help of these estimates, integrated samples with a total volume of 25 l were taken proportional to the flood and ebb flows in each channel. A proportional sample was composed of discrete samples taken at intervals of 30 minutes during flood or ebb. The volume of each sample varied between ca 0.5 and 5 liters and was proportional to the estimated flow in the channel at the moment of sampling. Separate integrated samples were taken over the ebb and flood tides from 3 meters below the surface and at two thirds of the total depth (17, 21, and 24 meters deep for the channels "Schaar van Rogge", "Hammen", and "Roompot" respectively).

The sampling points were situated near the deepest section of the channel, where currents are strongest and vertical differences in flow are minimal (personal communication Van der Ree, Deltadepartment, Zierikzee).

In addition, a fourth ship took proportional samples in the "Roompot", while moving around the channel, with the help of a pump whose rate of intake was continously adjusted so as to be proportional to the flow in the channel itself (pumping rate was between 2 and 15 liters per hour).

All samples were cooled on ice and brought to the laboratory within eight hours. Subsamples of 1.0 liter were filtered through glass fibre filters (Whatman GFC, pore size = 1 micron) and the filters frozen. The filters were subsequently analyzed for chlorofyll "A" and particulate carbon. Chlorofyll "A" was determined with a spectrophotometer after grinding and extraction in acetone. Carbon was determined with a Coleman carbon analyzer.

Table 2. Initial series of field measurements, August 11, 1976

Sampling place depth and tidal phase	Particulate organic carbon in mg/l = C	Chlorofyll "A" in mg/m^3	Transport of organic carbon in $kgx10^6 = \bar{C}xF$	Net export of partic. organic C in $kgx10^6$
1."Roompot" flood/ebb 3 meter	1.40 / 1.51	12.0 / 18.5	1.12 / 1.26	0.14
2."Roompot" flood/ebb 24 meter	1.93 / 1.86[1] 1.86	22.0 / 19.0		
3."Sch.v.R." flood/ebb 3 meter	1.45 / 2.35	22.0 / 32.5	0.39 / 0.79	0.40
4."Sch.v.R." flood/ebb 17 meter	1,90 / 3.10	16.5 / 37.5		
5."Hammen" flood/ebb 3 meter	2.00[1] 2.00 / 2.40	25.0 / 26.5	0.47 / 0.80	0.33
6."Hammen" flood/ebb 21 meter	1.95 / 3.55	24.0 / 28.0		
7."Roompot" flood/ebb 3 meter sample taken continuously with pump while moving about in channel	1.52 / 1.63	16.5 / 16.0		

[1] Particulate organic carbon subsampled and analyzed in duplo

3.2. Results

The results of the initial series of measurements are summarized in Table 2.

3.3. Discussion of results

The values for chlorofyll correlate fairly well with those for particulate organic carbon (correlation coefficient = 0.76). Roughly 40 to 70% of this carbon is present as fytoplankton (assuming that carbon = ca 50 x chlorofyll in fytoplankton).

Samples 4 and 9 were analyzed in duplo for particulate carbon (filtering of subsamples and carbon analysis were both done in duplo). The duplos are excellent and indicate that the precision of the carbon determination should be sufficient for our purposes (the expected difference between the mean concentration of organic carbon in ebb and flood-waters is ca 0.15 mg/l; see p. 9).

The sampling error involved may be considerably greater than the error in the organic carbon analysis. One source of error is the prediction of tidal flows over the various channels (see appendix 1, Fig. 1). The proportional sampling is based upon these estimates. The error in these estimates is roughly 8% by calm weather and 15% by rough weather (personal communication Schaap, Deltadepartment, Zierikzee). The estimation of tidal flows at a specific point in the entrance is subject to an error of roughly 5% and 10% by calm and rough weather when based upon measurements of current velocity (Schaap). The agreement between predicted and measured flows at the sampling point in the channel was good (see appendix 1, Fig. 2). The influence of the errors in flow estimation upon the calculation of import and export can only be evaluated if the variation of organic matter concentration with time is known. If the errors are random their influence will likely be small. A detailed error analysis would probably need to be done if measurements of the sort under discussion are carried out in the future.

Another source of error is the taking of samples at a fixed point in the entrance. If the horizontal distribution of organic matter is very heterogeneous this can cause a large error. The good agreement between

between measurements carried out from a vessel continuously sampling and moving around the channel and from a vessel taking discrete samples near the deepest point in the channel (see 1. and 7. in Table 2) suggests that this source of error is likely to be rather small. The samples taken continuously from a moving vessel showed higher concentrations than samples taken in one place at discrete intervals (1.52 and 1.63 mg/l compared to 1.40 and 1.51 mg/l) but the difference between ebb and flood samples for both methods is 0.11 mg/l and it is this difference which is used to calculate the net import or export.

From Table 1 it is clear that the variation of organic matter concentration with depth large is. Any measurements of mean import and export would have to be based on samples taken over at least three to four depths.

A number of depth profiles for current velocity measured at the sampling point in the channel "Hammen" are presented in appendix 2. These profiles suggest that current velocity varies little with depth. A predicted average flow in the channel over the entire water column can then most likely be used as a basis for proportional sampling at various depths.

The estimated transport of organic carbon through the various channels between 10:15 and 22:30 on August 11, 1976, is given in the last column of Table 2. The transport is equal to $\overline{C} \times F$ where $\overline{C}$ = average of particulate organic carbon concentrations measured at the two sampling depths and F = tidal flow through the channel (see appendix 1). The measurements indicate a considerable export to the North Sea, mainly through the "Hammen" and "Schaar van Roggenplaat", which is seemingly in contradiction with the considerable import predicted by the Polano model. The expected import however was a mean long term value. For a variable such as organic carbon, subject to large seasonal fluctuations, it is not possible to make any long term estimates on the basis of a single series of measurements.

3.4. Discussion of sampling method

During the sampling on August 11, 1976, weather conditions were ideal, sunny with little wind. With rough weather it is not possible for a boat to remain at anchor in the channel. Working with a water sampler on deck also becomes increasingly difficult. Since larger amounts of organic matter can be brought into suspension by wind and wave action it is advisable to make measurements also in rough weather.

A sampling procedure which is also operational under fairly rough conditions is the following. The boat is not anchored but moves in and out of the channel. Sample is taken continuously with a pump and the rate of intake varied proportionally with the flow in the channel. Intake of sample occurs only when the boat is drifting with the current. In this way no heavy ballast weights are needed to maintain the intake hose at the required depth. To obtain proprotional samples from various depths one can change the intake depth at regular intervals or use a number of intakes at different depths. With the latter method it is possible to take samples simultaneously at different depths.

A practical problem is that the division for environmental research of the Deltadepartment has only one boat equipped for working in such a fashion. At least two other boats would have to be made available and equipped on a regular basis for a series of measurements to be carried out.

The cost of a series of measurements such as described above is estimated and presented in appendix 3.

Alternative possibilities are sampling with the help of a helicopter (this method is presently being tested out by the Deltadepartment, Environmental Division) or with automatic water samplers which remain anchored at the sampling points. These alternatives are likely to involve rather high costs.

4. Conclusions

The initial series of measurements carried out on August 11, 1976 suggest that it is probably feasible, using the method described, to measure a net transport of organic matter between the Eastern Scheldt and the North Sea of the size predicted by the Polano method (ca.700 tons/day). The errors involved in the laboratory analysis of samples and in collecting samples in the field appear small enough so as not to seriously interfere with the measurements.

Such problems as the desired frequency of measurement and the timing of measurements with respect to spring and neap floods, weather, high and low water, etc. would have to be considered before a series of measurements is actually carried out.

Acknowledgements

Thanks are due to M. Knoester, J.C.H. Peeters and J. Al for their stimulating advice. Special mention should be made of the effort contributed by the field workers ("velddienst") and the lab section as well as the assistance offered by the Deltadepartment, Zierikzee and Hellevoetsluis, and the crews of the vessels "Delta", "Ventjager", "Orisant", and "Heerinck" without whom this work could not have been accomplished.

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Appendix 1

Fig. 1a. Flow prediction for August 11, 1976, over the tidal entrance "Roompot"

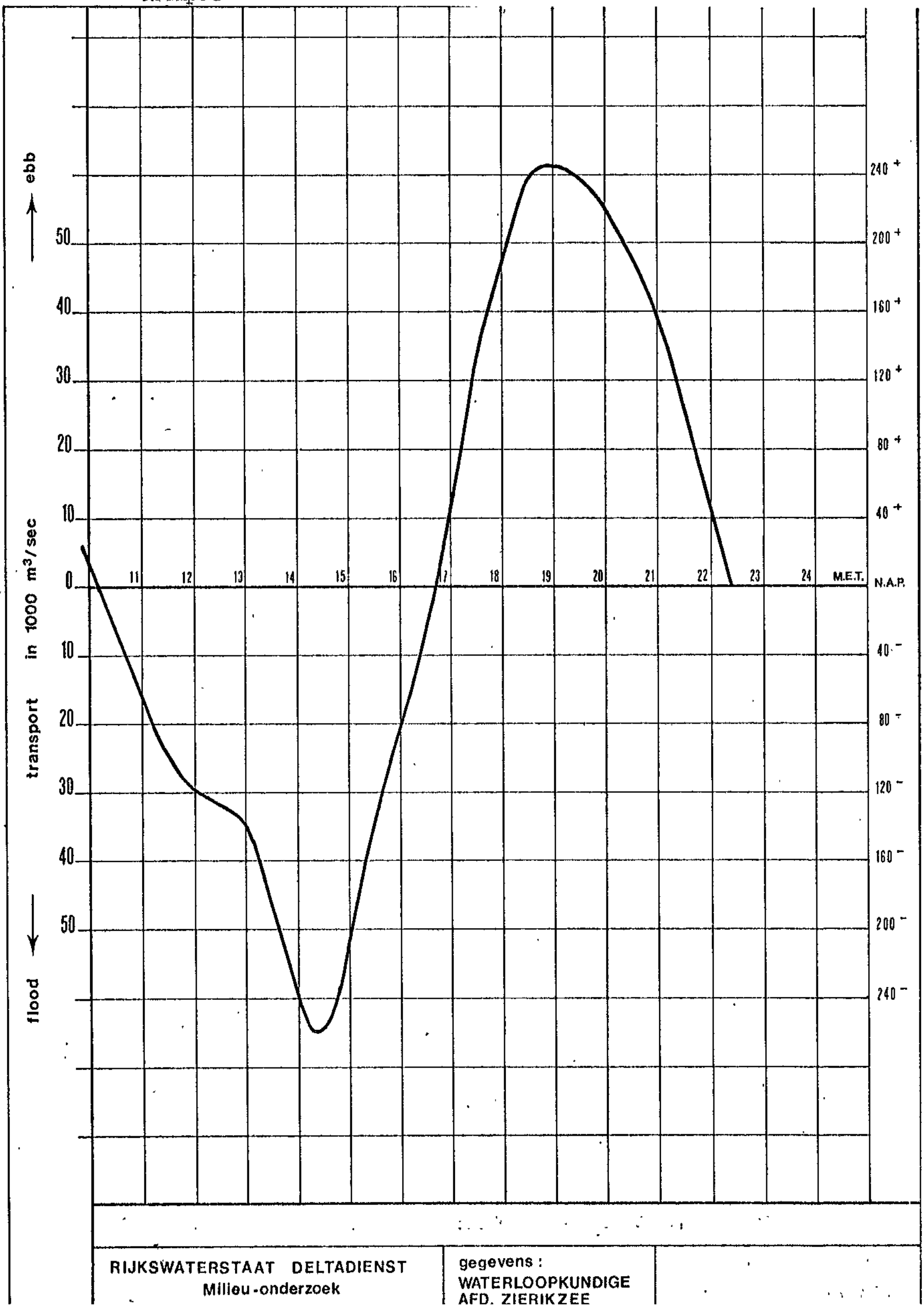


Fig. 1b. Flow prediction for August 11, 1976, over the tidal entrance "Schaar van Roggenplaat"

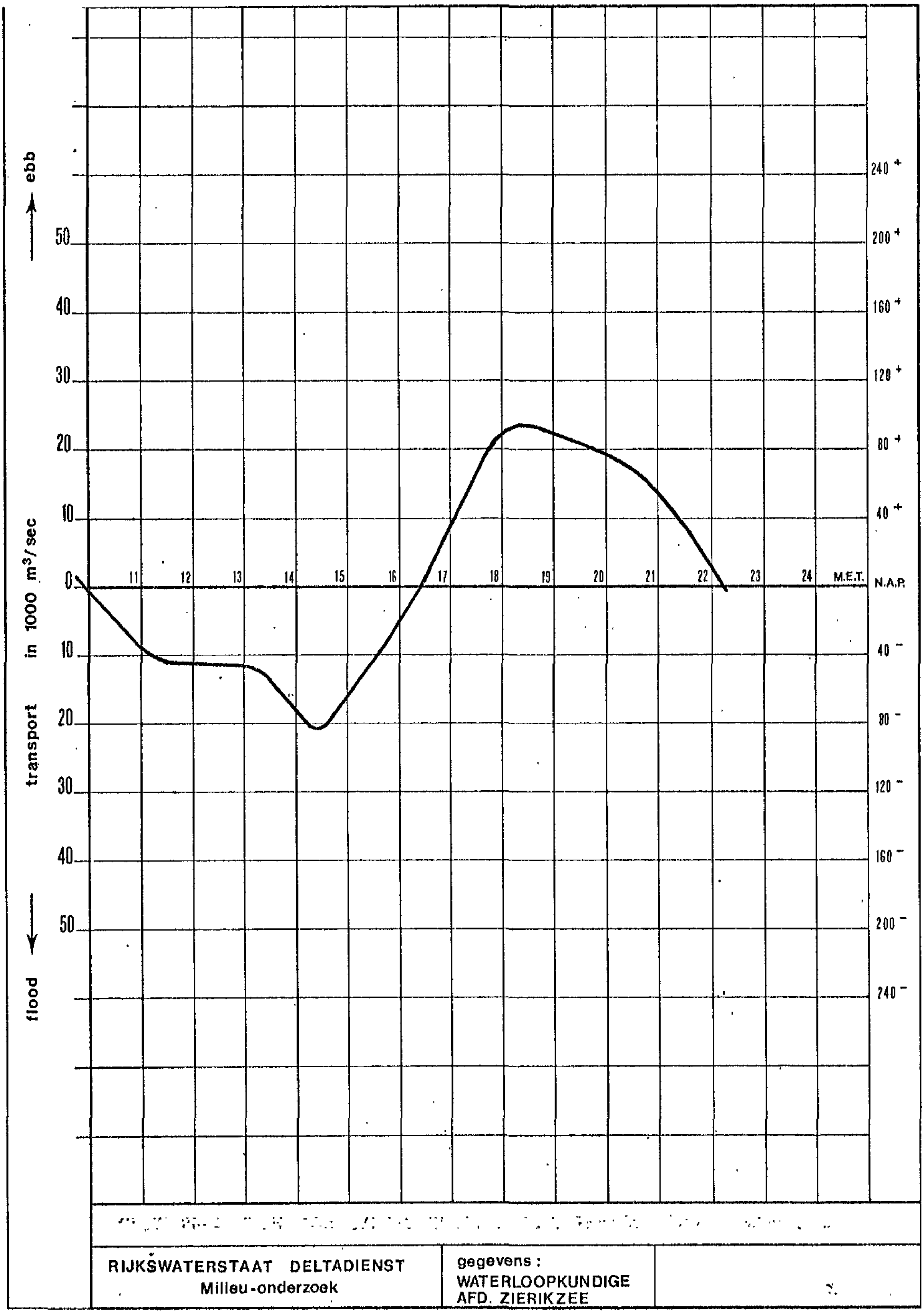


Fig. 1c. Flow prediction for August 11, 1976, over the tidal entrance "Hammen"

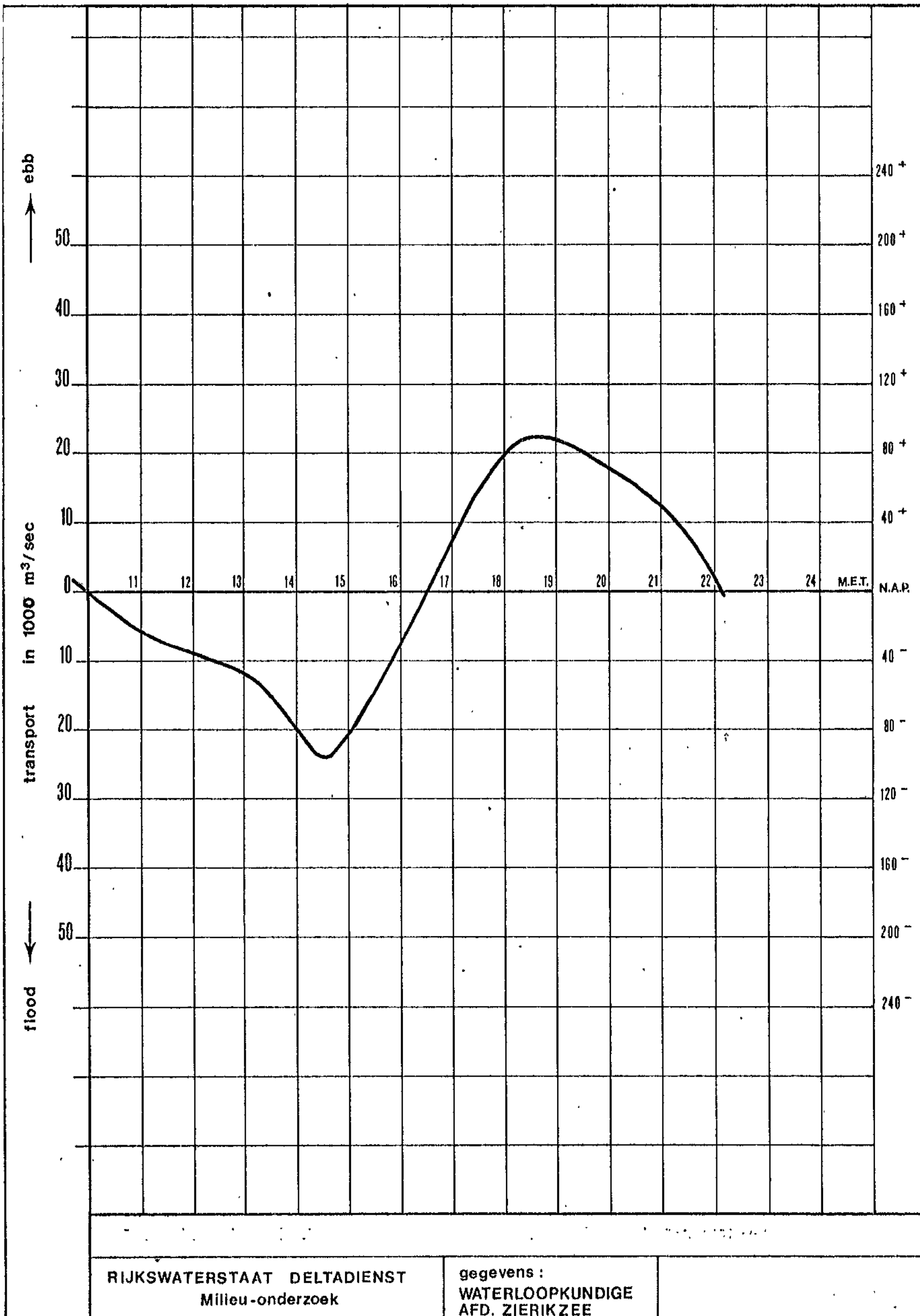
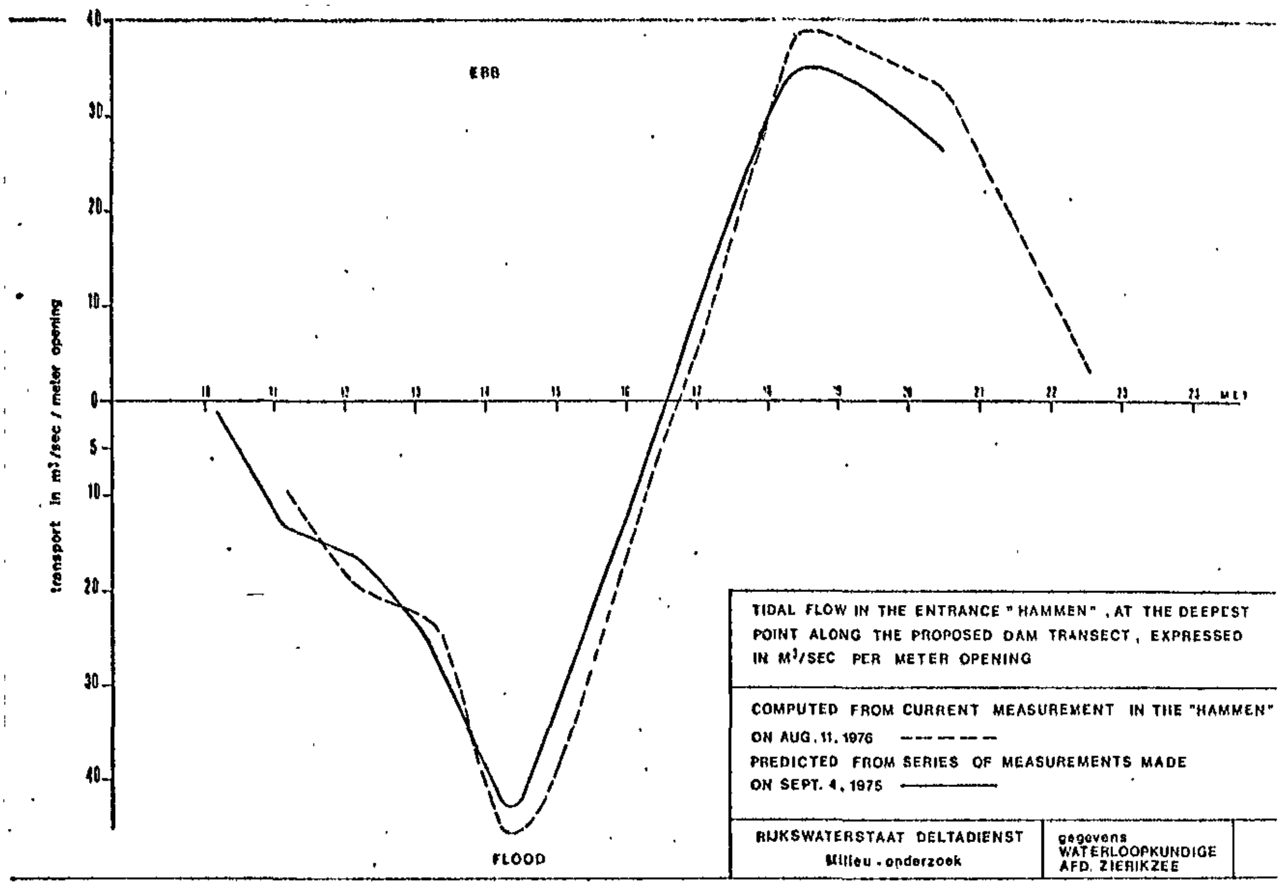
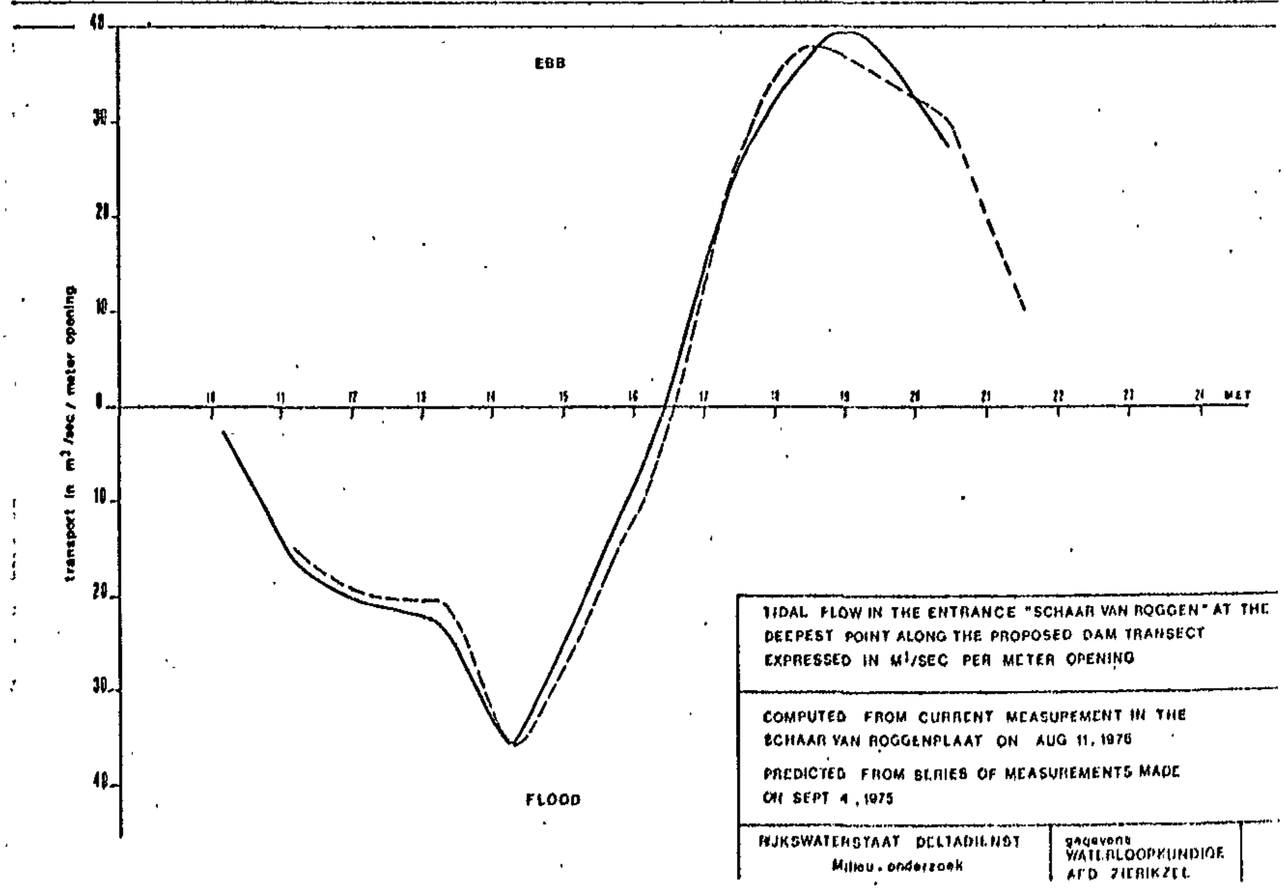


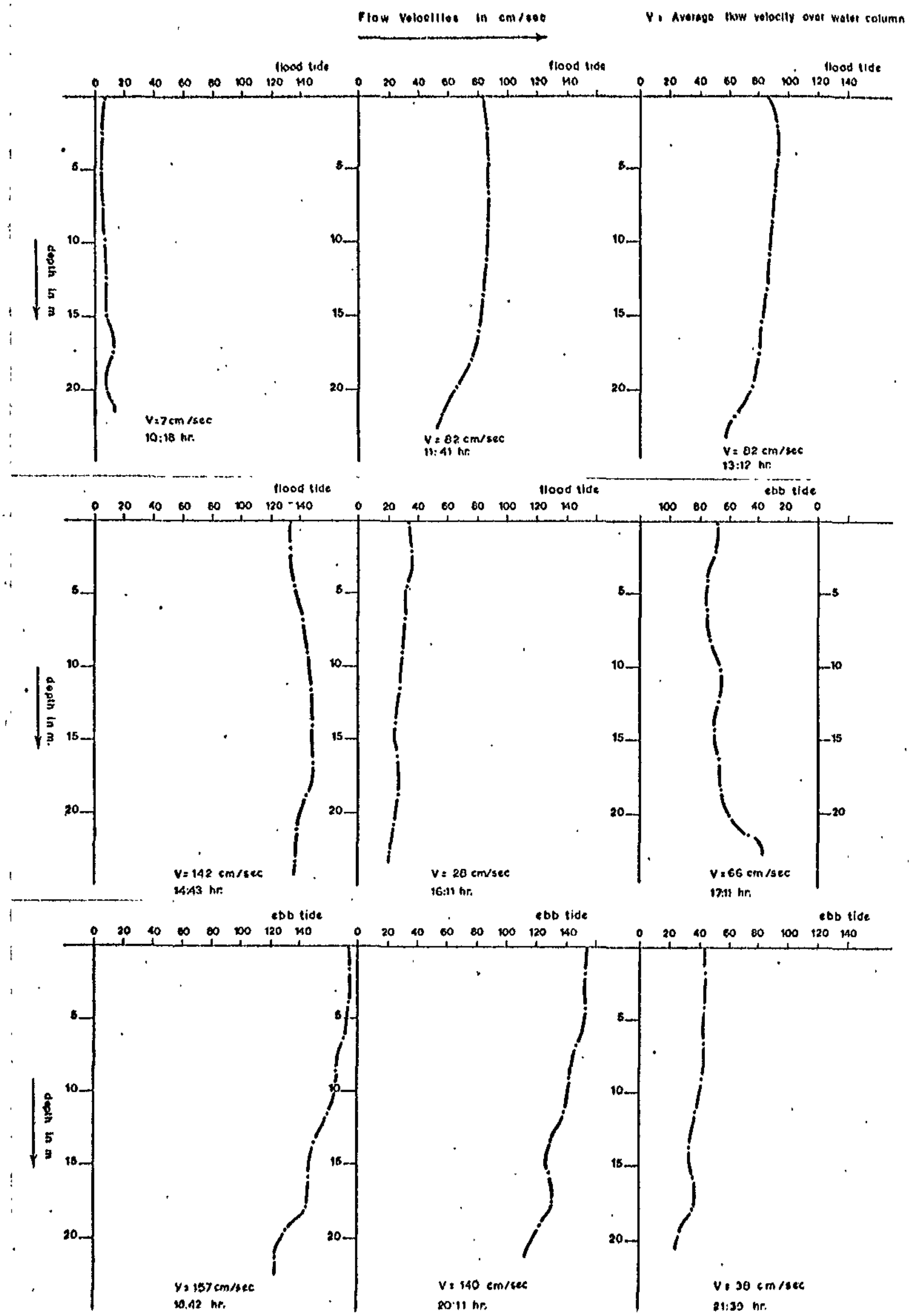
Fig. 2. Comparison of predicted and measured tidal flows at the sampling points in the "Hammen" and "Schaar van Roggenplaat" on August 11, 1976.





Appendix 2

Fig. 1. Depth profiles of tidal current measured on August 11, 1976, in the tidal entrance "Schaar van Roggenplaat" by deepest point.



Appendix 3

Cost in manpower and material for a series of twelve measurements during flood and ebb in three tidal entrances to the Eastern Scheldt.

1. Shipdays - 12 x 3 x 2 = 72

   4 x 1 x 2 = 8

   80 shipdays

   A shipday is taken here to be a workday of 8 hours
   A measurement is assumed to last 16 hours.
   The 8 extra shipdays are for a series of "duplo" measurements whereby on four dates one channel is sampled by two ships independently of each other.

2. Mandays necessary for sampling:

   12 x 3 x 3 x 2 = 216

   4 x 2 x 3 = 24

   240 mandays

   Each ship has a crew of two and one extra man for the taking of samples.

3. Mandays for analysis in laboratory:

particulate organic carbon	:	12 x 60 = 720	samples	= 20
chlorofyll analysis	:	12 x 18 = 216	"	= 7
dissolved organic carbon	:	12 x 18 = 216	"	= 2
ATP analysis	:	12 x 18 = 216	"	= 4
				33 mandays

   Proportional samples are taken from three depths in each channel giving 3 x 2 x 3 = 18 proportional samples per tidal cycle. In addition, ca 40 discrete samples are taken at successive intervals during the tidal cycle and analyzed for particular organic carbon. These measurements allow an estimate of the variation in carbon concentration during the tidal cycle. This in turn permits calculation of sampling error due to errors in the prediction of tidal flows in the channels.

4. Mandays for interpreting and reporting results:

Calculations	:	10
Drawings	:	5
Drafting report	:	20
Typing, etc.	:	5
		40 mandays

Total : **80 shipdays, 313 mandays**