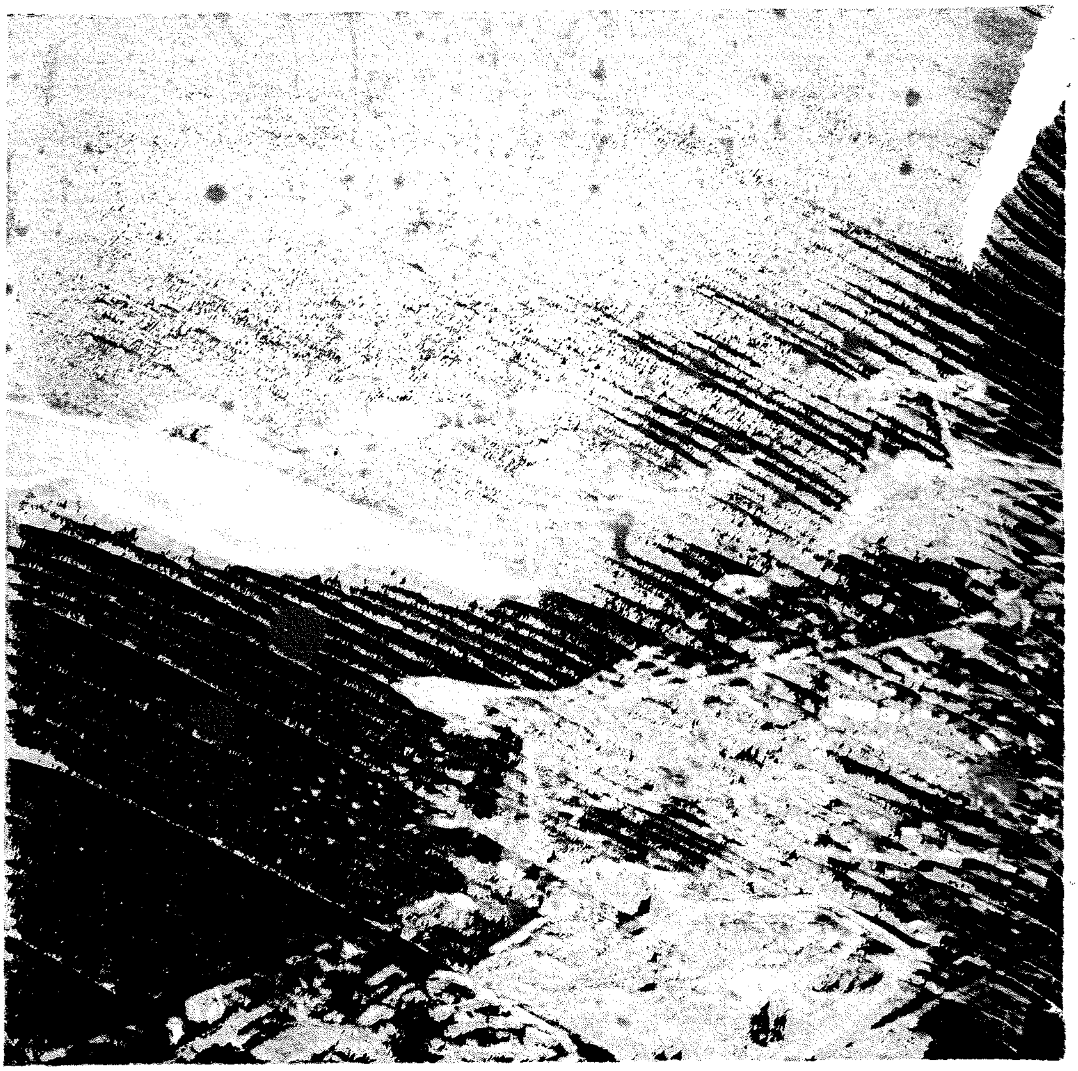
ADMINISTRAÇÃO DOS PORTOS DO DOURO E LEIXÕES

Hydro-morphological study Douro Estuary

Part 6

Set-up of a mathematical model



december 1982 / P613

PORT AND WATERWAY ENGINEERS

hydronamic bv
sliedrecht holland

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TABLE OF CONTENTS

1. INTRODUCTION

The Administracao dos Portos do Douro is confronted with the fact that future expansion of the port areas of Leixoes is limited by the surrounding hills and urbanisation. One of the alternatives for future expansion might be the creation of port facilities in the Douro estuary, where a relatively large, flat area is available.

However, the river entrance is rather unstable from a morphological point of view, so that regular dredging is required to maintain an access channel.

In order to eliminate the risk of unexpected morphological changes in the Douro estuary due to harbour works, APDL has decided to study the morphological aspects of the Douro bar thoroughly, and to make a design for a mathematical model to investigate the influence of harbour works in the area.
This study was offered to APDL by the Sociedade Portuguesa de Dragagens in January 1982. After receipt of the letter of adjudication from APDL, dated July 29th, 1982. Hydronamic bv was asked by S.P.D. to start the study.

The study is divided into six phases, viz:

a1. wave penetration calculation
a2. calculation of longshore transport
a3. calculation of the tidal prism
b. morphological evaluation

c. set-up of the mathematical model

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

In this report a description is given of a mathematical model which is able to simulate the morphological changes in the river mouth.

2. TYPE OF MATHEMATICAL MODEL

The general approach to calculate morphological changes in a coastal zone is the development of a two-dimensional hydromorphological mathematical model. Two-dimensional means that both magnitude and direction of current and sediment are calculated.

A one-dimensional model calculates only magnitude, the direction is defined by the lay-out of the branched network, cf. the HYDFLOW 1 model of the river between Crestuma and the sea. In an area with shallow, moving sandbanks, where the direction of the current is not defined beforehand, it is impossible to apply a one-dimensional model.

A three-dimensional model calculates the currents in three dimensions. Differences between the currents at the surface and at the bottom are taken into account. Such a model is required if very difficult density-current systems occur in the area. Three-dimensional models are extremely expensive and should therefore only be used if absolutely necessary.

The calculation scheme of a two-dimensional hydromorphological model is given in fig. 1. As can be seen, the calculation is carried out by four different calculation modules.

The difference between the various hydromorphological models is in fact a difference in computation method in each module.

The computation can be very detailed (and very accurate) or less detailed and taking into account less variables.

The main problem with a high quality model is that considerably computer time is required to make a time-step.
It is (financially) impossible to calculate a large number of tidal cycles with a model which includes all possible aspects.
Therefore it is necessary to investigate carefully the requirements for a mathematical model. One should not spend a lot of time, effort and money to get results which were to be expected beforehand.

As already stated in our proposal of January 1982, it was impossible to define beforehand the exact type of model which had to be applied for modelling the Douro mouth. The results of the previous phases of this study show which aspects are important for the description of the morphology of the area, and which consequently have to be built into the model.

The main conclusions from the studies of the boundary conditions, of the general morphology of the area and the field measurements made in November 1982 are that the morphological changes in the mouth of the river are limited to a relatively small area, but that changes occur with a high frequency. Another conclusion is that the sediment movement takes place in a relatively closed system.
The phenomena governing the sediment movement in the area are the tidal currents, the river discharge and the action of the waves.

The above facts indicate that a mathematical model describing the movements of the sediments in the Douro mouth, should be a model in two dimensions with a relatively small mesh-size (50-25 m) and should cover an area of approx. 2 x 3 km. In order to calculate the sediment movements, the current (magnitude and direction) and the wave (height, period and direction) have to be known for each meshpoint.

Because both currents and waves depend locally on the bottom topography, current pattern and waves have to be calculated applying the results of the former morphological calculation. The model, when built this way, is a simulation model. In principle, such a simulation model follows the reality by using either deterministic or stochastic input values. Deterministic values are tides (they can be predicted very accurately). Stochastic values are waves and river discharge (their probability distribution is known, but it is impossible to predict them exactly). So, the model will be a stochastic simulation model.

The disadvantage of a stochastic model is that such a model is unable to give exact predictions, but it can show clear tendencies.

(No one knows if there will be an extreme river discharge in 1984, therefore no one can know if the Cabedelo will be washed away in 1984).

The main requirements for a model for the Douro mouth are the ability to simulate bottom changes during a large number of tidal cycles, and to accommodate several values of river discharge and for a varying incoming waves.

On the other hand, the wave-penetration calculation in the model can be done relatively simply and a simplified method to calculate the two-dimensional current pattern can also be applied.

Wave-penetration occurs over short distances, so the influence of bottom friction can be neglected. Also because the waves all come from a westerly direction, the calculation method can be done in a simple way.

The calculation of the current pattern can also be done in a simple way, provided the river discharge plus the tidal discharge is known at the boundary of the model.
Because the area of the model is relatively small, the phase differences of the tidal wave between the boundaries of the model can be neglected. Also the water level differences between the boundaries can be neglected.
This simplifies the current pattern calculation considerably. In fact, it is only required to redistribute the discharges, known at the boundary, over the whole model.
A relatively fast computer program can be made to execute this redistribution.

3. WAVE MODULE

The main data provided by the wave module are wave height and wave direction at each mesh-point. The wave period remains constant during wave penetration. Because data are only required at the mesh-points, a calculation method will be used which calculates the wave data at mesh points only, see fig. 2. The wave data at point N, M are calculated using the data from the surrounding points (N-1, M-1), (N, M-1), (N-1, M). First the model tests if a wave can reach point (N, M) regarding the local water depth.

Then the 'average surrounding wave height', is calculated using the direction as weight factor. (If waves come at an angle less than 45 degrees, only point (N-1, M-1) is important; if waves come at an angle of less than 90 degrees only point (N, M-1) is important).

Subsequently, the average distance between the surrounding points and (N, M) is calculated.

Knowing the previous wave height, previous direction and the distance, the program is able to calculate the new wave height and wave direction applying the correct bottom slope and local wave length.

This calculation is carried out using the normal, linear wave theory, which is usually applied in wave penetration models.

4. CURRENT MODULE

4.1. Discharge at Boundary

One of the major imput parameters of the discharge redistribution module is the discharge at the boundary of the model.
Besides the phase of the tide (number of hours after H.W.), this discharge is a function of the freshwater discharge and of the type of tide (neap-tide, spring-tide, etc.).
Because the influence of the morphology of the river mouth on the tidal prism (and thus on the discharge) is relatively small, it is possible to calculate the discharges with a separate model.
The one-dimensional model of the Douro, as presented in volume 3 of this report, can be used very well for this purpose. However, the measurements in November indicated a significant influence of the salinity difference between seawater and freshwater. It is therefore advisable to make a small modification to the one-dimensional model and to include the density difference. This can be done quite easily by adapting the resistance values of the bottom by a factor representing the internal friction.

Thus the one-dimensional model has to be run for a number of freshwater discharges (say 5 cases) and a number of various tides (say 4 cases). Thus approx. 20 runs have to be made with this model. Each run gives the discharge as a function of time. The values found in this way, are stored on a data file in the computer.

The discharge redistribution module needs discharge data at the boundary, and can read the required data from the above mentioned data file.

4.2. Redistribution System

The discharge redistribution system reads the boundary data from a data file and transfers the discharge from each mesh-point to the adjacent mesh-points, taking into account the direction of the original discharge, the water depths in the adjacent points and the bottom slope.

In this way, a current pattern is created over the whole area describing the flow at a certain moment due to tidal action and river discharge.

This current pattern is assumed to be permanent during the time step.

4.3. Set-up Current and Longshore Current

Wave set-up is a function of the local wave height. Knowing the data from the wave module, it is quite simple to calculate the wave set-up at each mesh-point. When there are differences in set-up (thus differences in the average water level) between two adjacent points, there will be a current between these two points.

This current can be calcalated using normal hydraulic formulae for currents due to water level differences.
A longshore current is a current caused by obliquely breaking waves. The current can be calculated with the theory of radiation stress. Because wave heights and bottom contours are known for every meshpoint, the calculation of the longshore current can be executed by the computer.

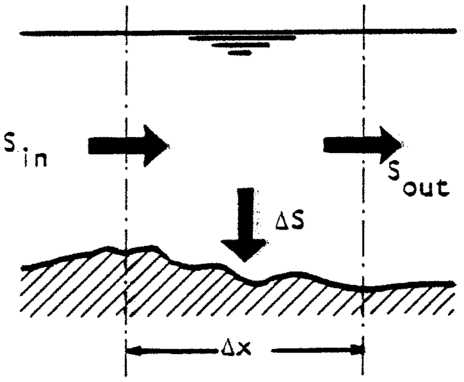
In fact, the set-up current and the longshore current are calculated in the same way as in the program BYKBAT. In vol. 2 of this report this is described in more detail.

4.4. Final Current Pattern

The current patterns from the discharge distributor, from the set-up current and from the longshore current can be added with the technique of vectorial adding. Non-linear interactions between these currents are neglected in this way, but in practical situations the non-linear effects are very small.

5. SEDIMENT TRANSPORT MODULE AND BED LEVEL MODULE

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



S is now expressed in m3/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 h, 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 element is the calibrated sediment transport formula.

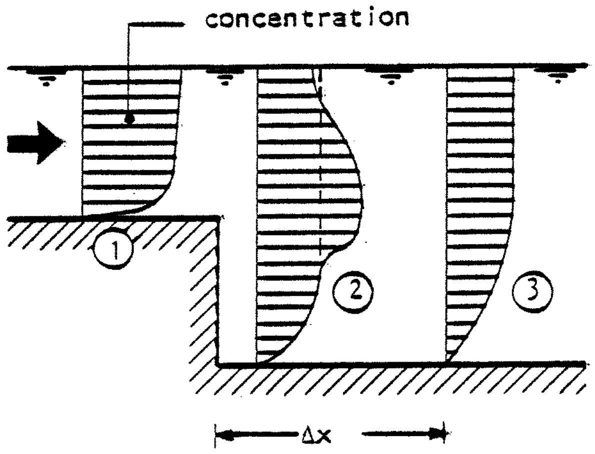
Sediment transport is calculated at each grid-point as a function of:

- velocity
- wave action (wave height and period)
- local water depth
- grain-size
- bottom roughness

The type of formula to be used is a Bijker-type or a Yalin-type bottom transport formula and a formula according to Battacharya for the calculation of the suspended load. The coefficients in these formulae have been determined from the results of the field measurements in November.
For a detailed description of the formulae to be applied, please refer to volume 4 of this report.

However, it is impossible to solve the differential equation $dh/dt = dS/dx$ continuously, and a numerical solution will always cause errors and simplifications in the answer.

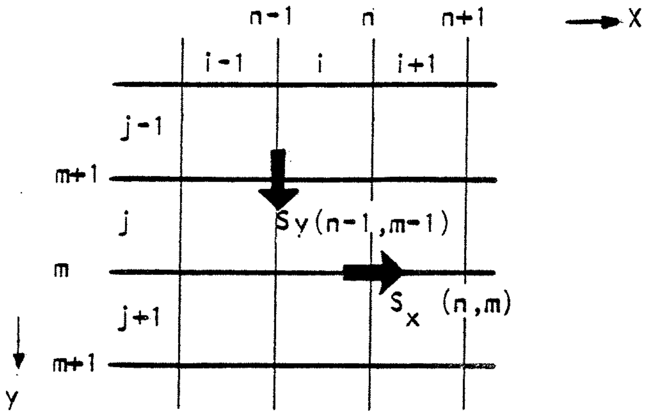
The main assumption we have to make is that after a distance Δx the sediment transport is fully adapted to the new transport capacity. For example, at point 1 we have a certain equilibrium of transport and at point 3 there is also an equilibrium. But at point 2 there is not yet an equilibrium. We assume that the distance Δx is big enough to allow adaption to the new equilibrium.



The sediment transport is calculated at grid points. The coordinates 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.



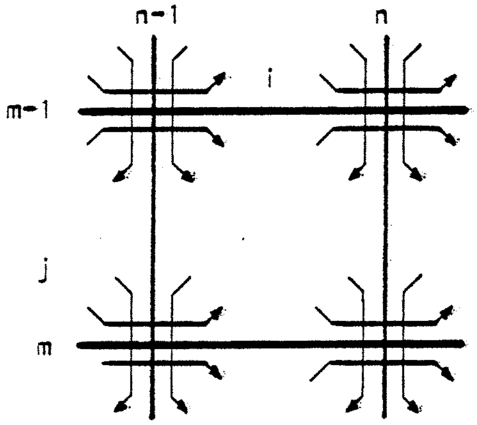
It is assumed that the sediment transport in the x direction comes for 50% from the square above left, and for 50% from the square below left from the grid point.

This sediment is presumed 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:

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



With this formula the new bottom level is calculated at each grid point. This new bottom level is the starting position for the next time step (see also fig. 1).

6. REQUIRED RUNNING METHOD

The structure of the mathematical model is given in figure 3. In element 1, a value from one of the discharge curves is chosen. This is done according to the probability distributions of those discharges (e.g. mean-tide is chosen twice as often as spring-tide). In element 2 a wave is chosen, also according the to probability of occurance of the waves. Then the discharge is distributed and wave influence and the sediment transport calculated, resulting in a new bottom. After increasing the time with one time-step, the complete calculation is repeated. This is done until the whole tidal cycle is completed (one computational cycle should be 25 hours, because the tide is partly semi-diurnal).

After completion of the tidal cycle, a new set of discharges and waves is chosen, and the next tidal cycle can be calculated.

In principle, 350 tidal cycles should be calculated in order to simulate the bottom changes in one year. However, this number can be decreased, because a number of cycles are identical. It is unnecessary to run them twice, multiplication of the results (bottom changes) with a factor 2 is enough.

7. CALIBRATION OF THE MODEL

Because the model is a stochastic model it is impossible to calibrate in a deterministic way. This is mainly caused by the fact that no long-term time series of wave data are available, but only wave statistics. Calibration should therefore also be done in a stochastic way.

Because very many hydrographic charts of the river mouth are available (from 1872 until now), they can be used for a stochastic calibration.

This should be done in the following way:

From each chart a number of characteristic properties are measured (like surface of the Cabedelo, distance between Cabedelo and Cantareira, depth in front of Meia Laranja etc).

Each chart may produce say 20 properties. These same 20 properties can be obtained from all 100 charts. Then the statistical values of each property can be calculated (like mean, standard deviation, skewness etc).

Then the bottom topography of 1872 is entered into the mathematical model and the model is run to represent a long period, say 100 years. It is quite unlikely that the calculated situation of 1972 will be identical to the actual situation of 1972, because the real sequence of storms is not followed. (The very high river discharge of 1962 will not occur in the model in 1962, but in another year).

But on average, the same morphological changes should occur in the model, as they occur in reality.

Then the same properties, as measured from the charts are also measured from the calculated results. From the calculated properties, the same statistical values can also be calculated.

Now one can calculate the correlation between the results from the model and the data from the charts.
The correlation coefficient calculated in this way is a measure for the reliability of the model.
Calibration of the model can be done to change the coefficients of the formulae in such a way that the above mentioned correlation coefficient is maximal.

8. ADDITIONAL REQUIRED INFORMATION

Most of the required information was collected during the measuring campaign of November 1982. See volume 4 on this subject.

In order to calibrate the hydromorphological model some statistical properties have to be measured from the 100 old charts, available at APDL.

This can be done quite quickly, directly from the original maps using a ruler and a planimetre. In this way it is unnecessary to make copies of all the maps.

More additional information is not required, but it is highly advisable to do a short additional measuring campaign at the end of April. In November, the conditions were a high river discharge and high waves at sea. In April, we expect hardly any river discharge and low waves. As already explained in the previous volumes, we can expect a somewhat different current pattern. We can derive this current pattern theoretically, but it is always better to adjust the theory to measurements.

The same is valid for the situation at sea. In November, we measured sediment transport during high waves, and we can calculate what will happen during low waves, but it is also better for sediment transport to adjust the theory to the measurements.

We therefore recommend that a short additional measuring campaign be carried out in April. During this campaign measurements will be made at approx. 5 stations. (In November we measured at 11 stations).

9. APPLICATION OF THE MODEL

The aim of the model is to predict the effect of man-made works on the morphology of the river mouth. The model suggested in this report can be used to determine the average long-term influence of certain works.

It is possible to build in the topography fixed structures, like harbour moles, quaywalls, etc.. Then the model is run to cover a number of years and one can see if there is a tendency in the morphological changes. (For example does the channel become deeper or wider ?).

With this model one can test beforehand the influence of various structures.

It is also possible to investigate the quantity of maintenance dredging work. This can be done in the following way:

> The model is run to represent one year; After one year the depth in the channel is compared with the required depth. If the depth is insufficient, the depth is increased, and the volume which has been removed is written down in a data file. This is done for a number of years.
>
> After the simulation, the data file contains a number of data, indicating the yearly dredging work. The average of these figures gives the average dredging work, but with the standard deviation, one can also calculate the chance that one has to do more dredging work during a year (because of bad weather).

The results of the simulations are presented as numbers, but can be made visual with contour maps and three-dimensional plots.
As an example of the three-dimensional plots, in figure 5 a plot is given of the detailed wave penetration model. The hydromorphological model will of course cover a smaller area, but will be much more detailed.

10. CONCLUSIONS

From the studies done until now and from the field measurements done in November 1982 (see vol 1-5 of this report) it follows that it is possible to make an operational mathematical model of good quality to simulate the morphology of the Douro bar. Special attention has to be paid to the rather frequent bottom changes in this area.

Fortunately, the method of flow calculation and wave influence can be simplified. If these calculations could not be simplified the running cost of the model would be extremely high (ten times more than the Tagus model) because of the small mesh-size and frequent bottom changes.

In this volume a model is described, which is able to calculate bottom changes in a stochastical way. Also a method is given to calibrate the model. For calibration, a statistical interpretation of the old hydrographic charts is required. It is further advisable to do a short additional measuring campaign in April, in order to test the hypothesis of flow during low river discharge and sediment transport during a relatively calm sea state.

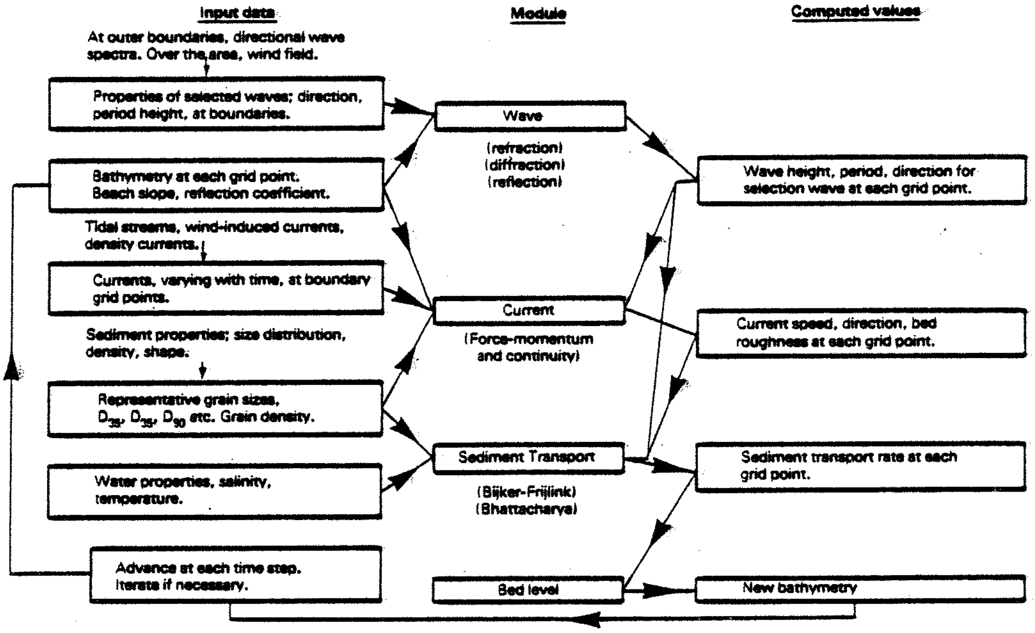


FIGURE 1: *MODULAR ARRANGEMENTS OF COASTAL MODELS.*

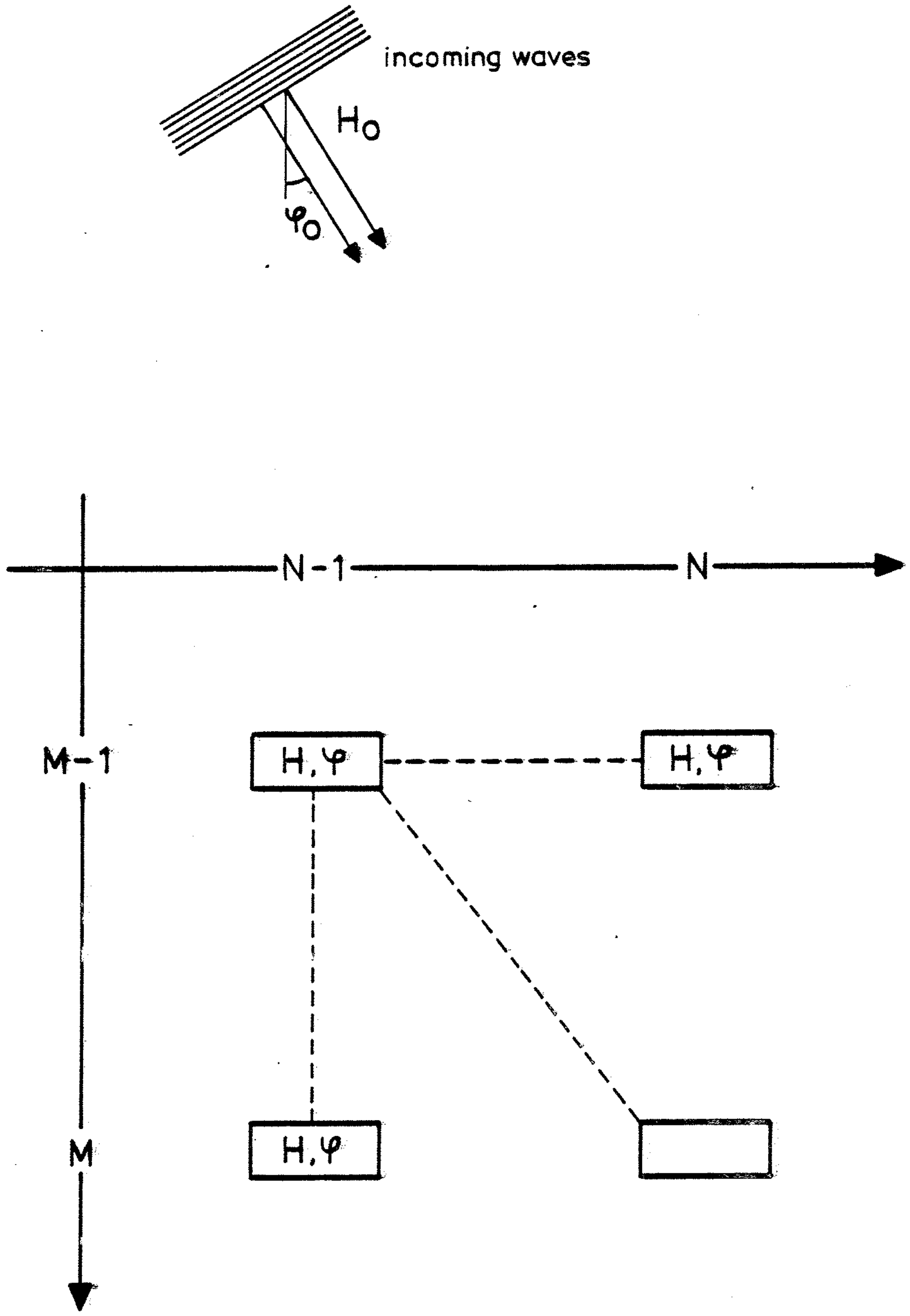


FIGURE 2: *SIMPLIFIED WAVE PENETRATION CALCULATION.*

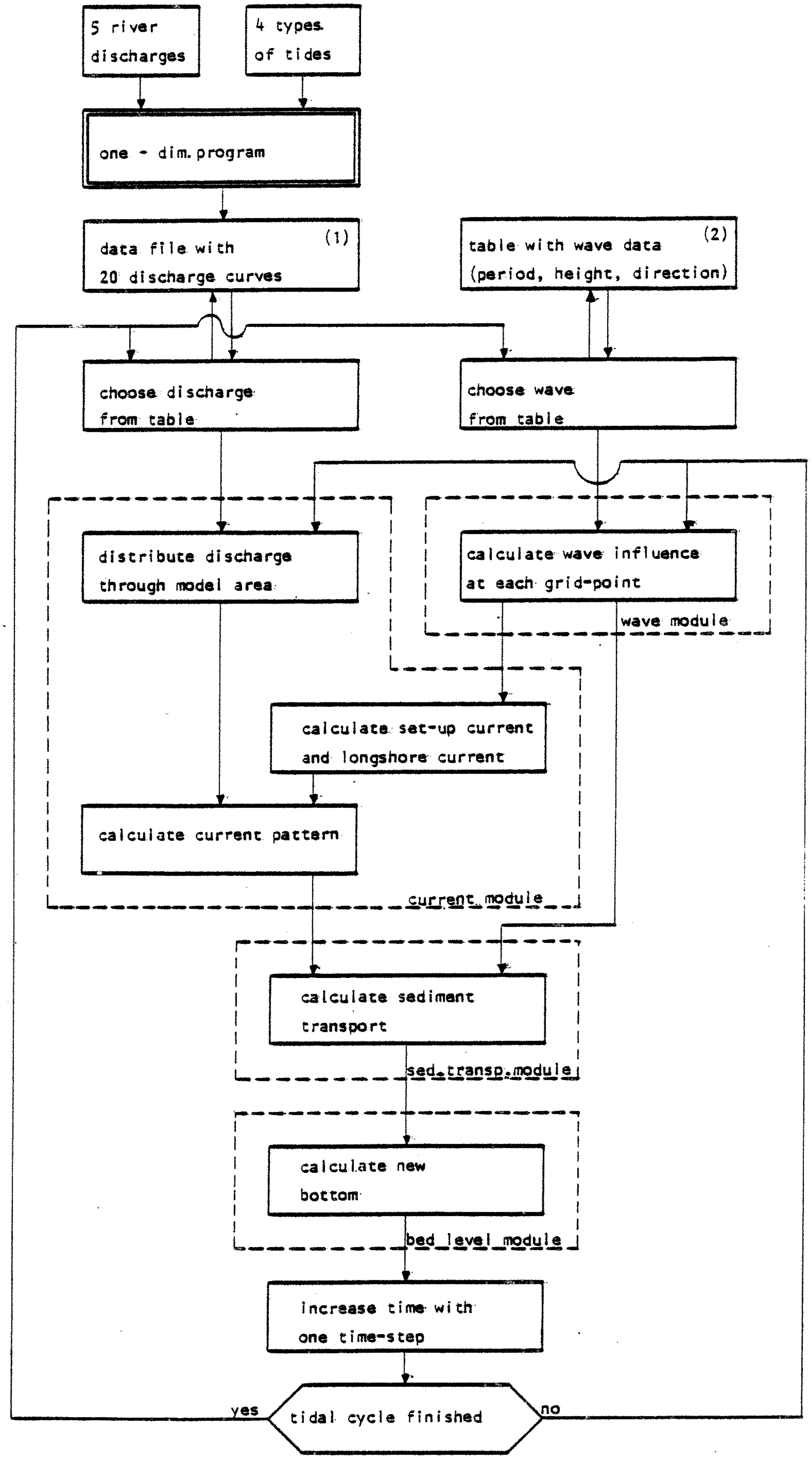


FIGURE 3: *FLOW-CHART OF THE DOURO HYDROMORPHOLOGICAL MODEL.*

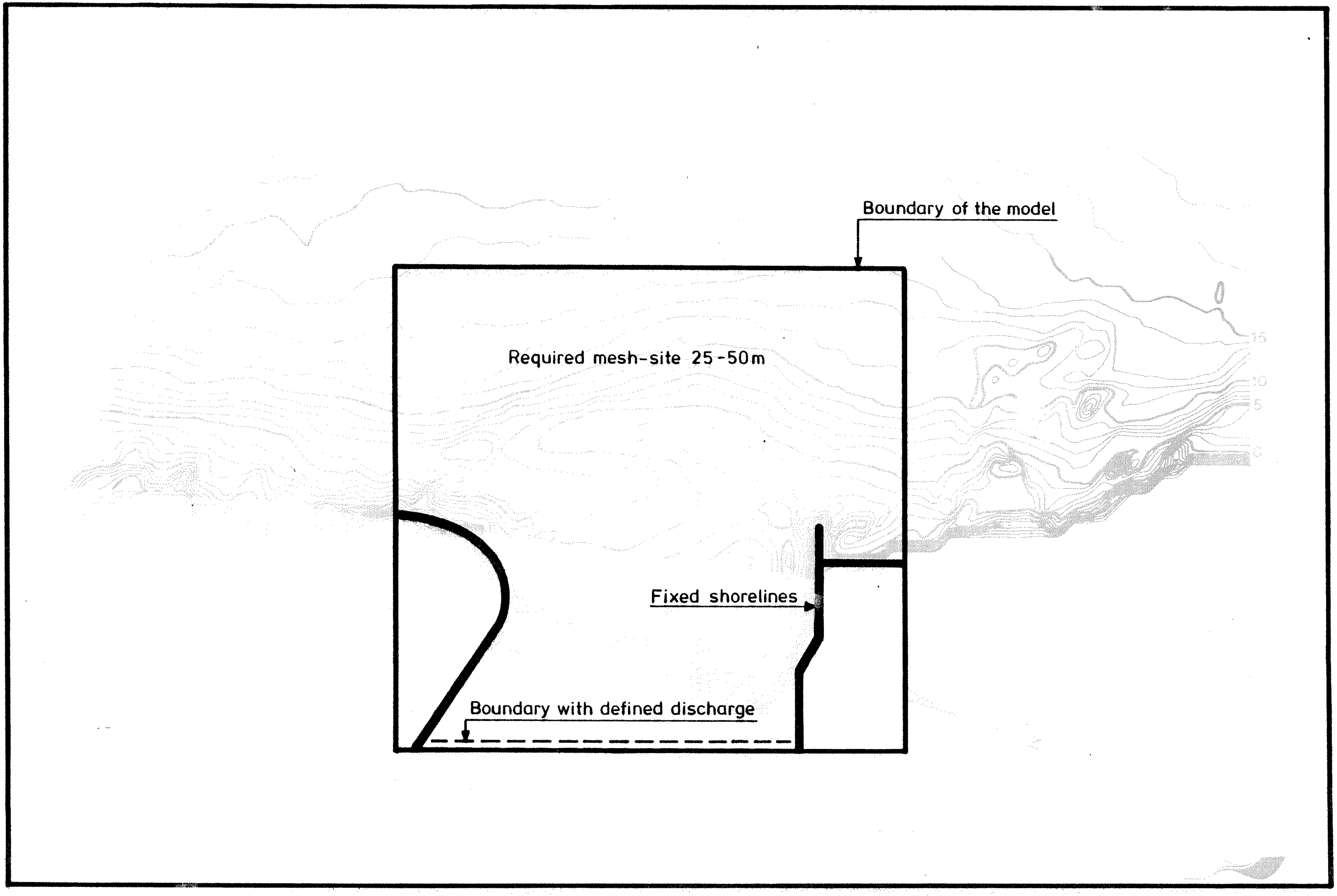


FIGURE 4: LOCATION OF THE MODEL.