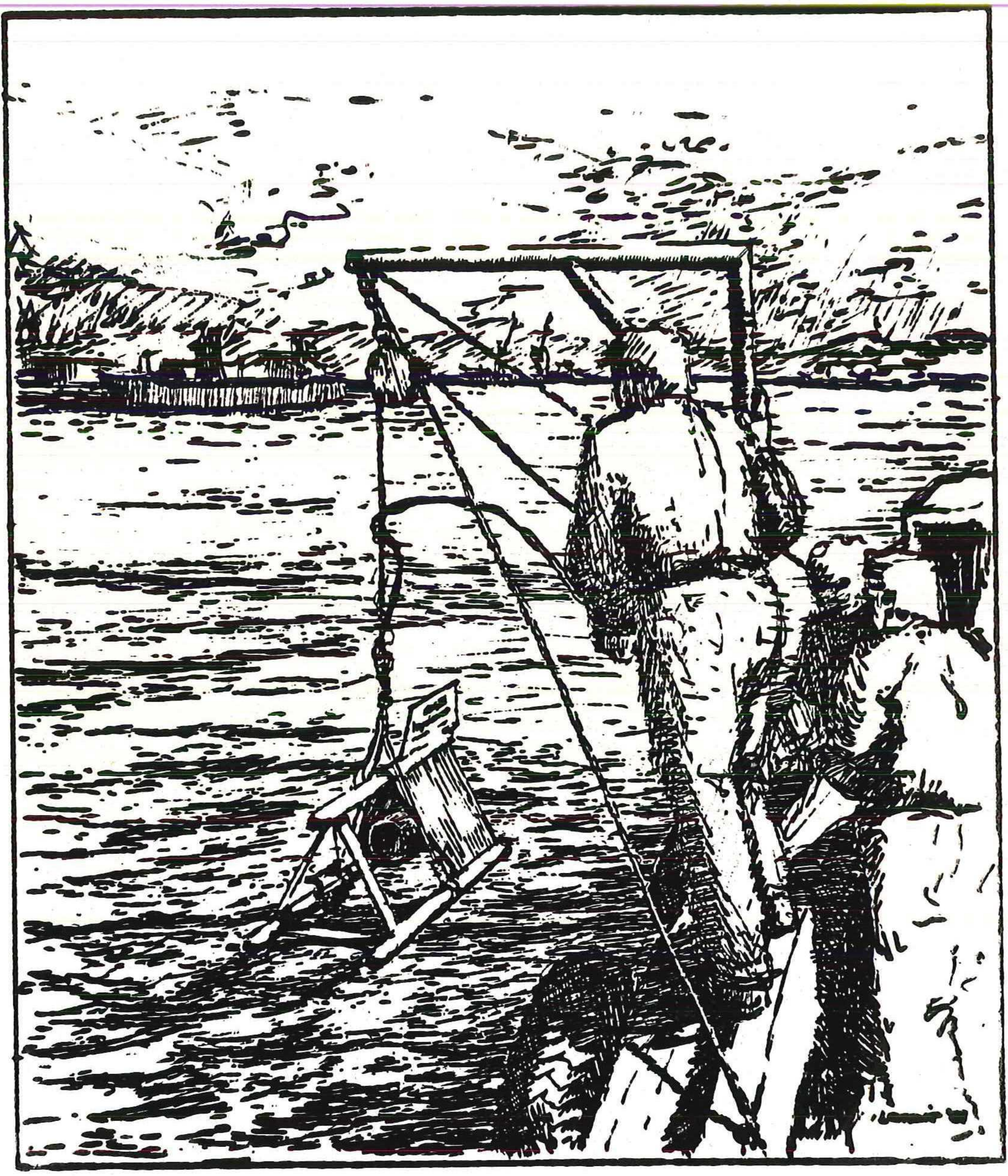
Verhagen

QUIMIGAL, QUIMICA DE PORTUGAL

Hydro - morphological study
part II
Calculation of expected siltation



May 1982 / P405

PORT AND WATERWAY ENGINEERS

hydronamic bv
sliedrecht holland

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hydronamic bv

CONTENTS PAGE

1. INTRODUCTION

To get a more detailed impression of the expected siltation in the access-channels to the Quimigal plants, Quimigal invited Hydronamic b.v. to study erosion and sedimentation behaviour along the access-channels. This study is a continuation of the study made by Hydronamic in 1979. The main problem in the 1979 study was that no calibration measurements were available. During this study these measurements have been made.
Another improvement with respect to the 1979-study is that for this study it was possible to use boundary values generated by the General Flow Model of the Inner Estuary, developed for A.G.P.L.

The total study consisted of two parts, field measurements and a mathematical model. The study was proposed to Quimigal by telex pma 1140/aq of September 30, 1981. A notice to proceed was given by Quimigal by telex 394/81 on October 1st, 1981.
The report dealing with the field measurements, dated November 1981, has already been forwarded to the client.
This final report deals with a mathematical study of the siltation in the Canal do Quimigal, using the Hydronamic hydro-morphological model. The study has been executed by mr. H.J. Verhagen and mr. G.J.A. Loman. The report was prepared by mr. H.J. Verhagen under the supervision of mr. A. Burgers, head of Hydronamic's Studies and Consultancy department.

2. THE MATHEMATICAL FLOW MODEL

With the use of a mathematical model the velocities in the Quimigal area have been calculated. This two-dimensional flow model is based upon a computational scheme developed by Leendertse for the Rand Corporation (U.S.A.). A more detailed description of this model is presented in Annex A.
The model requires as input the water levels on the boundaries, given as a function of time. These boundary-values have to be determined very accurate. We have done this with the General Flow Model of the Inner Estuary, which model we have developed and calibrated on assignment of A.G.P.L. This General Flow Model has a mesh-size of 250 m. It has been calibrated, using measured water levels and measured current velocities. All these measurements have been made by A.G.P.L. For the location of the General Flow Model and the locations of the calibration measurements, see fig. 1.

The detailed model of the Quimigal area is also indicated on figure 1. The mesh-size of this model is 83.33 m. In drawing 1-4 the calculated current patterns for high water, max ebb, low water and max flood are reproduced. The scale of the drawings is 1:10000; the velocity scale of the arrows is 1 cm = 1 m/sec.
In Annex B a number of diagrams with the velocity vs. time is presented.

3. THE SILTATION MODEL

The siltation model applied by Hydronamic is based on a calibrated sediment transport formula and on the calculated velocities.
With the sediment transport formula the amount of transported sediment is calculated as a function of time, velocity, stirring-up and grain-size.
The velocities follow from the flow model, stirring-up is caused by velocity and waves.
Because of velocity near the bottom and because of the orbital movement of the waves, sediment particles are stirred-up. The stirred-up particles are transported by the current. The model calculates in every mesh-point the quantity of sediment transport for each time-step. The difference in sediment transport between two subsequent mesh-points causes siltation and erosion. For each time-step this siltation or erosion is calculated. Mostly during one half of the tide siltation occurs, and during the other half erosion occurs. The resulting sedimentation or erosion can be calculated by adding all the bottom changes of each time step.
For a more detailed discussion can be referred to Annex C.

As described in the previous section the morphological model needs the hydraulic parameters at each grid point (current velocity, current direction and water level) plus some other values as wave height, wave period, bottom roughness and the grain size of the sediment.
The hydraulic parameters are read by the computer from the output of the hydraulic model.

The time step of the morphological model can be much longer than the time step of the hydraulic model. For the calculations of the Quimigal area a time step of 60 minutes gave a stable computational process.
The other values used in this calculation are a wave height of 50 cm and a wave period of 3 seconds. As already discussed in our report on the field measurements the influence of the waves is relatively small.
A wave of 0.5 m seems to be reasonable average for the whole year.
The bottom roughness used is 0.075 m, the grain size used is:
$D_{50} = 5\ \mu$, $D_{90} = 25\ \mu$. These values were also discussed in our report on the field measurements and were derived from the sediment transport measurements. These values do differ from the estimated values which we used in the 1979 study. The measurements revealed that the material is finer than we did assume in 1979.

The morphological model in fact calculates the siltation in tons/year. Because this unit is difficult to understand, the siltation is multiplied with a density. The model uses a standard density of 1600 kg/m^3.
This density is valid for sand. In case of mud a lower density has to be used. The expected density in the Quimigal area is 530 kg/m^3, and thus the results of the computer program have to be multiplied with 1600/530.
For a more theoretical discussion of the density is referred to Annex D. In this Annex also the value of 530 kg/m^3 is explained.

In fig. 2 the sedimentation, as calculated by the computer, is plotted. The values given in this figure are siltations caused by spring-tide, and with a density of 1600 kg/m^3. In the next chapter these values are quantified.

4. ELABORATION OF THE CALCULATIONS

In order to quantify the results from the morphological model in such a way that decisions can be made, 5 seperate areas are defined:

1. Canal da CUF-west
   Section from deep water until the bifurcation with Canal do Quimigal.
2. Canal da CUF-middle
   Section of 1000 m from the bifurcation in the direction of the old Quimigal harbour.
3. Canal da CUF-east
   Remaining section of the Canal da CUF, including the old harbour.
4. Canal do Quimigal
   New canal from bifurcation until turning basin near the new terminal.
5. Turning basin
   Turning basin in front of the new terminal.

On the next page the calculation of the siltation in each of this area is given. In the column "all points" the average siltation is calculated, using the bottom changes in all points. In the column "only positive points", the average siltation is calculated, using only those points where siltation occurs.

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Hydronamic b.v.
Port & waterway engineers
Sliedrecht - Holland

Siltation data Quimigal area

Calculation of bottom changes
=============================

SECTION NAME                   ALL POINTS           ONLY POSITIVE POINTS
                           N       X       S       N       X       S

Canal da CUF * west       64      -4      17      25      11      15
Canal da CUF * middl      22      10      21      15      18      23
Canal da CUF * east       20      31      38      20      31      38
Canal do Quimigal         72     -17      28      11      13      26
Turning Basin             53     -10     106      13     132     163

N = number of points
X = average siltation (cm/year)
S = standard deviation (cm/year)
    all with a density of 1600 kg/m3
The area of one meshpoint is  6889 square meters
```

To quantify maintenance dredging one should take only the positive values if one deals with sandy materials. The values under the heading "all points" have to be used in case of fine material.
In one deals with fine material, this material acts like a thick fluid. If there is a point with much siltation next to a point with much erosion the accreted material will flow to an eroded area (because this eroded area is deeper).

The calculations are performed for spring tide only, thus a whole year with spring tides only. In fact there are also neap tides and mean tides.
The real siltation (or erosion) can be calculated with the formula:

$$S = 0.25 * (S_s + 2 * S_m + S_n)$$

in which

S = real siltation
S_s = siltation caused by spring tide
S_m = siltation caused by mean tide
S_n = siltation caused by neap tide

From our experience we know that this relation can be simplified to:

$$S = \alpha * S_s$$

in which α is a constant for the area. The value of α mostly varies between 0.5 and 0.7; α is called the tidal coefficient.

This tidal coefficient can only be determined by calculating one spring tide, one mean tide and one neap tide. It is impossible to determine α from the water level differences during spring tide and neap tide.

However, α remains constant for an area, and we have determined α for the Siderurgia area quite accurate. We found a tidal coefficient of 0.57. This coefficient can also be used for the Quimigal area.

As stated in Annex D, the model calculates with a density of 1600 kg/m^3. This density has to be 530 kg/m^3.
This means that all results from the model have to be multiplied with a factor

$$0.57 * \frac{1600}{530} = 1.72$$

Using the first column of the computer output on the former page this gives the following values

Canal da CUF-west	- 7 cm	-
-middle	17 cm	26068 m^3
-east	53 cm	73023 m^3
Canal do Quimigal	-29 cm	-
Turning basin	-17 cm	-
		+
		99091 m^3

From the above follows that a yearly maintenance dredging of 100.000 m^3 has to be expected in the old CUF Canal between the bifurcation and the harbour. (Siltation in the harbour is included in this figure).

In the western section of the CUF-canal, in the Canal do Quimigal and in the turning basin there will be no siltation, according to this approach.

In the computer output is, besides the average value, also given the standard-deviation. A low value of the standard-deviation means that the siltation is about the same in every square of the area.
A high value of the standard-deviation means that the siltation varies very much for each square.

This happens especially in the turning basin. In the turning basin there is happening another phenomenon. The sediment transport model is based on fine material (5 micron). On the bottom of the turning basin the material is sand. But the model assumes that there is also fine mud. If there was fine mud, this mud would erode. But because there is no mud, it will not erode.

This means that the big erosion in the turning basin, but also in the other deep sections of the Cala do Montijo will not occur. If there was erosion, the eroded material would have been transported to the areas were the current is a little bit weaker, i.e. near the terminal berth and to an area south of the Montijo air base.
But because there is no eroded material, this sedimentation will also not occur.
This conclusion differs somewhat from the conclusion in our 1979 report. In 1979 we found (qualitatively) the same type of bottom changes in the turning basin and the Cala do Montijo. At that moment we did not have the detailed information on sediment properties. Having more information at this moment we have to revise our conclusion on the sedimentation in the turning basin.

In fact one has to conclude that there will be nearly no bottom change in the turning basin near to the liquid terminal. This is mainly due to the scouring of the tide through the new Canal do Quimigal.

It is very difficult to give an idea on the accuracy of these calculations, because in reality the siltation depends on seasonal influences (much wind, dry periods, etc.). The correlation between the transport formula and the measured transport was 71%. From this figure one may expect a possible error of 30%.
The error in the tidal factor is very low, and we may neglect this.

The error in the old Quimigal port may be somewhat bigger, because in the current-model the currents inside that harbour could not be reproduced very accurately. (This is due to the mesh-size of 83.33 m).

Summarizing we expect a siltation between 70000 and 130000 m^3/year in the Canal da Cuf east of the bifurcation. The siltation in the other channels and turning basin is small.

5. COMPARISON WITH MEASURED DATA

Recently we received soundings of the Canal da Cuf from Quimigal from 1980 and 1982. The interval between the two soundings was 22 months.
The siltation in the first kilometer east of the bifurcation was approx. 47500 m^3.
According to our model, there should be $\frac{22}{12} * 26068 = 47791$ m^3.

In the next kilometer the siltation was somewhat difficult to determine. Until cross-section 240 there was 57125 m^3. But the remaining 36300 m^2 of the harbour was not surveyed.
If one estimates that the siltation inside the harbour was approx. 1.20 m, (which is the siltation in the last sections measured), this gives 43560 m^3. Total 100685 m^3.
According to our model, there should be $\frac{22}{12} * 73023 = 132000$ m^3.

The difference of 30% in the last section is mainly caused by the difficulties in modelling the harbour correctly. (The used mesh-size of 83.3 m is too large for correct modelling the harbour)

6. SOME COMMENTS ON THE CHANGES IN THE CHANNEL CROSS-SECTION

In our report of 1979 we stated that the north-eastern slopes of the channel will tend to become steeper, and that the channel becomes narrower and moves somewhat in a western direction.
This means that we expected more siltation on the NE slope than on the SW slope, and that even erosion might occur on the SW slope.
The profiles which we received fully agree with our 1979 report.
See for example the profiles 194 and 196 in fig. 3.

7. CONCLUSIONS

7.1. Expected siltation in the Canal da Cuf

In our 1979 report we calculated for the Canal da Cuf a siltation of 32000 m^3 sand equivalent. Applying a mud density of 530 kg/m^3 this is 96900 m^3 of mud. At this moment, applying a more detailed current model and using the data from the sediment transport measurements, we find a value of 100000 m^3/year.
We have to conclude that our estimate of 1979 was of the correct order in terms of tons, but that the value in cubic meters is of course higher.

7.2. Expected siltation in the turning basin

With regards to the turning basin we do expect less siltation than we did in 1979, because if the differences in grain-sizes of bottom material between the shallow flats and the turning basin area. At this moment we expect only little siltation in the turning basin.

ANNEX A

Description of mathematical flow model

Introduction

The Tagus Estuary is the transition zone from unidirectional, time varying, fresh water flows of land drainage to the tidal, saline Atlantic Ocean. Water movements throughout the estuary are affected by both 'open' boundaries as well as by the 'closed' boundaries of the bottom configuration of the estuary.

The degree of salinity stratification depends on the location in the Tagus Estuary.
The calculated 'estuary number', acc. to Harleman and Abraham, indicates that the inner estuary belongs to a transition of the partially-mixed and well-mixed estuary class. This means that the vertical salinity gradient is diminished by the bed-frictional effects of the tidal currents.
This conclusion is also supported by field data. Although there is no strong vertical salinity gradient, there is some lateral and longitudinal variation. This depends chiefly on the upstream fresh water discharge.

Consequently, the tidal flow pattern in the comparatively shallow Tagus Estuary, which has no significant vertical salinity gradients, can powerfully and effectively be represented by depth-averaged mathematical flow modeling, based on the sound theory of the two-dimensional shallow water equations.

Mathematical background of Hydronamic's 2-D flow model

The mathematical 2-D flow model is based on the Leendertse programme description (1967), published by the Rand Corporation (USA).
Hydronamic improved the programme structure and the computational procedures in order to economize the computational time consumption as well as to stabilize the computational scheme.

An additional programme-package has been developed for the purpose of presenting the results graphically.

The model for non-steady 2-D horizontal flows is based on a finite difference representation of the partial difference equations of mass and momentum conservation.

These equations are the depth-averaged 2-D versions of the turbulent analogies to the 3-D Navier-Stokes momentum equations and the continuity equation.

The flow is assumed to be incompressible. The model allows for free surface conditions at the air-water interface.

Assuming the vertical acceleration is negligible compared to the gravity and omitting the forcing functions due to barometric pressure, Reynolds stresses and 'wave radiation' stresses, the equations of continuity of mass (i) and momentum (ii) become:

$$\text{(i)} \qquad \frac{\partial n}{\partial t} + \frac{\partial \ \{(h + \eta) \ U\}}{\partial x} + \frac{\partial \ \{(h + \eta) \ V\}}{\partial y} = 0$$

$$(\text{ii}_x) \qquad \frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} + g \frac{\partial \eta}{\partial x} - fV$$

$$+ \frac{g \ U \ (U^2 + V^2)^{\frac{1}{2}}}{(h + \eta) \ C_h^{\ 2}} - \frac{\tau_{wx}}{\rho \ (h + \eta)} = 0$$

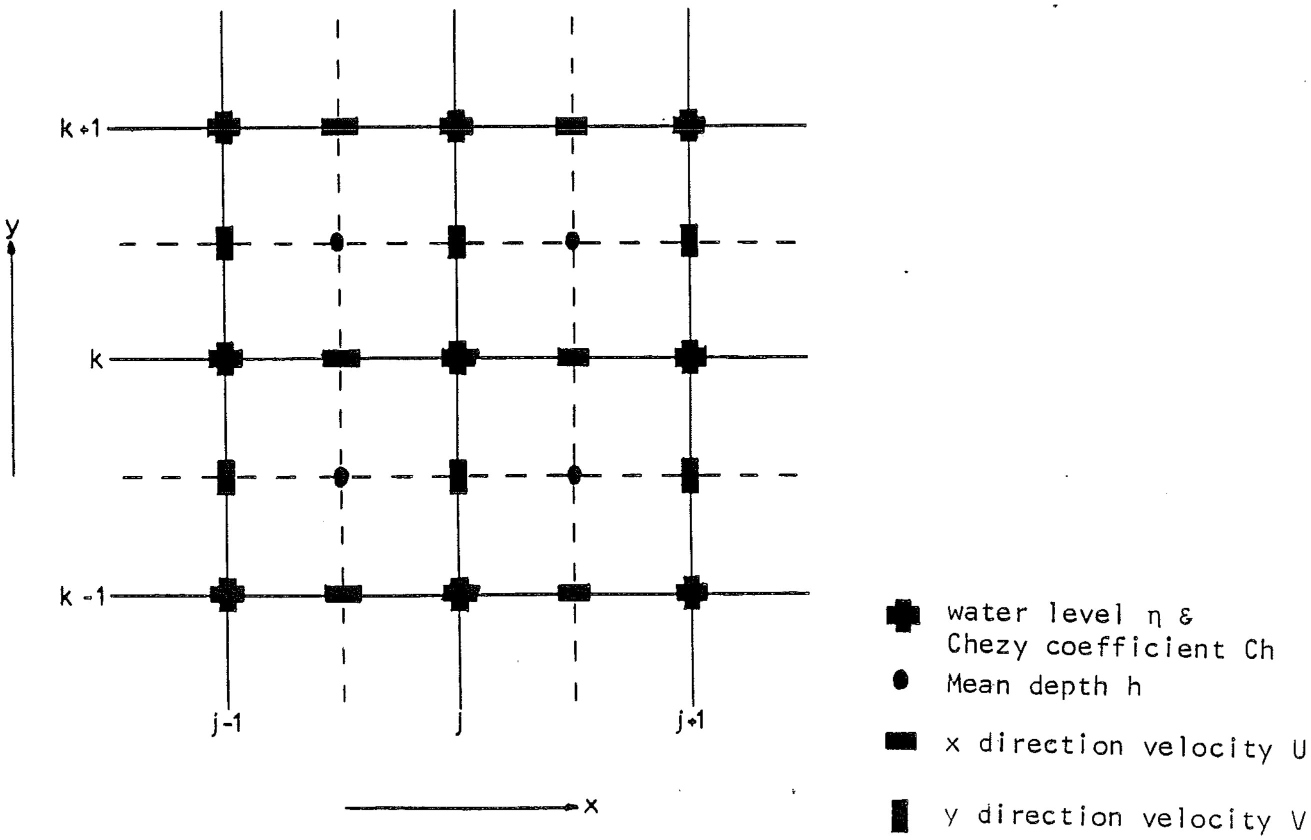
$$(\text{ii}_y) \qquad \frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} + g \frac{\partial \eta}{\partial y} - fU$$

$$+ \frac{g \ V \ (U^2 + V^2)^{\frac{1}{2}}}{(h + \eta) \ C_h^{\ 2}} - \frac{\tau_{wy}}{\rho \ (h + \eta)} = 0$$

where:

h	mean depth	(m)
η	water level above/below mean depth	(m)
U, V	depth-averaged velocity in x- and y-direction, respectively	(m/s)
f	Coriolis parameter as function of the earth's angular velocity and the latitude	(-)
g	gravitational acceleration	(m/s^2)
C_h	Chezy coefficient of bed roughness	($m^{\frac{1}{2}}/s$)
t	time	(s)
x, y	horizontal co-ordinates	(m)
τ_{wx}, τ_{wy}	x- and y-components of the wind stress	(N/m^2)

The equations of the interior flow field have been written by Leendertse as space-centered finite difference approximations on a space-staggered grid. The sketch below shows that space-staggered grid.



The computational procedure is a multi-operational, alternating direction, semi-implicit solution mode.

Each time step Δt is divided into two half-time step stages; each stage containes an implicit and explicit scheme which solves the x- and y- momentum equation separately and alternately. The non-linear terms are taken from a known time level resulting in imperfect time-centering.

Although Leendertse, using a Fourier stability analysis, proved that the above scheme is unconditionally stable, it can be shown in practice that a computation can be 'blown up' mainly due to the imperfect time-centered terms.

Hydronamic improved the above scheme considerably.

The non-linear instability, due to the inability of the model to transfer turbulent energy to scales smaller than twice the mesh-size, has been completely overcome by a weighted spatial velocity-averaging routine. Other features of the improved scheme are the allowance for nodes falling dry and the suppression of oscillations due to initial boundary conditions.

Based on previous experience with what works and what does not, the following stability condition has been developed:

$$\frac{\Delta t}{\Delta x} \left(2|U| + \sqrt{gh} \right) \leq 7$$

where:

Δt	computational time step	(s)
Δx	mesh-size of the square grid	(m)
$\lvert U \rvert$	velocity intensity at node n, m	(m/s)
h	water depth at node n, m	(m)
g	gravitational acceleration	(m/s^2)

The original Leendertse model has been developed in FORTRAN - IV programming code.

It was evident with the initial computational runs of the Tagus Estuary model that the amount of grid nodes made it uneconomical, although technically feasible, to use our in-house HP-3000 computer.
Therefore, the Hydronamic's non-steady 2-D flow model has been implemented on the CDC-750 Cybernet machine at Rijswijk, Holland, which has a storage of 400 K words.
The bulk of effort in making production runs on the CDC-computer is the pre- and post- processing of data from the in-house HP-3000 to the CDC-750 machine via an in-house Datapoint-disketter unit and vice versa.

Calibration procedure

The calibration stage of the Tagus Estuary flow model and the Quimigal Channel flow model involves the use of reliable field data.
Since the non-linear bed resistance term generally dominates the solution of the shallow water equations, the proper choice of the Nikuradse bed roughness r, to be employed for determining the Chezy coefficient, is essential.

To date, field measurements of the bed roughness in the Tagus Estuary are not available.

The empirical relationships between the bed roughness and the sediment grainsizes generally include the flow properties. Strictly speaking these formulae cannot be solved explicitly.

Assuming the following ranges of the parameters involved, the limits of the Nikuradse roughness can be determined accordingly.

flow velocity	U	0.10		1.50	m/s
water depth	h	1.00		40.00	m
grainsize	D_{50}	10	-	700	µm

Hence, the Nikuradse bed roughness may vary between r = 0.005 m and r = 0.80 m.

Generally, the Nikuradse bed roughness, observed in tidal environments, display the tendency to increase with decreasing, time-varying waterdepth. In this study, however, such a relationship is thought to be too arbitrary.

In the report, entitled 'Environmental Study of the Tejo Estuary', C.N.A./Tejo no7, issued July 1980, the following bed roughness classes were established in an arbitrary way:

depth class h (m)	Nikuradse bed roughness r (m)
73 - 40	0.0002
39 - 25	0.0010
24 - 10	0.0460
< 10	1.0000

The bed roughness r has been derived from the given Manning numbers n according to the Strickler-Chezy formula, $r = (25\ n)^6$.
The above suggests only a water depth dependance for the bed roughness.

In this study the calibration runs have been carried out with a single-valued Nikuradse bed roughness throughout the model. The calibration procedure has been based on available field data for Mean Spring Tide and Mean Neap Tide.

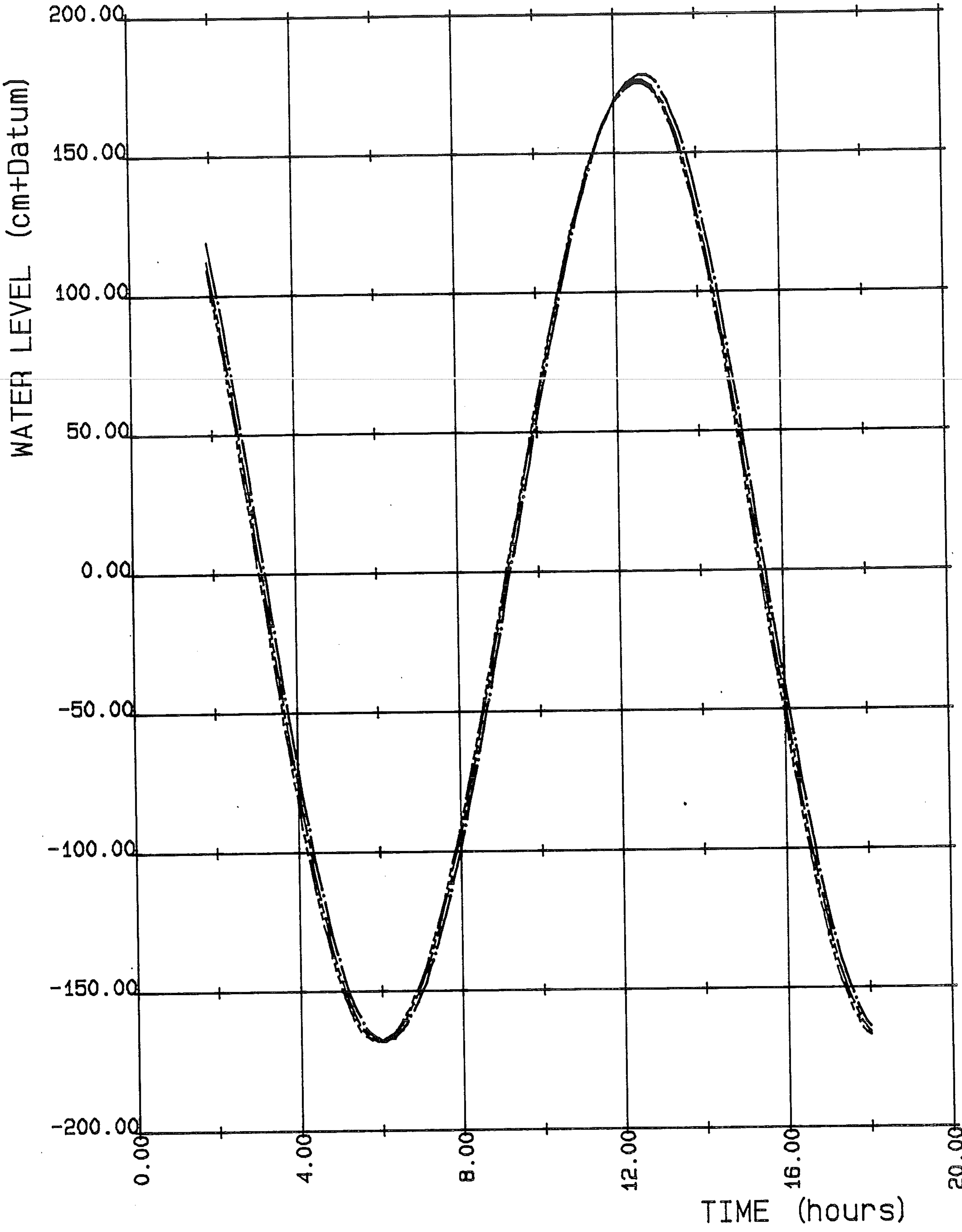
The results of the calibration runs with the Tagus Estuary flow model indicate that a single-valued bed-roughness of r = 0.35 m yields realistic flow velocities and water elevations, especially in the Quimigal Channel area. It should be noted that this value has only hydraulical relevance for the numerical flow modelling.
The value belongs to the range as described earlier. For the morphological calibration another roughness parameter will be employed, viz. the morphological bed roughness.

For the convenience of calibration and since in the Tagus Estuary tidal forces significantly dominate the average wind forces, it was decided to omit the windstress term.

Having herewith a calibrated Tagus Estuary flow model, the boundary conditions of the Quimigal Channel flow model can determined for facilitating production runs.

ANNEX B

Water level and velocity diagrams



Computed water level curves

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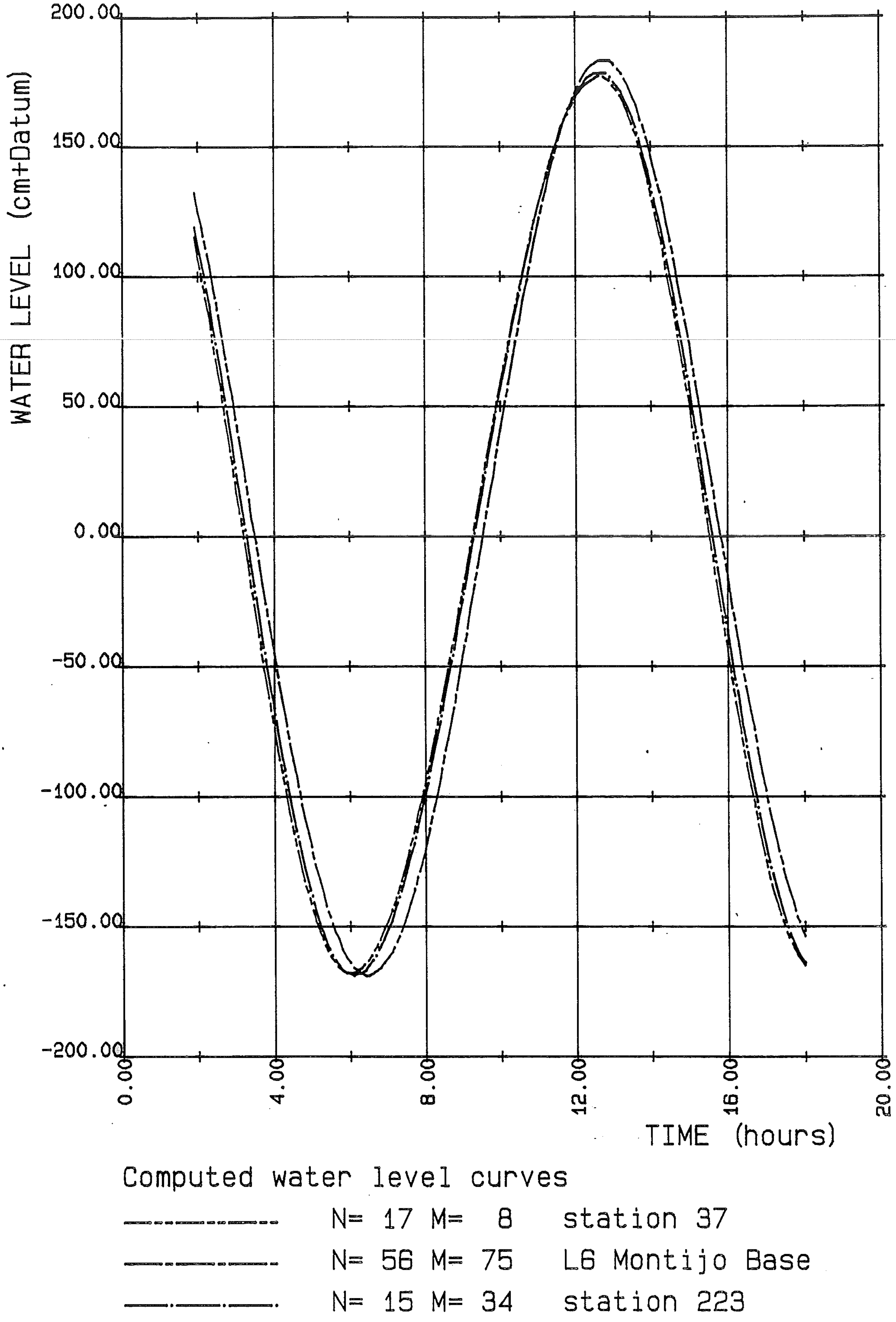
N= 7 M= 12 station 39
N= 36 M= 2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TIME (hours)
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N= 56 M= 75 L6 Montijo Base
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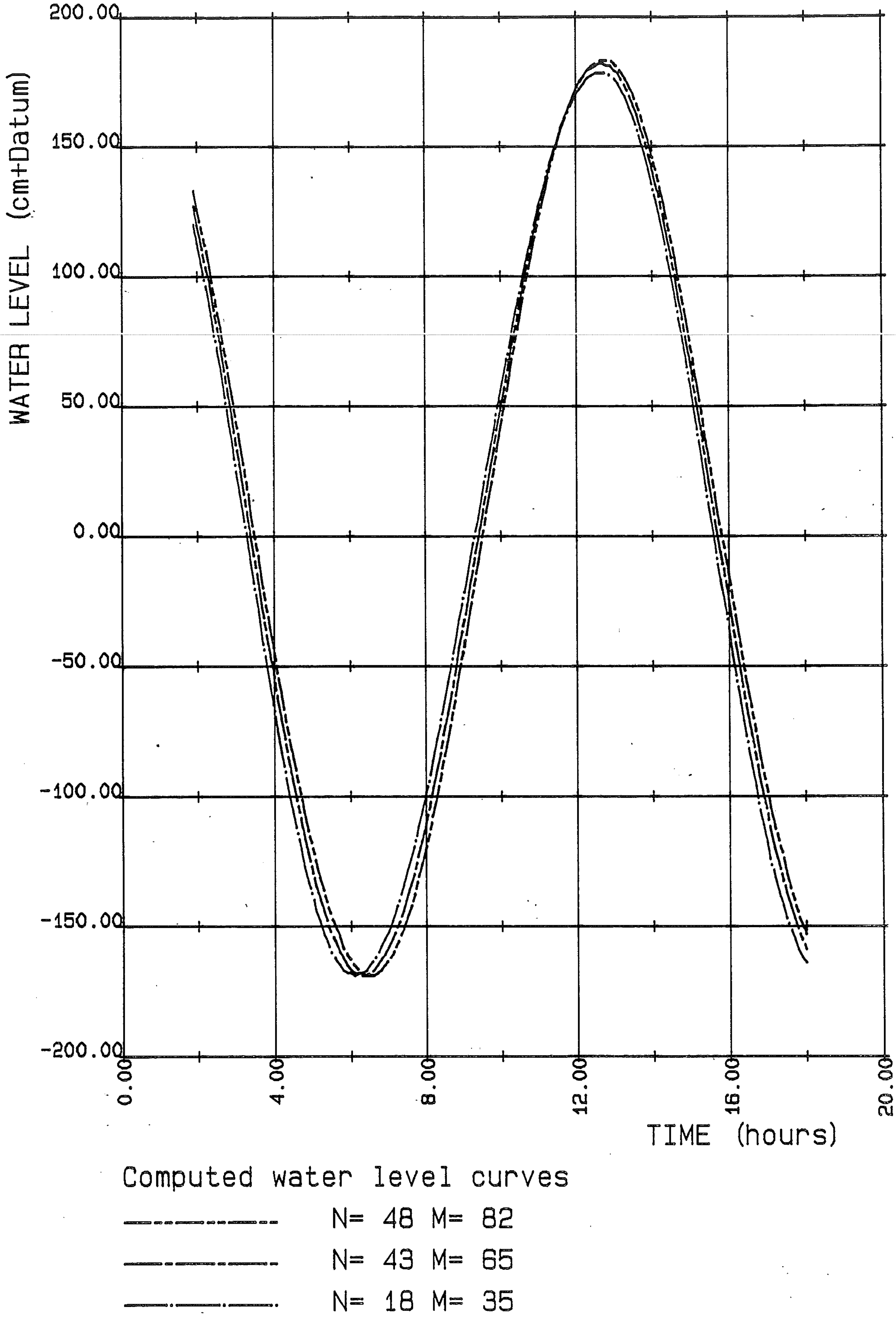
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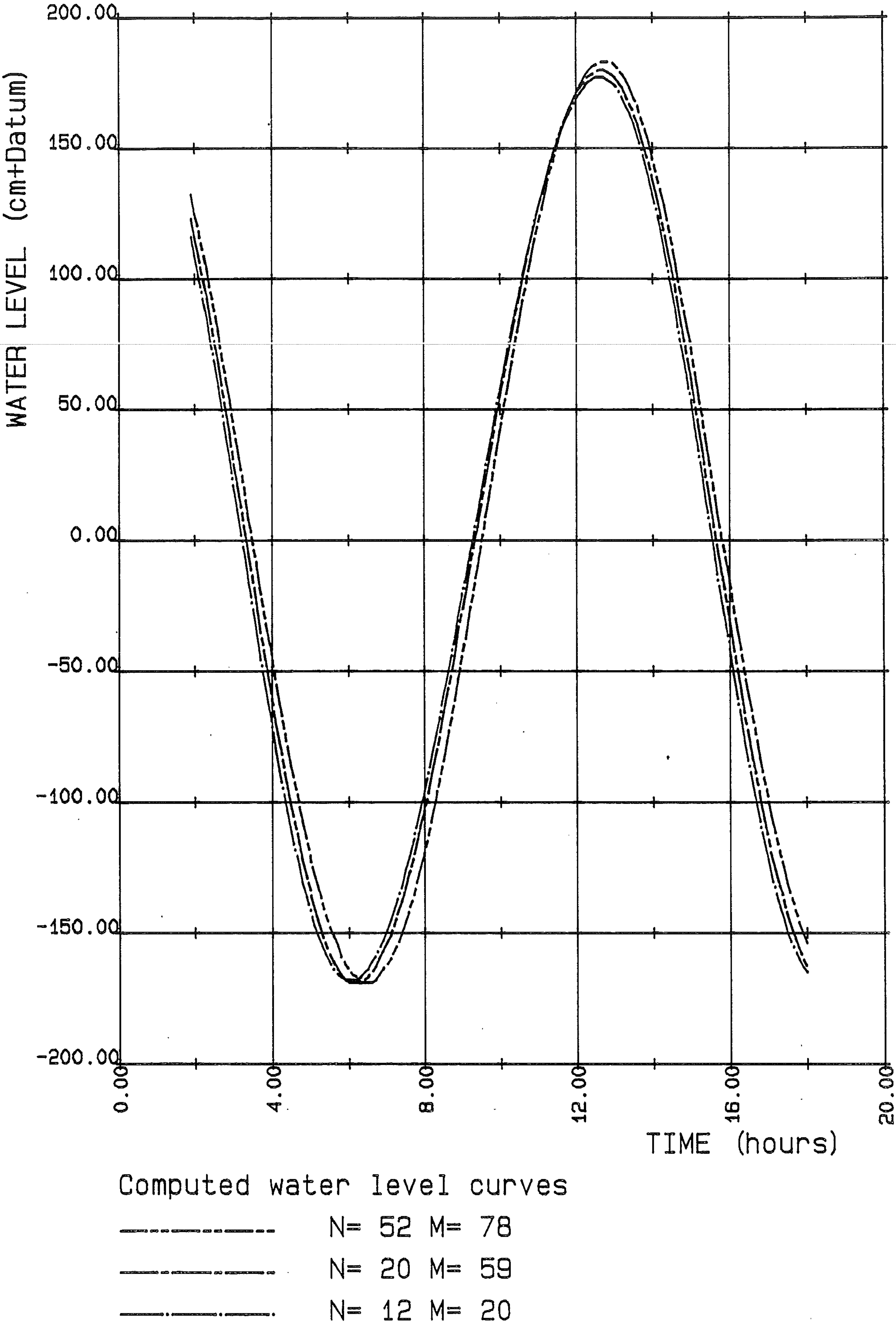
N= 18 M= 35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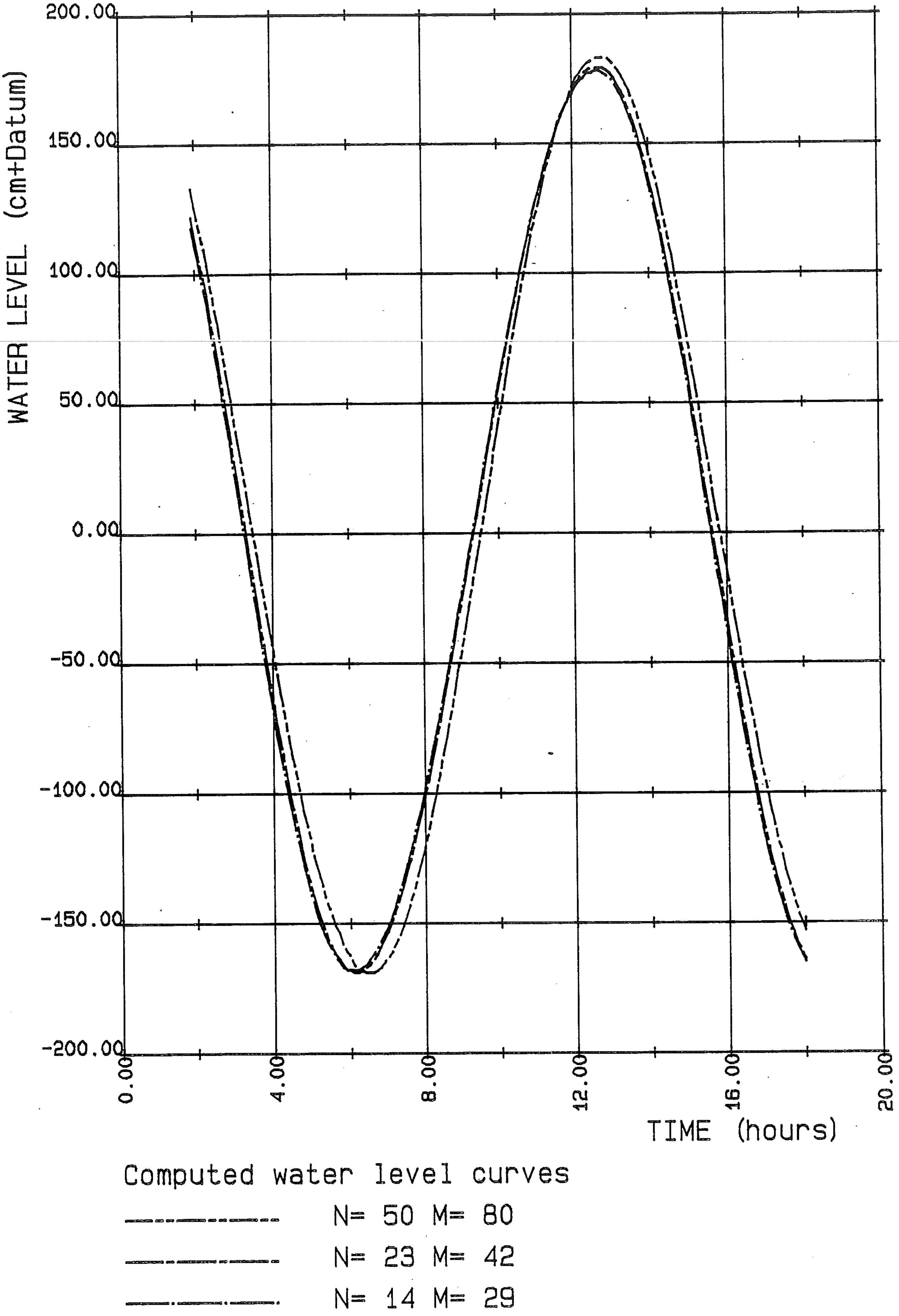
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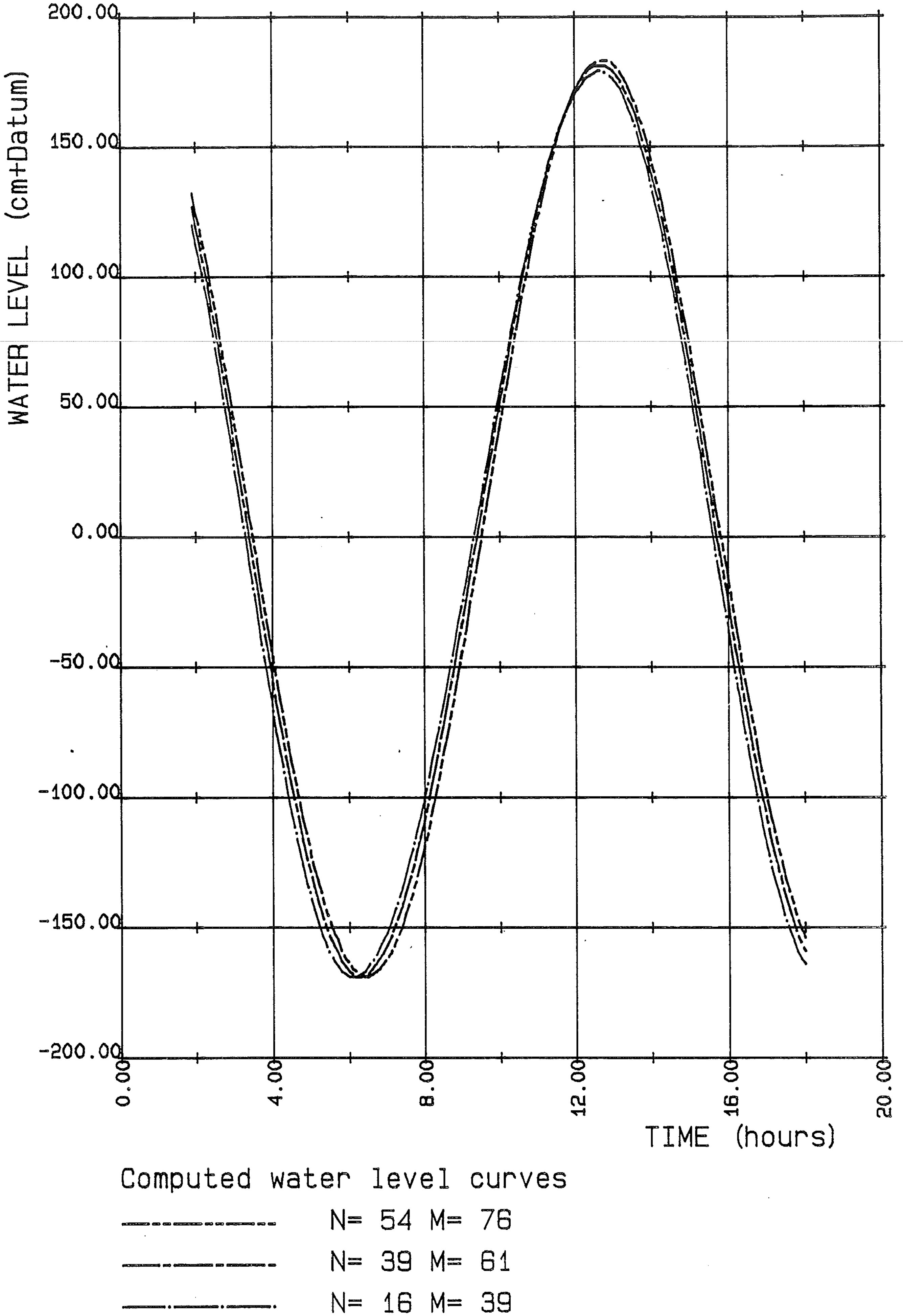
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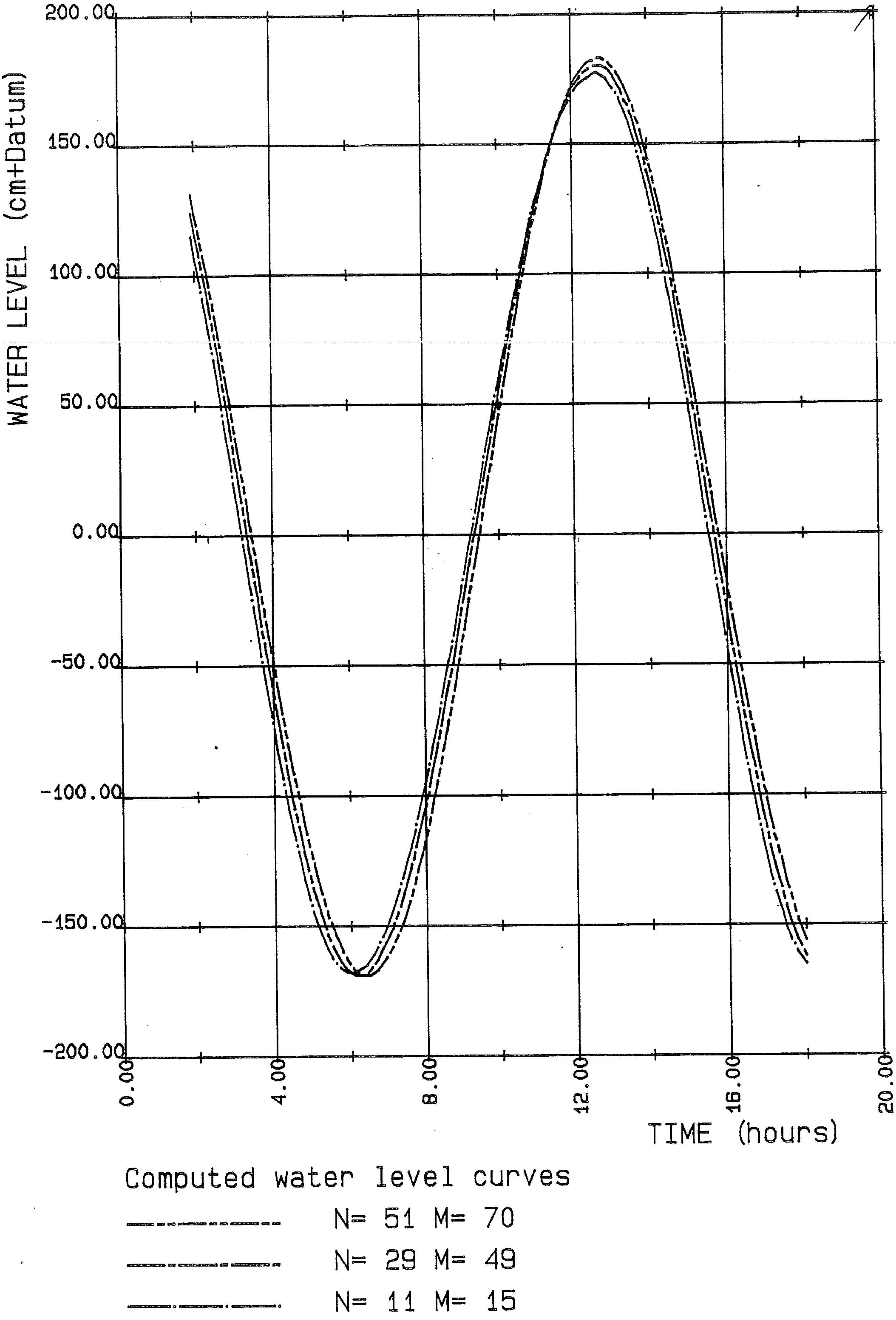
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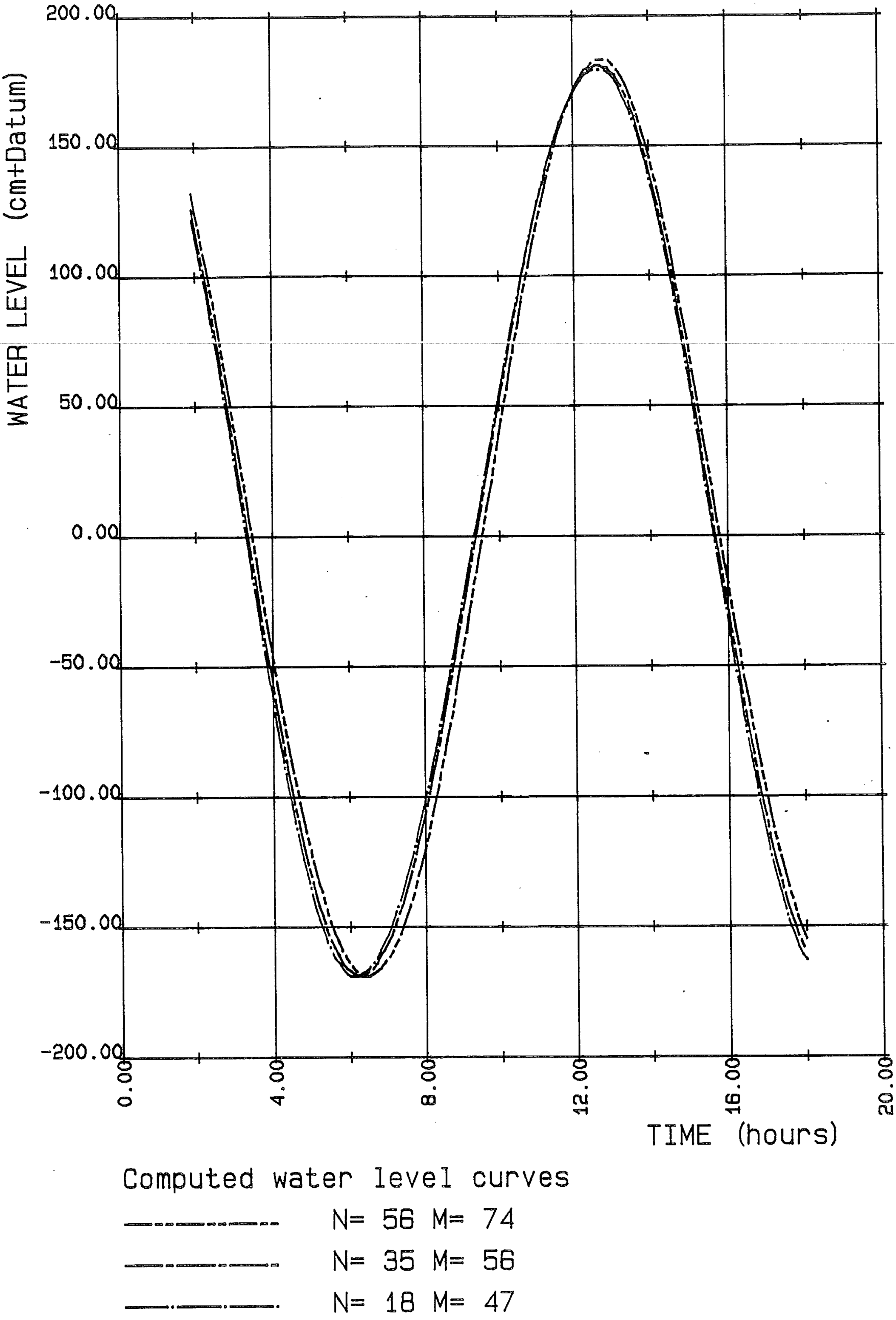
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TIME (hours)
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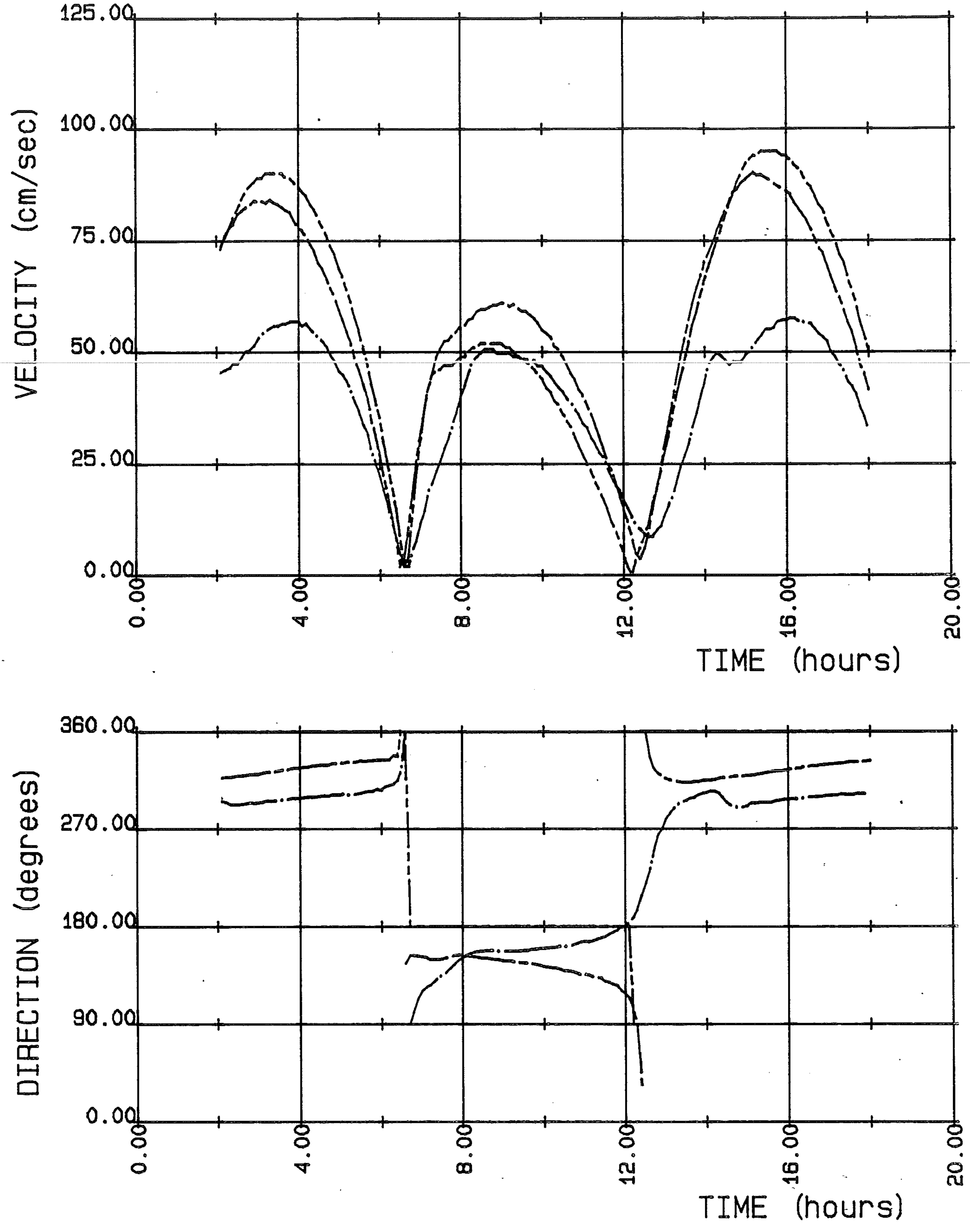
N= 35 M= 56
N= 18 M= 47

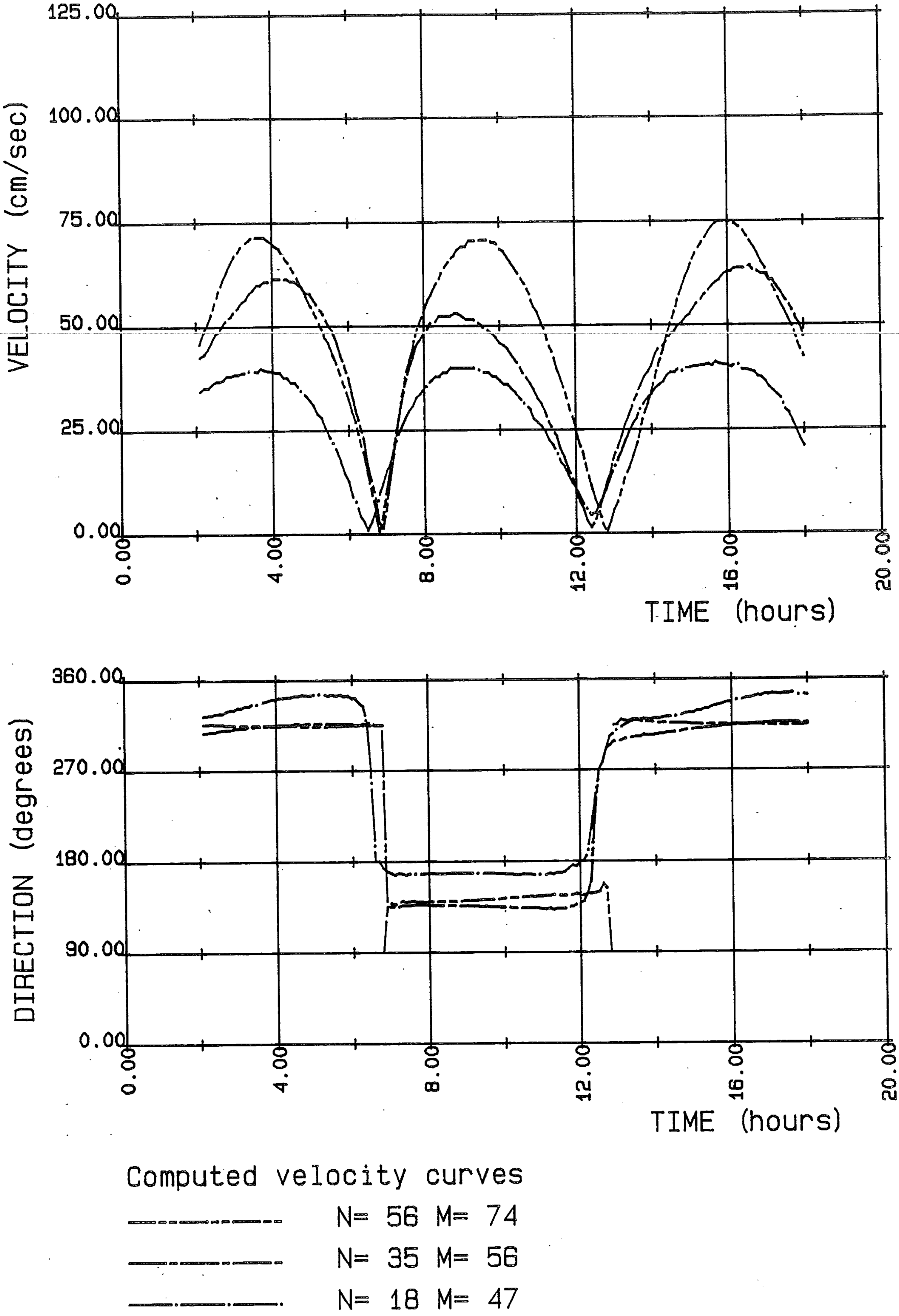


Computed velocity curves

— — - — — - — N= 7 M= 1 station 227

—— - —— - —— N= 7 M= 12 station 39

—— · —— · —— N= 36 M= 2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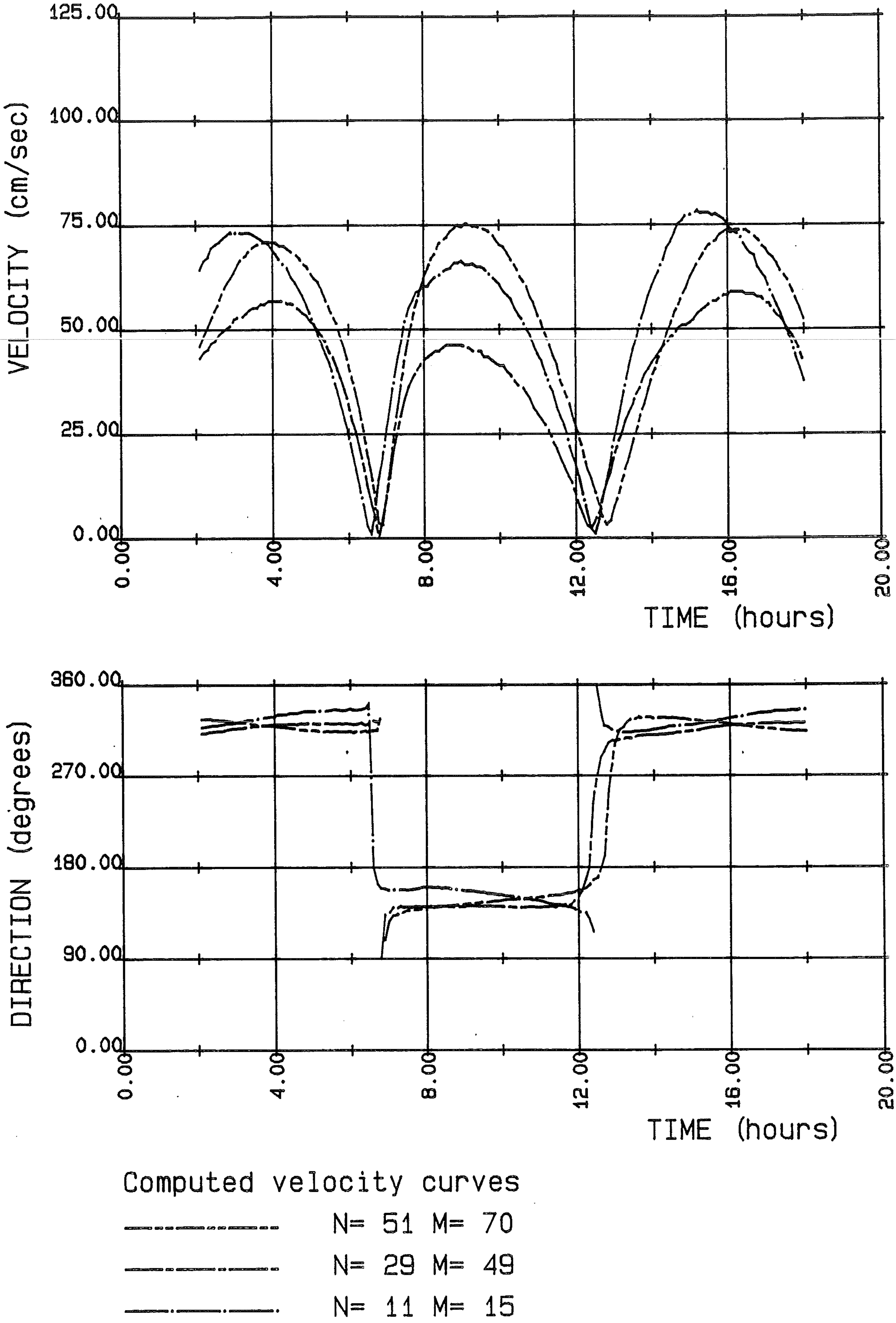
100.00
75.00
50.00
25.00
0.00
0.00
4.00
8.00
12.00
16.00
20.00
TIME (hours)
DIRECTION (degrees)
360.00
270.00
180.00
90.00
0.00
0.00
4.00
8.00
12.00
16.00
20.00
TIME (hours)
Computed velocity curves
N= 56 M= 74
N= 35 M= 56
N= 18 M= 47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VELOCITY (cm/sec)
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4.00
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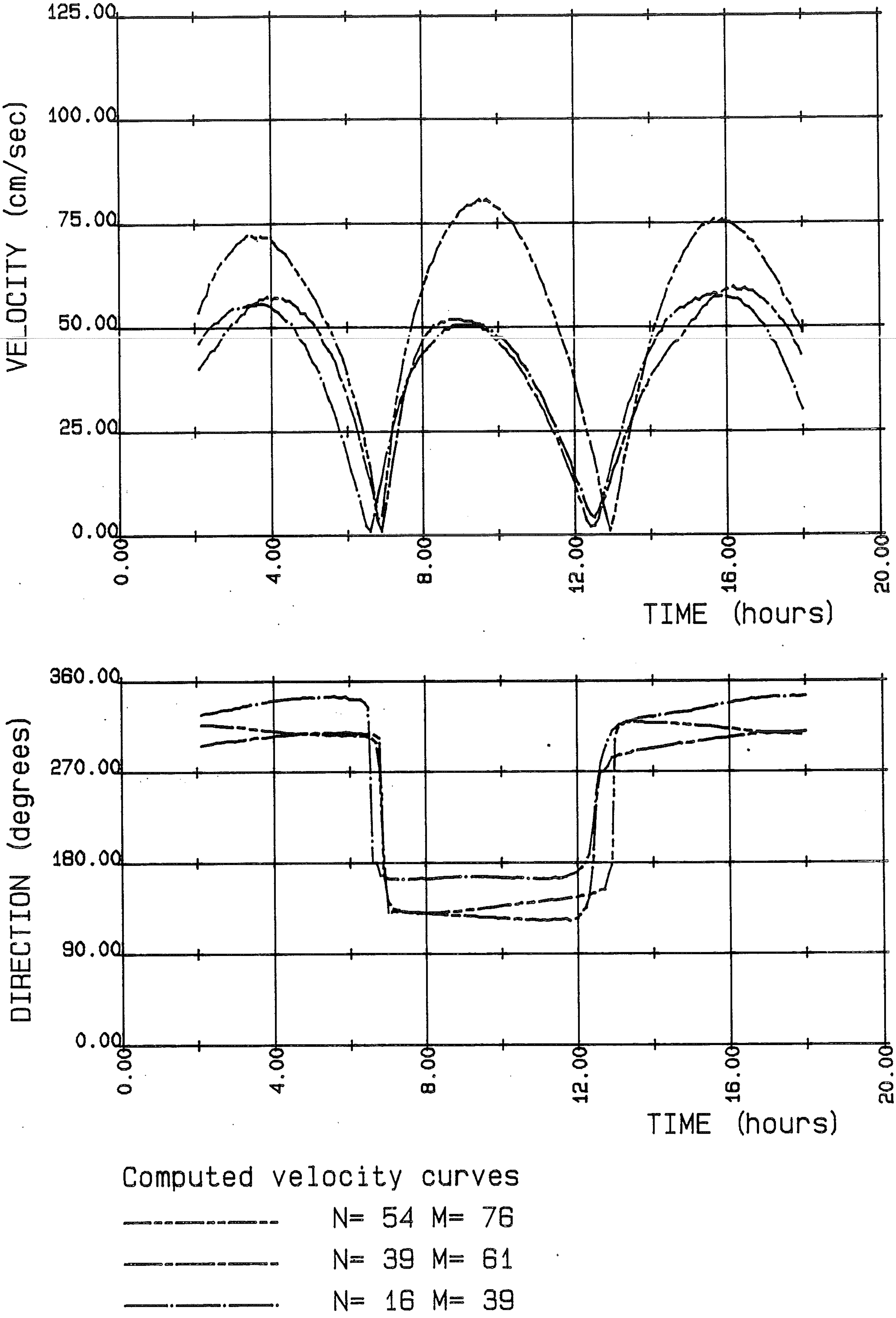
16.00
20.00
TIME (hours)
360.00
270.00
180.00
90.00
0.00
DIRECTION (degrees)
0.00
4.00
8.00
12.00
16.00
20.00
TIME (hours)
Computed velocity curves
N= 51 M= 70
N= 29 M= 49
N= 11 M= 15



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75.00
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25.00
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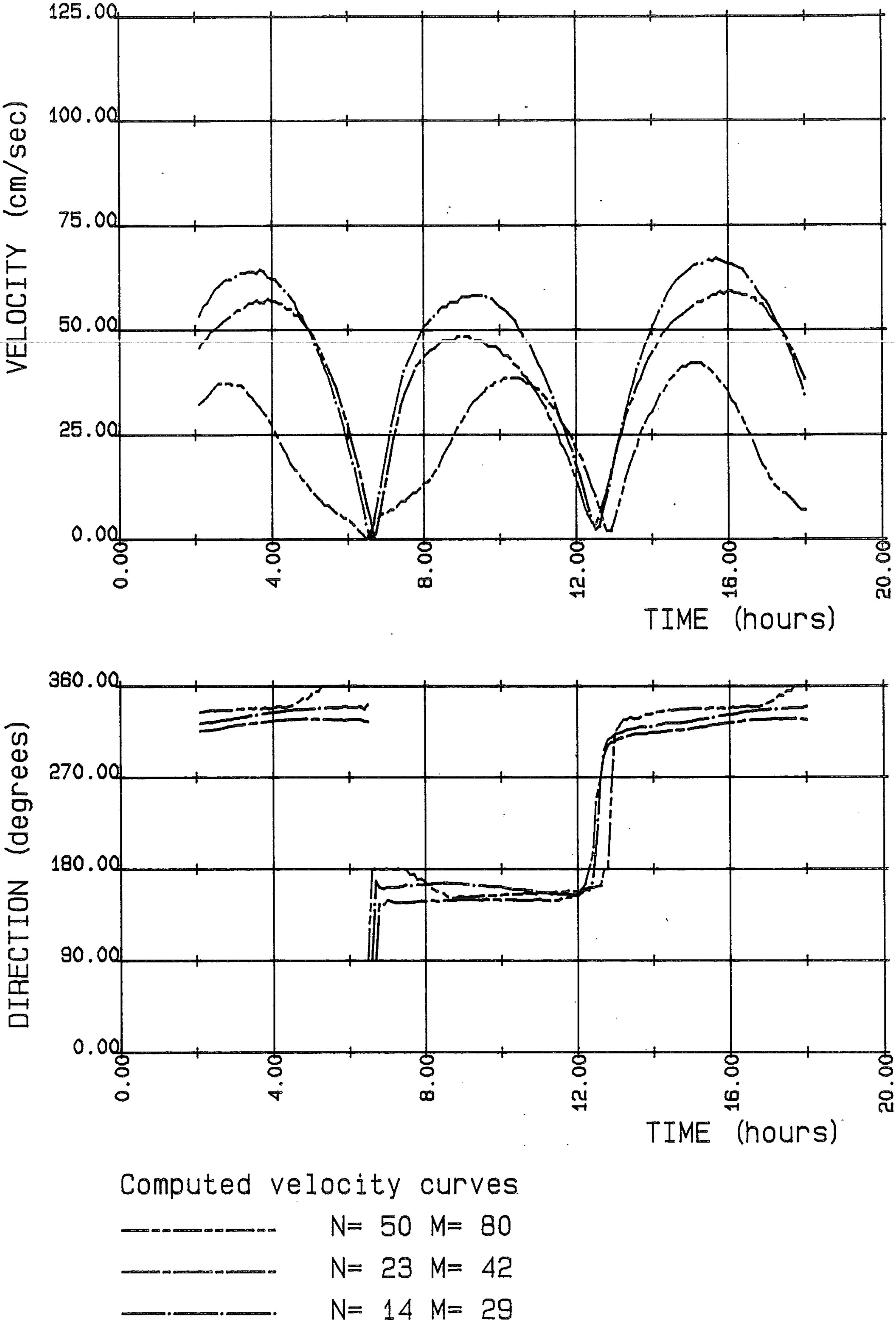
0.00
4.00
8.00
12.00
16.00
20.00
TIME (hours)
DIRECTION (degrees)
360.00
270.00
180.00
90.00
0.00
0.00
4.00
8.00
12.00
16.00
20.00
TIME (hours)
Computed velocity curves
N= 54 M= 76
N= 39 M= 61
N= 16 M= 39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25.00
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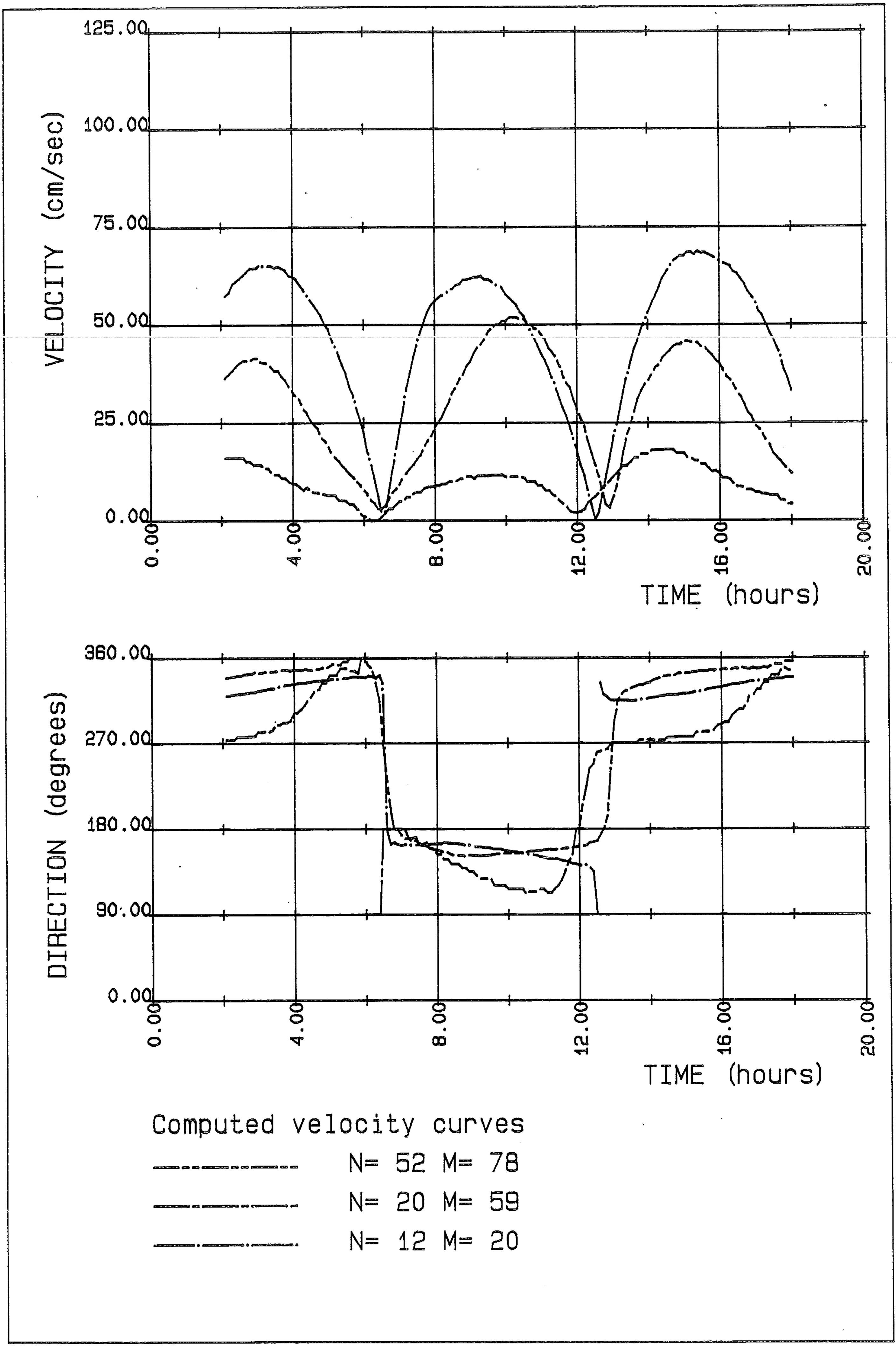
4.00
8.00
12.00
16.00
20.00
TIME (hours)
DIRECTION (degrees)
360.00
270.00
180.00
90.00
0.00
0.00
4.00
8.00
12.00
16.00
20.00
TIME (hours)
Computed velocity curves
N= 50 M= 80
N= 23 M= 42
N= 14 M= 29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VELOCITY (cm/sec)
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4.00
8.00
12.00
16.00
20.00
TIME (hours)
360.00
270.00
180.00
90.00
0.00
DIRECTION (degrees)
0.00
4.00
8.00
12.00
16.00
20.00
TIME (hours)
Computed velocity curves
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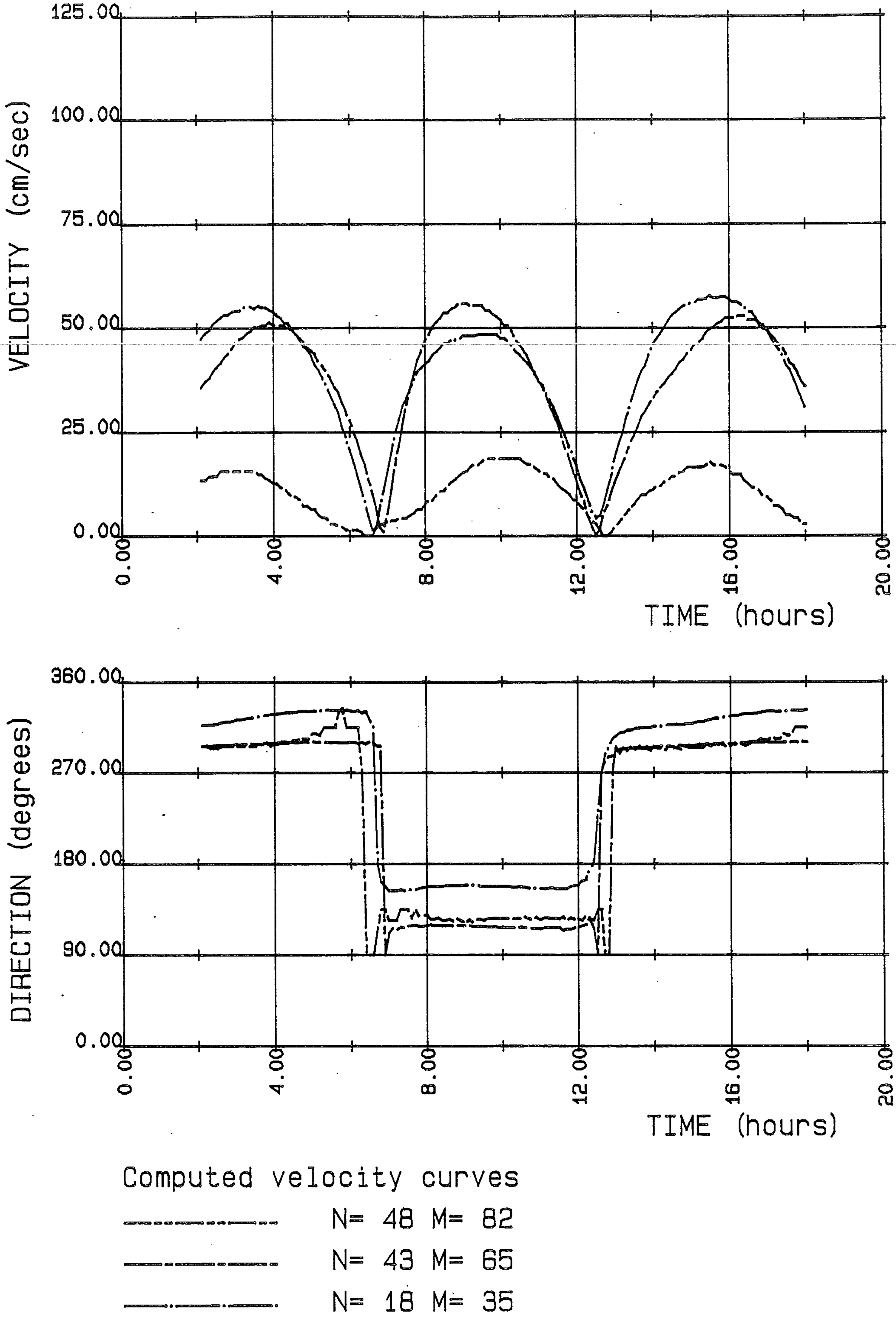
N= 20 M= 59
N= 12 M= 20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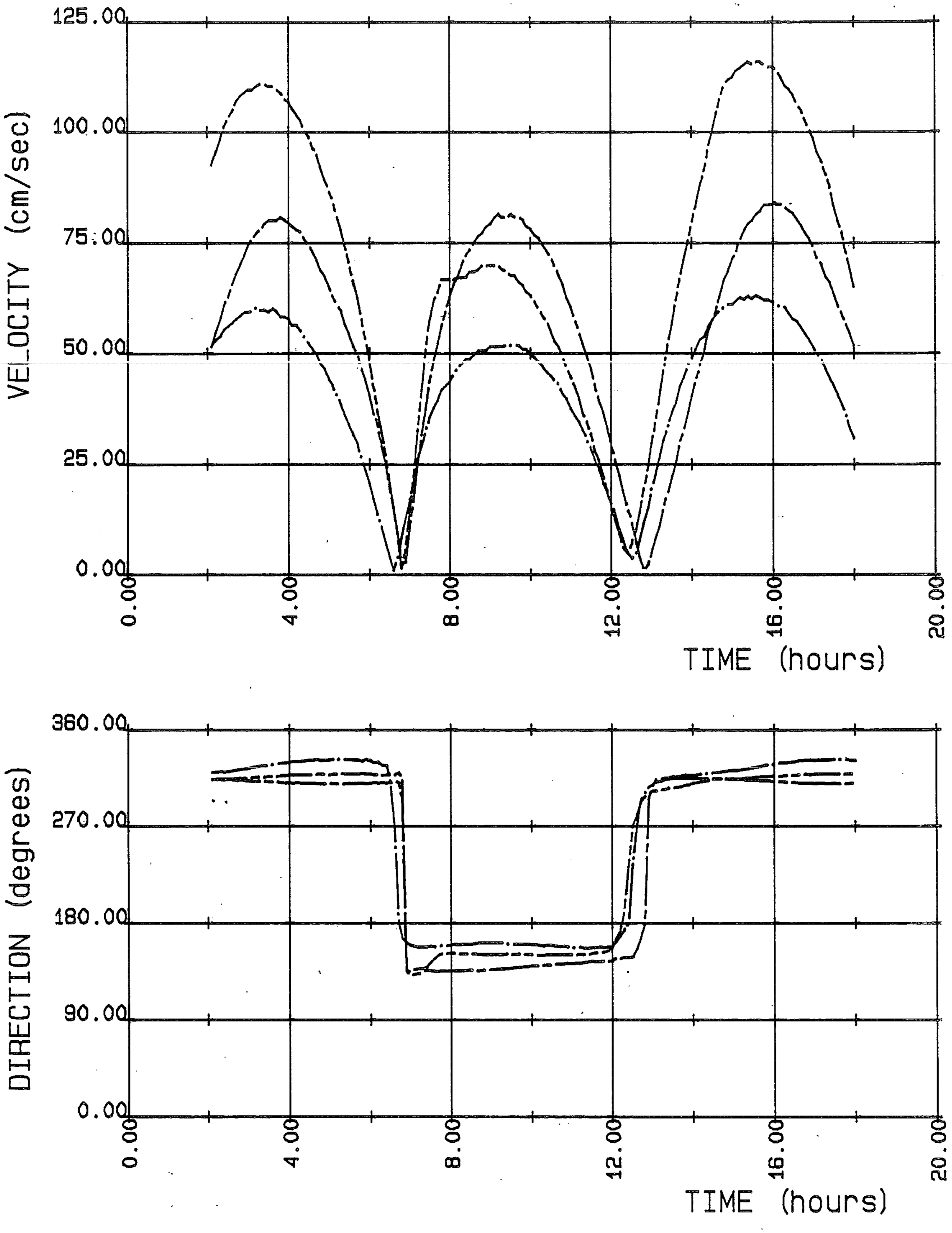
50.00
25.00
0.00
0.00
4.00
8.00
12.00
16.00
20.00
TIME (hours)
DIRECTION (degrees)
360.00
270.00
180.00
90.00
0.00
0.00
4.00
8.00
12.00
16.00
20.00
TIME (hours)
Computed velocity curves
N= 48 M= 82
N= 43 M= 65
N= 18 M= 35

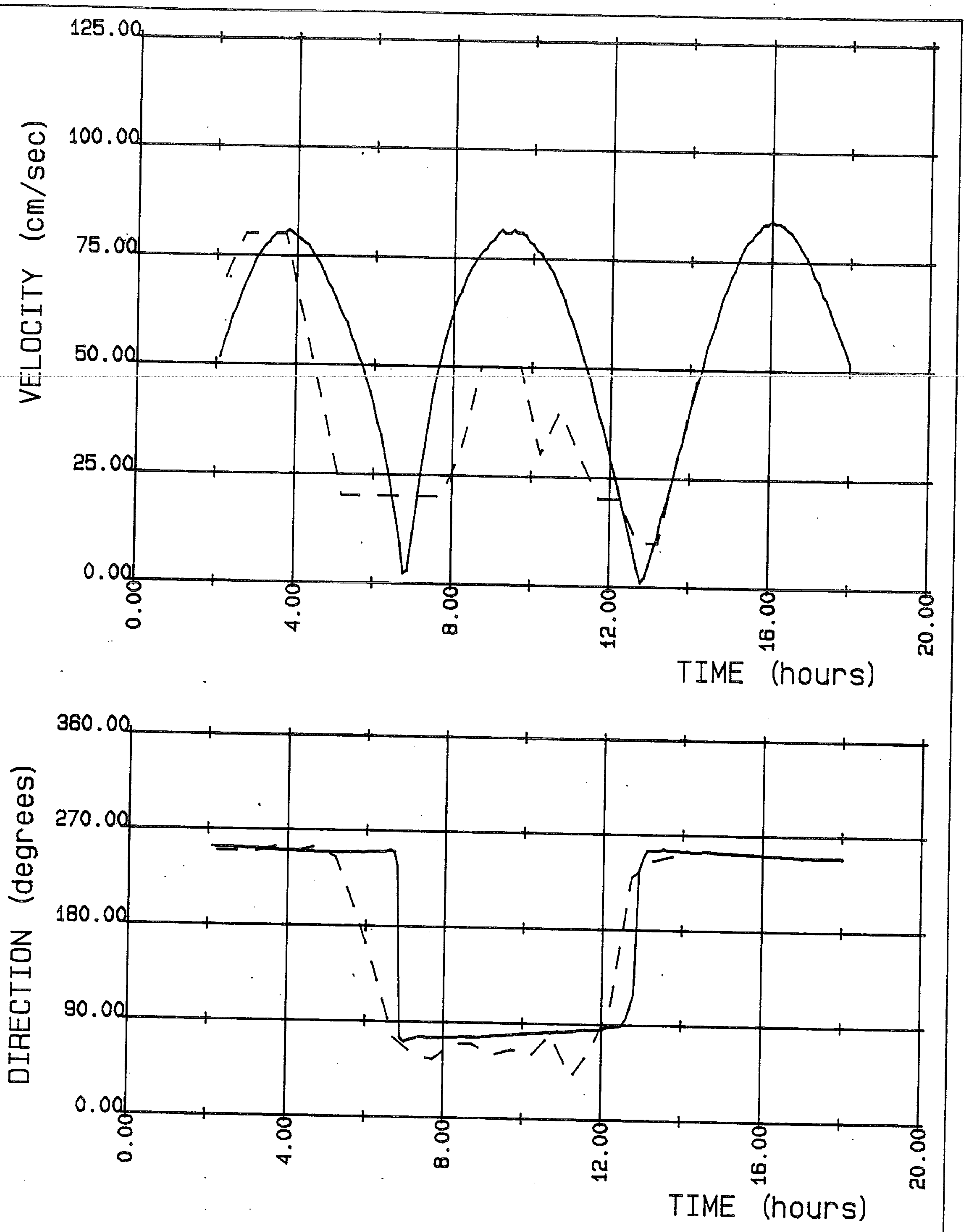


Computed velocity curves

N= 17 M= 8 station 37

N= 56 M= 75 L6 Montijo Base

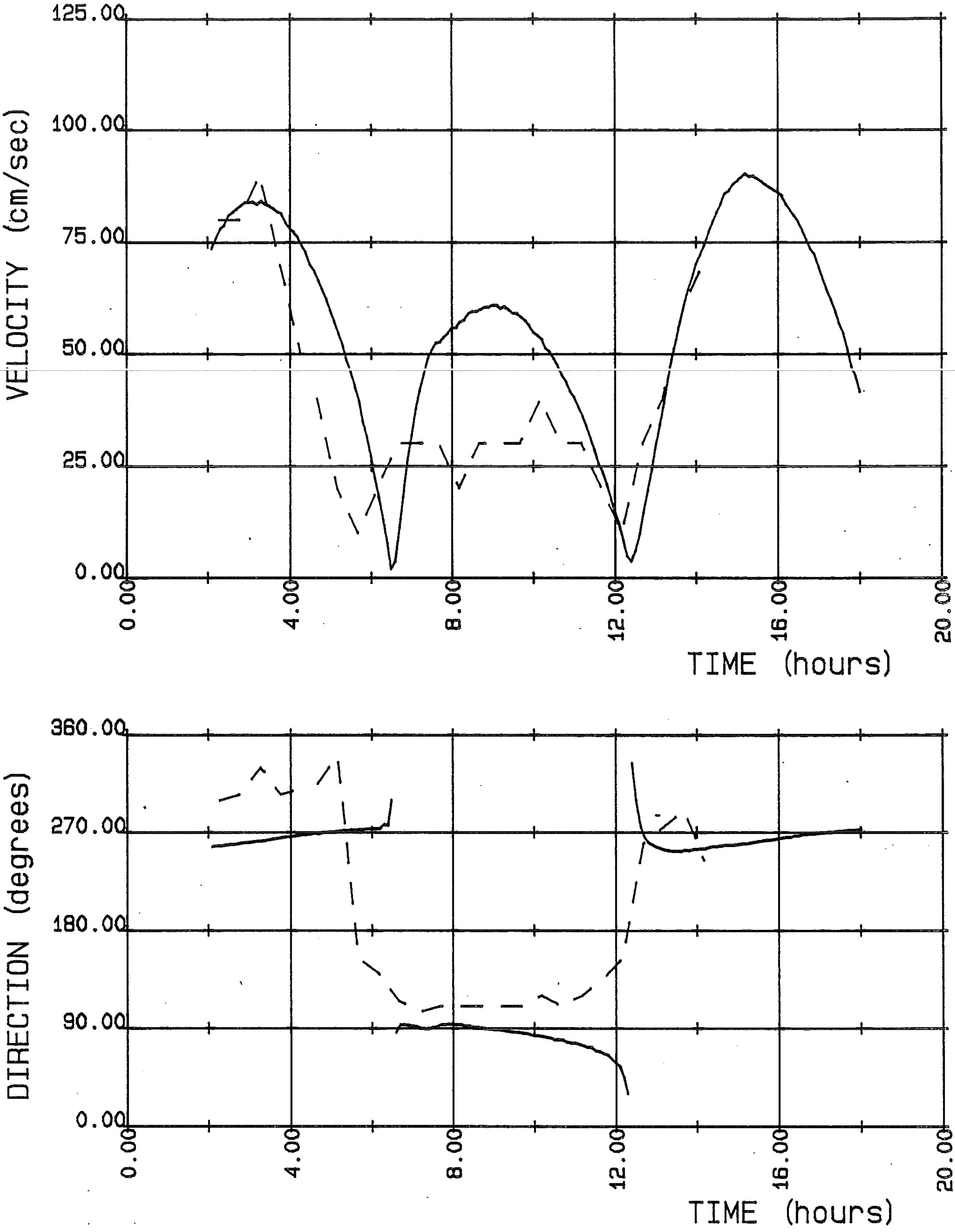
N= 15 M= 34 station 223



Velocity curve at station: 202

——— computed at N= 56 M= 75

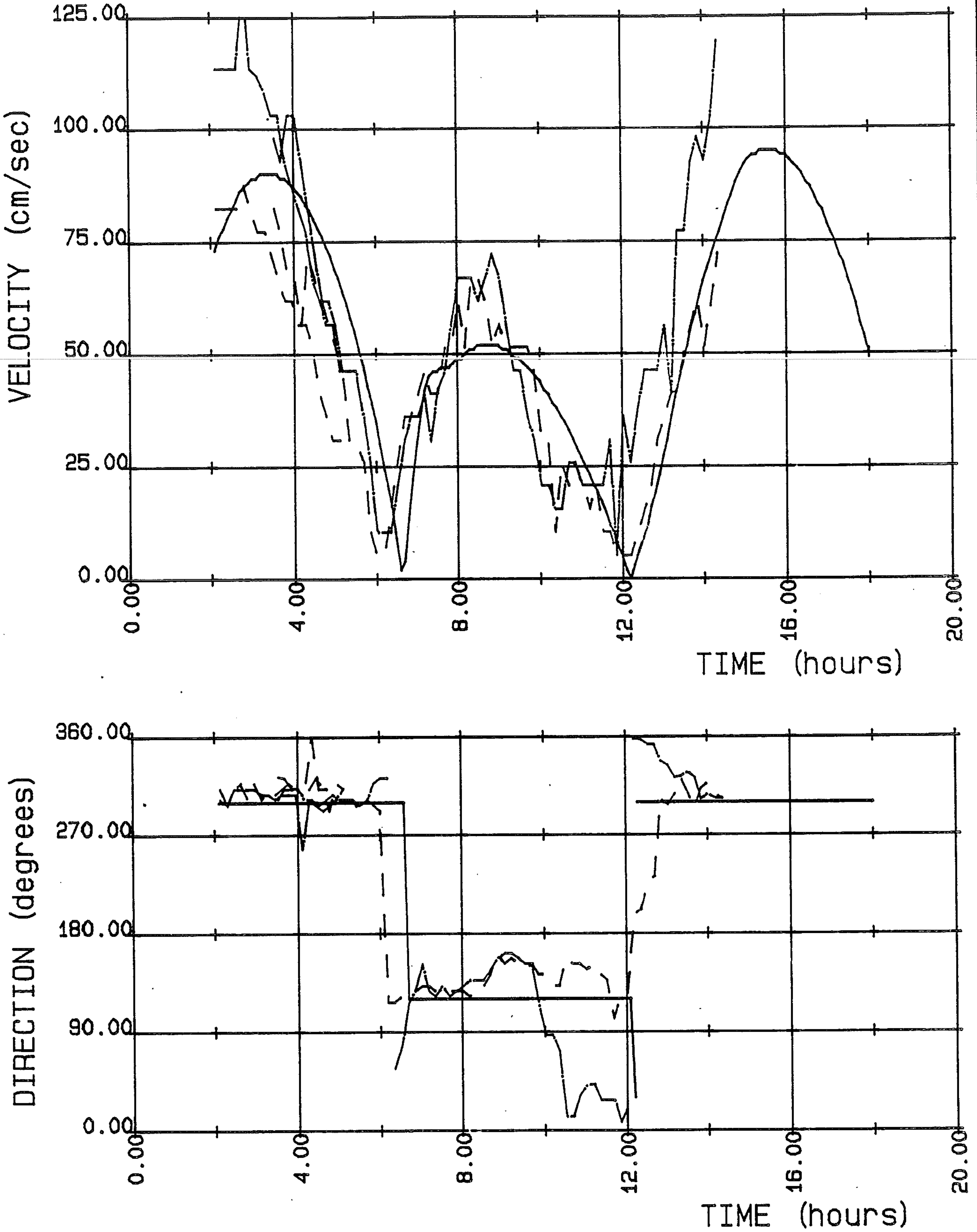
– – – measured March 21st 1973



Velocity curve at station: 39

———————— computed at N= 7 M= 12

— — — measured July 10th 1972

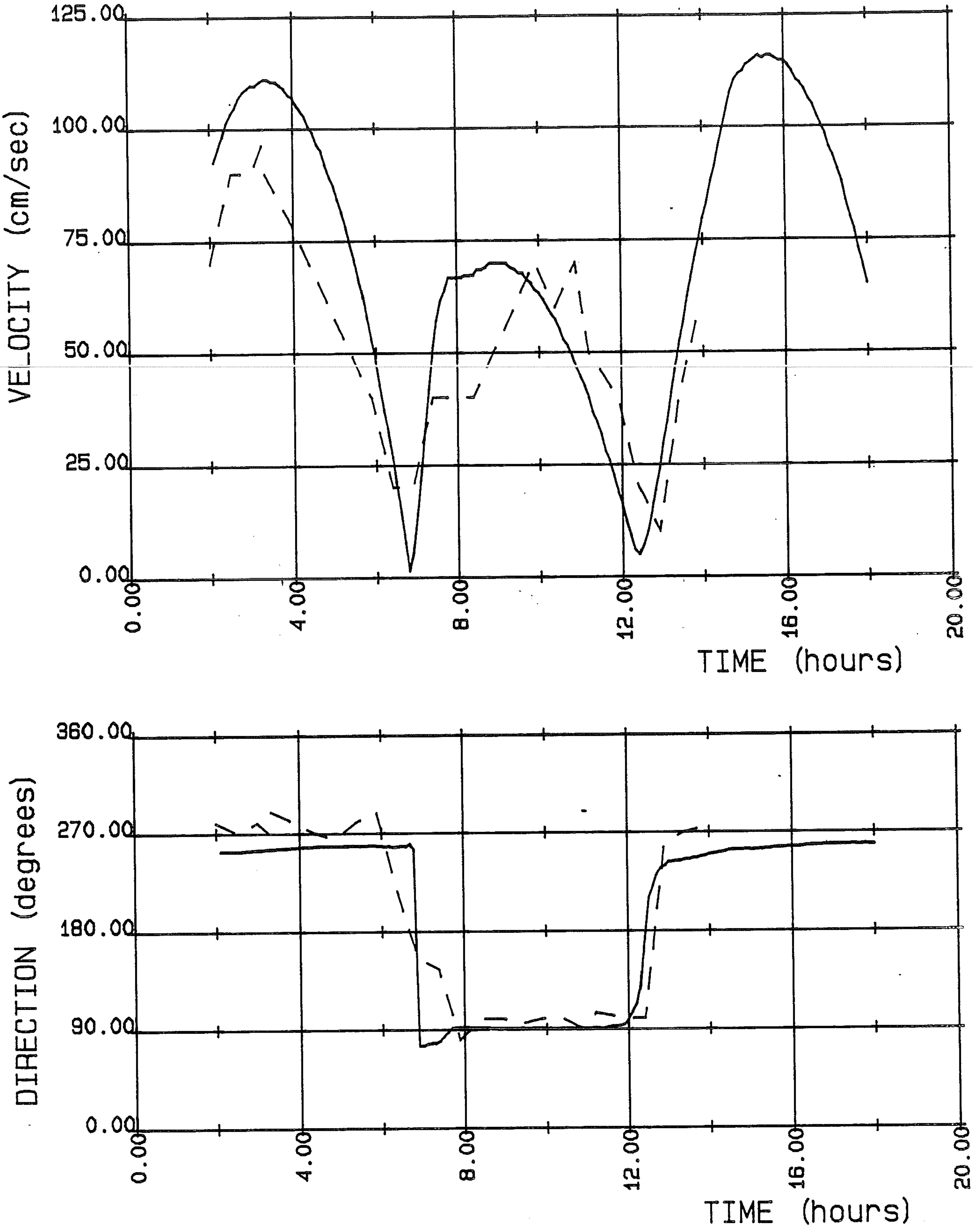


Velocity curve at station: 227

——————— computed at N= 7 M= 1

— — — measured 1m+floor April 6th 1981

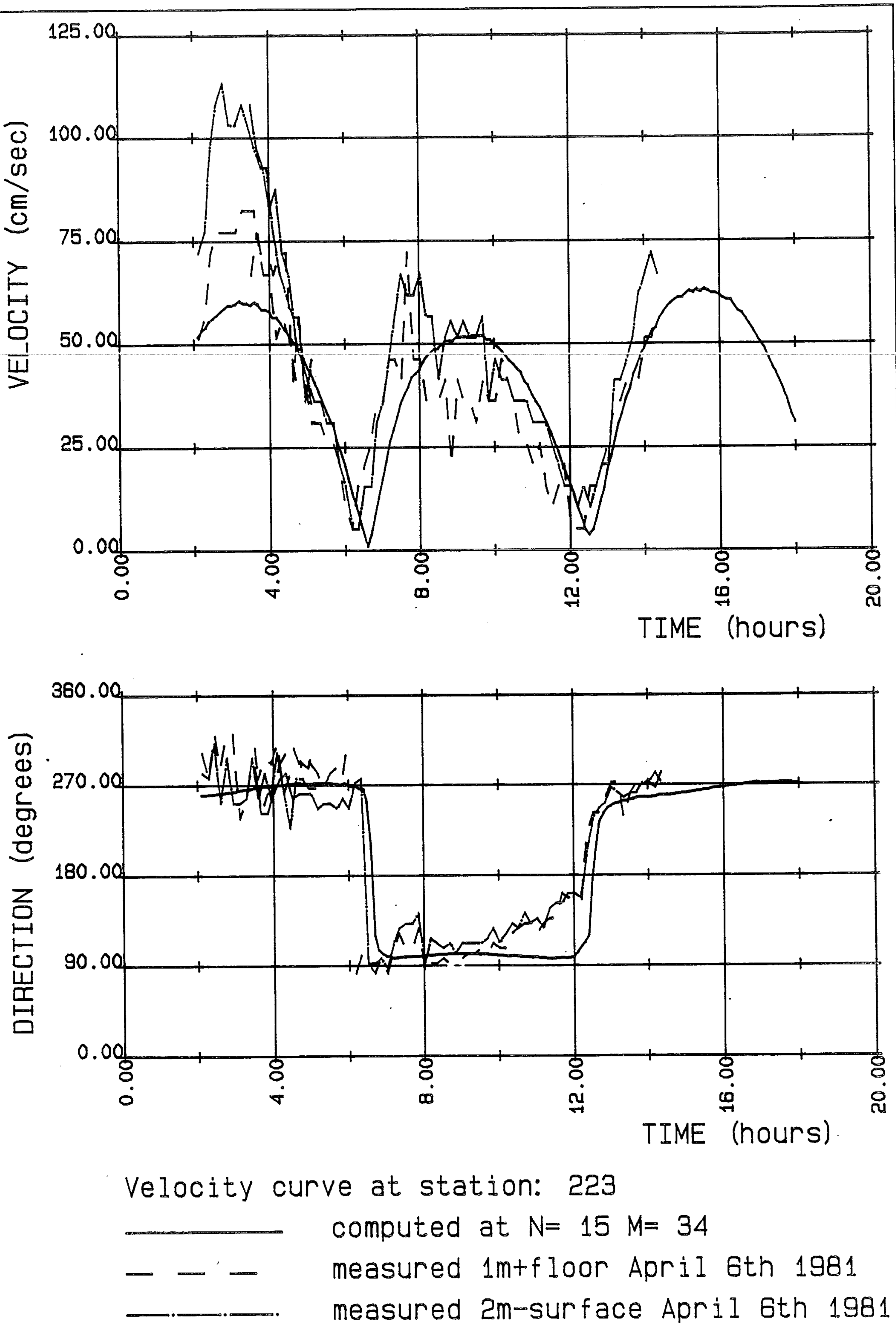
—·—·— measured 2m-surface April 6th 1981



Velocity curve at station: 37

——————— computed at N= 17 M= 8

— — — measured July 11th 1972



Velocity curve at station: 223

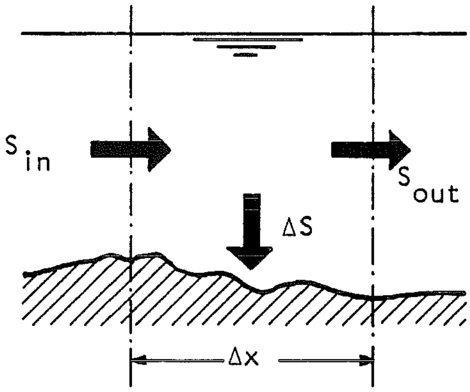
ANNEX C

The morphological model

Description of the mathematical model

Basic Elements

The model is based on two fundamental elements: the mass conservation equation and a calibrated sediment transport formula.



According to the mass conservation equation no sediment can disappear thus (during a certain time interval) the siltation has to be the difference between the incoming and the outgoing sediment transport.
In other words:

$$\Delta S = S_{in} - S_{out}$$

ΔS is now expressed in m^3/sec, per m width of the channel. A handier unit to express sedimentation is to use the increase in bottom level in m/sec or cm/year. If we call this increase in bottom evaluation Δh, we can write:

$$\frac{\Delta h}{\Delta t} = \frac{\Delta S}{\Delta x} = \frac{S_{in} - S_{out}}{\Delta x} \quad \text{(in m/sec)}$$

This can be transformed to the well known differential equation:

$$\frac{dh}{dt} = \frac{dS}{dx}$$

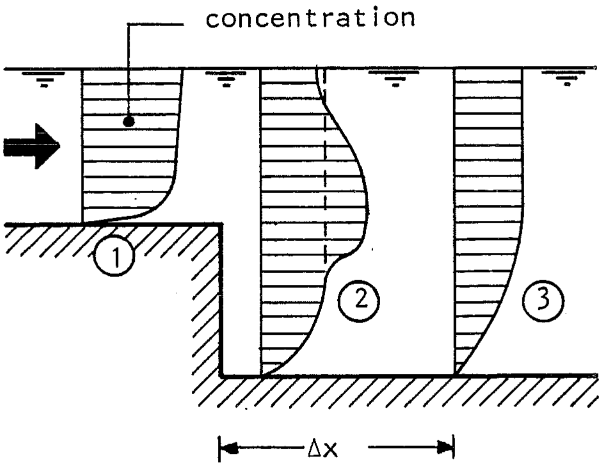
And in fact the mathematical morphological model is a numerical procedure to solve this equation.

The other basic elements is the calibrated sediment transport formula. The formula used is based on an analysis of the measured transport. The calibration-method is described in detail in section 4.1 and the inference was that a Bijker-type formula with a fictive D_{50} of 5 μm a fictive D_{90} of 25 μm and a morphological roughness of 0.075 m will give the best results.

Assumptions

Until now no assumptions have been made, which means that the model is completely valid.
However, it is impossible to solve the differential equation dA/dt = dS/dx continuously, and a numerical solution will always cause errors and simplifications in the answer.
The main assumptions we have to make are:

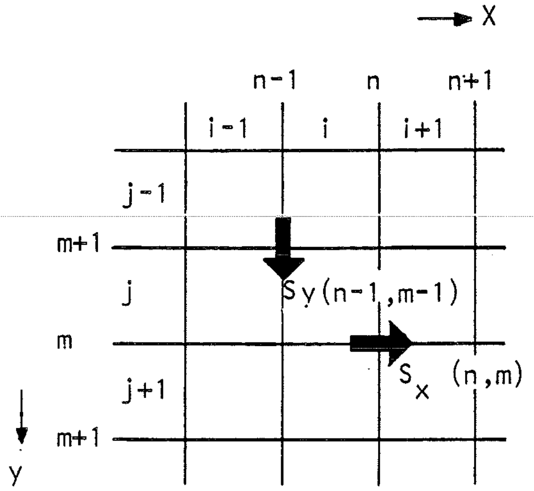
- After a distance Δx the sediment transport is fully adapted to the new transport capacity.
  For example at point 1 we have a certain equilibrium of transport. at point 3 there is also an equilibrium. But at point 2 there is not yet an equilibrium. We assume that the distance Δx is big enough to allow adaption to the new equilibrium. For fine material, the Δx = 100 m as used in our model is too small. The results of the mathematical model are therefore too pronounced.



- The bottom is identical everywhere in the model and can always be eroded. In reality there are some hard layers. These hard layers do not erode. Consequently the model may predict erosion at locations where it will not in fact occur.

- All important geometrical units must be a multiple of the used grid size Δx. In this case the grid size is 100 m. Thus the influence of structures and geometrical effects, smaller than 100 m cannot be determined. This effect has to be expected especially near abutments, small quay-walls etc.

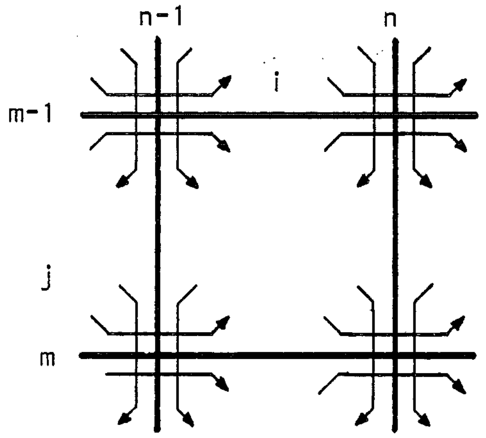
The computational grid



The sediment transport is calculated in grid points. The co-ordinates of the grid points are given as (n,m).

At each grid point the transport is divided into 2 components, the component in the x-direction and the component in the y direction.

The siltation is calculated in areas between the grid points.



It is assumed that the sediment transport in the x direction comes for 50% from the square above left,
and for 50% from the square below left from the grid point.
This sediment is pressumed to go for 50% to the square above right, and for 50% to the square below right of the grid point.

For the transport in the y-direction an identical scheme can be made.
The equation for the siltation in square (i,j) becomes.

$$\Delta h(i,j) = \tfrac{1}{2} S_x(n-1,m-1) + \tfrac{1}{2} S_x(n-1,m) - \tfrac{1}{2} S_x(n,m-1) - \tfrac{1}{2} S_x(n,m)$$
$$+ \tfrac{1}{2} S_y(n-1,m-1) - \tfrac{1}{2} S_y(n-1,m) + \tfrac{1}{2} S_y(n,m-1) - \tfrac{1}{2} S_y(n,m)$$

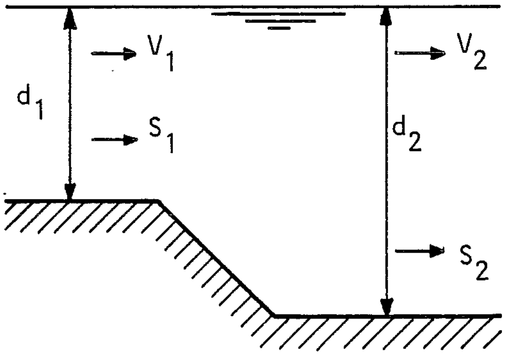
The relation between velocity and siltation

As discussed before, there is a fixed relation between current velocity and sediment transport. Siltation is the difference in sediment transport. So, siltation is also a function of the differences in the velocity. Therefore one cannot say on beforehand that an increase in the velocity will cause an increase or a decrease in the sedimentation.

This will be explained by two examples.

To simplify the examples the relation between velocity and sediment transport is expressed as:

$$S = av^b \quad (b \geqslant 1)$$



On the left side there is transport

$$S_1 = av_1^{\,b}$$

On the right side the velocity is

$$v_2 = v_1 \times \frac{d1}{d_2}$$

And the transport is

$$S_2 = av_2^{\,b} = av_1^{\,b}\left(\frac{d_1}{d_2}\right)^b$$

The siltation between 1 and 2 is consequently

$$\Delta h = S_1 - S_2 = av_1^{\,b} - av_1^{\,b}\left(\frac{d_1}{d_2}\right)^b = av_1^{\,b}\left[1 - \left(\frac{d_1}{d_2}\right)^b\right] \quad (1)$$

and because $1 - \left(\frac{d_1}{d_2}\right)^b$ is greater than zero, Δh is positive, and consequently in this example there is siltation.

Now, suppose that the velocity v_1 is increased (e.g. because of spring tide) with a factor x.

According to formula (1) the siltation becomes

$$\Delta h^1 = a(xv_1)^b \quad 1 - (\frac{d_1}{d_2})^b = x^b . \Delta h$$

The fact that both x and b are larger than 1 proves that in this example siltation is increasing with increasing velocity.

ANNEX D

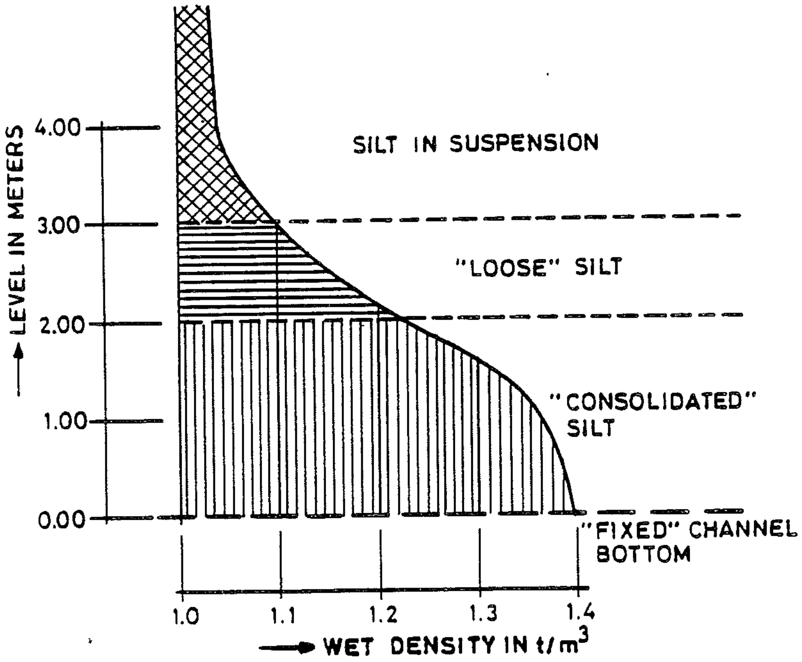
Relation between cubic meters, and tons

The units in which the sedimentation are expressed need some explanation. The mathematical model calculates the amount of siltation in tons of dry material. But such a unit is very difficult to imagine in relation to dredging work. Therefore the siltation is expressed in cm. In order to be able to calculate this transformation, the computer needs an assumption on the dry density of the soil. In the mathematical model a value of 1.6 tons/m^3 has been used. This is a value which applies to normally compacted soils with a pore volume of 40 per cent.

If the sedimentation was pure sand this value would also occur; in the present case, however, the material that is settling is much finer: it consists for the greater part of silt and clay particles.

From a survey elsewhere on densities of in-situ silt and clay at several locations where this material had been spouted under water or had settled due to natural sedimentation processes, as well as a brief investigation of in-situ densities occurring in the area concerned, we have to conclude that a dry density of 0,65 tons/m^3 is the maximum that we can expect for sedimentation in the present case.

The variation of the wet densities over the bottom in the areas where sedimentation occurs, will briefly indicated in the sketch.



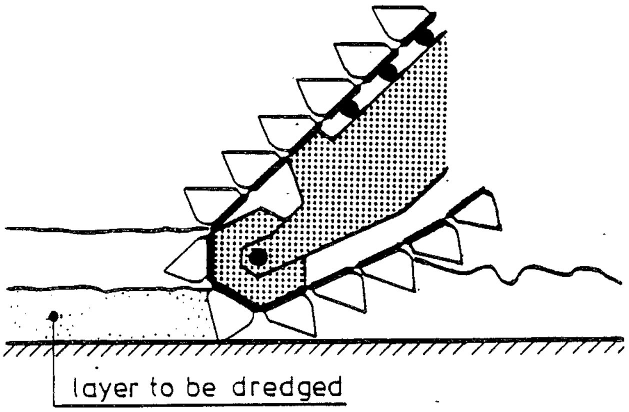
For comparison the relation between dry and wet densities and pore percentages has been indicated in the following table.

pore percentage	dry density (tons/m^3)	wet density (tons/m^3)
70%	0.80	1.50
75%	0.66	1.41
80%	0.53	1.33
85%	0.40	1.25
88%	0.32	1.20
90%	0.27	1.17

Due to the very small grain sizes, the fact that there will be a lot of clay particles in the sediment having properties that differ from normal quartz, and the fact that the material is constantly submerged, further consolidation after a number of years is not to be expected.

Taking the value of 1.2 tons/m^3 as the "nautical bottom" (see section 5.2), the average wet density of the material that has settled and will have to be removed in order to maintain the channel bottom at the original level is approximately 1.33 tons/m^3, which means a pore volume of 80 per cent and a dry density of 0.53 tons/m^3.

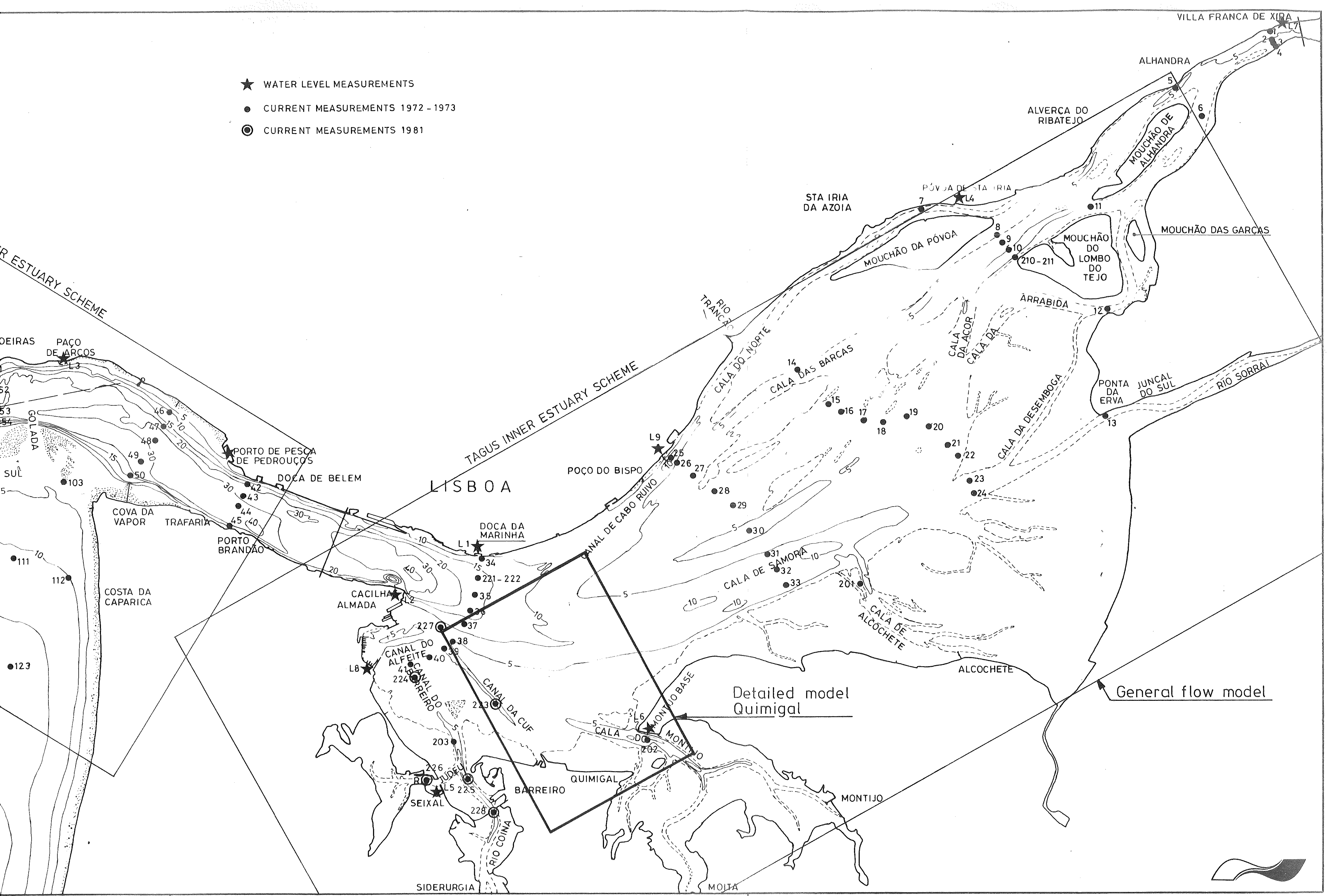
In the first years after channel construction the dry density of the material dredged during maintenance can be expected to be (much) higher if a bucket dredger is used. This is due to the fact that with a bucket dredger it is easy to overdredge in the original channel bottom. The material that has settled after construction of the channel and whose density is much less, is due to its high liquidity, lost and will remain for a great part on the bottom.



The way of dredging is indicated in the sketch.

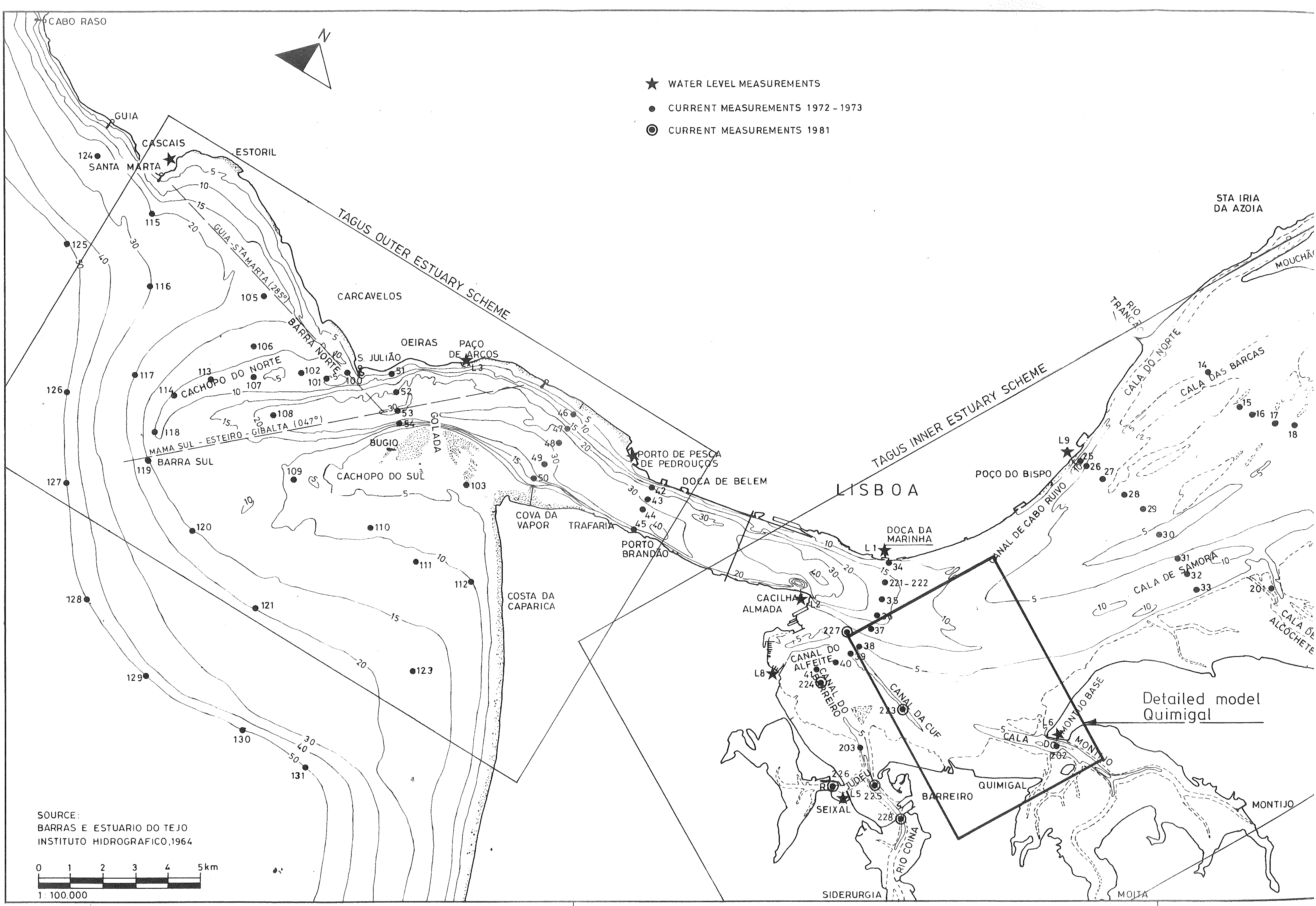
It is clear that after a few years (and in the case of heavy siltation this may be only one year) only material with low densities will be dredged.

The inference from the above is that we have to take into account a dry density of 0.53 tons/m^3 for the sedimentation. This also means that the material is very fluid and will spread over a wide area; it can not be expected that slopes of steeper than, say, 1:300 can be maintained by this type of material (pore volume 80 per cent; in fact "heavy water").



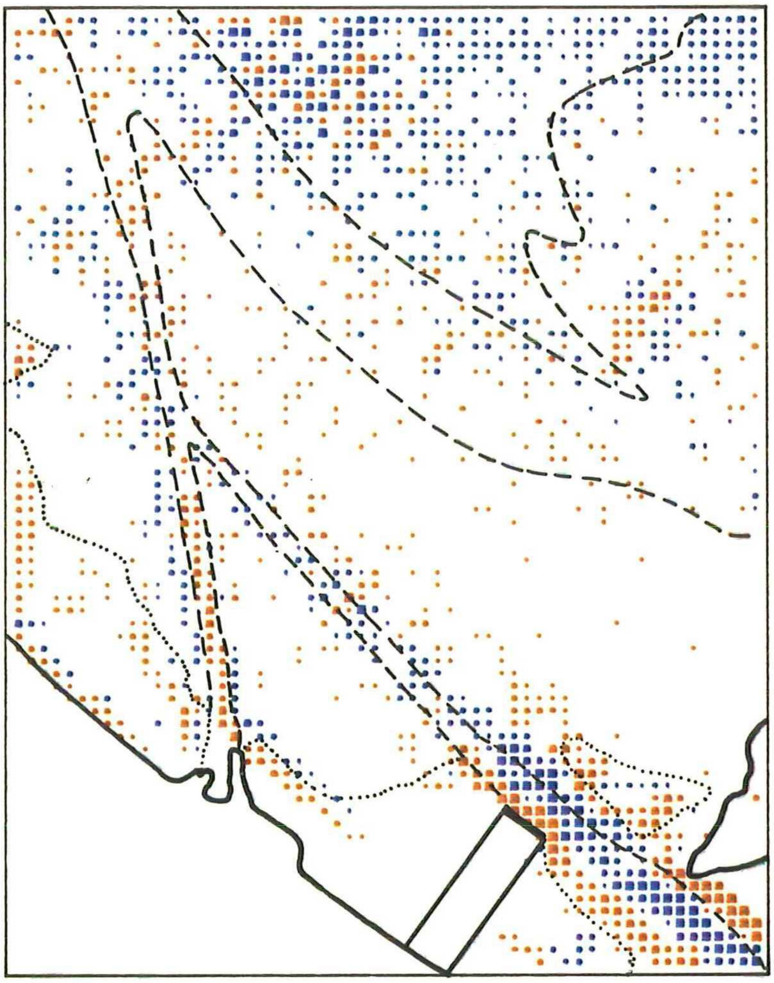
GRID LOCATIONS AND CALIBRATION STATIONS

FIGURE 1



SOURCE:
BARRAS E ESTUARIO DO TEJO
INSTITUTO HIDROGRAFICO, 1964

GRID LOCATIONS AND CA



QUIMIGAL

scale 1 : 50000

- ■ erosion of 100 cm or more
- ▪ erosion of 50 cm
- ■ sedimentation of 100 cm or more
- ▪ sedimentation of 50 cm

CALCULATED SILTATION PATTERN

FIGURE 2

COMPARISON OF TWO CROSS SECTIONS

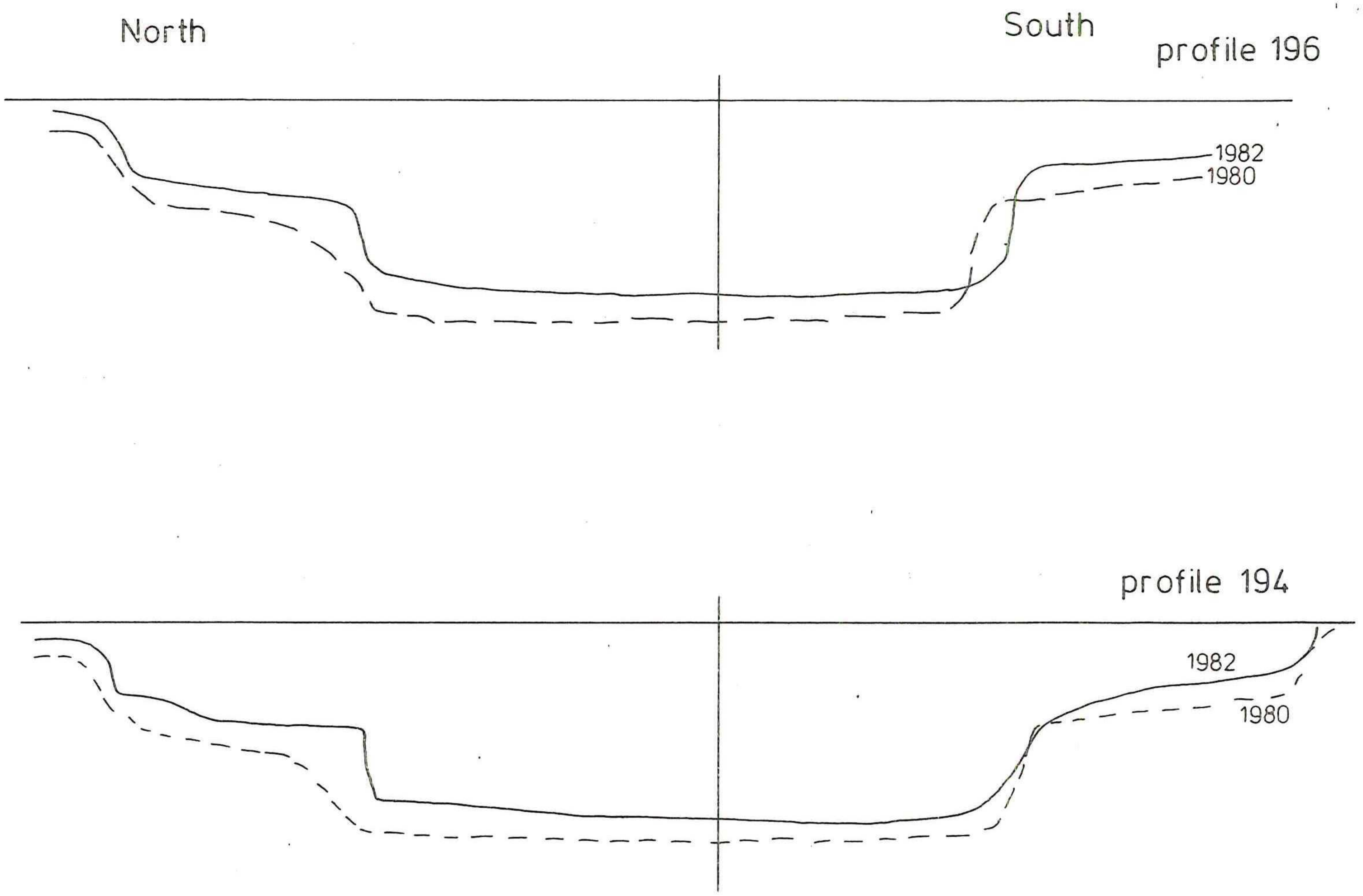


Figure 3