Hydro-morphological study
Tagus Estuary

Part 2
Estuarine circulation model

Volume 2.1
Text

June 1982 / P473

PORT AND WATERWAY ENGINEERS
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SUMMARY AND CONCLUDING REMARKS

The Lisbon Port Authority, Administracao Geral do Porto de Lisboa, has planned to develop management guides to assess the effects of man's interferences with the Tagus Estuary regime.

In order to acquire a thorough knowledge of the flow and sediment circulation, the Administracao Geral do Porto de Lisboa entrusted a comprehensive mathematical model study to Sociedad Portugesa de Dragagens (S.P.D.) of Lisbon, Portugal.

The mathematical study can be split up into operational models on wave penetration, flow circulation and morphology.

This Hydro-Morphological Study was carried out by Hydronamic B.V. of Sliedrecht, Holland on behalf of S.P.D., Lisbon.

This report presents the modelling results of the estuarine flow circulation in the inner and outer estuary. The estuarine flow circulation has been simulated by employing Hydronamic's 2-dimensional unsteady flow model. This model is an improved version of the Leendertse finite difference model for solving the simplified shallow water equations. The present model proved to be very stable, unlike the Leendertse model, and allows for tidal flats.

For computational considerations, the Tagus Estuary has been schematized into two square grids, laid over the outer and the inner estuary. Mesh-sizes of 200 m and 250 m have been chosen for both grids, respectively.

For effective use of computer capability, the simulation has been executed on the CDC 750/Cyber 176 machine at the Cybernet Centre of Rijswijk, Holland.

Simulation runs have been made for Mean Spring Tide and Mean Neap Tide under normal upstream river discharge conditions.

The procedure of computation starts from when field data were available. Reliable field data, forming the indispensable basis for calibrating and verifying the numerical models, have been assembled and analysed for their relevance to the modelling conditions.
The final results of calibration and verification have been presented graphically where possible.

Tagus Outer Estuary Model

For the calibration, Spring Tide has been used because of the availability of many field measurements. The calibration parameter is the bed roughness. A verification of the calibrated model could not be made as there were no relevant field data for Neap Tide conditions. Based on the results of the calibrated model it can be stated that the Tagus Outer Estuary model is quite reliable.

Tagus Inner Estuary Model

After examining the numerical results of Mean Spring Tide for similarities with the field data, it has been proved that a bed roughness of $r=0.20$ m yields very reasonable results. Mean Neap Tide has been employed for model verification. Taken into account the tidal and fresh water differences between field measurements, predictions and computed mean condition, it can be concluded that the model produces quite reasonable results.

From the above results it is thought that both models are adequate for the computation of future interferences.

All the computed results, as produced in the course of this study, have been stored on magnetic tapes.
1. INTRODUCTION
1.1. PROJECT SETTING

The Lisbon Port Authority, Administracao Geral do Porto de Lisboa, has planned to develop management guides to assess the economic worth of man’s interference with the regime of the Tagus Estuary. This plan is referred to as the Environmental Impact Study of the Tagus Estuary. One of the main tasks within the scope of this plan, is to investigate the flow patterns and sediment circulations of the estuarine waters, using both mathematical and physical models.

The Tagus Estuary is the transition zone from unidirectional, time varying fresh water flows of the Tagus River to the tidal, saline Atlantic Ocean. Water movements throughout the estuary are affected by any change in either fresh-water influx or the ocean tide; these movements are further governed by the configuration of the estuary and by winds. Winds contribute to vertical mixing of fresh and saline water by generating waves that also stir-up into suspension the sediment deposited in shallow areas.

In view of the favourable geographical location with respect to Western Europe, as regards promising deep-water ship handling prospects, the Tagus Estuary may become an important link in Portugal’s economy.

The results of physical and mathematical models will be used to predict and evaluate the effects of man’s interference, such as:

- dredging new navigation channels
- deepening existing channels
- reclaiming shallow areas as bases for industrial, harbour and recreational facilities.
- regulation of the upstream flow regime
- disposal locations for maintenance dredging
- urban and industrial waste disposal

In order to obtain a proper and reliable insight into estuarine water and sediment circulation, the Administracao Geral do Porto de Lisboa followed the hybrid modelling approach, viz physical and mathematical.

The Administracao Geral do Porto de Lisboa, henceforth called A.G.P.L., entrusted the physical model to the Laboratorio Nacional de Engenharia Civil, hereafter called
The distorted scales of the physical model encompassing the whole estuary amount to 1:500 in plan and to 1:70 in vertical.

The mathematical hydro-morphological model study was given to Sociedad Portuguesa de Dragagens (SPD) of Lisbon, Portugal and was carried out by Hydronamic BV, Sliedrecht, Holland on behalf of S.P.D.

1.2. TERMS OF REFERENCE

The Terms of Reference for the mathematical model study are based on the proposals mentioned below, submitted to A.G.P.L. by Hydronamic B.V., viz:

- Tagus Inner Estuary
  proposal for a two-dimensional mathematical model
dated: August 11th, 1980
  submitted to A.G.P.L. in a meeting on August 18th, 1980

- Port Extension Project Cova da Vapor–Bugio
  proposal for mathematical model studies;
  wave penetration model
tidal current model
sedimentological model
dated: October 20th, 1980
submitted to A.G.P.L. by letter
PMA/awo Cu 800.147-473 on November 21st, 1980

A notice to proceed was given by A.G.P.L. to SPD on February 18th, 1981.
The formal contract between AGPL and SPD was signed in June 1981.

The aim of the study is to have an operational mathematical model with which it is possible to predict and evaluate the hydraulic and morphological consequences of various interventions in the present state.
The mathematical study can be split up into 3 different operational models, viz:

- wave penetration model outer estuary
- estuarine circulation models outer and inner estuary
- morphological model outer estuary
This report presents the results of the estuarine flow circulation models of the inner and outer estuary.

The mathematical flow modelling study has been executed by Mr. G.J.A. Loman and Mr. H.J. Verhagen. The report was prepared by Mr. G.J.A. Loman under the supervision of Mr. A. Burgers, head of Hydronamic's Studies and Consultancy department.

1.3. SCOPE OF STUDY

The estuarine flow regime has been quantitatively estimated by employing a two-dimensional (2-D) numerical flow model. Hydronamic's numerical 2-D flow model for tidal wave propagation is an improved version of the Leendertse programme description, published by the Rand Corporation, USA (1967). The numerical flow model, such as used in this study, is an extremely effective device as well as economical since it can be used repeatedly.

To simplify the computation, the Tagus Estuary has been schematized into two square grids, laid over the outer and the inner estuary zone.

To acquire a thorough knowledge of the estuarine flow pattern there needs to be sufficient resolution of flow channels as well as land-water geometry to determine the mesh-size.

Secondly, the mesh-size also depends on how the computed results are used such as serving as input for morphological computations regarding the outer estuary.

Consequently mesh-sizes of $\Delta x = \Delta y = 200$ m and $250$ m have been chosen for the schematization of the outer and the inner estuary, respectively.

As a result, the following dimensions of the computational grids are derived:

\begin{itemize}
  \item Tagus Inner Estuary Grid
  \begin{itemize}
    \item length \( l_y \) = 38,500 m
    \item width \( l_x \) = 17,250 m
    \item declination y-axis \( \phi \) = +30 degrees to North
    \item mesh-size \( \Delta x, \Delta y \) = 250 m
    \item nodal array \( n \times m \) = 155 x 70 nodes
    \item total nodes \( N \) = 10,850 nodes
  \end{itemize}

  \item Tagus Outer Estuary Grid
  \begin{itemize}
    \item length \( l_y \)
    \item width \( l_x \)
    \item declination y-axis \( \phi \)
    \item mesh-size \( \Delta x, \Delta y \)
    \item nodal array \( n \times m \)
    \item total nodes \( N \)
  \end{itemize}
\end{itemize}
Figure 1.3.1. shows the location of both grids.

The procedure of computations starts from when field data were available. Besides detailed bathymetric surveys, field data on tidal elevations and flow velocities provide the indispensable basis for calibrating the numerical model regarding both schematizations. This involves the acquisition of reliable field data the interpreting their relevance to the modelling conditions.

Field data up to 1970 were extensively compiled and analysed in the following two reports:

i) Tagus Estuary,
   report on
   the analyses of the water motion in the Tagus Estuary
   by means of available data and the preparation of a
   program for supplementary field measurements,
   Report No.: P010, August 1969
   prepared for: A.G.P.L.
   by: Hydronamic B.V., Sliedrecht, Holland
   presented by: S.P.D. Lda, Lisbon

ii) Approach Channel Tagus Outer Estuary,
    report on
    a preliminary design of an approach channel,
    Report No.: P020, October 1971
    prepared for: A.G.P.L.
    by: Hydronamic B.V., Sliedrecht, Holland

The above mentioned field data were mainly obtained from the following institutes:

- Administracao-Geral do Porto de Lisboa (A.G.P.L.)
- Instituto Hidrografico (I.H.)
- Laboratorio Nacional de Engenharia Civil (L.N.E.C.)

Since 1970, more field data has become available on bathymetric surveys, local water elevations and flow velocities. These has been assembled, analysed and presented graphically where possible in the present study.
Simulation runs have been made for Mean Spring Tide and Mean Neap Tide under normal upstream river discharge conditions.

1.4. REPORT FORMAT

The report on the estuarine flow circulation model, part II of the hydro-morphological study concerning the Tagus Estuary consists of 4 volumes, viz.:

Volume 2.1: Text
Volume 2.2: Figures
Volume 2.3: Field measurements
Volume 2.4: Flow charts

The Text volume deals with the following chapters, accompanied by a brief overview:

chapter 1: Introduction
An outline is given of the project setting, the Terms of Reference for the Tagus Estuary study and the scope of this report.

chapter 2: Tagus Estuary Flow Regime
A description is given of the prototype conditions; available field data have been assembled and analysed for their applicability to the numerical flow models.

chapter 3: Numerical Simulation of Estuarine Flow
Hydronamic's 2-dimensional unsteady flow model has been described, including the subjects of model adjustment and verification.

chapter 4: Tagus Outer Estuary Model
This chapter deals with the final results of the tidal flow model of the outer estuary, including the calibration; Neap Tide and Spring Tide have been simulated.

chapter 5: Tagus Inner Estuary Model
This chapter deals with the final results of the tidal flow model of the inner estuary, including the calibration and verification; Mean Neap Tide and Mean Spring Tide have been simulated.
Prefatory to the report, the scope of this report has been summarized and concluding remarks have been given in 'Summary and Concluding Remarks'.

When referring to Tables, these can be found after each section; the first 2 table numbers correspond to the section in which they are dealt with. The same procedure has been applied to the numbering of figures.
2. TAGUS ESTUARY FLOW REGIME
2.1. DESCRIPTION OF PROTOTYPE

2.1.1. General

The maritime section of the Tagus Estuary is located between the river mouth in the Atlantic Ocean and Vila Franca de Xira, approx. 50 km upstream. In this area the saline tidal flow dominates the upstream fresh water influx.

The estuary has a fresh water influx from the Tagus River, the Sorraia River and to a lesser extent from the Coina River, the Judeu River and several small creeks. The Tagus River, the main contributor of fresh water, originates in Spain and enters Portugal near Vila Velha de Rodao.

The catchment area upstream from Vila Velha de Rodao amounts to approx. 56,500 sq km; the catchment area upstream from Vila Franca de Xira, including that of the Sorraia River is approx. 82,000 sq km. The tide prism of the Tagus Estuary amounts to approx. $7.5 \times 10^8$ cum for an average tidal amplitude of 1.3 m.

This maritime estuary comprises the following sections:

i) the river mouth and the outer zone
ii) the river entrance
iii) the inner estuary

Figure 2.1.1. is a sketch map of the inner and outer Tagus Estuary.

2.1.2. The river mouth and the outer zone

The large bay between Cabo Raso and Cabo Espichel is where the Tagus River flows into the Atlantic Ocean. The main river mouth is usually defined by the towers Torre do Bugio and Torre de S. Juliao, situated on a small island and on the northern bank, respectively.

The river mouth consists of two main flow channels, viz.:

- Barra Sul
  This large channel lies in between the shoals of Cachopo do Norte, to the north-west side, and Cachopo do Sul, to the south-east.
A minimum water depth of approx. 15.00 m was established by means of capital dredging, carried out in 1967 and 1972. Subsequent hydrographic surveys indicate that this depth seems to have remained stable. The navigation lane along this channel coincides with the Mame Sul light line of Gibalta and Esteira, having a direction of -47°00'00".

- Barra Norte
  This channel is located between the shoal Bico de Pato and the beaches of Carcavelos and Estoril. The navigation light line is established by the light towers of Santa Marta and Guia, situated in the vicinity of Cascais. Ship draught limit ranges between approx. 7 m and 10 m, depending on the tidal stage.

Other smaller flow channels are Golada and the channel nearby Cova da Vapor. The unstable shallow channel, Golada, intersects the shoal Cachopo do Sul, just north of Torre do Bugio. The channel nearby Cova da Vapor shortcuts the flow at the shoal Cachopo do Sul.

In the western part of the bay, a large submarine delta has been gradually developed, built up of fine to coarse sand. In the southern part a deep submarine valley of approx. 2,000 m in depth borders the bay.

The Tagus River outlet and the outer zone will be henceforth called 'Tagus Outer Estuary'.

2.1.3. The river entrance

The narrow, deep entrance of the Tagus River extends from the line Torre de Belem-Trafaria up to the line Lisboa-Cacilhas. This tail-shaped entrance has a width of approx. 2 km and a maximum depth of approx. 45 m below the datum level. This zone is usually called 'Corredor do Tejo' and will hereafter be referred to as 'Tagus Corridor'.

2.1.4. The inner estuary
Estuarine Circulation Model, Tagus Estuary

The inner estuary is a roughly pear-shaped reservoir approx. 30 km long and varying in width from approx. 15 km at the northern upstream section to 2 km at the downstream entrance of the Tagus Corridor, just south of Lisboa. The semi-enclosed estuary covers an area of approx. 350 sq km. The deep section of the estuary near Lisbon is called 'Mar da Palha'. The maximum water depth in this section is approx. 40 m below the datum level.

The estuary, henceforth called 'Tagus Inner Estuary', contains several sub-basins or breaks, like the breaks of Judeu, Coina, Lancada and Moita.

The inner estuary consists of a complex system of natural flow channels as well as man-made navigation channels, intersecting several shoaly areas and sandy islands. The northern and eastern portions of the inner estuary are relatively shallow, falling partly dry during low water conditions.

The following islands are situated in this area:

Mouchao do Povoa
Mouchao do Lombo do Tejo
Mouchao de Alhandra
Mouchao da Garcas

The main natural flow channels are the following:

Cala de Samora
Cala das Barcas
Cala da Acor
Cala do Norte
Cala do Montijo
Cala de Alchocete
Cala da Desemboga
Cala da Arrabida

The man-made navigation channels have been listed below:

Canal do Alfeite
Canal do Barreiro
Canal de Cabo Ruivo
Canal da CUF
Canal do Quimigal

*) Remark: Since the date of field measurements determines the conditions for calibration of the numerical model, the Canal do Quimigal as well as the Quimigal Terminal, which were constructed afterwards, have been excluded from the numerical flow simulation.
2.2. ACQUISITION AND INTERPRETATION OF FIELD DATA

2.2.1. General

The field data, relevant to this study, have been outlined in the following paragraphs and are listed below:

- reference level and grid
- bathymetry
- tidal elevations and tidal range
- tidal flow velocities
- fresh water discharge
- salinity distributions
- bed roughness

These data were mainly obtained from the following institutes or firms:

- Administracao - Geral do Porto de Lisboa (A.G.P.L.)
- Instituto Hidrografico (I.H.)
- Hidrotecnica Portugesa (.H.P.)
- Sociedade Portuguesa de Dragagens Lda (S.P.D.)

2.2.2. Grid and Datum

In this study the grid from the Instituto Hidrografico has been used. The position is expressed in metres Easting and Northing or in metres Meridian and Perpendicular, respectively. The origin of this system is located offshore, south-west of Portugal.

The reference level established by Instituto Hidrografico amounts to 2.08 m below the Mean Sea Level (MSL) at Cascais. This level is in this study referred to as Chart Datum (CD).

2.2.3. Bathymetry

Sounding charts of the whole Tagus Estuary are available at the A.G.P.L. and at the I.H.
During 1964-1967 a comprehensive survey programme was carried out by the I.H. commissioned by the A.G.P.L. This resulted in 42 sounding charts on a scale of 1:5,000, embracing the Tagus Inner Estuary, the Tagus Corridor and the Tagus Outer Estuary. Figure 2.2.1. shows the general arrangement of the above mentioned charts, including their chart numbers.

The whole Tagus Estuary is also covered by an A.G.P.L. sounding chart, updated to 1974, on a scale of 1:50,000, called 'Barras e Estuario do Tejo'.

2.2.4. Tidal elevations and tidal range

There is a scarcity of simultaneous measurements of water levels at various locations in the Tagus Estuary, which should form the indispensable basis for the model boundary conditions as well as for the calibration.

In this study the calibration procedure of the numerical models has been based on the available results of 2 measurement-campaigns; these concern recordings of tidal elevations at reference stations and flow velocities at various locations in the Tagus Estuary. Figure 2.2.2. shows the keyplan of the station numbers.

During March 1973 water levels were simultaneously recorded for the A.G.P.L. at the following stations:

<table>
<thead>
<tr>
<th>station no.</th>
<th>station name</th>
<th>recording period</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>Terreiro do Paco</td>
<td>13.03 - 27.03</td>
</tr>
<tr>
<td>L2</td>
<td>Cacilhas</td>
<td>13.03 - 27.03</td>
</tr>
<tr>
<td>L3</td>
<td>Paco de Arcos</td>
<td>13.03 - 27.03</td>
</tr>
<tr>
<td>L4</td>
<td>Povoa de Sta. Iria</td>
<td>16.03 - 23.03</td>
</tr>
<tr>
<td>L5</td>
<td>Seixal</td>
<td>20.03 - 23.03</td>
</tr>
<tr>
<td>L6</td>
<td>Montijo Base</td>
<td>20.03 - 23.03</td>
</tr>
<tr>
<td>L7</td>
<td>Vila Franca de Xira</td>
<td>16.03 - 23.03</td>
</tr>
<tr>
<td>L9</td>
<td>Cabo Ruivo</td>
<td>16.02 - 23.03</td>
</tr>
</tbody>
</table>

These measurements are presented graphically in 'Field Measurements'; Volume 3 of this report.

The recordings were statistically analysed for:

- mean water level (MWL)
Estuarine Circulation Model, Tagus Estuary

- duration of mean rise (DMR)
- duration of mean fall (DMF)
- phase difference at High Water (Δt HW)

for a reference station

These results have been compiled in Table 2.2.1. The results indicate that the DMR-value is larger than the DMF-value, except for Vila Franca de Xira. The DMR-value has its largest value at the upstream side of the Tagus Corridor near Lisbon; this gradually becomes smaller in the upstream and downstream directions.

The tidal elevations, recorded on March 13th and 25th, 1973, are nearly equal to the Mean Neap Tide conditions; the recordings of March 18th and 19th, 1973 for the Mean Spring Tide conditions.

In the southern section of the Tagus Inner Estuary current measurements were carried out for Siderurgia Nacional EP on April 6th, 13th, 14th and July 2nd, 1981. During these observations at Spring and Neap Tide the tidal elevations at the stations L1 and L5 were simultaneously recorded. The above mentioned recordings of tidal elevations have been used in the calibration procedure of the numerical flow models.

Simulation of Mean Spring Tide and Mean Neap Tide requires information on the elevations at the open boundaries of the numerical models. The estuarine flow pattern within the schematized Tagus Inner Estuary depends on the tidal elevation curves, given at the upstream boundary near Vila Franca de Xira and at the downstream boundary in the Tagus Corridor between Lisbon and Pedrouços.

The tidal elevations at the ocean boundary of the Tagus Outer Estuary scheme have been derived numerically from a large scale (750 m mesh-size) 2-D flow model of the Atlantic Coast region encompassing this Tagus Outer Estuary scheme. Tidal elevation curves for these boundaries have been derived from the tidal data given for Lisbon, Cascais, Sesimbra and Peniche.

The required boundary elevations have been taken from the most plausible tidal range data as listed in Table 2.2.2. The tidal range data, extracted from various sources, vary in their given values. Almost every source consulted presents tidal data on mean water level, tidal amplitude and phase lags which differ from other sources. This pluriformity of data may lead to misunderstandings.
Consequently, a list of the most likely tidal range data has been set up for this study. The sources have been listed below:

(i) 'Tabela de Mares', 1981 & 1982, Volume I, Portugal, Instituto Hidrografico

(ii) 'Guia 1981', Administracao-Geral do Porto de Lisboa

(iii) 'Carta topo-hidrografica das Barras e Estuario do Tejo', Escalar 1/50,000, 1974, Administracao-Geral do Porto de Lisboa

(iv) 'Carta hidrografica da Foz a Vila Franca de Xira', Escala 1/60,000, 1964-1974, Instituto Hidrografico

As regards the Tagus Outer Estuary flow simulation, the mean tidal range data have not been employed due to insufficient detailed tidal phase information. Therefore, two specific days have been chosen representing the boundary elevation curves for Spring Tide and Neap Tide. The two days have been arbitrarily chosen from the Tabela de Mares, 1982, as predicted for January 11th and 19th, respectively.

2.2.5. Estuarine flow velocities

As mentioned earlier the comprehensive measurement campaign of 1972-1973 also provides field data about the flow intensities and flow direction as function of the depth. Figure 2.2.2. shows the keyplan of the station numbers throughout the Tagus Estuary. Since in this study the numerical simulation considers only the depth-averaged flow circulation the measured data were averaged over the depth. These field data from the various stations, to be employed for calibration, have been compiled in Table 2.2.3. Tidal elevations from measurement during this campaign were not available. Therefore, the predicted tidal data for the reference station L1, Terreiro do Paco, presented in this Table, were taken from the Admiralty Tide Tables 1972 and 1973 for the Doca da Marinha (Porto de Lisboa), and may differ from the actual tidal conditions.
The current measurements of 1981, carried out by I.H. for Siderurgia Nacional EP, provide more detailed information about the flow pattern in and around the channels in the southern part of the inner estuary. Figure 2.2.2. shows the station numbers, running from station 223 to station 228 inclusive.

The date of measurement, the station numbers and the measured tidal data for the reference station have been listed in Table 2.2.3.a and 2.2.3.b.

The flow intensity and direction were measured 2 m below the water surface and 1 m above the bottom.

All the measured data of both campaigns have been presented as flow diagrams in Volume 2.3 of this report.

2.2.6. Fresh water discharge

Most of the fresh water enters the Tagus Inner Estuary via Vila Franca de Xira. Although the outlet of the Sorraia River into the inner estuary is located near Ponta da Erva, the discharge of this catchment area flows mainly into the Tagus River via a tributary upstream from Vila Franca de Xira.

Consequently, only one fresh water boundary has been employed in the numerical model of the inner estuary.

In the past decades discharge measurements were carried out just downstream from Vila Velha de Rodao. The discharges, measured fortnightly during 1954-1968, have the following characteristics:

<table>
<thead>
<tr>
<th>percentage of exceedance</th>
<th>fortnightly discharge at Vila Velha de Rodao (cum/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>40</td>
</tr>
<tr>
<td>50</td>
<td>160</td>
</tr>
<tr>
<td>10</td>
<td>750</td>
</tr>
<tr>
<td>1</td>
<td>2000</td>
</tr>
</tbody>
</table>

A discharge at Vila Franca de Xira can be derived by from the available data on rainfall, run-off ratio's and the increase of the catchment area.
Taking into account the estimated results outlined in the report, "Esgotos de Lisboa", 1941, an increase ratio of 1.5-1.6 for the above mentioned discharge seems reasonable.

Nevertheless, in the report of Ferreira Lemos of A.G.P.L., entitled "Estuario do Tejo", an average measured discharge of about 350 cum/s was mentioned at Santarem, based over a period of 59 years. The inference from this figure when compared with the available data for Velha de Rodao, is that the long-term discharge ratio for Vila Franca de Xira will be larger than 1.5-1.6, viz. approx. 2.4, inclusive the Sorraia River discharge.

This may produce the following rough discharge characteristics for Vila Franca de Xira:

<table>
<thead>
<tr>
<th>percentage of exceedance</th>
<th>predicted discharge at Vila Franca de Xira (cum/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90%</td>
<td>95</td>
</tr>
<tr>
<td>50%</td>
<td>385</td>
</tr>
<tr>
<td>10%</td>
<td>1800</td>
</tr>
<tr>
<td>1%</td>
<td>4800</td>
</tr>
</tbody>
</table>

A minimum discharge of approx 20 cum/s is maintained by means of the Castelo de Bode reservoir.

From available discharge measurements of 1972-1973 the following period-averaged discharges can be derived for Vila Franca de Xira:

<table>
<thead>
<tr>
<th>period</th>
<th>daily discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td>March 23th - 29th, 1972</td>
<td>1270 cum/s</td>
</tr>
<tr>
<td>March 15th - 20th, 1973</td>
<td>290 cum/s</td>
</tr>
</tbody>
</table>

Daily discharges, measured at Santarem from October 1980 till October 1981, as submitted by H.P., exhibit an average discharge of approx. 95 cum/s with a monthly standard deviation of 66 cum/s.

It will be clear from the above, that large annual variations in the fresh water discharge can occur.

2.2.7. Salinity distributions
Estuarine Circulation Model, Tagus Estuary

Salt water enters the inner estuary during the rising tide. The longitudinal, lateral and vertical salinity distribution in the Tagus Estuary is predominantly affected by the fresh water influx. The vertical salinity gradient may be diminished by bed-induced turbulence of the tidal currents. The longitudinal as well as the lateral salinity distribution depend mainly on the mixing of fresh water as function of the geometry of the estuary.

In the Hydromonic report (1969) the longitudinal distribution has been derived for some stations, from the only available data, as function of the fresh water influx. It was shown that the average salt intrusion length depends largely on the fresh water discharge. The maximum salinity is equal to about 36%.

The degree of mixing in the whole estuary can also be empirically approximated by determining the "estuary number" $E$, as deduced by Harleman and Abraham. When the $E$ value is relatively small the estuary is strongly stratified and density currents occur to an overwhelming extent. On the contrary, the estuary is well mixed if the $E$ value exceeds approx. 0.15, so the larger the estuary number, the more estuary mixing that is to be expected.

The estuary number $E$ has been defined as:

$$E = \frac{P \cdot Fr^2}{Q \cdot T}$$

where:
- $P$: tidal prism, i.e. the volume of sea water entering the estuary in a mean tide
- $Fr$: Froude number
  $$= \frac{U}{\sqrt{gd}}$$
- $U$: maximum flow velocity in the estuary mouth
- $d$: mean depth in the estuary mouth
- $Q$: fresh water influx
- $T$: tidal period

The following data have been used for determining the average estuary number:
Estuarine Circulation Model, Tagus Estuary

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>7.5 \times 10^8 cum</td>
</tr>
<tr>
<td>U</td>
<td>1.3 m/s</td>
</tr>
<tr>
<td>d</td>
<td>30 m</td>
</tr>
<tr>
<td>T</td>
<td>44400 s</td>
</tr>
<tr>
<td>Q</td>
<td>385 cum/s</td>
</tr>
</tbody>
</table>

Hence, the estuary number $E$ has been calculated as approx. 0.21.

For extreme river discharges, however, the estuary number may be smaller than the 0.15 mentioned earlier.

Generally speaking, the calculated estuary number indicates that the Tagus Inner Estuary belongs to a transition between the partially mixed and the well mixed estuary classes. These conclusions are supported by field data, which do not show a strong vertical salinity gradient.

The above implies that the flow circulation in the Tagus Estuary can be reliably represented by depth averaged flow simulation.

2.2.8. Bed roughness

Reliable field data on bed roughness are necessary for the calibration procedure. A proper choice of the Nikuradse bed roughness is essential, especially since the non-linear bed resistance term generally dominates the solution of the shallow water equations.

To date, no field measurements are available of the bed roughness throughout the Tagus Estuary. Therefore, empirical relationships have been used for estimating the bed roughness from the flow velocities and the sediment grain sizes.

Bottom samples, taken in the outer and inner estuary, reveal that two types of sediment can be expected, viz:

- fine silty mud
- coarse sand, at some places full of shells.

This clustering effect has also been proved from the sieve results of the bottom samples, taken by H.P. for Soros Associates, in the area between Cacilhas and Seixal in 1981. Coarse sand may be expected at places where strong velocities occur. Silty mud can be expected at places where siltation dominates.
Throughout the estuary both clusters may be characterized as follows:

* coarse sand, shell-laden

<table>
<thead>
<tr>
<th>grainsize</th>
<th>mean (μm)</th>
<th>standard deviation (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D50</td>
<td>500</td>
<td>250</td>
</tr>
<tr>
<td>D90</td>
<td>5000</td>
<td>2500</td>
</tr>
</tbody>
</table>

* fine silty mud:

<table>
<thead>
<tr>
<th>grainsize</th>
<th>mean (μm)</th>
<th>standard deviation (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D50</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>D90</td>
<td>125</td>
<td>350</td>
</tr>
</tbody>
</table>

Assuming the following ranges for the parameters governing the bed roughness, the limits of this so-called Nikuradse roughness can be determined empirically using the resistance graphs of Einstein-Barbarossa (1952) and Shen (1962):

- flow velocity $U$: $0.05 - 1.50$ m/s
- water depth $h$: $0.30 - 80.00$ m
- grainsize $D50$: $15 - 500$ μm

Hence, the Nikuradse bed roughness may vary between $r = 0.005$ m and $r = 1.0$ m.

Generally, the Nikuradse bed roughness, observed in tidal environments, displays the tendency to increase with decreasing water depth. In this study, however, such a relationship is thought to be too arbitrary.

In the report, "Environmental Study of the Tejo Estuary", C.N.A./Tejo No 7, issued July 1980, the following bed roughness classes were established in an arbitrary way:

<table>
<thead>
<tr>
<th>depth class $h$ (m)</th>
<th>Nikuradse bed roughness $r$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>73 - 40</td>
<td>0.0002</td>
</tr>
<tr>
<td>39 - 25</td>
<td>0.0010</td>
</tr>
<tr>
<td>24 - 10</td>
<td>0.0460</td>
</tr>
<tr>
<td>&lt; 10</td>
<td>1.0000</td>
</tr>
</tbody>
</table>

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

In this study the numerical models have been calibrated by employing a single valued Nikuradse bed roughness throughout the model schematizations. It should be noted that the bed roughness, providing the best resemblance for the computed and the measured flow field, is only relevant for the numerical flow modelling.
<table>
<thead>
<tr>
<th>no.</th>
<th>name</th>
<th>M.W.L.</th>
<th>D.M.F.</th>
<th>D.H.R.</th>
<th>ΔH_W</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>ť̅₁ⁿ⁻¹</td>
<td>ť̅₁ⁿ⁻¹</td>
<td>ť̅₁ⁿ⁻¹</td>
<td>ť̅₁ⁿ⁻¹</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(m + C.D.)</td>
<td>(dec. hrs.)</td>
<td>(dec. hrs.)</td>
<td>(dec. hrs.)</td>
</tr>
<tr>
<td>L1</td>
<td>Terreiro do Paço</td>
<td>2.20</td>
<td>5.73</td>
<td>6.63</td>
<td>-</td>
</tr>
<tr>
<td>L2</td>
<td>Cacilhas</td>
<td>2.16</td>
<td>5.68</td>
<td>6.60</td>
<td>0.23</td>
</tr>
<tr>
<td>L3</td>
<td>Povo de Arcos</td>
<td>2.20</td>
<td>6.01</td>
<td>6.32</td>
<td>0.25</td>
</tr>
<tr>
<td>L4</td>
<td>Povoa de Sta. Iria</td>
<td>2.27</td>
<td>6.20</td>
<td>6.12</td>
<td>0.20</td>
</tr>
<tr>
<td>L5</td>
<td>Seixal</td>
<td>2.33</td>
<td>5.69</td>
<td>6.38</td>
<td>0.21</td>
</tr>
<tr>
<td>L6</td>
<td>Montijo Base</td>
<td>2.27</td>
<td>5.81</td>
<td>6.43</td>
<td>0.15</td>
</tr>
<tr>
<td>L7</td>
<td>Vila Franca de Xira</td>
<td>2.57</td>
<td>6.76</td>
<td>5.55</td>
<td>0.27</td>
</tr>
<tr>
<td>L9</td>
<td>Cabo Ruivo</td>
<td>2.29</td>
<td>5.95</td>
<td>6.42</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Note: M.W.L. = Mean Water Level, D.M.F. = Duration of Mean Fall (from High to Low Water), D.H.R. = Duration of Mean Rise (from Low to High Water), ΔH_W = phase difference at High Water with Terreiro do Paço.

Table 2.2.1: Statistical Analysis Stage Observations, Tagus Estuary, March 1973
<table>
<thead>
<tr>
<th>station</th>
<th>Mean Spring Tide</th>
<th>Mean Neap Tide</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M.W.L. (m + C.D.)</td>
<td>a (m)</td>
</tr>
<tr>
<td>no.</td>
<td>name</td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>------------------</td>
<td>---------</td>
</tr>
<tr>
<td>2</td>
<td>Pedrouços</td>
<td>2.10</td>
</tr>
<tr>
<td>L1</td>
<td>Terreiro do Paço</td>
<td>2.20</td>
</tr>
<tr>
<td>L2</td>
<td>Cacilhas</td>
<td>2.20</td>
</tr>
<tr>
<td>L4</td>
<td>Povoa de Sta. Iria</td>
<td>2.35</td>
</tr>
<tr>
<td>L5</td>
<td>Seixal</td>
<td>2.25</td>
</tr>
<tr>
<td>L6</td>
<td>Montijo Base</td>
<td>2.25</td>
</tr>
<tr>
<td>L7</td>
<td>Vila Franca de Xira</td>
<td>2.50</td>
</tr>
<tr>
<td>L9</td>
<td>Cabo Ruivo</td>
<td>2.25</td>
</tr>
</tbody>
</table>

reference station: Terreiro do Paço

sources: A.G.P.L.

M.W.L. Mean Water Level

a tidal amplitude

Δt<sub>HW</sub> phase difference at High Water with station L1 Terreiro do Paço
### Table 2.2.3.a.: Flow measurements, Tagus Estuary

<table>
<thead>
<tr>
<th>station no.</th>
<th>date of measurement</th>
<th>tidal data at Terreiro do Paço</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>H.W.L. (m + C.D.)</td>
<td>$\delta$ (m)</td>
<td>time of H.W. (dec. hrs)</td>
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<tr>
<td>8</td>
<td>March 31st 1972</td>
<td>2.15</td>
<td>1.45</td>
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</tr>
<tr>
<td>15</td>
<td>April 17th 1972</td>
<td>2.20</td>
<td>1.50</td>
<td>18.72</td>
<td></td>
</tr>
<tr>
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<td>2.15</td>
<td>1.85</td>
<td>17.22</td>
<td></td>
</tr>
<tr>
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<td>2.15</td>
<td>1.45</td>
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<td></td>
</tr>
<tr>
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<td>2.25</td>
<td>1.75</td>
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</tr>
<tr>
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<tr>
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<td>15.83</td>
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<td>16.22</td>
<td></td>
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<tr>
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<td>16.08</td>
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<td>June 2nd 1973</td>
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<td>1.93</td>
<td>17.33</td>
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<td>15.27</td>
<td></td>
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<td>15.27</td>
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<td>1.83</td>
<td>17.63</td>
<td></td>
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<td>1.70</td>
<td>18.38</td>
<td></td>
</tr>
</tbody>
</table>

- **M.W.L.**: Mean Water Level
- **$\delta$**: Tidal Amplitude
- **H.W.**: High Water
<table>
<thead>
<tr>
<th>station no.</th>
<th>date of measurement</th>
<th>tidal data at Terreiro do Paço</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>M.W.L.</td>
</tr>
<tr>
<td>221</td>
<td>July 11th 1972</td>
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<td>221</td>
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<tr>
<td>227</td>
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</tbody>
</table>

M.W.L. Mean Water Level
Å Tidal Amplitude
H.W. High Water

Table 2.2.3.b.: Flow measurements, Tagus Estuary
3. NUMERICAL SIMULATION OF ESTUARINE FLOW
3.1. INTRODUCTION

3.1.1. Scope

During the past two decades the discipline of computational hydraulics has emerged, by which various hydraulic problems, previously beyond the hydraulic engineer's capability to solve, have now become tractable. One such problem, which is of primary interest in this study, is the estuarine flow circulation, induced by tidal waves as well as by fresh water flows of land drainage.

Numerical models of various types, to be used for the flow circulation mentioned above, are all based on approximations of the governing equations representing the fundamental laws of mass and momentum conservation.

Since the flow circulation in the comparatively shallow Tagus Estuary does not show significant salinity gradients, the following simplified assumptions may be made for the governing flow equations, viz.:

- the vertical fluid depth is much less than the horizontal scale of the tidal motion;
- the vertical pressure distribution is effectively hydrostatic;
- the fluid does not exhibit vertical stratification;
- the fluid is incompressible;
- the fluid density is constant.

Using these assumptions, the numerical model can be based on the solutions of the shallow water equations. These equations are the depth-integrated versions of the turbulent analogies to the 3-dimensional Navier-Stokes momentum equations and the mass conservation equation.

Given the required information on the physical characteristics of the bathymetry and the forcing functions, the circulation can be computed at each point in horizontal space and time in terms of three variables: the 2 horizontal components of the depth-averaged flow velocity and the elevation of the free surface above a reference datum. Such a numerical model, referred to as 2-dimensional, has been employed in this study.

The above results can in turn be used as an input for other models dealing with the transport of suspended substances, such as the sediment, also of interest in this study.
Estuarine Circulation Model, Tagus Estuary

3.1.2. Numerical and physical flow models

As shown in the previous paragraph, the flow and sediment circulation in the Tagus Estuary can be modelled as 2-dimensional. This can be done numerically as well as physically by means of a scale model.

The advantages and the drawbacks of both model types have been briefly outlined here for the purpose of elucidating their specific utility values.

In physical scale models the horizontal estuarine flow circulation can closely resemble reality if there is turbulent flow. The main shortcoming of a fixed-bed scale model is the need to comply with the law of scales, which may involve conflicting requirements. For example, exaggeration of the depth, prescribed by turbulent flow requirements, can lead to flow separation, due to the exaggerated bed slopes, which do not exist in reality. A second drawback of physical models is that comprehensive estuarine models are very expensive, especially if the effect of various bed configurations has to be investigated.

In large physical scale models the Coriolis force on account of the earth’s rotation has also to be properly modelled, which implies the use of a large number of rotating devices.

The advantage of the physical model is the ability to represent properly the lateral and longitudinal turbulence regarding dispersion of substances.

Movable-bed scale models, however, can only function as a qualitative management guide since the model is limited by complex adjustment of bed material sizing.

For a numerical model the schematization may result in more or less disregarding detailed physical information. This degree of schematization depends on how the results are used. The limitations of a numerical model may also be caused by an imperfect approximation of the governing equations.

One important advantage of a numerical model is the ease and the flexibility in using the boundary conditions. Input data as well as output data can be stored for future use. The numerical model is a particularly powerful, economical means of predicting the flow patterns for various optional situations. In combination with a sediment continuity model, the accretion and erosion of bed sediment can be quantitatively predicted.
Another great advantage of the numerical model is that results can be produced quite quickly, especially if some interferences in an existing model have to be studied. For instance, results of an estuarine simulation of a modified outer or inner Tagus Estuary model can be obtained within 1 to 2 weeks, depending on the size of interference.

3.1.3. Numerical methods

Two solution procedures are at present available for the differential equations of the shallow water wave. These are the finite difference method and the finite element method.

In the case of the finite difference method (FDM) space and time are presented by a regular, square lattice of mesh points at distances Δx and Δy and by a chosen time step Δt. The variable at a mesh point is described as a function of the variables at other grid points in such a way that for the limit of zero increment of Δx, Δy, Δt these finite difference equations are consistent with the differential equations. With the FDM the approximation of these equations is relatively straightforward, but the schematization into a regular mesh grid may introduce difficulties. For an irregular boundary geometry the "staircase" schematization results in loss of accuracy near such boundaries; secondly, the mesh spacing, required to represent the most detailed area, must be used throughout the model region.

For the finite element method (FEM), the model region is divided into small, discrete elements, usually triangular in shape. Each element has a fixed number of nodes at which the solution is computed. Within each element the solution is interpolated among the computed nodal values by a polynomial, having degrees of freedom equal to the number of nodes in that element. For a certain time level the unknown coefficients of the simultaneous equations, relating the variables of each element, are found from the equation of motion and the boundary conditions. This requires a comparatively large computer core memory. The time integration is usually identical to time stepping techniques, as employed for the FDM. However, most of the FEM models, having been developed for tidal flow simulation, are explicit in time owing to computer core memory restrictions, resulting in a relatively large number of computer time units being used.
Finite difference methods have traditionally been used to solve the shallow water equations and, unlike the finite element methods, successful replete computer programmes have already been documented. Bearing in mind the above mentioned properties, and in view of the availability of in-house computer core memory Hydronamic developed a finite difference model for the computation of 2-dimensional unsteady flow, based on a semi-implicit computational method as published by Leendertse (1967). This numerical model has already successfully been applied to various flow problems investigated by Hydronamic.

3.2. HYDRONAMIC'S 2-D UNSTEADY FLOW MODEL

3.2.1. General

A numerical flow model's potential can be defined by the following terms:

- capability and flexibility
- numerical stability & accuracy
- operational efficiency
- functional utility

The comprehensiveness of the shallow water equation determines largely the capability to simulate a wide range of flow types; the flexibility to permit schematization is intrinsic to the numerical method selected.

Numerical stability and accuracy depend upon the finite difference approximations and the computational scheme selected.

The operational efficiency depends upon the skillful set up of an effective numerical scheme and the transformation into a sound, replete computer programme.

The functional utility depends upon its ability to interact with a programme package designed to facilitate in- and output data, handling and graphical representation.
3.2.2. Shallow water equations

Hydronamic's 2-D unsteady flow model has been based on a simplified version of the shallow water equations. In the equations below the forcing functions of barometric pressure, wind stress and wave radiation stress have been omitted and the turbulent Reynolds stresses have been disregarded. As regards the Tagus Estuary, the forces omitted do not dominate the solution as the tidal force does. Disregarding the lateral turbulent stresses is justified as the lateral velocity gradients are relatively small throughout the schematizations of the inner and outer estuaries. This leads to the following set of coupled equations of conservation of mass (i) and momentum (ii):

\[
\frac{\partial n}{\partial t} + \frac{\partial}{\partial x} \left[ (h + n) U \right] + \frac{\partial}{\partial y} \left[ (h + n) V \right] = 0
\]

\[
\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} + \frac{\partial}{\partial y} \left[ (h + n) g \right] - f U + \frac{g U (U^2 + V^2)^{1/2}}{(h + n) C_r^2} = 0
\]

\[
\frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} + \frac{\partial}{\partial x} \left[ (h + n) g \right] - f V + \frac{g V (U^2 + V^2)^{1/2}}{(h + n) C_r^2} = 0
\]

where:

- \text{x, y} horizontal co-ordinates (m) (see figure below)
- \text{t} time (s)
- \text{h} bathymetric water depth relative to reference plane (m)
- \text{n} free surface elevation relative to reference plane (m)
- \text{U, V} vertically integrated velocities in x- and y- direction, respectively (m/s)
- \text{g} gravitational acceleration (m²/s²)
- \text{Cr} Chezy coefficient of bed roughness (m²/s)
- \text{f} Coriolis parameter as function of the (1/s)

Chapter 3: Numerical simulation of estuarine flow page 33
To obtain a solution for the shallow water equations, the physical situation must be defined. Model input data must be given, such as:

- bed roughness
- latitude of region of interest
- bathymetry
- closed and open boundary geometry
- open boundary conditions

3.2.3. Computational scheme

The equations of the interior flow field have been defined by Leendertse as space-centered difference approximations on a space staggered grid. The sketch below shows that space-staggered grid. The grid spacing $\Delta x$, $\Delta y$ is a constant for both directions. On the space-staggered grid the variables $U$, $V$, $n$ and $h$ are described at different mesh points.
The advantage of such a scheme is that in the formula for the variable, operated in time, the spatial derivatives for the linear terms are centrally located.

The difference equations are expressed in an alternating direction implicit manner so that for each computing cycle two successive time level operations are performed. The first operation is taken from time \( n\Delta t \) to time \( (n+1/2)\Delta t \); and the second operation from \( (n+1/2)\Delta t \) to \( (n+1)\Delta t \), where \( n \) is the integer time step and \( \Delta t \) the time increment.

In the first operation \( n \) and \( U \) are obtained implicitly and \( V \) explicitly; in the second operation \( n \) and \( V \) are obtained implicitly and \( U \) explicitly.

Leendertse did not take the convective inertia terms as completely centered in time because of computational considerations.

The consequences of this as regards the Tagus Estuary model will now be dealt with.
Estuarine Circulation Model, Tagus Estuary

Resulting model instabilities have been overcome by a proper time and space centering of the non-linear terms.

The present Hydronamic flow model provides the option for an improved time integration by means of additionally performed iterations to determine the variables in the non-linear terms.

Along the boundaries the finite difference approximation mentioned above becomes complicated if maintaining a similar computational scheme. At the closed boundaries, the velocity perpendicular to the boundary is assumed to be zero. In terms where information outside the open boundary is required, backward and forward differences have been adopted. For reasons of stability, Leendertse omits these kind of terms. In the Hydronamic flow model, a weighted interior differencing scheme has been employed for the convective terms at the open boundaries.

The computation of tidal flats appeared to be extremely difficult if the model was to remain economical. Various criteria to check the submergence potential of flats have been tested during this study. The flow simulation on tidal flats becomes quite complicated on account of the requirements of conservation of mass. It appears that the criteria selected greatly affect the shape of the tidal curve. The implemented tidal flat module is thought to be accurate and reliable.

The model can require a large number of time-varying boundaries. At some mesh points the water levels must be given. Linear interpolation of amplitudes and phases have been used for points lying in between on the open boundaries. In this study a simple method called "2-cosine-method" has been used for prescribing the instantaneous water levels for the given nodes. The tidal boundary curves of the Tagus Estuary may be expressed as the composition of a falling and a rising cosine curve, both having different periods. (see sketch below)
3.2.4. Computational properties

Numerical accuracy

The present finite difference scheme, being space-centered for the interior field, is accurate up to the 2nd order, viz $O(\Delta x^2)$. This indicates that a change in $\Delta x$ to $\Delta x/2$ will reduce the truncation error to $1/4$ of its original value.

The semi-implicit time stepping scheme is accurate up to a transition of the 1st and 2nd order, viz $(\Delta t - \Delta t^2)$. After some iterations the scheme is thought to have the 2nd order accuracy with a truncation error of $O(\Delta t^2 + \Delta x^2)$.

Numerical consistency

In solving the shallow water equations, the use of an inconsistent finite difference scheme is undesirable, particularly if mass and momentum are to be conserved. The difference schemes as employed in the model all resemble the difference equation in the limit as $\Delta x, \Delta t$ approach to zero.
Numerical stability

Generally, numerical flow models for the simulation of 2-dimensional horizontal flow can display two instabilities, viz:

- Instability due to the non-linear terms in the governing equations.
- Instability due to exceeding the convergence ratio of both physical and numerical celerity.

As regards the linear instability this may be caused by the creation of waves at the beginning of the computation. When the boundary conditions are imposed instantaneously, shock-like waves can disturb the solution. After the exceedance of the convergence ratio, resembling a Courant-like constraint, the computation is blown up within a few steps. The convergence ratio depends on the type of adopted time stepping scheme and on how the spin-up of the model has been done from rest.

In the Hydrodynamic flow model a "cold start" procedure has been developed using the dissipating function of the bed shear stress.

Non-linear instability is due to the inability of the mathematical model to transfer turbulent energy to scales smaller than twice the mesh-size. Physically, the turbulent energy is dissipated by viscous effects. Non-linear instability is characterized by a gradual growth of discontinuities in the water level and the components of the flow velocity. After examining some technical literature, it appears that various techniques have been developed to suppress these artificial, disturbing waves.

It has been shown by Leendertse, by means of a Fourier stability analysis, that the difference method as proposed by him is stable for the linearized form. In practice, however, it often turns out that slight disturbances with a wave length of 2Δx gradually develop. This effect was also encountered during the initial tests of the Tagus Inner Estuary model. It has taken much effort to tackle this computational snake in a reliable way, i.e. without affecting the original solution too much. The procedure adopted in the Hydrodynamic flow model is the spatial averaging of the computed velocity field after a few steps by using a weighted smoothing operator. This procedure acts like an energy dissipator for very small spurious waves.
In effect, this routine simulates more or less the contribution of the disregarded turbulent lateral stresses.

To date, there is still a lack of adequate numerical stability criteria for computational schemes regarding non-linear flow equations.

It is suggested by Vreugdenhil (1975) to impose the following upper limit on the Courant-Friederichs-Levy (CFL) stability constraint when applying the Leendertse scheme:

\[ \Delta t \frac{\sqrt{gh}}{\Delta x} < 5 \]

Based on the experience with the Tagus Estuary models as to what works and what not, the following stability constraint has been developed:

\[ \Delta t \left(2|U| + \frac{\sqrt{gh}}{\Delta x} \right) < 7 \]

When imposing the latter constraint the improved version of the Leendertse model appears to be more stable, i.e. more economical.

3.2.5. Programme implementation

The improved Leendertse flow model has been written in FORTRAN-IV programming code. At the start of this study the programme was implemented on the in-house HP-3000 computer. Until then the size of all the flow problems solved was such that it fitted into its core memory. The central core memory allows for a maximum data segment of 64,000 bytes. However, the size of the computational grid for the Tagus Estuary exceeds this limit. Consequently, a system was developed for handling arrays that otherwise would not fit into the core, viz. a virtual array handler. This also required a revision of the structure of the existing flow programme. Although the system handled the array size of the Tagus Estuary models, the system worked rather uneconomically, resulting in a huge consumption of computation time units.
Estuarine Circulation Model, Tagus Estuary

The flow programme laid such a heavy load on the HP-3000 operating system, that job sessions could only be scheduled for outside business hours. This resulted in computations lasting more than 1 week.

For convenience and effective use and taking into account the instabilities encountered during the first experiments, the programme has been implemented on the CDC 750/Cyber 176 machine at Rijswijk, Holland. The data block of the Tagus Inner Estuary model just fits into the central core memory. At the Cybernet Centre at Rijswijk the operating system of the Cyber 176, model 750, allows the user of a central core memory of 400,000 octal words of 60 bits.

3.2.6. Data processing

The bulk of effort in making flow simulation runs lies in the pre- and postprocessing of the in- and output data, respectively.

An input data processor has been developed for the purpose of presenting the input data block in a form that can be readily used by the simulation programme. The input data processing programme has been implemented on the CDC Cyber 176 machine.

The output data processor package is designed to make charts and graphs of simulated results and field data. The programme package has mainly been implemented on the in-house HP-3000 machine.

The data processing on the CDC Cyber 176 machine is controlled by its Network Operating System. This system allows remote batch job processing from in-house Datapoint 1500 terminals, encompassing input/output devices, like diskette, tape and printer units.

From the diskette or tape, the computed results are transmitted to the in-house HP-3000 machine for processing by the graphical programme package.

Plots up to a size of A3 are made by HP7221A plotters, employing HP2621P terminals. Larger flow charts are made by means of a Datapoint 1150 terminal/tape unit and a Calcomp 1051 plotter in combination with a DEC/PDP11 computer.

All the computed results, as produced in the course of this study, have been stored on magnetic tapes.
3.3. MODEL CALIBRATION AND VERIFICATION

The calibration of flow velocities and tidal elevations in both Tagus Estuary models has been a major effort. The depth array has been determined from the various survey charts as mentioned in chapter 2. Furthermore, the coordinates of the stations at which field data were taken, had to be transferred to the closest available points in the computational grid.

The first step in the calibration process was the land/water geometry which followed from the schematization of the bathymetry. Narrow channels in the computational grid have to obey the rules for flow schematization, which prescribe for example that every flow cell within the grid must share at least one node of the adjacent flow cells.

Tidal flats have also been checked for their proper submergence and for their effect on the shape of the tidal elevations.

A proper choice of the bed roughness is essential since the bed resistance generally dominates the solution. Further details on the calibration and verification of the models are given in the sections 4 and 5.
4. TAGUS OUTER ESTUARY MODEL
4.1. INTRODUCTION

The bottom configuration of the outer estuary has been schematized into a square computational grid with a mesh-size of $A_x = A_y = 200$ m. Figure 1.3.1. shows the borders of the computational grid. The above mesh-size has been chosen so that sufficient resolution of the main channels and the land-water geometry are obtained. The computational characteristics of the numerical scheme are:

- **length** $l_y$: 19,800 m
- **width** $l_x$: 11,800 m
- **mesh-size** $\Delta x, \Delta y$: 200 m
- **nodes** $n \times m$: 100x60
- **time step** $\Delta t$: approx. 50 s.

Since the above computational grid has comparatively many open boundaries and since tidal data at the ocean boundaries are lacking, an overall model has been constructed with a mesh-size of 750 m. This overall model of the outer estuary embraces the tidal level stations at Lisbon, Cascais, Sesimbra and Peniche.

The boundary conditions for Mean Neap Tide and Mean Spring Tide could not be completely determined from the available tidal range data due to the lack of information on the phase lags.

Therefore the tidal data for a Spring Tide and Neap Tide have been arbitrarily chosen from the Tabela de Mares, 1982, viz. January 11th and 19th, respectively. The chosen Spring Tide has a larger tidal amplitude than that given for Mean Spring Tide; the Neap Tide has a smaller amplitude than that given for Mean Neap Tide.

The results of the overall model have been used as input for the boundary conditions of the Tagus Outer Estuary scheme. The duration of the tidal simulation is 18 hours real time. As the model has to be started from rest, the numerical results only become reliable after approx. 2 hours real time simulation.

The computed results are presented graphically by means of:

1. **nodal water level graphs**

Chapter 4: Tagus Outer Estuary Model
ii) nodal flow intensity & direction graphs
iii) flow charts

4.2. CALIBRATION

The initial numerical runs employed a single-valued bed roughness of $r = 1.00$ m.
For calibration the Spring Tide has been used because of the availability of many field measurements.
During the process of calibration, the bed roughness has been changed to a best fit value of $r = 0.40$ m. This value belongs to the expected range as discussed in paragraph 2.2.8. This value is only relevant for the hydraulic modelling.
The results of the final calibration run are presented in the following section.
A verification of the calibrated model is usually required for another tidal condition, for instance Neap Tide.

Since however, no field data on Neap Tide are available the verification could not be made.
Based on the comparisons between the best fits of the numerical results and the measurements for Spring Tide, it can be stated that the Tagus Outer Estuary model is quite reliable.

4.3. SPRING TIDE

4.3.1. Water level

Figures 4.3.1. to 4.3.13., inclusive, contain the water elevations of the stations. The water level is expressed in cm + Datum, where Datum refers to the Mean Water Level at Cascais, equal to $2.08$ m + CD

The imposed open boundary condition may be represented by the following local data:
Estuarine Circulation Model, Tagus Estuary

<table>
<thead>
<tr>
<th>boundary</th>
<th>MWL (m+CD)</th>
<th>a (m)</th>
<th>Δt HW (s)</th>
<th>DMF (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doca de Belem</td>
<td>2.17</td>
<td>1.720</td>
<td>1440</td>
<td>23940</td>
</tr>
<tr>
<td>Cascais</td>
<td>2.08</td>
<td>1.625</td>
<td>0</td>
<td>22320</td>
</tr>
<tr>
<td>S.W. of Barra Sul</td>
<td>2.07</td>
<td>1.610</td>
<td>-90</td>
<td>22500</td>
</tr>
<tr>
<td>S. of Costa da</td>
<td>2.07</td>
<td>1.630</td>
<td>-90</td>
<td>22500</td>
</tr>
<tr>
<td>Caparica</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

where: MWL Mean Water Level
a tidal amplitude
Δt HW phase lag at High Water
DMF duration of mean fall

The duration of a tide cycle is equal to 45,000 seconds.

4.3.2. Flow velocity

The computed flow intensity and direction are shown in Figures 4.3.14 to 4.3.23 inclusive. The direction is expressed in azimuth degrees.

In the list below an overview of some maximum flow velocities is presented.

<table>
<thead>
<tr>
<th>station number</th>
<th>max. flood velocity (m/s)</th>
<th>max. ebb velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>42</td>
<td>0.71</td>
<td>0.63</td>
</tr>
<tr>
<td>44</td>
<td>1.21</td>
<td>1.81</td>
</tr>
<tr>
<td>46</td>
<td>0.45</td>
<td>0.36</td>
</tr>
<tr>
<td>48</td>
<td>0.95</td>
<td>1.08</td>
</tr>
<tr>
<td>50</td>
<td>0.64</td>
<td>1.20</td>
</tr>
<tr>
<td>52</td>
<td>1.04</td>
<td>1.52</td>
</tr>
<tr>
<td>54</td>
<td>1.27</td>
<td>1.74</td>
</tr>
<tr>
<td>100</td>
<td>1.10</td>
<td>0.62</td>
</tr>
<tr>
<td>102</td>
<td>0.81</td>
<td>0.66</td>
</tr>
<tr>
<td>103</td>
<td>0.86</td>
<td>1.12</td>
</tr>
<tr>
<td>108</td>
<td>0.51</td>
<td>1.07</td>
</tr>
</tbody>
</table>

In figures 4.3.24. to 4.3.43 inclusive, the computed and measured velocity have been drawn. The predicted tidal data at Terreiro do Paco used for the measurements can be found in Table 2.2.3. For comparison, it can be assumed that the tidal flow intensity is proportional to the square root of the tidal amplitude, $V \propto \sqrt{a}$. 

Chapter 4: Tagus Outer Estuary Model
The computed flow field is shown by 2 A4 format colour flow charts. Figure 4.3.44. and 4.3.45. represent flood and ebb tide conditions, respectively.

Compositions of flow charts and sounding chart are made on a scale 1:50,000. Drawing numbers 4.1 to 4.4 inclusive illustrate the Low Water, Flood Tide, High Water and Ebb Tide. The velocity scale is 1 in 100. The flow intensity and direction show clearly the velocity pattern in and around the flow channels, viz: Barra Norte, Barra Sul, Golada and the gully near Cova da Vapor.

4.4. NEAP TIDE

4.4.1. Water level

Figures 4.4.1. to 4.4.13. inclusive present the water elevations at the stations. The water level is expressed in cm + Datum, where Datum refers to the Mean Water Level at Cascais, equal to 2.08 m + CD

The open boundary conditions may be illustrated by the following local tidal data:

<table>
<thead>
<tr>
<th>boundary</th>
<th>MWL (m+CD)</th>
<th>a (m)</th>
<th>Δt HW (s)</th>
<th>DMF (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doca de Belem</td>
<td>2.12</td>
<td>0.619</td>
<td>450</td>
<td>23220</td>
</tr>
<tr>
<td>Cascais</td>
<td>2.08</td>
<td>0.569</td>
<td>0</td>
<td>22320</td>
</tr>
<tr>
<td>S.W. of Barra Sul</td>
<td>2.08</td>
<td>0.564</td>
<td>-90</td>
<td>22680</td>
</tr>
<tr>
<td>S. of Costa da Caparica</td>
<td>20.8</td>
<td>0.574</td>
<td>-90</td>
<td>22500</td>
</tr>
</tbody>
</table>

4.4.2. Flow velocity

The computed flow intensities and directions are shown in Figures 4.4.14 to 4.4.23 inclusive. The direction is expressed in azimuth degrees. In the following an overview is given of some maximum flow intensities.
<table>
<thead>
<tr>
<th>station number</th>
<th>max. flood velocity (m/s)</th>
<th>max. ebb velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>42</td>
<td>0.11</td>
<td>0.19</td>
</tr>
<tr>
<td>44</td>
<td>0.19</td>
<td>0.61</td>
</tr>
<tr>
<td>46</td>
<td>0.09</td>
<td>0.13</td>
</tr>
<tr>
<td>48</td>
<td>0.14</td>
<td>0.34</td>
</tr>
<tr>
<td>50</td>
<td>0.10</td>
<td>0.42</td>
</tr>
<tr>
<td>52</td>
<td>0.18</td>
<td>0.46</td>
</tr>
<tr>
<td>54</td>
<td>0.21</td>
<td>0.61</td>
</tr>
<tr>
<td>100</td>
<td>0.25</td>
<td>0.17</td>
</tr>
<tr>
<td>102</td>
<td>0.28</td>
<td>0.19</td>
</tr>
<tr>
<td>103</td>
<td>0.25</td>
<td>0.45</td>
</tr>
<tr>
<td>108</td>
<td>0.15</td>
<td>0.26</td>
</tr>
</tbody>
</table>

Figures 4.4.24. and 4.4.25. show the flow pattern in colour on A4 format for flood and ebb tide. Drawing 4.5.-4.8. represent the flow charts on a scale of 1:50,000 for Low Water, Flood Tide, High Water and Ebb Tide.
5. TAGUS INNER ESTUARY MODEL
Estuarine Circulation Model, Tagus Estuary

5.1. INTRODUCTION

The bathymetry of the inner estuary has been schematized into a square lattice with a mesh-size of $\Delta x = \Delta y = 250$ m. This mesh-size is considered to meet the requirements of sufficient resolution of the main channels. The schematization has been based on the sounding charts as shown in Figure 2.2.1.

In order to produce a reliable velocity field near the physical open boundaries, the model schematization has been extended mathematically, resulting in non-physical channels leading to the two open boundaries. The borders of the physical and mathematical grid are shown in Figure 1.3.1.

The computational characteristics of the latter are listed below:

- **length** $l_y$ = 38,500 m
- **width** $l_x$ = 17,250 m
- **mesh-size** $\Delta x, \Delta y$ = 250 m
- **nodes** $n \times m$ = 155x70
- **time step** $\Delta t$ = approx. 70 s.

The upstream and downstream open boundaries in the mathematical scheme coincide with approx. Vila Franca de Xira and Pedroucos, respectively.

In the present model, open boundary conditions are prescribed only by the elevations of the free water surface. These have been interpreted from the tidal range data as given in Table 2.2.2. The time-harmonic shape of the tidal curve is identical to the analysed field data, as presented in Table 2.2.1.

The duration of the simulated tidal flow amounts to 18 hours real time. Owing to the spin-up of the model from rest, the numerical results become reliable after approx. 2 hours real time. This means that, the implemented "cold start" procedure appears to be very effective.

The computed results are presented in graphical form by as follows:

1) nodal water level graphs
2) nodal flow intensity & direction graphs
3) flow charts
5.2. CALIBRATION AND VERIFICATION

The numerical experiments were started with a single-valued bed roughness of \( r = 0.70 \) m. Mean Spring Tide has been taken for calibration purposes. When comparing the numerical results with the representative field data, it appears that a lower value of the bed roughness will probably produce a better resemblance. After executing some simulation runs, it has been concluded that a bed roughness of \( r = 0.20 \) m gives reasonable results. This value belongs to the range as discussed in paragraph 2.2.8.

The results of the calibrated Mean Spring Tide simulation are presented in the following section.

As one tidal situation has been calibrated, production runs can be made after verifying the model to a different flow condition. In this study Mean Neap Tide has been employed for model verification. The results of this simulation are satisfactory, when compared with the few relevant field data. These results are presented in a following section.

Taken into account the facts that the field measurements of flow velocities are all taken at different days, that the numerical model represents a “mean” situation, and that the reference data on tidal elevations and tidal phase have been obtained by prediction, the above results are in reasonable agreement with the field observations. Therefore, the model is thought to be adequate for the computation of future interferences.

5.3. MEAN SPRING TIDE

5.3.1. Water level

Figures 5.3.1. to 5.3.11. inclusive show the water level curves of some stations. The water level in the graphs is expressed in cm + Datum. Datum refers to the Mean Water Level at the downstream boundary, equal to 2.14 m + CD.
The following open boundary conditions have been imposed:

<table>
<thead>
<tr>
<th>boundary</th>
<th>MWL (m+CD)</th>
<th>a (m)</th>
<th>Δt HW (s)</th>
<th>DMF (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>downstream</td>
<td>2.14</td>
<td>1.66</td>
<td>0</td>
<td>20955</td>
</tr>
<tr>
<td>upstream</td>
<td>2.44</td>
<td>1.70</td>
<td>3500</td>
<td>24380</td>
</tr>
</tbody>
</table>

where: MWL = Mean Water Level
a = amplitude
Δt HW = phase lag at High Water
DMF = duration of mean fall

The duration of a tide cycle amounts to 44,400 seconds.

From the computed curves the tidal range data of the level stations have been determined; these have been listed in Table 5.3.1.

When comparing these results with the observed tidal data range for Mean Spring Tide a relatively good resemblance can be shown (see Tables 2.2.1., 2.2.2. and 2.2.3.).

The computed levels can be examined for similarities with the observed levels, representing the most likely Mean Spring Tide condition, viz. March 18th and 19th 1973 and July 2nd 1981.

Figures 5.3.12. to 5.3.17. inclusive show both these curves for the level stations L1, L2, L4, L5, L7 and L9, respectively.

The measured curves may deviate from the computed results due to slightly different tidal and fresh water conditions.

The imposed boundary conditions mean a fresh water influx of approx. 850 cum/s at Vila Franca de Xira. This can be considered as normal.

Knowing this, the computed curves fit the measured curves quite well.

5.3.2. Flow velocity

The computed flow intensity as well as the flow direction are represented by Figures 5.3.18. to 5.3.28. inclusive. The direction corresponds to azimuth degrees.
In order to obtain an impression of the flow intensities, the maximum flood and ebb velocities have been tabulated below for some stations.

<table>
<thead>
<tr>
<th>station number</th>
<th>max. flood velocity (m/s)</th>
<th>max. ebb velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>0.13</td>
<td>0.18</td>
</tr>
<tr>
<td>12</td>
<td>0.14</td>
<td>0.42</td>
</tr>
<tr>
<td>13</td>
<td>0.56</td>
<td>0.27</td>
</tr>
<tr>
<td>24</td>
<td>0.69</td>
<td>0.71</td>
</tr>
<tr>
<td>30</td>
<td>0.73</td>
<td>0.71</td>
</tr>
<tr>
<td>36</td>
<td>1.23</td>
<td>1.18</td>
</tr>
<tr>
<td>201</td>
<td>0.52</td>
<td>0.57</td>
</tr>
<tr>
<td>202</td>
<td>0.65</td>
<td>0.56</td>
</tr>
<tr>
<td>210-211</td>
<td>0.32</td>
<td>0.83</td>
</tr>
<tr>
<td>223</td>
<td>0.54</td>
<td>0.59</td>
</tr>
<tr>
<td>224</td>
<td>0.45</td>
<td>0.55</td>
</tr>
<tr>
<td>226</td>
<td>0.66</td>
<td>0.56</td>
</tr>
<tr>
<td>227</td>
<td>0.85</td>
<td>0.79</td>
</tr>
<tr>
<td>228</td>
<td>1.03</td>
<td>0.79</td>
</tr>
</tbody>
</table>

For calibration purposes, the measurements at some stations have been plotted alongside the computed results in Figures 5.3.29, up to and including 5.3.43. Table 2.2.3. illustrates the predicted/measured tidal data at Terreiro do Paco. From small deviation from the tidal amplitude $a$, as compared to the computed value, it may be assumed that the resulting velocity is proportional to $\sqrt{a}$. For example, the computed velocity should be compared with a 94\% reduction of the measured velocities on April 6th 1981, (computed $a=1.71$ m, measured $a=1.92$ m).

Some differences may occur in small channels due to ill-resolution of such channels in the computational grid of 250 m.

The computed flow field is represented by 2 A4-format colour velocity charts, representing the maximum flood and ebb flow, see Figures 5.3.44. and 5.3.45.

Secondly, 4 flow patterns are made on charts on a scale of 1:100,000, representing the Low Water, Flood Tide, High Water and Ebb Tide conditions. See Drawings 5.1. to 5.4. inclusive.

The velocity scale amounts to 1:100.

These flow charts show the flow intensity, the flow direction and the bathymetry.
These charts illustrate clearly that the flow pattern reflects the complex gully system of the Tagus Inner Estuary.
At Low Water it is shown that a large shoal area falls dry.
Table 5.3.1: Computed tidal range data

<table>
<thead>
<tr>
<th>station</th>
<th>M.W.L.</th>
<th>A</th>
<th>ΔtHW</th>
<th>D.M.R.</th>
<th>D.M.F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>no.</td>
<td>name</td>
<td>(m + C.D.)</td>
<td>(m)</td>
<td>(min)</td>
<td>(min)</td>
</tr>
<tr>
<td>L1</td>
<td>Terreiro do Paço</td>
<td>2.17</td>
<td>1.71</td>
<td>0</td>
<td>399</td>
</tr>
<tr>
<td>L2</td>
<td>Cacilhas</td>
<td>2.15</td>
<td>1.70</td>
<td>0</td>
<td>405</td>
</tr>
<tr>
<td>L4</td>
<td>Povoa de Sta. Iria</td>
<td>2.30</td>
<td>1.78</td>
<td>27</td>
<td>309</td>
</tr>
<tr>
<td>L5</td>
<td>Seixal</td>
<td>2.22</td>
<td>1.71</td>
<td>6</td>
<td>363</td>
</tr>
<tr>
<td>L6</td>
<td>Montijo Base</td>
<td>2.21</td>
<td>1.77</td>
<td>6</td>
<td>375</td>
</tr>
<tr>
<td>L7</td>
<td>Vila Franca de Xira</td>
<td>2.44</td>
<td>1.70</td>
<td>42</td>
<td>333</td>
</tr>
<tr>
<td>L8</td>
<td>Arsenal do Alfeite</td>
<td>2.26</td>
<td>1.72</td>
<td>0</td>
<td>399</td>
</tr>
<tr>
<td>L9</td>
<td>Cabo Ruivo</td>
<td>2.17</td>
<td>1.78</td>
<td>18</td>
<td>304</td>
</tr>
</tbody>
</table>

A  tidal amplitude
M.W.L. Mean Water Level
D.M.F. Duration of Mean Fall (from High to Low Water)
D.M.R. Duration of Mean Rise (from Low to High Water)
ΔtHW phase difference at High Water with Terreiro do Paço
5.4. MEAN NEAP TIDE

5.4.1. Water level

Figures 5.4.1. to 5.4.8. inclusive represent the computed water level curves at some stations.

The water level in the graphs is expressed in cm + Datum.

This Datum, referring to Mean Water Level at the downstream boundary, amounts to 2.14 m + CD.

The following open boundary conditions have been employed for simulation of Mean Neap Tide.

<table>
<thead>
<tr>
<th>boundary</th>
<th>MWL (m+CD)</th>
<th>a (m)</th>
<th>Δt HW (s)</th>
<th>DMF (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>downstream</td>
<td>2.14</td>
<td>0.72</td>
<td>0</td>
<td>20955</td>
</tr>
<tr>
<td>upstream</td>
<td>2.50</td>
<td>0.75</td>
<td>2500</td>
<td>24380</td>
</tr>
</tbody>
</table>

The computed tidal range data have been tabulated for the level stations in Table 5.4.1.

The simulation of Mean Neap Tide can be considered as a verification of the calibrated model.

Figures 5.4.9. and 5.4.10. show the measured as compared to the computed curves at station L1 and L2, respectively.

It may be concluded from the points presented above that the model properly reproduces the Mean Neap Tide water elevations.

5.4.2. Flow velocity

The computed flow intensities and directions at some stations are shown in Figures 5.4.11. to 5.4.18. inclusive.

The measured and computed flow graphs have been plotted for comparison in Figures 5.4.19. to 5.4.23., inclusive.

In spite of the ill-resolution of some channels concerned, the resemblance is quite accurate.

An impression of the maximum flow intensities is given below for some stations.
<table>
<thead>
<tr>
<th>station number</th>
<th>max. flood velocity (m/s)</th>
<th>max. ebb velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>0.02</td>
<td>0.11</td>
</tr>
<tr>
<td>13</td>
<td>0.22</td>
<td>0.18</td>
</tr>
<tr>
<td>22</td>
<td>0.20</td>
<td>0.26</td>
</tr>
<tr>
<td>30</td>
<td>0.31</td>
<td>0.44</td>
</tr>
<tr>
<td>36</td>
<td>0.55</td>
<td>0.64</td>
</tr>
<tr>
<td>201</td>
<td>0.23</td>
<td>0.28</td>
</tr>
<tr>
<td>202</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>210-211</td>
<td>0.03</td>
<td>0.63</td>
</tr>
<tr>
<td>223</td>
<td>0.25</td>
<td>0.27</td>
</tr>
<tr>
<td>224</td>
<td>0.22</td>
<td>0.26</td>
</tr>
<tr>
<td>226</td>
<td>0.26</td>
<td>0.29</td>
</tr>
<tr>
<td>227</td>
<td>0.38</td>
<td>0.43</td>
</tr>
<tr>
<td>228</td>
<td>0.43</td>
<td>0.44</td>
</tr>
</tbody>
</table>

Flow charts, on A4 format and in colour, are shown in Figures 5.4.24. and 5.4.25., representing the Flood and Ebb Tide conditions during Mean Neap Tide.

Drawings 5.5. to 5.8. inclusive represent the Low Water, Flood Tide, High Water and Ebb Tide, respectively, on a chart scale of 1:100,000 and a velocity scale of 1:100.
Table 5.4.1: Computed tidal range data

<table>
<thead>
<tr>
<th>no.</th>
<th>name</th>
<th>M.W.L. (m + C.D.)</th>
<th>a (m)</th>
<th>Δt HW (min)</th>
<th>D.M.R. (min)</th>
<th>D.M.F. (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>Terreiro do Paço</td>
<td>2.15</td>
<td>0.75</td>
<td>0</td>
<td>405</td>
<td>335</td>
</tr>
<tr>
<td>L2</td>
<td>Cacilhas</td>
<td>2.15</td>
<td>0.75</td>
<td>-3</td>
<td>408</td>
<td>332</td>
</tr>
<tr>
<td>L4</td>
<td>Povoa de Sta. Iria</td>
<td>2.22</td>
<td>0.81</td>
<td>18</td>
<td>339</td>
<td>461</td>
</tr>
<tr>
<td>L5</td>
<td>Seixal</td>
<td>2.15</td>
<td>0.77</td>
<td>3</td>
<td>399</td>
<td>347</td>
</tr>
<tr>
<td>L6</td>
<td>Montijo Base</td>
<td>2.15</td>
<td>0.79</td>
<td>3</td>
<td>393</td>
<td>347</td>
</tr>
<tr>
<td>L7</td>
<td>Villa Franca de Xira</td>
<td>2.50</td>
<td>0.75</td>
<td>58</td>
<td>336</td>
<td>404</td>
</tr>
<tr>
<td>L9</td>
<td>Cabo Ruivo</td>
<td>2.18</td>
<td>0.80</td>
<td>12</td>
<td>390</td>
<td>350</td>
</tr>
</tbody>
</table>

a  tidal amplitude
M.W.L. Mean Water Level
D.M.F. Duration of Mean Fall (from High Water to Low Water)
D.M.R. Duration of Mean Rise (from Low Water to High Water)
Δt HW phase difference at High Water with Terreiro do Paço