Guidelines for the use of computational models in coastal and estuarial studies

Flow and sediment transport models

A J Cooper
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Report SR 456
July 1996

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Summary

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Computational models are frequently used to assess the impact of engineering works in coastal and estuarial waters. With the increasing use of computational hydraulic software by civil engineers and scientists not involved in model development it is essential that comprehensive guidelines on the limitations and assumptions of such models are widely available. In selecting a model for a particular application it is important that the engineer be aware of the range of models available, the processes they can represent, the underlying assumptions on which the models are based, their limitations and the solution method used. In order to address this issue, HR Wallingford was commissioned in 1993 by DOE to develop guidelines for engineers on the selection and application of computational models for estuarial engineering studies. The guidelines incorporate flow and sediment transport models and wave transformation and disturbance models.

In the first stage of this project, completed in March 1994, a review of computational models in engineering use for hydraulic studies in the UK was made. This review covered models representing wave transformation, harbour wave disturbance, flow, sediment transport and ship manoeuvring, movement and mooring, (Reference 1). During this first stage it became evident from industry contacts that very few ship manoeuvring and movement models are used by non-specialists and that many such models are still under development. As a consequence, the production of guidelines for such models would be premature and so they were not included in the second stage of the project.

The guidelines for the computational models produced in the second stage of this project are based on the results obtained in part from applying computational models to a series of benchmark tests and also from many years experience at HR Wallingford of this type of modelling for engineering studies. This report contains the guidelines for flow and sediment transport models, together with details of the flow model benchmark tests and results. The guidelines for wave transformation and wave disturbance models are presented in the companion report, Reference 2.

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1 Introduction

1.1 Background

Computational models are frequently used to assess the impact of engineering works in coastal and estuarial waters. With the increasing use of computational hydraulic software by civil engineers and scientists not involved in model development, it is essential that comprehensive guidelines on the limitations and assumptions of such models are widely available. In selecting a model for a particular application it is important that the engineer be aware of the range of models available, the processes they can represent, the underlying assumptions on which the models are based, their limitations and the solution method used. In order to address this issue, HR Wallingford was commissioned in 1993 by the DOE to develop guidelines for engineers on the selection and application of computational models for estuarial engineering studies. The guidelines will incorporate flow and sediment transport models and wave transformation and disturbance models.

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1.2 Aims

The aim of the present work is to relate the situations in which the use of a computational flow or sediment transport model may be contemplated to the various forms of model available. A further aim is to provide guidance as to the value of the results that may be obtained in such situations using the different models. This question relates in principle to the kind of model (for example a 1D flow model or a full 3D hydrodynamic model), the behaviour of particular examples of each different kind of model and the modelling approach to take in order to get the best results from the chosen model.

The present report concerns itself primarily with the first issue so that an engineer wishing to use a computational flow model in a coastal or estuarial study will be provided with guidance on the class of model to use. Some preference between different individual models may also appear, depending on whether a particular model has the features required for the study, for example, modules to simulate a required pollutant. It is not intended to differentiate here between different professionally produced computational model products, they are considered to be generally capable of carrying out the model simulations they are advertised as being able to do. Reference to a standard validation document for a model (prepared according to guidelines agreed by European Hydraulic Laboratories, Reference 3) may also give a valuable insight into a model's capabilities and track record.

1.3 Methodology

The approach adopted for the benchmark testing of flow models was to first of all identify a number of real situations, to which flow models can be applied. The selected benchmark tests are based either on situations described in the literature or are based on studies carried out at HR Wallingford. These test cases were then used to illustrate which kinds of model (for example a 1D flow model or a full 3D hydrodynamic model) are most appropriate for certain real situations.

For sediment transport predictions the choice of model is very dependent on the characteristics of the site and of the sediment itself. Sediment transport models are less well established than flow models and there is much greater uncertainty associated with their use. As a consequence there are very few well established test cases, and benchmark test data is not available for such tests for the full range of situations. Therefore the approach used for sediment transport models is to formulate guidelines based on the physics of the particular problems to be solved.

1.4 Organisation of the report

The remainder of the report is organised as follows. The types of computational model considered are described in Chapters 2 and 3. The guidelines for the application of flow and sediment transport models are presented in Chapters 4 and 5 respectively. The selection of benchmark test cases is described in Chapter 6 and the results discussed in Chapter 7. Finally, conclusions from this study are given in Chapter 8.

2 *Guidelines for computational flow modelling*

2.1 Types of computational flow model

Types of flow model were reviewed in Reference 1 and the following main types identified:

- fully 3D flow models
- hydrostatic pressure 3D flow models
- Boussinesq 2DH models
- hydrostatic pressure 2DH models
- 2D 2 layer models
- hydrostatic 2DV models
- 1D models

Further details of the different kinds of model are provided in Reference 1.

Clearly in choosing to use a model it is necessary to bear in mind the need to reproduce the required phenomena, but also to realise that a fully 3D model may, in many cases, require a much larger computer and much longer runtimes than a 1D model, with the other models taking generally an intermediate amount of computing resources. This of course means that longer runtimes are feasible using the lower dimension models (eg years) whereas the 3D models may be used for very short term modelling of a small area of complex flow.

The most commonly applied form of flow model is the 2DH model that solves the shallow water equations. Part of the purpose of this study is to establish when such a model is or is not the most appropriate for a particular task.

Some examples of commercially available models are given below. The list is not intended to be fully comprehensive, but to provide an illustration of the models that are available.

2.1.1 Fully 3D flow models

SSIIM (Olsen, Reference 4)
PHOENICS (CHAM, Reference 5)
CFX (previously FLOW3D ,CFDS, Reference 6)
FLUENT (Reference 7)
SYSTEM3 (DHI, Reference 8)
FLOW3D (FLOWSCIENCE, Reference 9)

Fully 3D models have so far rarely been applied to estuary and coastal modelling applications, their original starting point is usually industrial flows (without a free surface). Even without free surface treatment they may be of value, for example to simulate the flow over a dredged channel where the flow complexity is mainly near to the bed. Some models, for example CFX, have been converted to 2DH hydrostatic pressure codes to carry out coastal studies.

2.1.2 Hydrostatic pressure 2DH models

TELEMAC2D (LNH Paris, Reference 10)
TIDEFLOW2D (HR Wallingford, Reference 11)
TRISULA (Delft Hydraulics, Reference 12)
MIKE21 (DHI, Reference 13)
DIVAST (Bradford University, Reference 14)

At present, 2DH models are the most popular, because they give a good description of the depth-mean flow. Grid resolution in 2DH models can be achieved by using a patched grid (TIDEFLOW, DIVAST), a curvilinear orthogonal grid (DIVAST, TRISULA) or a finite element grid (TELEMAC). Figure 1 shows examples of the different types of grid.

2.1.3 Hydrostatic 2DV models

TIDEFLOW2DV (HR Wallingford, Reference 15)

While still not extensively used, the layered model may be of much value in simulating saline intrusion and sediment transport in narrow estuaries. Applications to date include the tidal Thames, Southampton Water and the Tees estuary.

2.1.4 Boussinesq models

MIKE21 (DHI Reference 13)

Boussinesq models are mainly applied to modelling waves in harbours rather than to tidal flows.

2.1.5 Hydrostatic pressure 3D models

TELEMAC3D (LNH Paris, Reference 16)
TIDEFLOW3D (HR Wallingford, Reference 17)
TRISULA (Delft Hydraulics, Reference 12)
TRIVAST (Bradford University, Reference 18)
RMA10 (King, Reference 19)
ADCIRC (Vicksburg,US Army Corps of Engineering, Reference 20)

Hydrostatic 3D models are very much used in oceanographic applications (eg North Sea). The existing models differ in terms of their discretisation of the governing equations. In the horizontal domain, the grid may be represented using finite differences (TIDEFLOW3D, TRIVAST), with a curvilinear orthogonal grid (TRISULA), or finite elements (TELEMAC3D, RMA10, ADCIRC). In the vertical the grid can be horizontal flat planes (TIDEFLOW3D, TRIVAST) or sigma coordinates in which the layers occupy a specified proportion of the depth (TELEMAC3D, TRISULA), Figure 2 shows examples of these approaches. Another method is to use a spectral expansion where the variation in the vertical is represented as a sum of basis functions over the whole depth (Reference 21). This method does not usually go well with modelling the transport of a density field. Turbulence models may also vary but a mixing length theory is usually available.

2.1.6 1D models

ISIS (HR/Halcrow)
MIKE11 (DHI)

1D models are very extensively used in narrow estuaries and rivers where density current effects and lateral variations need not be included.

2.2 Comments on the uses of computational flow models

At present, flow modelling studies of coasts and estuaries make much more use of the hydrostatic pressure 2DH models than of any other kind. This is, on the one hand, because these models are very often adequate tools for the flow simulation required, and, on the other hand, because 3D models have not been available at the time or have been very expensive to use.

It is important to realise that, depending on the use to which the model is to be put, exactly the same body of water may be well simulated with a 2DH model or may require a 3D model. If it is only the depth mean current and the water level that is required then a depth-averaged model will almost always be satisfactory. However if, for example, the sediment exchange between an estuary and a tidal basin is required then a 3D model may be necessary. Similarly the depth mean current and water level will be adequately modelled with a 2DH model in a coastal area with wind action, but the transport of pollutants in such an area may only be accurately simulated by using a 3D flow model. Many similar comments apply to 1D models of estuaries and 2DV models. The 2DV model can represent the process of saline intrusion that cannot be adequately simulated in a 1D model.

It appears therefore that guidelines must start from the use to which the model is to be put and not just the characteristics of the water body, in order to establish the class of model that must be applied.

One particularly important class of applications of flow models is that of sediment modelling. The choice of sediment model that is to be used will have an influence on the choice of flow model. Normally a 2D sediment transport model will require input from a 2D flow model and so on. Exceptions include the use of a 2D flow model to drive a single point sediment transport model which takes as input the model depth-integrated currents, to predict the behaviour of sediment on the bed over a long time including processes of consolidation etc. Also a 2D flow model can, under certain situations, provide input to a 3D model of sediment transport. This applies if flow stratification is not too important but sediment stratification is important. Selection of models for sediment transport modelling is described in more detail below in Chapter 3.

2.3 Guidelines for the selection of computational flow models

An important distinction in flow modelling is between models for which the sole output is the fluid flow (for example compilation of a tidal atlas, storm generated flows, input to navigation studies) and those where the transport of some quantity or quality (heat, sediment, pollution) is also required. While the former type of modelling is usually satisfactorily modelled with a depth-integrated 2DH model if depth mean current and water level is the required output, the transport model will often require a 3D flow model. If surface currents are required for input to simulation of navigation of vessels then a 3D model may sometimes be necessary. Heatflow modelling in particular almost always requires a 3D model as the heat causes stratification of the water column and the buoyancy causes spreading of the heated plume.

In the following we identify several typical situations in which flow models are required and advise on the most appropriate model to be used.

2.3.1 Pollutant transport in an estuary

If the estuary is narrow enough that the interest is only in how far along the estuary the pollutant has travelled and not the distribution across the estuary then a 1D flow model will often be satisfactory. However if the estuary is stratified then it may be important to use a 2DV model as the pollution may not mix into the upper layer (for example, if it is discharged into the lower layer). In this case the 1D model would overpredict the dilution of the effluent as it assumes the pollutant is completely mixed across the cross section. If it is required to know how the pollutant is distibuted across the estuary width then a 2DH model is required and if the estuary is also stratified then a 3D or 2D2L model is required. For this purpose one would normally use a hydrostatic flow model as hydrostatic pressure deviations in estuary modelling are usually very small.

Note that if it is required for any reason to model the rise of the pollutant from a discharge at the bed then either an integral jet model or a full hydrodynamic 3D flow model with turbulence and buoyancy effects is required.

2.3.2 Flow over a trench or channel

The flow over a channel dug into the bed may create an eddy at the bed confined within the channel. It may be considered important to predict the rate of sediment infill in the channel. For this purpose a 3D hydrodynamic model appears to be necessary as a 3D hydrostatic model cannot reliably predict such flow features. Normally such a model would not be applied to model the whole estuary or coastal area but be used in addition to a 2DH model.

2.3.3 *Effect of engineering works on sediment transport in an estuary*

In general there is a strong current variation across even a narrow estuary that leads to different sediment behaviour. Thus there may be muddy banks at the sides of an estuary but sandy channels in the middle. For this reason a 1D approach may not be appropriate except in the more canalised reaches of an estuary where such effects are small. A 2DH approach is most often used. If there is important saline stratification then it may be necessary to use a 3D or 2D2L hydrostatic model. Under some circumstances it may be useful in narrow estuaries to use a 2DV approach. Because these models are rather quick to run, a long period (spring-neap cycle) can readily be run and the model also includes the gravitational circulation effect so that the turbidity maximum can be modelled.

A more complex phenomenon that does require a 3D model for simulation is the lateral density driven circulation that can exist in some estuaries, especially on the flood, that causes surface convergence of the flow (as in the Conwy estuary, see Section 5.4).

2.3.4 *Pollutant transport in a coastal zone*

Normally a 2DH flow model is used and it may work very well. In order to model the vertical spreading of the pollutant field it may be useful to use the 2DH flow field to drive a random walk pollutant model that includes spreading of the pollutant in the vertical. If there is no important stratification then the 3D random walk model can be run with input from a 2DH flow model, by making some assumption as to the vertical profile of the current. Where stratification does occur (and sometimes in the presence of a windfield even without stratification) it may be necessary to use a 3D flow model, as in the case of St Andrews Bay (Reference 22). Again it is possible that the pollutant field fails to reach the surface in stratified conditions and the model needs to take this into account. The comments about a plume rise model in Section 2.3.1 above apply also in this case.

2.3.5 *Siltation and flushing in a marina, harbour or basin*

Very often a 2DH flow model is used for these purposes. This is satisfactory for many purposes but care is needed if the salinity varies during the tide. Because the flushing of the harbour may be low the salinity in the harbour can lag behind that outside leaving a strong salinity gradient even though the estuary outside of the harbour shows no sign of stratification. The salinity difference between inside and outside the harbour can give rise to a much larger exchange of water than that due to the tidal current alone, which enhances the flushing and may increase the rate of siltation. Should this be the case then a model including vertical variation of velocity and salinity is required.

Even without any salinity variation if there is a large eddy formed in the harbour mouth then a 3D flow model may be required in order to simulate the secondary flow that may be important, for example, in causing sediment to enter the harbour at the bed.

In some circumstances where high mud concentrations are experienced it may be necessary to incorporate a model of fluid mud flow (see Section 3.2.6).

2.3.6 *Flows induced by storm surges*

Normally the main requirement of a storm surge study is to predict the water level. This should be accurately achieved by a depth integrated 2DH flow model. Only if it is required also to model the current field (which may show much larger currents near to the surface due to wind action) is a 3D model needed.

2.3.7 *Long term water quality modelling (months or years)*

Long term modelling requires the use of comparatively few model cells in order to make runtimes acceptable, especially as there may be a large number of water quality variables (typically 10-20). Special 3D flow models have been created for this purpose using comparatively low resolution in the horizontal but with several layers in the vertical because the water quality parameters are affected by processes, such as light penetration, that can give rise to important through-depth variations. 2DV models which also have rather few cells are also very useful for long-term simulations where cross-estuary variations are not important.

2.3.8 *Flows through structures*

Flows through structures can generally be treated in two possible ways; either by specifying some resistance coefficient or discharge/head relationship for the structure or by actually modelling the flow through a structure. In the former case the enhanced resistance or discharge/head relationship can be included in a 2DH flow model or a 3D hydrostatic flow model (see Reference 23).

If the flow through the structure is to be modelled in detail then a 2DH model might be used for flow through a vertical piled structure or a fully 3D model for flow through a sluicegate or similar. Such models may need good resolution, a turbulence model and low numerical error. Permeable breakwaters can be modelled as a degree of blockage in a standard model or a groundwater flow model may be used if more detail is required.

2.3.9 *Floods*

Normally in floods it is the water level and its rate of rise and fall that is required. Usually for this purpose a 1D flow model including flood plain volume or a 2DH model is satisfactory. For the simulation of the current speeds during a flood event a 3D flow model may prove to be essential.

2.3.10 *Dispersion of cooling water*

Unlike most pollutants heat has an active effect on the flow by altering the density of water. For a power station cooling water discharge, unless it is very small, a 3D hydrostatic modelling approach is called for as the cooling water usually occupies only the top half of the water column. Sometimes a discharge at the bed gives rise to a phenomenon called "instability" where the plume may divide into two plumes while it rises to the surface. This phenomenon can only be successfully modelled using a fully 3D flow model with turbulence model and buoyancy included. See also Section 2.3.13.

2.3.11 *Flows in bends*

In estuary bends there may be secondary flows with the current vectors at the surface tending to point more to the outside of the bend and those at depth pointing more to the middle of the bend. This implies a helical pattern of streamlines. Such flows may have important implications for pollutant transport (tending to spread it over the cross section) and for sediment transport (tending to move it to the inside of the bend). Some form of 3D flow model is needed to reproduce such secondary flows.

2.3.12 *Tidal eddies*

Eddies tend to form behind headlands and manmade structures. They can be simulated in 2DH flow models or 3D models and care is needed in the choice of the viscosity value or turbulence model as well as in the choice of wall condition (free slip, no slip, friction coefficient). If there is too much viscosity then the eddy may not exist at all or it may be too feeble. Sedimentation in eddies is caused by a secondary flow at the bed carrying sediment towards the centre (as in tea leaves in a cup). This process requires modelling in 3D. Also possible is that von Karman vortex streets may be created by the eddies shedding from behind structures such a bridge piers or islands. To obtain such shedding eddies more care is required in the selection of turbulence model in a 2D or 3D model, usually a very low viscosity must be used (Reference 24).

2.3.13 *Intakes*

Flows in the vicinity of intakes (and many other structures), if they are to be modelled in detail, require the use of a fully 3D flow model. A fully 3D model may also be needed to model the selective withdrawal that may occur with an intake located at the bed underneath a stratified water column.

2.3.14 *Modelling very large areas*

When modelling very large areas of sea it may be the case that the density of the water has a large effect on the flow (called "geostrophy"). This causes a flow around a sea basin in an anticlockwise direction in the northern hemisphere, such as occurs for example in the North Sea and the Adriatic. This kind of flow is well represented by 3D hydrostatic models, including density effects and Coriolis force, which have been used for many years for oceanographic applications (where pressures are accurately hydrostatic). See Reference 25 for further details.

2.3.15 *Deltas and complex channel systems*

These are usually modelled with 1D flow models that include the capability to model loops and multiple channels (Reference 26). If salinity intrusion is of interest then a 2DV model could be used.

2.3.16 *Effects of sea level rise*

Studies of sea level rise (Reference 27) usually make use of 2DH flow models as the aim is to study the effect of the rise of sea level on the tidal level and the tidal currents in the estuary and to see whether the effect is likely to change the existing balance of flood and ebb currents of the estuary.

2.3.17 *Impact of the sediment on flow*

The existence of "lutoclines" or "turboclines" - places where there are very strong vertical gradients of the sediment concentration can have a significant effect on the flow as the water bodies containing higher and lower sediment concentrations have different density (Reference 28). In such a case modelling may require a 3D model including the transport and density of the sediment and its feedback on the flow.

2.3.18 Rip currents and breaking-wave induced flows

These phenomena require a wave model to be used to specify the breaking wave stresses that drive the rip currents. Normally the stresses are input to a 2DH flow model in which rip currents may occur adjacent to breakwaters although some recent work has involved entering the stresses into a 3D hydrostatic flow model in order to simulate the returning underflow in the surf zone.

2.4 Advice on use of 2DH models for tidal flow problems

Some general advice on the use of 2DH flow models, based on 20 years experience of their use at HR are included here.

2.4.1 Selection of area to cover

This depends to some extent on data availablity. For estuaries it is often best to model the whole estuary either using greater resolution in the area of interest or having a smaller separate submodel. For coastal regions it is often best to use an offshore no flow boundary along the direction of the dominant tidal current (if it is known). If the current is complex near to the shore then large model cells may be useful to take the boundary to where the flow is more shore parallel.

It is often best not to place a boundary at a sharp point in the coastline, such as a headland, where an eddy may be expected. In this case it may be worthwhile to place the boundary beyond the sharp point.

Even if data is only available at certain points, it may still be possible to treat these as internal points and apply the observed values (or computed values) at the model boundary and then compare these at the observed point.

It is generally best to locate boundaries at physical solid boundaries where possible (eg do not model half of an estuary or strait, with large elements one could model all the estuary for little extra cost).

An existing model of a larger area can supply boundary conditions (see below) but can also define location of eddies, offshore streamlines etc. It is worth drawing the proposed model on top of the existing model to see whether it looks appropriate.

It is often useful to set-up and run a simple model before a survey campaign takes place as this gives a better idea what data are required. This can avoid the collection of data which cannot subsequently be used and also avoid the possibility of collecting insufficient data. In particular placing current meters in areas of very weak current or near to eddies or in regions of strong shear should be avoided.

2.4.2 Resolution required

Clearly the hydraulic flow must be resolved. This usually requires several (5 or more) cells across any channel and several cells around any island. Resolution of the eddies behind an island or structure requires several cells. Away from the coast and any features of interest larger cells can in general be used.

If a plume is to be modelled using an advection-diffusion model then the plume needs to be resolved by the grid even if the grid is then smaller than necessary to resolve the hydrodynamic flow. A random walk plume model, on the other hand, can overcome this need for a finer grid by having its own finer grid that it uses for output.

Where strong bed gradients occur (for example at the continental shelf edge) then it is best to have a change of a factor of less than two in the water depth at two nodes of the same element. This may require some increase of resolution in the sharp gradient area.

2.4.3 Selection of boundary conditions

The selection of boundary conditions may depend on data availability (use a level boundary where data is available etc). In many places the level is very nearly constant so may be applied at some distance from the observed position (sometimes at the far end of the model).

Estuary models often just use level at the seaward end and discharge at the landward end. Occasionally a level may be applied at the landward end but it may not generate such reliable results.

In coastal areas it may not be a good idea to apply the water level at both ends if they are not very far apart. If the level is quite different then it may work but the user should beware that the flow through the model will be enormously affected if either set of levels is not accurate. To do this the levels must be measured simultaneously on the same tide. It is usually better to specify the water level at one end and velocity or discharge at the other. The velocity may be set constant along the boundary or vary as the square root of the depth. The user should be careful as in reality there will be times of the tide when the water is going in opposite directions at the on and offshore ends.

A valuable approach to boundary specification especially if a larger area model exists is to use a linear combination of water level and current speed at the boundary. This gives a "radiating", weakly reflecting or soft boundary condition that tends to allow waves generated in the model domain to leave the model.

3 Guidelines for sediment transport models

3.1 Types of sediment transport model

Whilst the flows that occur in estuaries and coastal situations are frequently very repetitive, for example with similar current speeds on each spring tide, the rate of sediment transport may be a great deal more variable. It depends not only on the currents but also on the waves present, other features such as wind and human activity (including navigation and dredging) and most importantly the sediment properties. For these reasons sediment transport modelling prediction is as yet at a much lower level of certainty than the modelling of waves and flows.

Sediment transport models can be classified like flow models according to dimensionality, for example:

- 3D
- 2DH
- 2DV
- 2D 2 layer
- 1D
- Point models
- Particle (Lagrangian) models

However, for the prediction of sediment transport it is not only important to understand the hydrodynamics (which are driving the sediment transport) but it is also important to adequately represent the physics of the sediment transport mechanism. Inaccuracies in the representation of the hydrodynamics will lead to uncertainties in the magnitude of the sediment transport and identification of the most important sediment transport mechanisms. However, inadequate representation of the physical properties of the sediment itself may lead to greater uncertainties.

Much research work is being undertaken to examine the important physical processes and sediment properties which control the different sediment transport mechanisms. In the 1980's much of this work was undertaken in laboratory settings. More recently it has been accepted that in-situ measurements have to be made to ensure that the properties of natural, undisturbed, sediments are being examined. Some of these in-situ measurements are relatively straightforward, others require specialist instrumentation which tends to be operated by only a few organisations. In the absence of detailed information on the sediment properties at a particular site, it is possible to make useful predictions of sediment transport by applying some sensible assumptions on the nature and properties of the sediment and to use this as a basis for a series of sensitivity tests. Indeed this is an approach which can help to identify the requirements for a field monitoring exercise. However, application of appropriate assumptions needs to be undertaken with care. Therefore sediment transport models rather more than flow and wave models are only useful engineering tools in experienced hands. In such hands they can usefully be applied to optimise the design of engineering works and to quantify (within certain limits) the likely rates of accretion and erosion.

In order to focus on the requirement of using a sediment transport model that represents the required mechanisms it is more useful to group sediment transport models depending on the processes represented, in particular:

- bedload (sand) models. Saturated and unsaturated
- suspended load (mud) models
- models including formation, flow and entrainment of fluid mud
- models with mixtures of sandy and muddy sediments
- models which represent the evolution of the muddy bed at a single location
- models which represent the dispersion of a plume of sediment at concentrations above background
- models which represent the long term dispersion of material placed on the sea bed.
- models which can predict the long term morphological evolution of an area

These model types have been discussed in Chapter 5 of Reference 1. Selection of the appropriate type of model will depend upon a thorough understanding of the important sediment transport mechanisms occurring in the area to be modelled. It is not the intention within this report to discuss the means to identify the important sediment transport processes in detail. References 29 and 30 provide background to the important processes occurring.

Most of the commercially available computational flow models are available with sediment transport modules which can be used to examine many of the different types of problem that are of interest. However, in some cases, for example the prediction of the movement of fluid mud, only specialist models presently exist. Unfortunately model availability does not reflect the complexity of the problems to which the model can be applied. Examples of commercially available sediment transport models are not given in this report.

3.2 Guidelines for the use of sediment transport models

For sediment transport studies there are three phases:

i) assessment,
ii) modelling and
iii) field investigation

The assessment phase should always be undertaken first. Modelling and field investigations may or may not be required. They may be required together or one after the other. Field investigations may be necessary prior to the sediment transport modelling, alternatively pilot modelling may be required in order to identify the key processes which will require specialist field measurements against which to validate the sediment transport modelling. The assessment phase of a study should identify the requirements.

In the following sections some guidance is provided on the use of sediment transport modelling techniques for some of the different types of estuarial and coastal problems. The guidance is not exhaustive or generic and its purpose is to identify some of the important issues and factors to consider. It is important to recognise that it is the particular problem to be solved that determines the approach to be taken.

It is not possible in this chapter to describe in full the approach to be taken for each of the generic problem types described below. For sedimentation in harbours and marinas recently a study has been completed which does address the generic problem (see Reference 31). However, for the other areas described below there is no real guidance available on determining the important mechanisms. It is here that experience is required in identification of mechanisms and appropriately applying the various sediment transport modelling techniques that are available.

In the following several typical situations are identified where sediment transport predictions are required. Advice is given on the type of model which can be used based on many years experience at HR Wallingford of many years of this type of modelling.

3.2.1 *Effect of engineering works on sediment transport in an estuary*

Consideration should be given to both the hydrodynamic regime and the sediment regime of the estuary in an attempt to identify the dominant processes that will be responsible for evolution of the estuary following the engineering works. Therefore choice of appropriate hydrodynamic models is important.

If it can be established that the estuary works will have only a local impact then it will be adequate to limit consideration only to the vicinity of the works.

Alternatively it may be necessary to consider the engineering works in the context of the whole estuary system. This is an approach which is currently being favoured by those with a responsibility for estuary management and conservation. A number of approaches presently exist for considering the estuary wide impact of the works. These include placing the impact of the works in the context of the natural/historical variability of the estuary (Reference 32) and examining the impact of the works for a wide range of hydrodynamic conditions that can occur in the region (tides, storms, floods etc) and determining the envelope within which the impact of the works lies.

If it is necessary to consider the long term impact of the works on the estuary as a whole, then it may be necessary to adopt regime (otherwise known as "top-down" or "estuary system") approaches to the impact. References 33 and 34 provide a background to this approach. This type of approach in isolation will not yield the timescale for change but will identify the final equilibrium form that the estuary will adopt. For this type of approach it is necessary to assume that the estuary is in some form of equilibrium with the hydrodynamic, geological and sediment regimes.

Long term process based morphological modelling (otherwise known as "bottom-up") is still in early stages of development for use in estuarine environments although some applications have been successfully undertaken in tidally dominated estuaries (see for example Reference 35). Process based approaches to impact studies presently have the advantage that the same models set up for the design of the engineering works may also be appropriate for considering the longer term impacts of the development. However, they do suffer at present from very long simulation times. In many cases this makes them impractical.

Hybrid modelling (a combination of the "top-down" and "bottom-up" approaches) is seen as the way forward with respect to provision of a tool for estuary management (Reference 27). Examples of the successful application of this type of approach are presented in Reference 34.

Simple models are required to model long term. To date only 1 D flow models have been used as part of the hybrid approach and 2 D flow models are typically used as the basis of process based morphological modelling.

3.2.2 *Effect of engineering works on sand transport on the coast*

Where structures extend from the shore through the surf zone they will interrupt the natural drift of sand along the foreshore. Wave action is the dominant effect here so that a priority is to have a representative local wave climate. The wave climate can be used as input to one-line models such as HR's BEACHPLAN model. Many different relationships exist for calculation of littoral drift (see Reference 30). The relationship chosen should be calibrated for the specific application, against the observed evolution of the coastline.

In some cases, such as the development of coastal ports and marinas, it is necessary to determine the by-passing of sand around the structure. Currents may be the dominant factor in deeper water affecting the transport. In these cases it will be necessary to use a combination of wave and flow models for representative conditions to determine the bypassing over the period of interest. The results can then be fed back into the one-line model. For this type of modelling it is necessary to consider the storm events carefully as they will probably account for most bypassing and they may also be associated with flow patterns that are not tidally driven.

3.2.3 *Sand transport into a trench or channel*

In the following sections it is assumed that the sediment transport mechanism is one of wave and current action mobilising sandy bed material and then the current transports material into the trench/channel. Note that ideally the sand transport relationship that is to be used will be validated against specialist field measurements, but in the absence of this an appropriate relationship from the literature can be assumed (see Reference 30).

Hydrodynamics

It will be necessary to have information on both wave and flow conditions in the vicinity of the trench/channel. Depending upon the nature of the problem it may also be necessary to resolve the impact of the trench/channel on the local wave and flow patterns. Often it will be important to consider this for the waves so as to identify the impact on the adjacent coastline.

Modelling sand transport at fixed points

The simplest approach is to assume saturated sand transport and to calculate the potential sand transport at locations on either side of the trench/channel and in the trench/channel base. This may be repeated at different locations along the length of the trench/channel. The differences between the sand transport at the different locations can be used to calculate the potential infill. Note that with this approach it is assumed that there is instantaneous settling of sand from suspension when the transport rate decreases.

It is unlikely that either the wave or flow conditions are uniform so it may be necessary to establish monthly, seasonal or annual climates of sand transport at the different locations and thereby determine the infill over a fixed period. This probabilistic approach may require sensitivity tests to determine the significance of variations in wave activity at different water levels. The flow model may need to be run for different tidal ranges and possibly for wind and wave induced flows as well.

Modelling sand transport with a section model

An alterative approach is to use the probabilistic approach described above to identify the most important hydrodynamic conditions (in terms of sand transport) and then to use these as the input to a dynamic section model (for example the HR INFILL model, Reference 36). The advantage of this approach is that the assumption of instantaneous settling does not have to be made. The model can be used to investigate the impacts of changing the trench/channel profile. This type of model can also be used to allow for the feedback of bed evolution on the hydrodynamics. A disadvantage of this type of model is that it must be assumed that along channel variations in the trench/channel profile are small.

Modelling sand transport with a 2DH model

From a probabilistic analysis of wave and tidal climates at the location of interest it may be possible to identify a small number of combinations of tide type and wave condition with which to represent the sediment transport over the period of interest (Reference 37). These conditions can then be run in the flow and wave models and the predicted infill rates summed according to the appropriate weighting factors. The key factor in this method is determining the representative hydrodynamic conditions and weighting factors with which to run the 2DH sediment module. This approach will not necessarily provide a better answer than either of the preceding approaches.

Modelling sand transport with a morphological model

In this approach an area model which allows for feeding back the impact of the bed evolution on the hydrodynamics is applied (Reference 38). Again the key factor is in determining the representative hydrodynamic conditions and weighting factors. The other important aspect, which affects the practicality of the morphological modelling approach is the frequency with which the bed will require updating (Reference 39).

3.2.4 *Mud transport into a trench/channel*

This is a more complicated problem than for sand infill and will require careful identification of the important mechanisms which could contribute to trench/channel infill. Consideration should be given to:

- natural variability of suspended sediment concentrations,
- variability of suspended sediment concentrations due to construction activities,
- correlation of storm and flood events with suspended sediment concentrations,
- presence of near bed high concentration layers
- the possibility of wave action mobilising or fluidising mud on nearby banks
- the erosion and deposition thresholds for the mud
- the rates of consolidation of the mud
- the settling properties of the mud
- possible effects of stratified flow
- slumping of channel/trench sideslopes

Having ascertained through assessment which are likely to be the main mechanisms for infill then appropriate modelling and measurement methodologies can be developed.

3.2.5 *Siltation in a marina, harbour or basin*

There are a wide range of models which can be used for this purpose. Many of these are sediment transport process modules which are part of a flow modelling suite. This area has been the subject of a recent comprehensive review carried out for DOE which is presented in Reference 31.

3.2.6 *Movement of fluid mud*

Because fluid mud can move quite differently to the water above it, for example flowing down a slope in the bed into a channel, it has to be treated in the model as a separate fluid layer. This requires specific models (in 2D or 3D) that include the processes associated with fluid mud. A model of the formation, movement, settling and destruction of fluid mud is described in Reference 40.

3.2.7 *Resuspension of material associated with dredging activity*

Dredging activities lead to the resuspension of some bed material into the water column. This may be short term during dredging, transport and placement or it may be longer term associated with resuspension of material form the disposal site. The extent to which the dredging activities alter the properties of the material is an area of ongoing research. However, the main assumptions and approximations that usually need to be made concern the following:

- the release rate of the material from the dredging activity,
- the initial mixing of the released material
- the settling velocity of the resuspended material
- the erosion properties of the placed material,
- the consolidation properties of the placed material,
- the fluidisation of the placed material
- the hydrodynamics at the site of interest.

These assumptions are discussed in Chapter 7 of Reference 41.

Having chosen a range of values for the above assumptions it is possible to undertake a set of sensitivity tests using appropriate plume modelling techniques. These might include random-walk techniques or more simple Gaussian approximations. In many cases it is not necessary to have an accurate representation of the hydrodynamic climate.

Consideration of longer term stability or erosion of material placed on the seabed requires determination of the hydrodynamic climate at the site (waves, water depth, current speed and direction) in much the same way as described in Section 3.2.3.

3.2.8 *Morphodynamic modelling*

It may be required to model sediment transport for long periods together with the change to the bed elevation as sediment is deposited, eroded and consolidated so as to predict the morphodynamic change. Very often wave effects are important. As simple models are needed to model long-term evolution, it is usually best to use a 2DH flow model for this purpose. When the morphodynamic change is computed it should be remembered that estuary channels can move about in an irregular and unpredictable way even before any engineering works are carried out. Consequently it is both difficult to calibrate a model and to disentangle the effect of the works from the normal development.

In some circumstances where high mud concentrations are experienced it may be necessary to incorporate a model of fluid mud flow (see 3.2.6).

4 Selection of test cases for flow modelling

The approach adopted for the benchmark testing of flow models was to first of all identify a number of real situations, to which flow models can be applied. The selected benchmark tests are based either on situations described in the literature or are based on studies carried out at HR Wallingford. These test cases were then used to illustrate which kinds of model (for example a 1D flow model or a full 3D hydrodynamic model) are most appropriate for certain real situations.

Clearly different classes of flow model have greater or less competence to handle certain physical processes that may be considered important in a particular situation. The physical processes of most general interest are described in Section 4.1. The benchmark test cases, together with an indication of which physical processes might be considered important, are presented in Section 4.2.

4.1 Processes in estuary, coastal and harbour hydrodynamics

The following physical processes are considered in this study:

Tidal complexity In modelling large areas there may be null points for certain tidal constituents (water level variations with different periods of oscillation corresponding to the harmonics of the time the sun or moon takes to travel round the earth). Such null points for tidal constituents are called amphidromic points. They can result in very different tides at nearby locations, for example, in the Solent where a double high water occurs, and nearby Portland where there is double low water. In estuaries, a nearly sinusoidal tide at the mouth can be amplified and greatly distorted up the estuary eg the Severn estuary. Such behaviour is particularly extreme in cases where the estuary is of such a length (typically 100km) as to be resonant with the main tidal constituent. Shorter estuaries may have higher constituents in resonance, so the shape of the tide curve may change as the constituent is amplified upstream.

Wind induced flow The wind blowing over the sea produces a surface stress on the water that can raise surges that may result in flooding in coastal regions. Where tidal currents are not strong, the wind-induced current may be comparable to or stronger than the tidal current.

Secondary flows in curving flow If the flow is curved (eg a river bend or eddy caused by a breakwater) the centrifugal force is greater at the surface where the current is larger. Therefore there is a flow towards the middle of the bend or eddy at the bed and away from it at the surface.

Complex geometry Estuaries have naturally complex geometry both in the shape of the coastline and in the existence of channel networks.

Density induced flows In an estuary or coastal region, the water density may vary due to the variable temperature and salt and sediment concentration. This can give rise to gravitational circulation whereby lighter water (eg fresh) tends to spread over heavier (eg salty) water. This can give rise to stratification where there is an increase in density downward in the water column which has an important effect on how pollutants spread out.

Wetting and drying areas Typically in estuaries the area that is wet at high water may be considerably greater than that which is wet at low water. The wetting of initially dry areas is a feature also of situations where coastal flooding occurs due to storm surge or the breaking of a flood barrier. Estuary models need to be able to accommodate the change in the boundary of the wet area during the course of the tide.

Eddies Eddies (also called gyres or recirculations) can form in bays and harbours. Their strength in a numerical model depends on the treatment of turbulence.

Turbulence Turbulence comprises the chaotic flows that frequently occur in nature. The energy of turbulence can be created, transported and dissipated and various forms of turbulence model can be used to simulate the effects of turbulence. Different turbulence models are available in some of the numerical models. The most commonly used turbulence models for estuary and coastal application are : uniform eddy viscosity, Prandtl mixing length and k-epsilon. Note that all models discussed here solve the equations for the mean flow with any small scale or short period fluctuations averaged out and modelled in terms of mean flow parameters.

Transport of sediments and pollutants Very often the goal of a modelling exercise will extend beyond hydrodynamic simulation to include also the modelling of sediment transport or pollutant. The scope of the hydrodynamic model (area covered, tide type, run duration, resolution) will then be determined in large part by the requirements of the transport model.

Currents caused by wave action Particularly in regions of weak tidal current, the currents generated by waves can be important. They are predicted by specifying the wave radiation stresses in a model of wave action (at all points in the model domain) and then adding the wave stresses at each point in the flow model (if necessary distributed in the vertical direction). Special action may be required at boundaries if a flow in or out of the model domain is driven by the stresses.

4.2 Selected test cases

A summary is given here of the test cases which were examined. These were selected to be representative of the range of sites typically investigated by engineers in the UK. It was also necessary that a range of computational model techniques have been applied.

4.2.1 Mersey estuary

Important processes:

- Tidal complexity
- Complex geometry
- Density induced flow
- Wetting and drying areas
- Turbulence
- Flows and structures
- Transport of sediments and pollutants

Appropriate flow models:

- 1D MERMAID
- 2DH TIDEFLOW2D
- 2DH TELEMAC2D
- 2DH DIVAST
- 2DH TIDEFLOW2D with subgrid detail
- 3D TIDEFLOW3D
- 2D 2 layer TIDEFLOW2D2L

4.2.2 *Severn Estuary and Bristol Channel*

Important processes:

- Tidal complexity
- Complex geometry
- Wetting and drying areas
- Transport of sediments and pollutants

Appropriate flow models:

- 1D (Heaps)
- 2DH TIDEFLOW2D
- 2DH TELEMAC2D
- 2DH DIVAST
- 3D (Wolf)

4.2.3 *Southern North Sea*

Important processes:

- Tidal complexity
- Complex geometry
- Density induced flow
- Wind induced flow
- Turbulence
- Transport of sediments and pollutants

Appropriate flow models:

- 2DH intercomparison (Southern North Sea/English Channel)
- 3D TIDEFLOW3D
- 3D spectral model (Davies)
- 3D flow model (Backhaus)

4.2.4 *Conwy Marina*

Important processes:

- Density induced flow
- Eddies
- Turbulence
- Transport of sediments and pollutants

Appropriate flow models:

- 2DH TIDEFLOW2D
- 2DH TELEMAC2D
- 3D TIDEFLOW3D

The test cases outlined above do not cover the use of fully 3D models which are not yet in frequent use. The most frequently used models (2DH, 3D hydrostatic and 1D), however, are well represented.

5 Tests and results

5.1 Test case - Mersey estuary

5.1.1 Introduction

The Mersey estuary has an interesting and unusual form (Figure 3) in that the seaward end of the estuary comprises the Narrows which are narrower and deeper than the rest of the estuary. Currents there are large - of the order of 2m/s on spring tides. The tidal range is also large, 8.7m at Princes Pier on a mean spring tide, and the tide becomes very distorted further up the estuary with a long ebb and very rapid flood. Simultaneous data on spring tidal levels on 29 July 1980 are available from the work of West (Reference 42) at several points in the estuary. These measurements make an excellent starting point for the benchmark tests. Salinity effects on flows in the Narrows are believed to influence sediment transport despite the high currents and strong vertical mixing (see Price and Kendrick, Reference 43). Observations of through-depth variation of tidal residual current are available at a point in the Narrows from the work of Prandle et al (Reference 44).

A large number of computational flow models have been run for the Mersey estuary. They include a 1D model (Reference 45), a number of 2DH models (References 46 to 48), a 2D 2 layer model (Reference 49) and a 3D flow model (Reference 50). Both of these latter models include the effect on the flow of salinity variations. Also of interest is a 2DH model with representation of subgrid geometry detail in order to resolve processes on the extensive drying flats in the estuary (Reference 51). These different models have all proved to have value for the specific purposes for which they were built; the 1D model for long term water quality, the 2DH models for impacts of engineering work and the 3D and 2D 2 layer model to represent the gravitational circulation effect.

5.1.2 1D model (MERMAID, HR Wallingford)

The 1D MERMAID model of the Mersey estuary (developed by HR Wallingford, Reference 45) consists of 65 elements each 1000m long (see Figure 4). The model extends from well outside the Mersey estuary to the tidal limit. The model assumes there are lines across the estuary where the tidal level is constant. This may not be true, so the model predicts a mean water level along a cross-section. This kind of model cannot include the effect of cross-estuary variations eg banks and channels, except as tables of cross-sectional area against water level. Despite the one dimensional schematisation the tidal propagation is reasonably accurate when compared to the observations of West (Figure 5). Calibration of the tidal level was achieved by use of a bed roughness length of 0.1m for elements 1-33 (see Figure 4 for element locations), 0.05m for elements 34-55 and lower values landward of there. These values correspond to an estuary that becomes smoother further upstream. The change of shape of the tide from a nearly sinusoidal form at the mouth to a very long ebb and sudden rise (at all locations landward of Hale) is well reproduced. Upstream in the model (eg Randle's Sluices) the rise of the tide in the model tends to be delayed relative to observations, this may be related to the model resolution. The tide level at low water at Stanlow is rather high in the model (about 1m higher than observed). This discrepancy at Stanlow appears to be a feature of all the numerical models examined indicating possible doubt about this observation, especially as good agreement is also shown at Hale.

5.1.3 2DH model (TIDEFLOW2D, HR Wallingford)

The TIDEFLOW2D model, developed by HR Wallingford, has been applied to the Mersey estuary in the context of modelling a proposed tidal power generating barrage (Reference 46). A 1D model is often not satisfactory to predict the effect of engineering works on currents and sediment transport and a 2DH model is usually used instead. The 2D model can predict current patterns that can be used as input to vessel navigation studies as well as for predicting where erosion and acretion may occur after any engineering works.

A TIDEFLOW2D model of the Mersey estuary and Liverpool Bay with a uniform square grid of size 75m, was set up. As the barrage location considered during this study was near to the Narrows, the upper part of the estuary was represented in less detail than the seaward part. The calibration plot of simulated tidal levels compared to the West levels is shown in Figure 6. In order for the model tide to begin at high water a repeating tide is simulated and the observed data from high water to low water plotted before that from low water to high water although the latter occurred first in the observations. The calibration process involved identifying areas of rock, sand and muddy bed and assigning them bed roughness values of 0.10, 0.04 and 0.01m respectively. The low water level at Stanlow again tends to be higher than observed. In Figure 6 the tide is shown in advance of the observations on the rising tide. However, closer inspection reveals that the rising tide has a similar displacement at all locations indicating approximately correct propagation of the rising tide from the Narrows up to Randle's sluices (so the low water channel may be better represented in this model compared to the 1D model). This demonstrates that adequate resolution of the bathymetry in a 2DH model can result in a good simulation of the tidal propagation.

5.1.4 2DH model (DIVAST, Mersey Barrage Company)

Like the TIDEFLOW model used in the studies described above, DIVAST (written by Falconer and applied by the Mersey Barrage Company) uses a finite difference numerical method based on a square grid. DIVAST was run with grid sizes of 150m (Mersey estuary and Liverpool Bay) and 75m (of the estuary only). The simulated water levels at the West locations are shown in Figure 7 for the 150m grid model (Reference 47). The present model used a roughness length of 0.02m uniformly throughout the model, later models in the study used a variable bed roughness. As with the models mentioned above, the low water level at Stanlow is rather high in the model and the tide is a little late at Widnes. This is a consequence of the coarse resolution of the low water channel that is achieved with a grid of 150m. A comparison between the flows simulated in the TIDEFLOW and DIVAST flow models, both with grid sizes of 75m, was made and very similar results were found, both with and without a tidal barrage, demonstrating that such 2DH models generally give quite similar answers if carefully applied.

5.1.5 2DH model (TIDEFLOW2D with subgrid detail, HR Wallingford)

In order to be able to represent wetting and drying (inter-tidal) areas in greater detail a new model was developed at HR Wallingford, based on the TIDEFLOW2D model but with the ability to take some account of subgrid detail (Reference 51). This was achieved by interpolating the estuary bathymetry onto a finer grid than that used by the flow model, from which tables of wetted area and volume against water level for each model cell were computed.

The standard TIDEFLOW2D model, with a gridsize of 300m, was first applied to the Mersey Estuary (Figure 8). The roughness length was again specified to vary according to the bed type with values of 0.2m, 0.1m and 0.01m for the areas of sandy bed, rocky and muddy bed. With this gridsize the tidal propagation obtained was not very good, for example the low water at Widnes was about 2m higher than observed. This is a consequence of the lack of resolution of the low water channel. Subgrid detail of the bathymetry was then included in the model (still with gridsize 300m). This was achieved by incorporating tables of the area on each face of a cell at each water level and of the volume of the cell. An extra feature was the inclusion in some cells of subgrid channels and an improved representation of the model resistance formulation when subgrid detail and channels are included (see Reference 51 for details) . These improvements gave a better resolution of the large drying area of the estuary which was reflected in the better ability of the model to reproduce the drying process near to low water. This resulted in an improvement to the model representation at low water (almost correct low water level at Widnes, Figure 9). However the rising tide at Widnes was still quite late compared to the observations (about 1 hour late).

5.1.6 2DH model using finite elements (TELEMAC2D, LNH)

The TELEMAC2D hydraulic model software originates from Laboratoire Nationale d'Hydraulique in Paris (Reference 10). It uses a very flexible unstructured finite element grid of triangles allowing finer resolution to be achieved in some parts of the model compared to that in others.

The TELEMAC2D model has been applied to the Mersey estuary plus part of Liverpool Bay using the model grid shown in Figure 10 , the grid size is generally greater than 150m. The representation of the coastline and of the channel above Hale can be seen to be facilitated by the use of an unstructured finite element grid of triangles. The simulation was carried out using a Chezy bed friction coefficient of 50. The tidal propagation is shown in comparison with the observations by West in Figure 11 (Reference 48). The tidal propagation generally shows good correlation with the observed values. The model has the advantage that if it required to resolve an engineering work then local mesh refinement can be used to do so without needing to change the rest of the grid.

5.1.7 3D model (TIDEFLOW3D, HR Wallingford)

The TIDEFLOW3D model, developed at HR Wallingford (Reference 30), was applied in order to represent the flow in the Mersey estuary including the effect of longitudinal salinity gradients in driving a gravitational circulation in the Mersey Narrows. Although the currents are high on a spring tide and there is very little vertical density variation, there is nevertheless a residual flow that is landward near to the bed and seaward near to the surface with a strength of the order of 0.1 m/s (Reference 44). This residual flow is expected to have an impact on suspended sediment transport because the sediment is mainly found in the lower part of the water column where it experiences the landward residual tending to retain sediment within the estuary.

The TIDEFLOW3D model of the Mersey Estuary had a gridsize of 150m in the horizontal direction and 8 layers in the vertical which were separated by horizontal planes. The first such horizontal plane was below the level of low water so the entire tidal range was contained within the surface layer of the model. The model covered Liverpool Bay as well as the Mersey estuary itself. There were therefore 8 layers in the area of the Narrows but fewer model layers in the large shallow area of the estuary landward of the Narrows. The model was again calibrated by comparison with the levels measured by West (Figure 12) again specifying different bed roughnesses in areas of different bed type. The calibration is generally not as good as that achieved with a finer grid 2D model. An approximate representation of the measured salinity distribution (ignoring salinity variation in the vertical) was input to the model as an initial condition. After running the model to a repeating spring tide condition the simulated flows through the Narrows were analysed and a residual flow over the course of a single spring tide was found to give a broadly similar, if slightly smaller, residual flow compared to that measured (Figure 13).

After this successful calibration the model results were used in a 3D simulation of suspended sediment transport.

5.1.8 2D 2 layer model (TIDEFLOW2D2L, HR Wallingford)

A 2D 2 layer model was also applied to the Mersey Estuary and Liverpool Bay, Reference 50. There were grid sizes of 300m in the Mersey estuary (not fine enough to resolve the tidal propagation accurately in the upper estuary), 900m in Liverpool Bay, and 2700m at the seaward limit. All of these grid areas were joined dynamically, ie each part of the grid affected the other parts during a single timestep. A representation of the salinity field was incorporated and the water column split into two layers separated by an interface at 6 m above the bed. As with the 3D model, most of the Mersey estuary was only represented by one layer in the model. Compared to the 3D model it was rather difficult to represent the gravitational circulation in the Narrows due to lack of vertical resolution, but a circulation of the correct direction (landward in the bed layer and seaward in the surface layer, Figure 14) was obtained. It appears to be necessary to use adequate vertical resolution for modelling such delicate residual flow phenomena. After calibration, the model was used to simulate suspended cohesive sediment in Liverpool Bay and the distribution of heavy metals and their fate.

5.1.9 Conclusions

A comparison of a number of numerical flow models of the Mersey estuary has been carried out. The 2DH models from different sources were found to give results generally in good agreement with the observations of water level taken at a number of sites in the estuary simultaneously.

Because of the complex bathymetry of the Mersey estuary, with its extensive drying flats, tidal propagation can only be accurately represented in models that have a certain level of resolution of the bathymetry. This includes the 1D model in which the estuary cross section is accurately reproduced using a look-up table of cross-sectional area as a function of water level. Nevertheless a 1D model clearly cannot be used to assess the effects on tidal currents of building major engineering works for which a 2DH model is required. 2DH models with a gridsize of larger than about 150m are not readily able to reproduce the shape of the tide upstream at Hale, unless extra resolution can be provided by use of subgrid scale detail in the bathymetry.

If it is required for the purposes of a study to simulate the effect of the density field in driving a residual current in the Narrows, seaward at the surface and landward near to the bed, then this can be achieved by using a 2D 2 layer or 3D flow model including the salinity field. The 3D model with its greater vertical resolution was found to give a better representation of the residual flow in the Narrows which is observed to be about 0.1m/s at a particular site.

5.2 Test case - Bristol Channel and Severn Estuary

5.2.1 Introduction

A substantial amount of computational modelling has been associated with the Severn estuary since the physical model work by Gibson in 1933 (Reference 52). The computational models considered here that have been applied to the whole Bristol Channel/Severn Estuary system (Figure 15) include 1D models, 2DH models of various types and some 3D models. A wide ranging set of observations of water level and currents was carried out by HR in 1980 (References 53-54).

The natural frequency of oscillation of the Bristol Channel/Severn estuary is very close to that of the tide and therefore a resonance phenomenon occurs that gives rise to large tidal amplitudes. The tide in the Severn Estuary rises to the second largest in the world at Avonmouth and the currents in the Shoots are as large as 4m/s on spring tides. Further up the estuary the tide curve becomes so strongly distorted that a well-known tidal bore is seen on spring tides. At low water extensive areas of tidal flats can be seen.

A model intercomparison exercise has been recently carried out by the Foundation for Water Research with the example of modelling Barnstaple Bay in Devon (Reference 55). The results are available to members of the Foundation for Water Research and the exercise concentrated on ease of use and application to pollutant dispersion modelling. A number of models were found to give a good reproduction of the hydrodynamics of the Bay although there were problems with some of the observational data that were supplied for the calibration of the models.

Also a number of flow models have been used to investigate the pattern of residual tidal flows in the vicinity of Swansea Bay and Nash Bank. Residual flows are a very sensitive indicator of a model's performance as they are a measure of the difference between flood and ebb currents. These residuals will be considered further below including some observed values.

5.2.2 1D flow model (Heaps)

Heaps (Reference 56) applied a 1D flow model to the Bristol Channel and Severn estuary. The Severn estuary and Bristol Channel from Sharpness at the landward end to the mouth at approximately a line from Milford Haven to Bude were discretised with 37 sections (Figure 16). Notwithstanding that in this estuary the tidal elevation is not in reality constant along the cross-section lines, the model produced acceptable variation of the M2 tidal phase and amplitude along the estuary when compared to observations (Figure 17), demonstrating the resonant tidal phenomenon. The phase, however, shows important two dimensional effects at the seaward end of the model (sections 20 and above, where the observed phase on the Welsh bank is almost constant) that the 1D model cannot reproduce.

The model was used to demonstrate the effect on the tidal propagation of a barrage (represented as a complete blockage of the estuary) at different locations within the estuary.

5.2.3 2DH model (TIDEFLOW2D, HR Wallingford)

A number of different 2DH models have been used to represent the tides in the Bristol Channel/Severn estuary system. They include two TIDEFLOW2D models used in the first instance (Bondi study, Reference 57) to simulate the effect of a tidal power generating barrage and in the second (with a grid twice as fine, Reference 38) as the basis of environmental simulations. The greater resolution required in the Severn estuary as opposed to the Bristol Channel was achieved in both of these models by the use of patches of different gridsize (eg 4500m, 1500m, 500m for the Bondi model and twice as fine for the later model). The areas of different size grid in these models (shown by dotted lines in figure 15) were updated fully dynamically (ie each part of the model affected the other parts at each timestep). Both models were compared with a set of simultaneous tidal level measurements along the estuary made for this purpose in 1980 (Reference 53). Good agreement of levels was found (Figures 18 and 19) although (as in the case of the Mersey estuary) there is some tendency for the tide to be late at the upper end of the model. However this effect is not very great bearing in mind the very large distortion and amplification the tide undergoes from the mouth to Sharpness. It can also be seen that the finer grid model tends to show a rather better reproduction of the observed tide.

In addition to comparison of water levels it is considered that another good indicator of model performance is the residual flows (current vectors averaged over a tidal cycle) that a model predicts. This is especially the case in Swansea Bay and Nash Bank where model residuals are available for different models and some observations are also available.

The model residual currents in this area (for the finer grid model) are shown in Figure 20. The general features of the observed residual flows (Figure 21, taken from Reference 70) are clearly reproduced in the TIDEFLOW2D model. Differences in observed circulations between bed and mid-depth can clearly only be simulated with the use of a 3D model.

5.2.4 2DH model (DIVAST, University of Bradford)

The DIVAST 2DH model (written by Falconer of the University of Bradford and applied by Bullen and partners) has also been applied to the Bristol Channel/Severn estuary system (Reference 60). The residual flows in the area of Swansea Bay and Nash Bank are published and shown in Figure 22. The results are very strikingly similar to the TIDEFLOW results shown in Figure 20, in respect of the general flow around Swansea Bay (anticlockwise gyre at the Westen end flow division in the north east) and around the banks (clockwise circulations) demonstrating how these computational models can give consistent results when properly applied.

5.2.5 2DH finite element model (TELEMAC, LNH)

A TELEMAC2D finite element model of the Severn Estuary and Bristol Channel has recently been set up to study the flows in the vicinity of Nash Bank (Reference 60). The model covers a very similar area to the TIDEFLOW model and uses a variable finite element grid of triangular elements (Figure 23). The general tidal propagation in this model is quite satisfactory (Figure 24). The residual tidal flows in the Nash Bank and Swansea Bay area are again very similar to those resulting from the finite difference models. Figure 25 shows the currents interpolated on to a square grid for ease of viewing). The residual gyre in the western part of the Bay and the flow divison in the north east and the clockwise residual flows around the banks are evident.

5.2.6 3D model (Wolf, POL)

A 3D flow model using finite differences in the horizontal domain and spectral expansion in the vertical direction has been run for the Severn estuary (Reference 61). Density effects (which are possibly important if lateral circulations are caused) are not included. The resulting residual flows for an M2 tide are shown in Figure 26, the pattern of residual flows in the area of Swansea Bay and Nash Bank are rather similar in the surface and bed (which is inevitable in view of the exclusion of any density driven effects) and similar to those produced by the various models described above.

5.2.7 Conclusions

A 1D model of the Bristol Channel and Severn Estuary cannot reproduce the fact that lines of equal phase and tidal amplitude are different in the Bristol Channel. Consequently the real tide cannot be well reproduced there although the general distribution of tidal amplitude and phase up the estuary can be reproduced. The 2DH models generally perform well at reproducing the tide up to Avonmouth or beyond, including the distortion of the tidal shape and large amplification. Particularly if the grid is coarse there tends to be some lag of the tide behind observations at Avonmouth, which is accentuated further upstream. Models that can include a finer grid resolution in the area where the tide is very distorted are desirable.

The comparison between different 2DH and 3D models of the tidal current residuals in Swansea Bay and Nash Bank is very encouraging. The models which are well applied can predict generally a very similar pattern of residuals to that observed.

5.3 Test case - Southern North Sea

5.3.1 Introduction

Many computational model studies of tidal, residual and wind-induced flows in the Southern North Sea have been carried out. The tide includes important amphidromic points, including one off the coast of Norfolk, so any model of the area has to be able to cope with tidal complexity, for example there is a very small tide at Lowestoft and large tide in the Wash. The effect of Coriolis force (due to the earth's rotation) is significant and the model may also need to be run using spherical coordinates (taking account of the fact that the earth is not flat on large scales) if a large area is to be modelled. Also north of Flamborough Head a front between different density water masses is observed. To the north of the front the sea becomes stratified in summer with the surface water warmer than it is in winter while the bed water is at a similar temperature to that in winter.

Computational models applied to this case include a large selection of 2D models (eg finite difference, finite element). A model intercomparison exercise for 2D models has been carried out (References 63-64) where the model boundaries and boundary conditions were specified so a comparison of model results could be undertaken. This is described in 5.3.2 below.

A wide variety of 3D models have also been applied. They are described in 5.3.3 below.

5.3.2 2DH model intercomparison exercise - Tidal Flow Forum

A test case for the tidal modelling of the Southern North sea and part of the English Channel was set. The area of the modelled domain (Figure 27), the bathymetry and the boundary conditions to be applied were all specified so that an accuracy comparison between the different models would be possible. The models contributed to the exercise included finite difference and finite element models with a range of different numerical techniques. Not only the organisations that replied immediately have contributed to this exercise. Other organisations have subsequently applied their own models, notably ADCIRC2D (Reference 20).

The boundary conditions were specified as a number of tidal constituents from which the tide curve for the period in question could be constructed. The output took the form of both plots of tidal constituents and time histories at certain coastal locations.

The model exercise demonstrated that the models were all well able to reproduce the main features of the tide in the area modelled. Reference 64 concluded that "It appears that all of the Tidal Flow Forum results obtained so far are almost of the same order of accuracy. Even if one computation appears slightly better than the others, our lack of confidence in the reliability of the reference harmonic constants and the limited sample size keep us from drawing definitive conclusions".

5.3.3 3D hydrostatic models

Davies (Reference 65)

This flow model has a grid size of 1/3 deg latitude by 1/2 deg longitude, ie approximately 37km by 27km and extended to the shelf edge (see Figure 28). The model solves the tidal flow equations including the wind stress. The 3D hydrostatic equations are written for a spherical earth and do not include density effects.

A Galerkin expansion is used in the vertical rather than using a finite difference grid. This approach, which consists of the vertical variation being expressed as the sum of a number of continuous basis functions, has the advantage that the resulting velocity distribution is represented as a continuous function of the depth rather than being computed at a finite number of levels. The vertical eddy viscosity in this model is taken to depend on the square of the depth mean current, but its value is independent of the position in the water column. The bed friction coefficient is taken to be .005, which is twice the value adopted in depth integrated models because the friction is based on near bed current instead of the depth mean current. The model has been calibrated for M2 (the dominant tidal constituent) tidal elevations and currents. It was found that in the absence of a wind the residual current does not vary strongly in the vertical direction (Figure 29). However the wind induced current, based on the annual mean windstress in each model cell, was found to vary strongly in magnitude and direction with depth (Figure 30). The conclusion is that a 3D model is needed for a realistic simulation of residual flows in the North Sea including the effect of the wind.

Backhaus and Maier-Reimer (Reference 66)
A 3D model was built of the area shown in Figure 31 using horizontal interfaces between the layers. The grid size used is about 22km with a spherical grid. The model uses a finite difference grid in the vertical rather than the Galerkin expansion method. There are ten layers with interfaces at 0, 10, 20, 30, 60, 100, 150, 200, 250, 350 and 700m. This makes it difficult to compute the pattern of residual currents at the bed and such patterns are not presented. Again an M2 tide was simulated.

Runs with and without wind are included as in the previous paper but runs with and without the density field are also presented (Figure 32). The density field is a prescribed time-independent 3D field. The effect of including the density variations is greatest in the area of the Norwegian coastal current. Even for vertically well mixed winter conditions Backhaus concluded that the residual currents driven by the horizontal density gradients are significant.

TIDEFLOW3D (Reference 66)
Many models have been applied to modelling the North Sea in recent years, the experience at HR Wallingford with the TIDEFLOW3D model is in many ways typical. The model was run with a spherical grid of approximately 20km with salinity and temperature fields corresponding to different times of the year. The fields were transported by the computed flows for a period of a few M2 tides. Residual flows (eg Figure 33) were then computed for different periods in the year including both the relevant density and wind fields as input to a further study of sediment and heavy metal transport.

5.3.4 Conclusions
A number of different modelling approaches have been found to be of value for different purposes in the Southern North Sea. 2DH models are of use especially for the transport of dissolved materials and for storm surge elevation. A Tidal Flow Forum intercomparison exercise carried out in 1988-9 found a very similar level of accuracy from different model approaches to modelling the tide in the Southern North Sea and English Channel.

The simulation of other phenomena in the North Sea such as the currents resulting from wind blowing over the sea and the effect of density variations requires the use of 3D models. Different approaches have been used. For example, a spectral expansion in the vertical direction which is efficient for computing 3D flows but cannot readily incorporate a transport equation for the density field. For longer term and sediment and pollution transport modelling a transport equation must be solved and the vertical direction divided into elements using the flat planes or sigma planes approach.

5.4 Test case - Conwy marina
5.4.1 Introduction
Data was collected on the flows at the entrance to Conwy marina in October 1993. The use of the Acoustic Doppler Current Profiler (ADCP) technique resulted in extensive through tide and through depth as well as across the width information on flows into and out of the marina during a spring tide. This data provides a rare opportunity to compare computational models with real world observations in a situation of weak tidal currents.

The following models were chosen to make the comparison:

TIDEFLOW2D -	A finite difference model developed at HR Wallingford
TELEMAC2D -	A 2D finite element modelling system from LNH Paris
TIDEFLOW3D -	A model, developed at HR Wallingford, that enables the effect of density differences to be taken into account in simulating the flow.

This exercise enables the following comparisons to be made:

- Finite difference and finite element solutions of the 2D shallow water equations
- 2D depth-integrated flow model and 3D flow model
- all 3 models compared with the extensive observed current data

5.4.2 *Review of the ADCP data*

On the 16 October 1993 the vessel with the ADCP on board crossed the entrance to Conwy Marina (a distance of about 100m or less at low water) between two fixed positions at intervals of half an hour to an hour for a whole spring tide period. The ADCP was running while the vessel was moving so that the east-west and north-south velocity components at each depth (except near surface and bed) were measured across the entrance effectively simultaneously. The east-west velocity component is the one that represents flow into and out of the marina and this is presented in colour plots of velocity across the section and in the vertical in Figure 34. In this figure blue represents inflow and yellow represents outflow. It is noticeable that while inflow dominates during the flood and outflow during the ebb the observations almost always show some area of both inflow and outflow at the same time. This is especially true on the late flood where the observations show that inflow is occurring over the southern half of the entrance and outflow over the northern half.

Note that the ADCP is unable to measure currents in the top 2m of the water column and that the currents close to the bed may be influenced by the proximity of the bed (Reference 67).

5.4.3 *Descriptions of the model setting up*

The 2D and 3D TIDEFLOW models were based on the same bathymetry of the same modelled area and the same boundary conditions of water level at the seaward end (Deganwy Narrows) and water velocity at the landward end (see Figure 35). The velocity boundary condition was taken from an existing model of the whole estuary (Reference 68) that had previously been calibrated against an extensive data set of flow measurements in 1978. The TELEMAC-2D model was able to cover a larger area, up to Conwy bridge, (see Figure 36) with finer resolution of the marina entrance because of the use of the variable sized grid of triangles. The water level boundary at the seaward end was the same as for TIDEFLOW and the discharge boundary at Conwy bridge was taken from the same model of the whole estuary as for the TIDEFLOW model.

5.4.4 *The model results*

TIDEFLOW2D

Initially in running this model some waves were found in the modelled water levels and velocities. These were discovered to be a result of the flood wave reflecting at the model landward limit. In order to get a more realistic representation of the tidal level in the model a radiating boundary condition was established at the landward limit of the model which allows the flood wave to pass unreflected. When this boundary condition was implemented in the 2D flow model the results appeared to be reasonable. A representation of the tidal currents in Conwy marina 4 hours after high water are shown in Figure 37. The ebb tide current out of the marina can be seen to be mainly concentrated at the northern end of the entrance. This result is contradictory to the ADCP observations (Figure 34) that show inflow occurring at the northern end of the entrance for most of the ebb tide period. Sensitivity tests were carried out on the model selection of eddy viscosity value but the model always showed maximum outflow towards the northern end of the entrance throughout the ebb period.

During the flood tide (see Figure 38 showing HW+9.5 hours) an eddy forms across the whole width of the marina entrance . This behaviour is confirmed by the ADCP observations that show inflow at the southern end of the entrance and outflow at the northern end during most of the second half of the flood tide.

The simulated currents within the marina are always very weak (of the order of 0.1m/s or less).

TELEMAC2D model

The TELEMAC model solves the same equations of motion as the TIDEFLOW2D model, but does so on a triangular grid of finite elements and in this case also over a rather larger area (going as far landward as the bridge). The TELEMAC2D model during the ebb tide (Figure 39) shows a very similar pattern of flow to the TIDEFLOW2D model ie the flow is primarily out of the entrance towards the northern end. As before this result is not in agreement with the observations. The flood flows also show a pattern of vectors that closely resembles the TIDEFLOW2D ones (Figure 40), showing an eddy occupying the width of the entrance. The modelled flows inside the marina are again weak throughout the tide. The agreement between the TIDEFLOW2D and TELEMAC2D models can be seen to be closer than the agreement between either model and the observations.

TIDEFLOW3D model

In view of the considerable difference in the observed flow during the ebb tide where the flow at the northern end of the entrance is consistently going out in both of the models. The observations however show it going in during this period, it was therefore decided to look more closely at the available data. Following a common procedure, because there is no freshwater flow into the marina it had been assumed that density effects would not be important. However it is known that density effects are very important in the Conwy estuary as a very well defined scum line forms up the middle of the estuary on the flood tide due to the advancing tide being more saline than water already in the estuary and so sinking to the bed and drawing floating material to a line up the middle of the estuary. Even more relevantly, observations were made by Robert West & Partners in 1990 (Reference 69) when the marina was rather deeper than in 1993. The results for two stations at either end of the entrance to the marina show differences in salinity between surface and bed of up to 14 ppt at the southern station and up to 10 ppt at the northern station. These results seem to indicate that the water in the marina has a different salinity to that just outside in the estuary. This density difference would be expected to drive an exchange flow in the entrance to the marina going out at the surface and in at the bed during the flood (when the water in the estuary is saltier) and vice versa during the ebb, when the estuary is fresher. These results would tend to be stronger in the second half of the flood or ebb as the first half is taken up with the change from fresher to saltier or vice versa. This assumes that as the water has to go in and out of the marina entrance the salinity in the marina will lag behind that in the estuary and also not become either as fresh or as salty as in the estuary. The exchange flow is added to the tidal interchange so that during the ebb the surface inflow may oppose the tidal outflow or may be strong enough to overcome it.

The Robert West data shows in the second half of the flood tide, velocities out of the marina, at the southern end, in the upper part of the water column and the expected inflow underneath. At the northern end there is strong inflow beneath the surface but the flow is reduced approximately to rest above. These results fit in with the idea of an exchange flow outward at the surface and inward below during the flood tide, added on to the tidal flow. During the ebb tide a very similar pattern of exchange flow is observed in reverse.

In order to model this flow, where density effects are as important as the tidal flow a 3D TIDEFLOW model was used. This model includes a representation of the salinity as well as tidal level and current. As salinity values generally were not available boundary conditions were based on a curve with maximum value 30 ppt and minimum 13 ppt based on the maximum and minimum values found during the West survey. The salinity was taken to be a maximum at high water and a minimum at low water, it was applied as a boundary condition at both the seaward and landward boundary. In the model the water density depends on the salinity so that if density differences exist between the marina and estuary then an exchange flow can be driven.

The model was run for a test with three model layers. The surface layer extended from the surface to surface -1.6m, the middle layer the next 1.6m and the bed layer the rest of the water column. As the layers float with the water surface it is possible that layers that are present at high water may not exist at low water when the water is shallower.

The velocity vectors for the ebb phase are shown in Figures 41 and 42 (surface and middle layers). At the surface the inflow at the northern end can now be seen (the direct opposite of the depth-integrated flow model) and the flow is inward across the whole entrance. Underneath the flow is ebbing. This behaviour corresponds to the exchange flow expected and demonstrated by the Robert West data. The ADCP data during the ebb tide also shows a tendency to flood flows near the surface (currents in the top of the water column cannot be measured with the ADCP) and the flood current tends to be largest close to the bed showing a general exchange flow.

During the flood the surface flow tends to be generally ebbing but the bottom layer shows the large eddy across the entrance that is observed and also shown by the 2D flow models. The ADCP results show the eddy very clearly (inflow to the south, outflow to the north) but evidence of the exchange flow can also be seen (at 10.03 during the flood the flow is ebbing at the surface across the whole width of the entrance).

It was decided not to make very detailed comparisons between the model and the data because both the ADCP and West data show extremely large variations of a seemingly random kind, a reflection of the fact that the currents here are very small. Nevertheless it is clear that in reality a strong exchange flow occurs during the tide and a standard 2D depth-integrated flow model gives results considerably at variance with the observations. A 3D flow model including the effect of the salinity on driving gravitational flow can represent the correct processes and gives more realistic results. It also follows that for practical applications regarding harbour flushing or sediment exchange a numerical or physical model that does not take account of the variation of salinity may give rise to misleading results.

5.4.5 Conclusions

The comparison of three numerical models with the data from two survey campaigns has been carried out. It has been found that the 2DH flow models (TIDEFLOW2D and TELEMAC2D) give very similar results for the flows between the marina and the estuary. On the other hand neither model gives good agreement with the pattern of flow on the ebb tide, although both models represent well the large eddy in the marina mouth during the flood tide.

The use of a 3D flow model including the effect of salinity gives a result in better agreement with the observations because it can represent the exchange flow that occurs on both the flood and ebb tide, and is dominant on the ebb tide. The exchange flow is a feature of both sets of survey data.

It can be concluded that if there are significant variations in the salinity during the tide outside of a harbour or tidal basin then it is likely (if the harbour has one entrance) that the density effects will make a significant contribution to the exchange of sediments and pollutants between the marina and the estuary.

6 Conclusions

6.1 Flow modelling

1. A number of tests cases have been considered and the treatment of those cases with different hydrodynamic flow models assessed. At present flow modelling studies of coasts and estuaries make much more use of the hydrostatic pressure 2DH models than of any other kind. This is, on the one hand, because these models are very often adequate tools for the flow simulation required, and, on the other hand, because 3D models have not been available at the time or have been very expensive to use. Nevertheless all of the tests cases have shown, to a greater or lesser extent, that 3D modelling can be of great value.

2. The Mersey test case shows that different forms of 2DH model, including finite difference and finite element models, can represent the tidal propagation in an estuary. Nevertheless if it is important (for example in modelling sediment transport) to simulate the 3D pattern of residual currents, then this can be achieved by a 3D hydrostatic flow model.

3. The Severn Estuary case again shows that the flows can be well represented by different forms of 2DH model, in this case in order to simulate the tidal residual flows within the estuary. In a situation where the tide becomes rapidly distorted up the estuary, it can be valuable to use a model that can increase resolution in the area of interest. This can be achieved either by the use of finite elements or by using different size finite difference cells dynamically linked together.

4. The test case of the North Sea has shown that tidal complexity over a large sea area, including an amphidromic (null) point of the leading tidal constituent, can be adequately modelled with different 2DH modelling methods, provided Coriolis force is included in the model. The sea is stratified in summer so that while the depth-mean currents and water level can be modelled with a depth integrated model, a 3D model is needed if the transport of sediment or particulate pollutant is to be modelled during the summer period. Different strategies can be used (eg finite differences in the vertical - either with flat planes or sigma coordinates- or an expansion in terms of basis functions). The method of expanding the vertical in terms of basis functions is not generally used where transport is to be considered, so finite difference models are usually required for transport modelling.

5. The case of Conwy Marina is one where the flow cannot be adequately represented with a depth-mean model as there are times during the tide when water is simultaneously entering and leaving the marina at different levels in the water column. This occurs even though the Conwy is regarded as a well mixed estuary because of the variation with time of the salinity at the mouth of the marina.

6. All of the test cases, which are typical of estuarine and coastal situations around the UK, show that the same water body can be well represented either with a 2D depth integrated model or a 3D model depending primarily on the purpose for which the model exists. It is clear that for modelling the transport of sediments and pollutants a greater use of 3D models than at present will be normal in the future.

6.2 Sediment transport modelling

1. Sediment transport modelling is as yet at a much lower level of certainty than the modelling of waves and flows. Sediment transport models, rather more than flow and wave models, are only useful engineering tools in experienced hands. In such hands they can usefully be applied to optimise the design of engineering works and to quantify (within certain limits) the likely rates of accretion and erosion.

2. There are three phases to a sediment transport study: assessment, modelling and field investigation. An assessment should always be undertaken first. Optimum application of modelling and field investigation may involve an iteration process.

3. It is important to adequately represent the physics of the dominant sediment transport mechanism(s) in the area of interest. Selection and application of the appropriate type of sediment transport model will depend upon a thorough understanding of these mechanisms.

4. In the absence of detailed information on the sediment properties at a particular site it may be possible to make useful predictions of sediment transport by applying some suitable assumptions on the nature of the sediment and to use these as a basis for a series of sensitivity tests.

5. In sediment transport modelling, rather more than flow and wave modelling, the selection of appropriate modelling strategies from the many available is often not clear. One, two or three dimensional model tools, with rather different physical processes embodied, or even no simulation models at all, may be selected by different practitioners. High dimension models with many physical processes included are available and under development, but many studies will continue to be carried out based on simple methods. Such techniques will also be successful if based on a correct assessment of sediment transport mechanisms.

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Figures

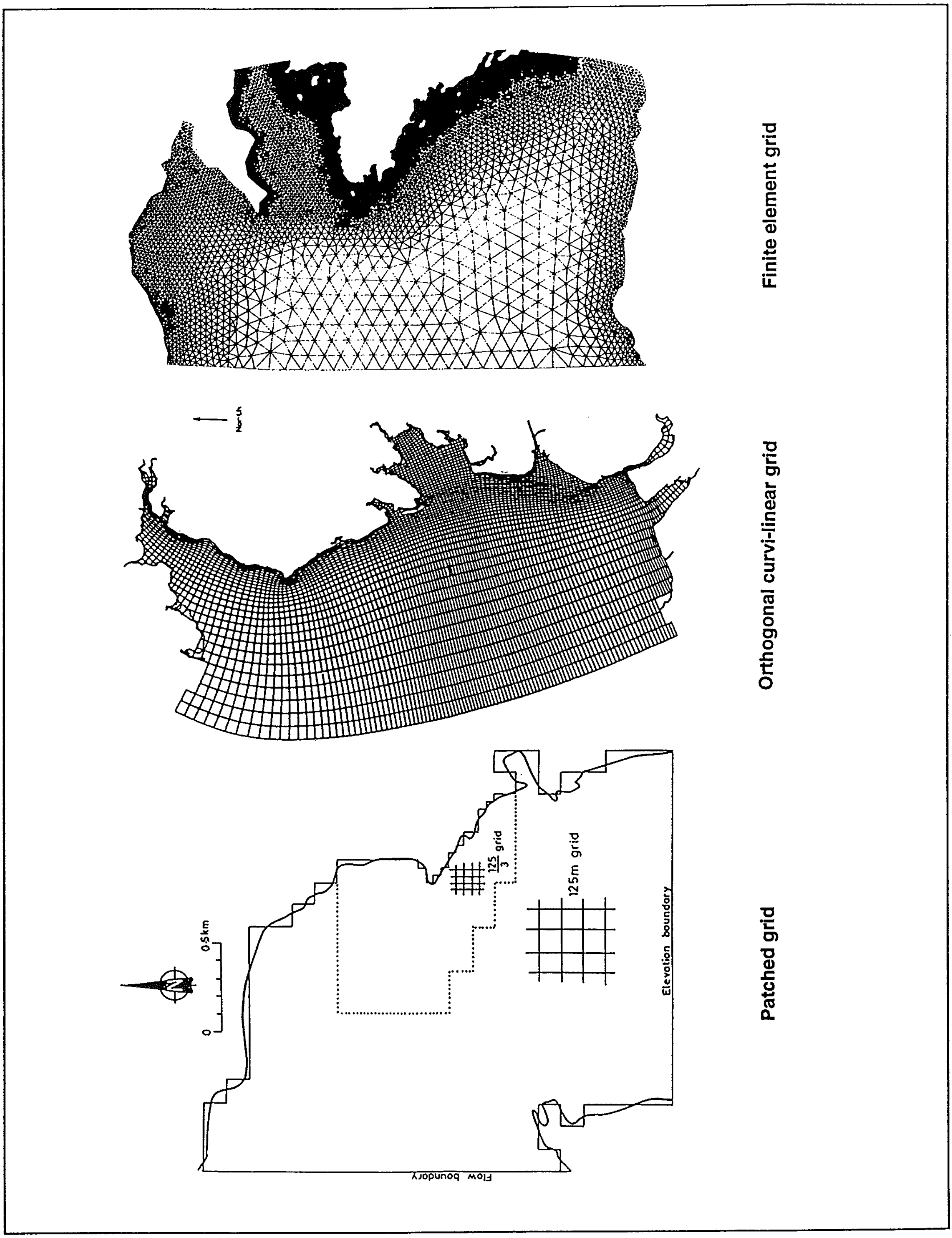


Figure 1 Grids used by finite element, finite difference and curvilinear grid models

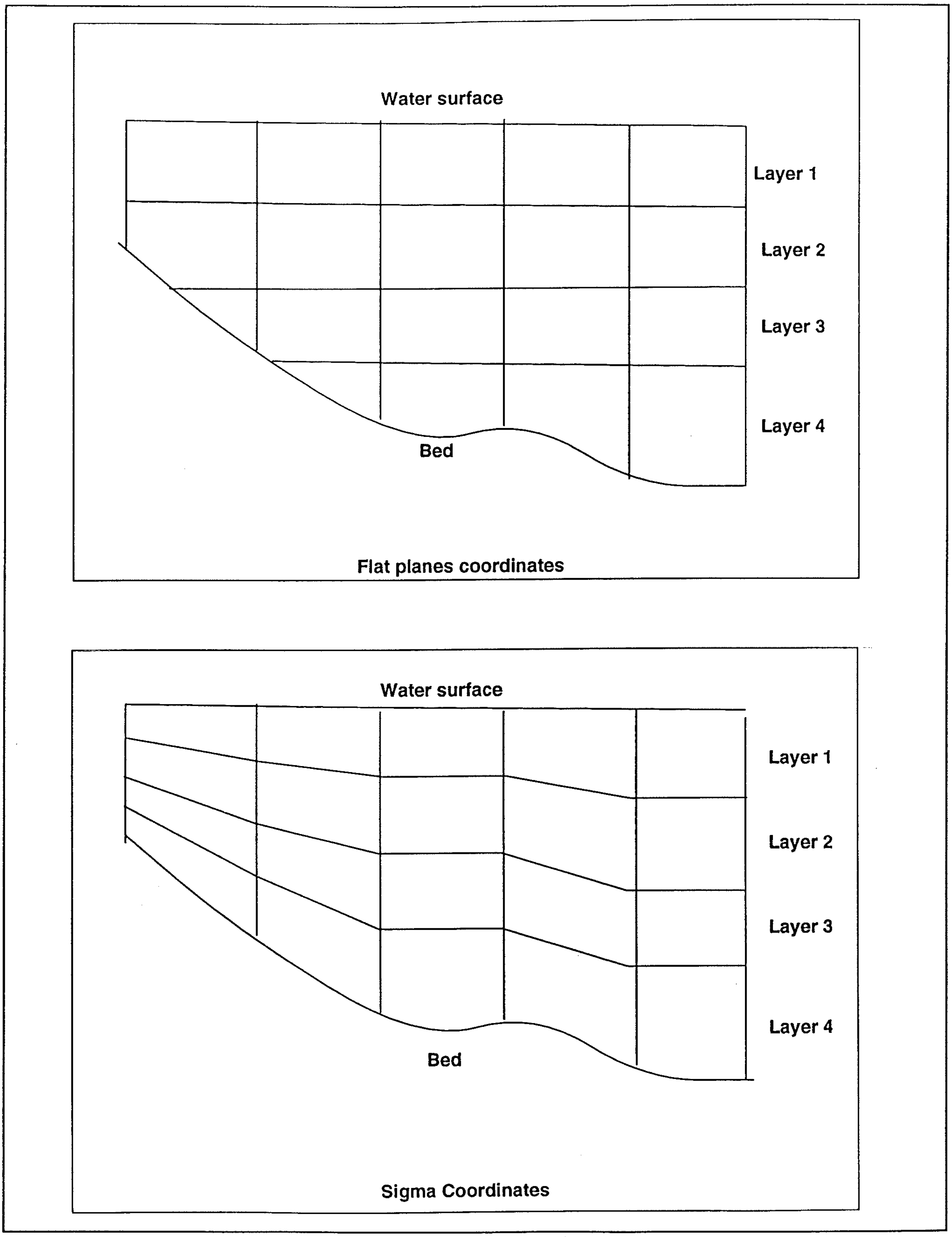


Figure 2 Grid used in the vertical plane in 3D models

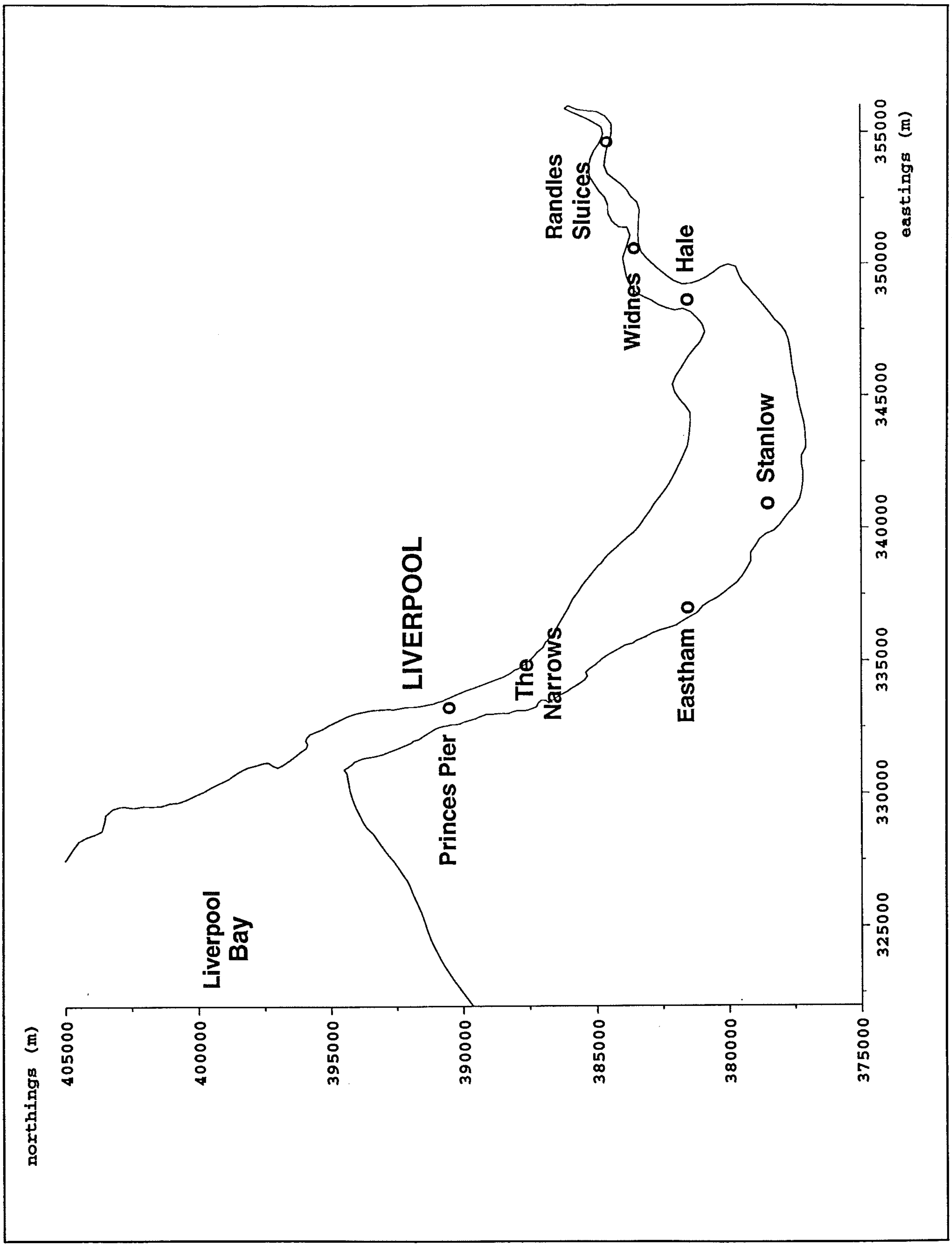


Figure 3 Mersey estuary, plan

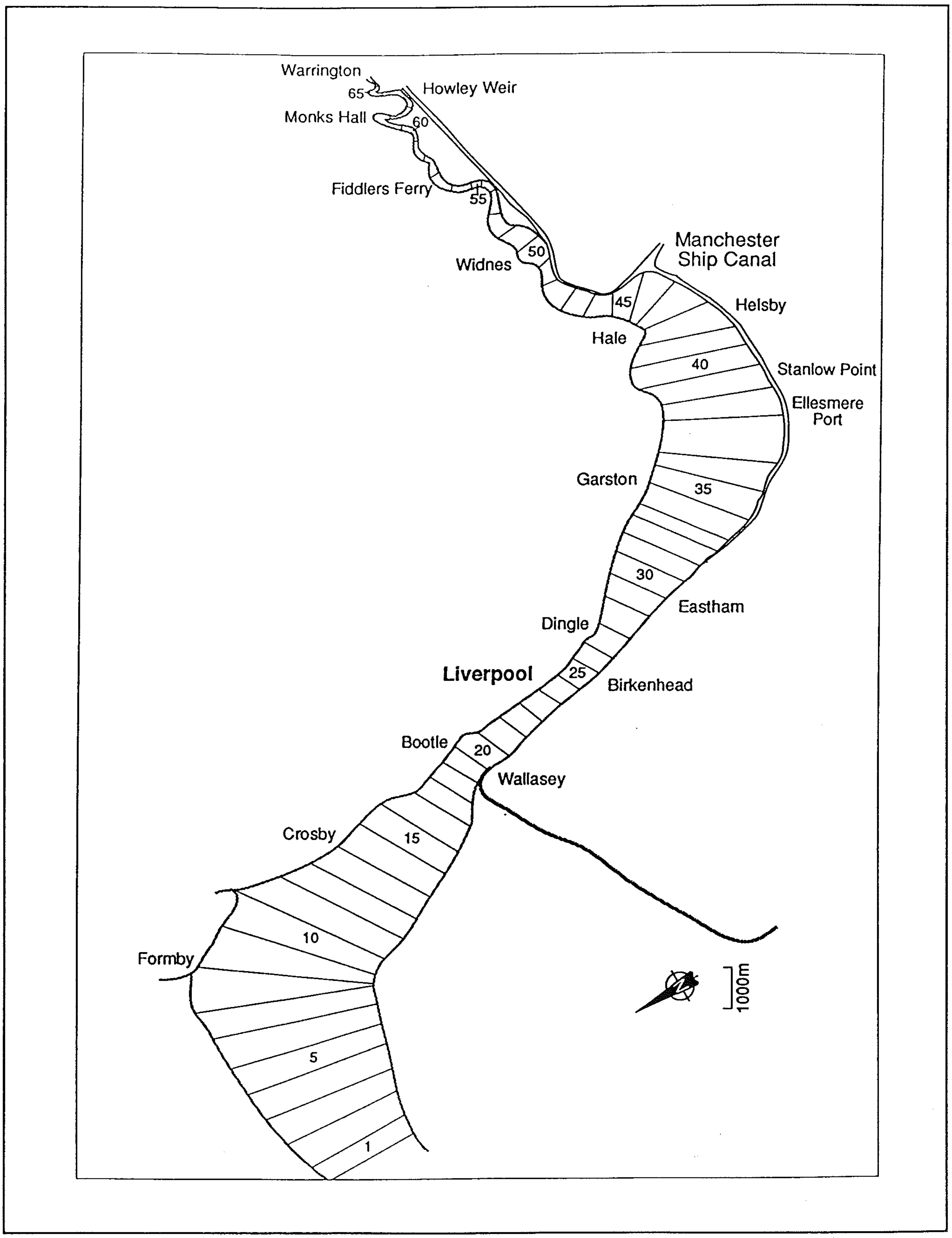


Figure 4 Discretisation in MERMAID

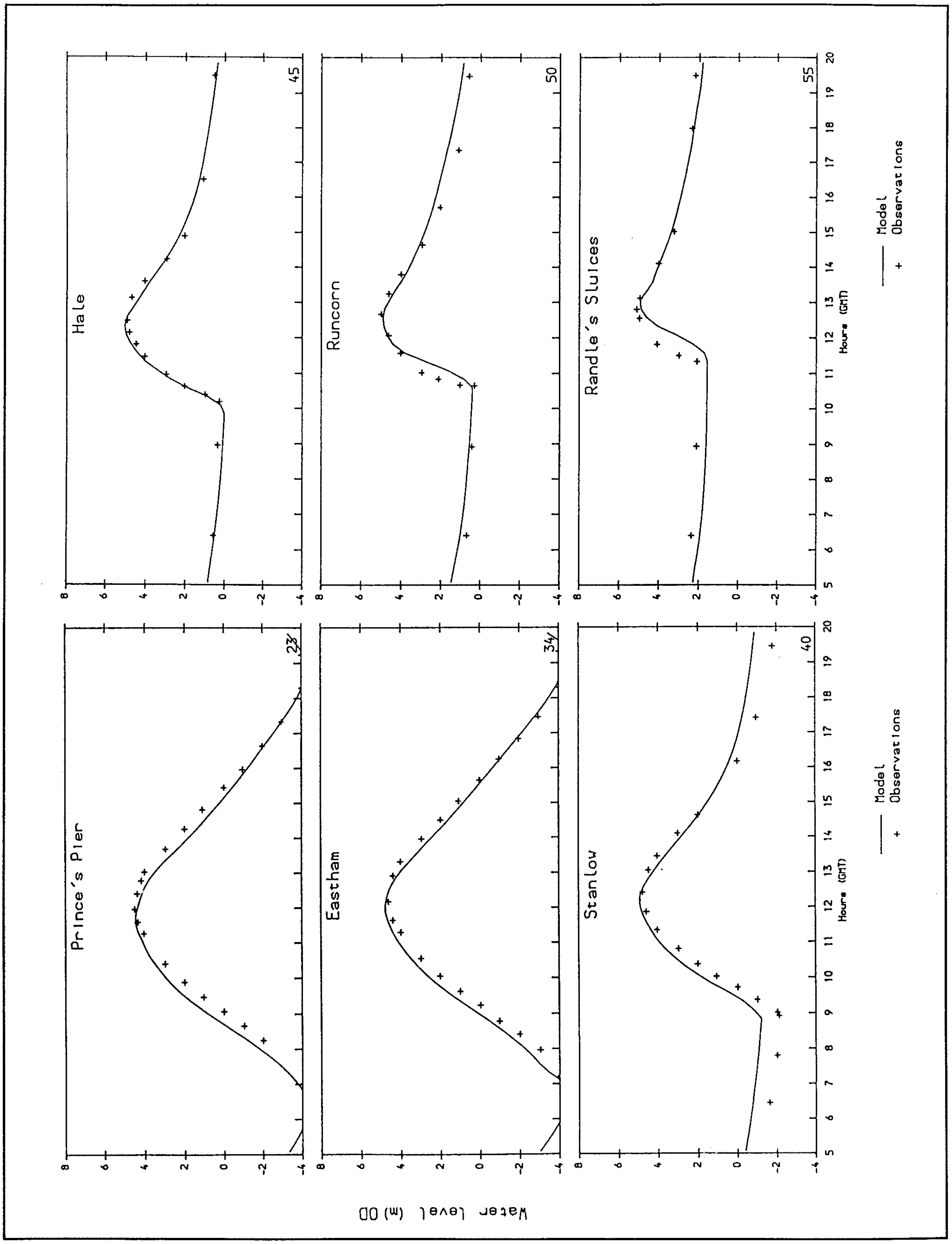


Figure 5 **MERMAID model - West water level comparison**

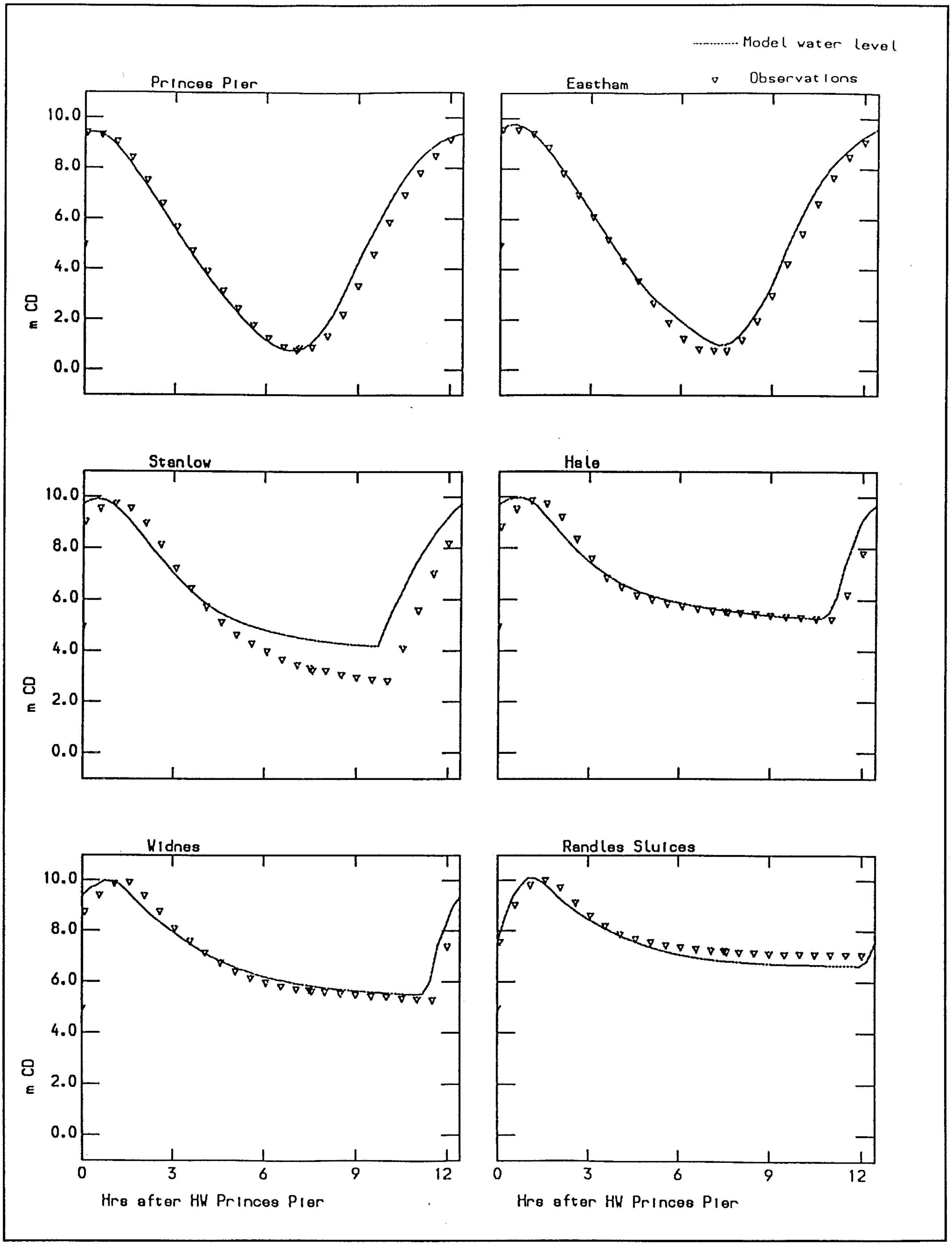


Figure 6 **Mersey 75m TIDEFLOW model - West water level comparison**

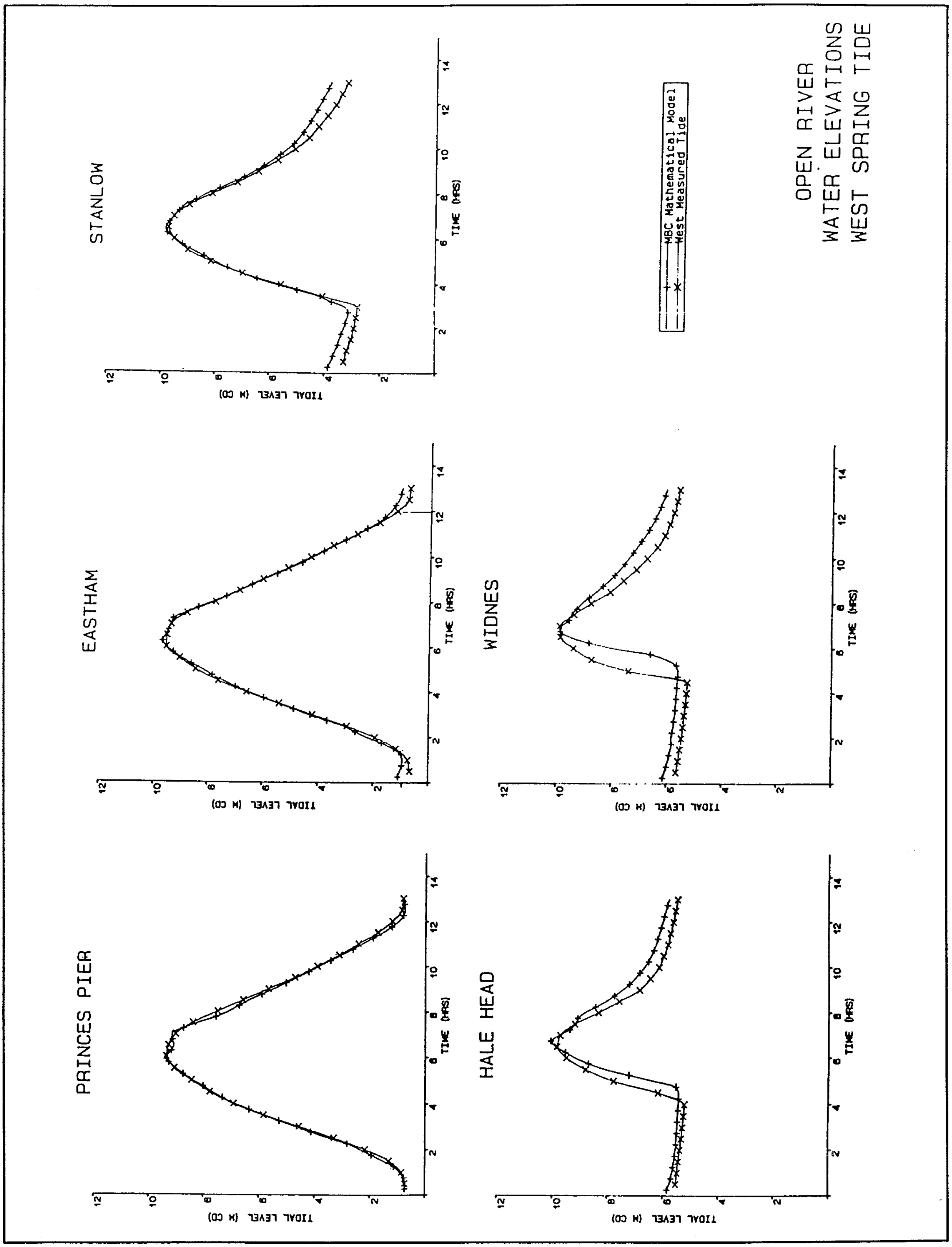


Figure 7 **Mersey DIVAST 150m grid model - West water level comparison**

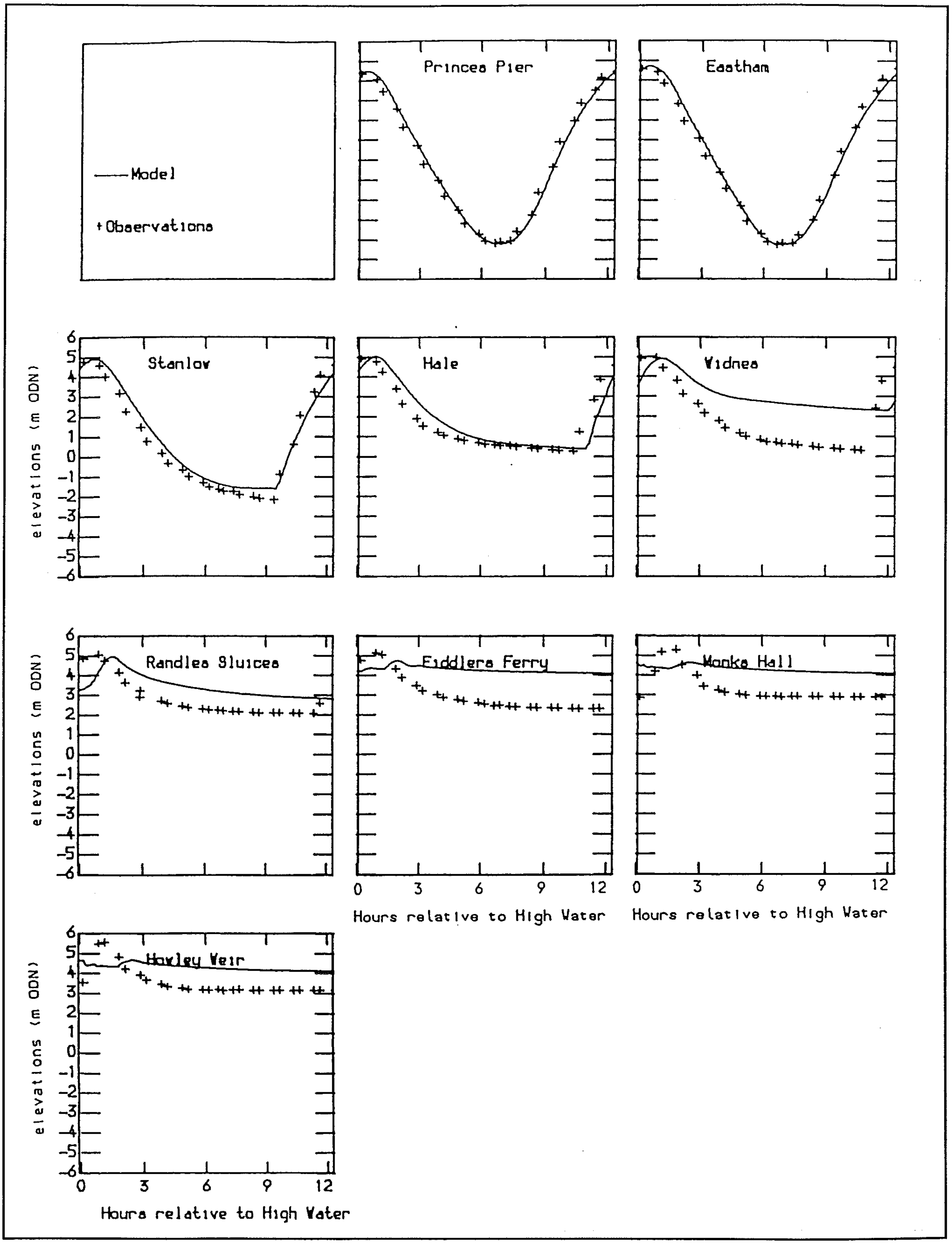


Figure 8 **Mersey TIDEFLOW2D without subgrid detail - West water level comparison**

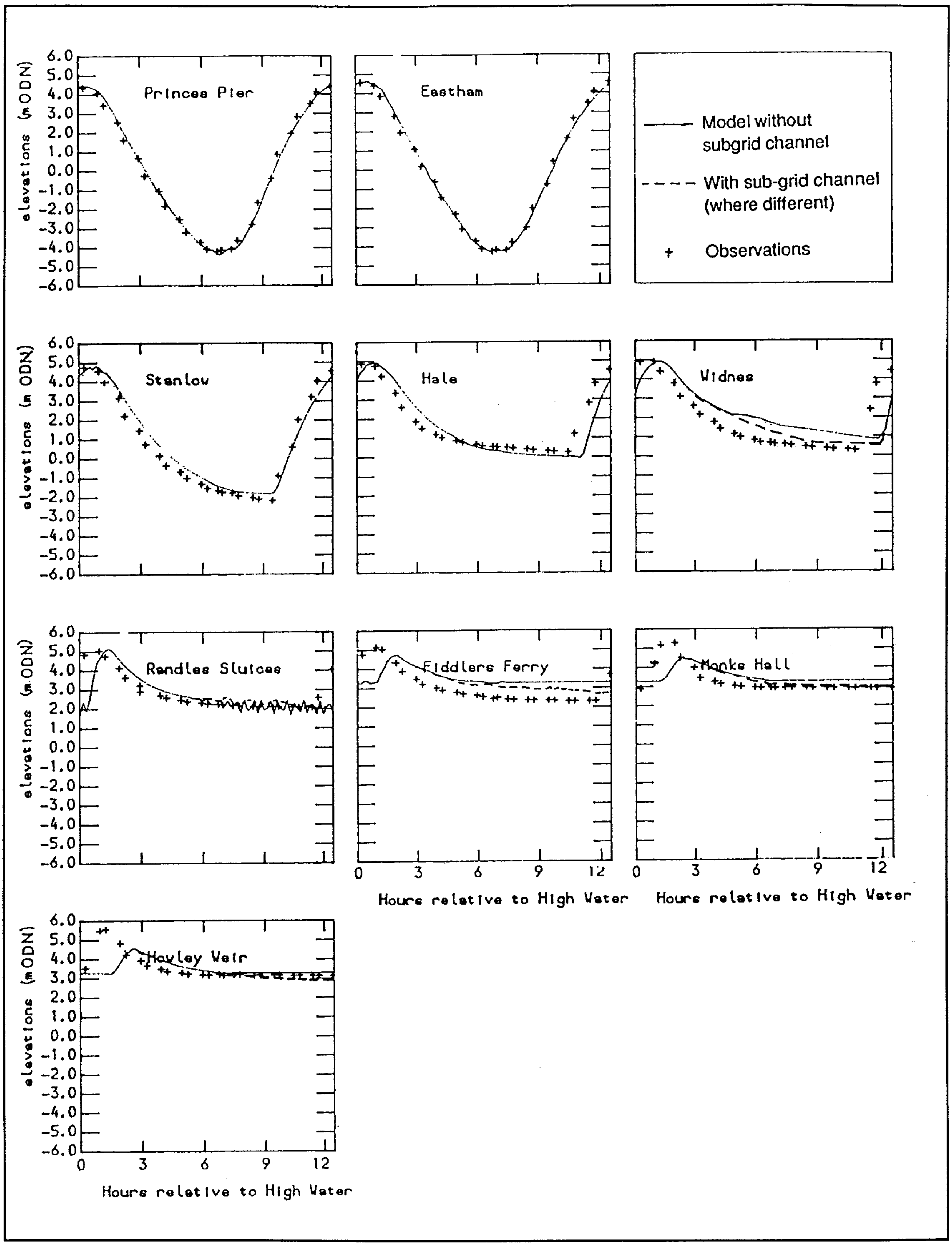


Figure 9 **Mersey TIDEFLOW2D with subgrid detail - West water level comparison**

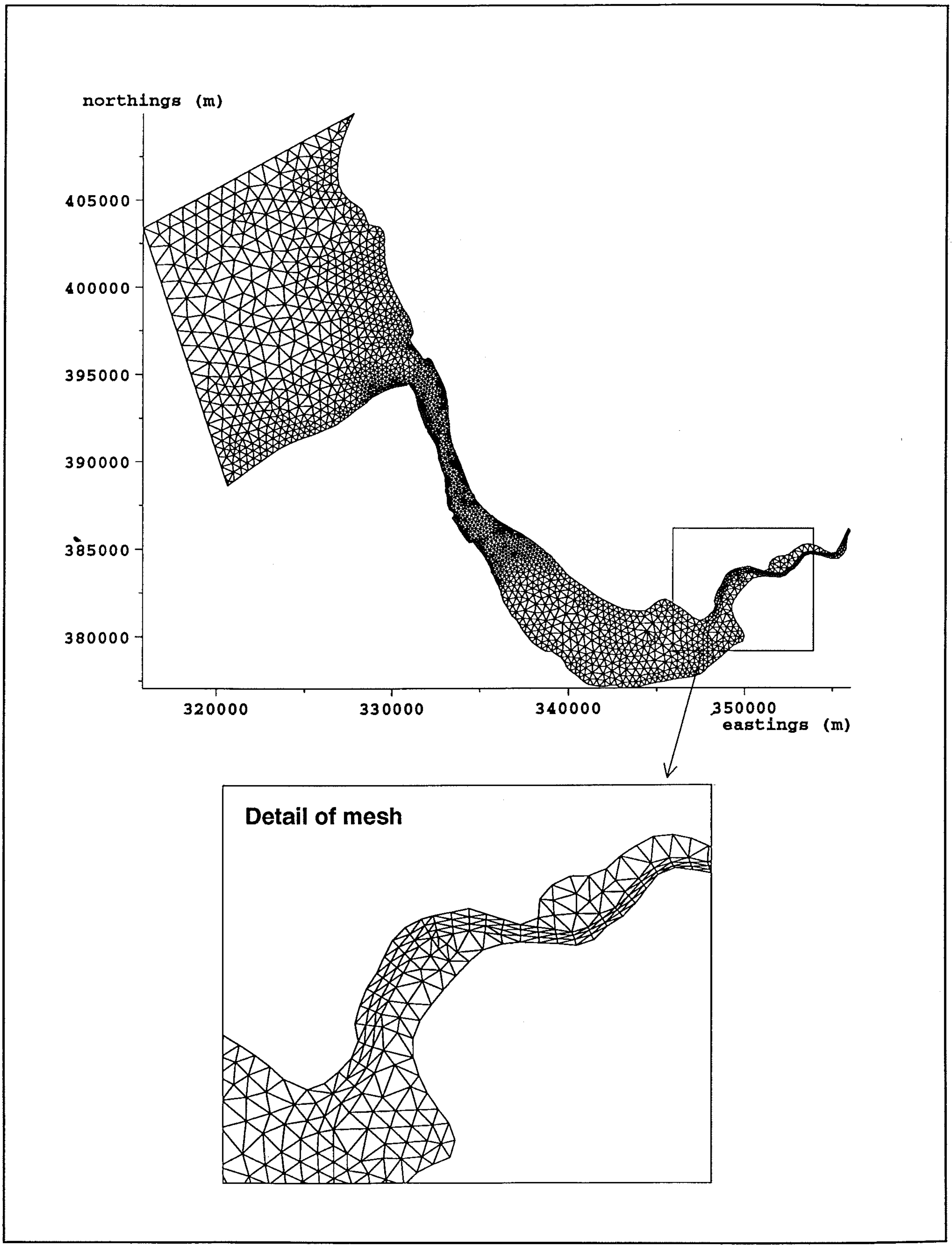


Figure 10 Mersey TELEMAC2D model grid

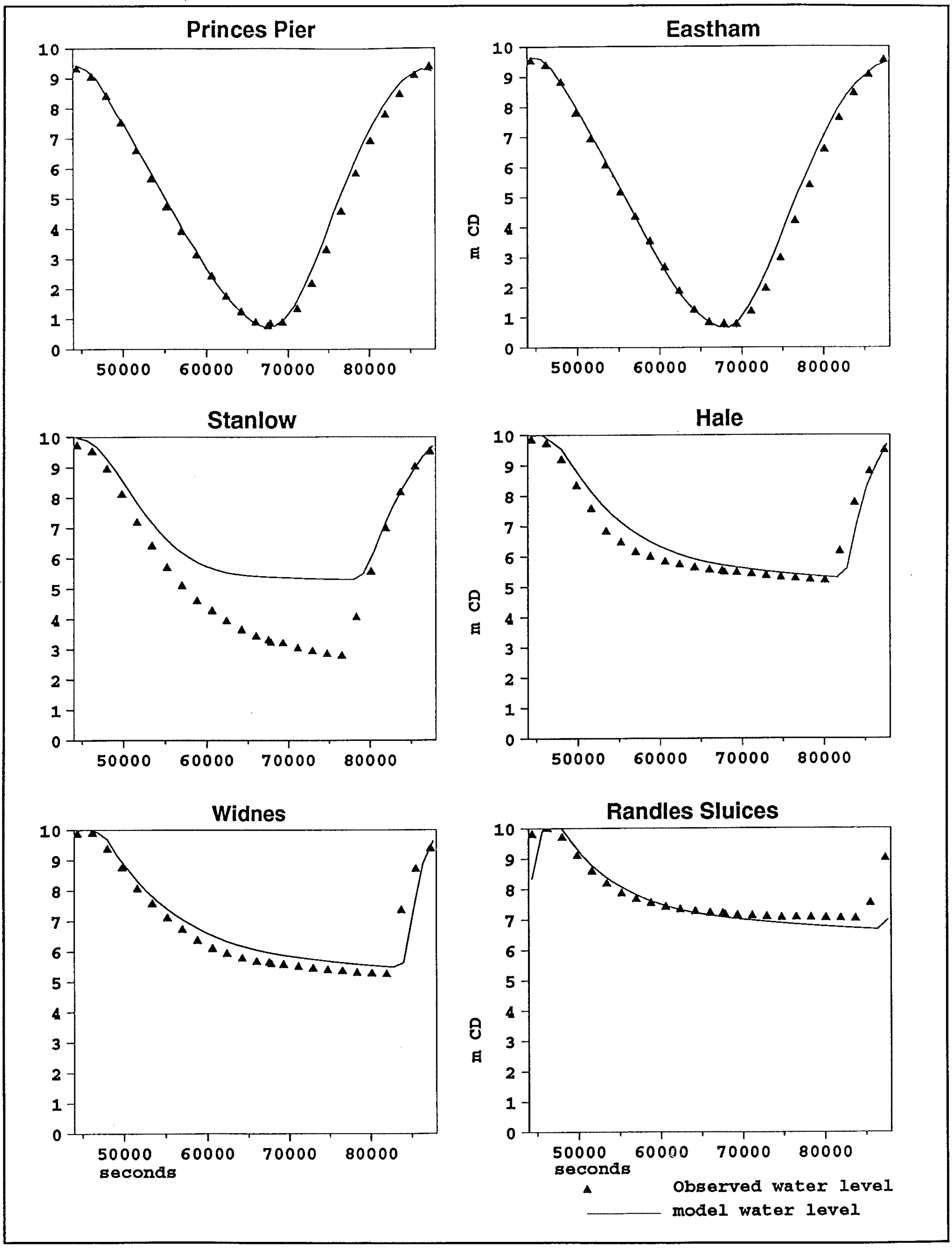


Figure 11 Mersey TELEMAC2D model - West water level comparison

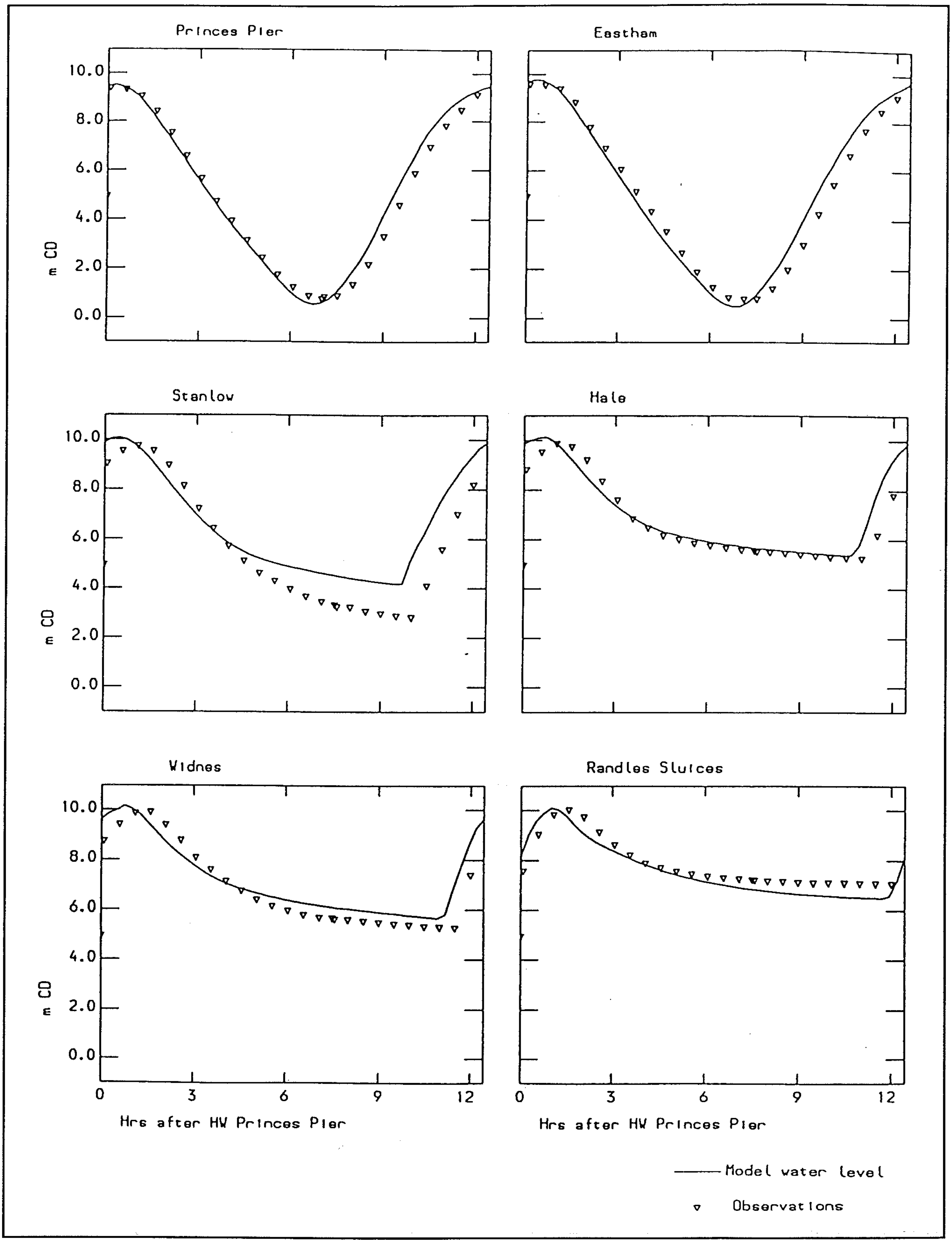


Figure 12 **Mersey TIDEFLOW3D model - West water level comparison**

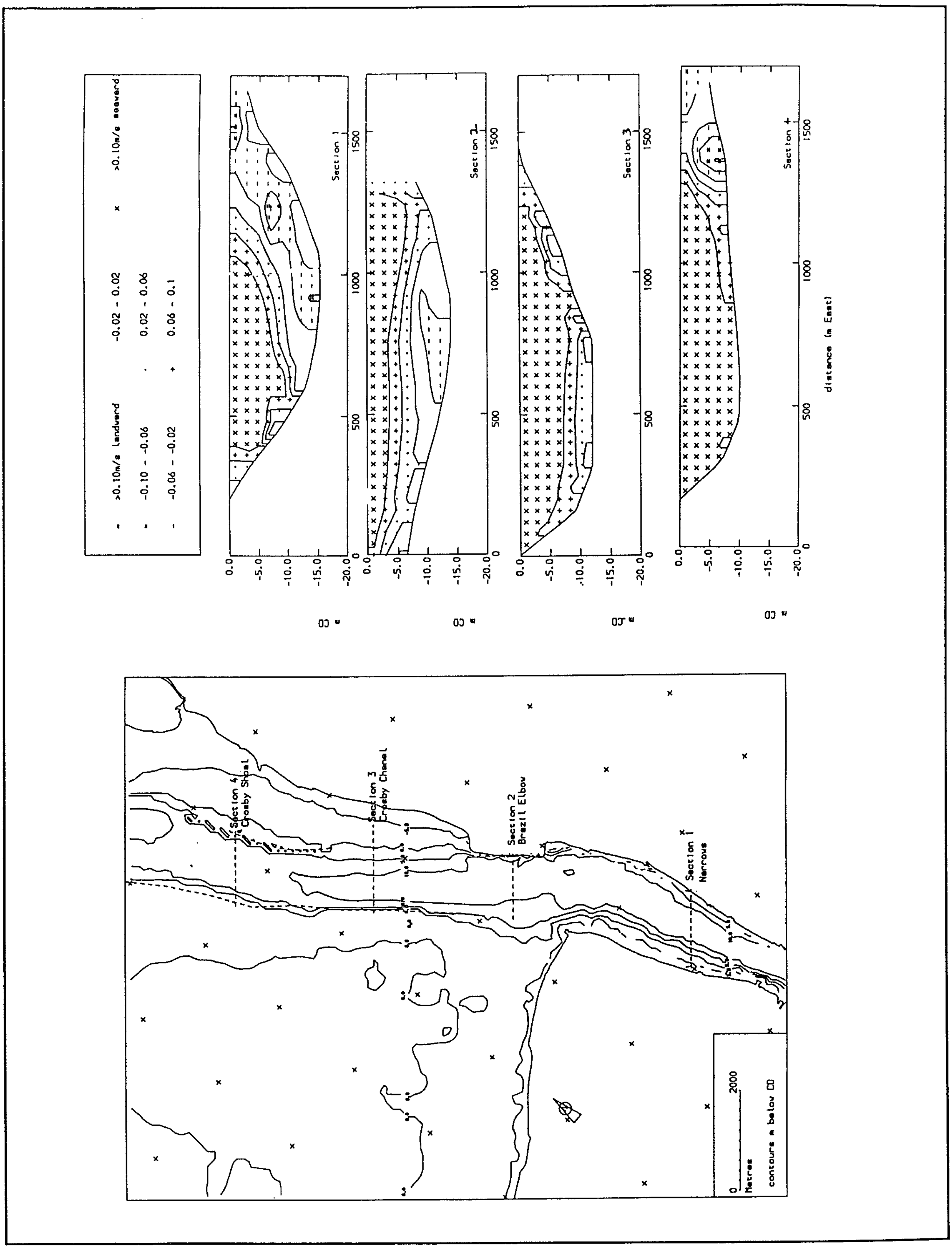


Figure 13 Mersey TIDEFLOW3D model residual currents in the Narrows

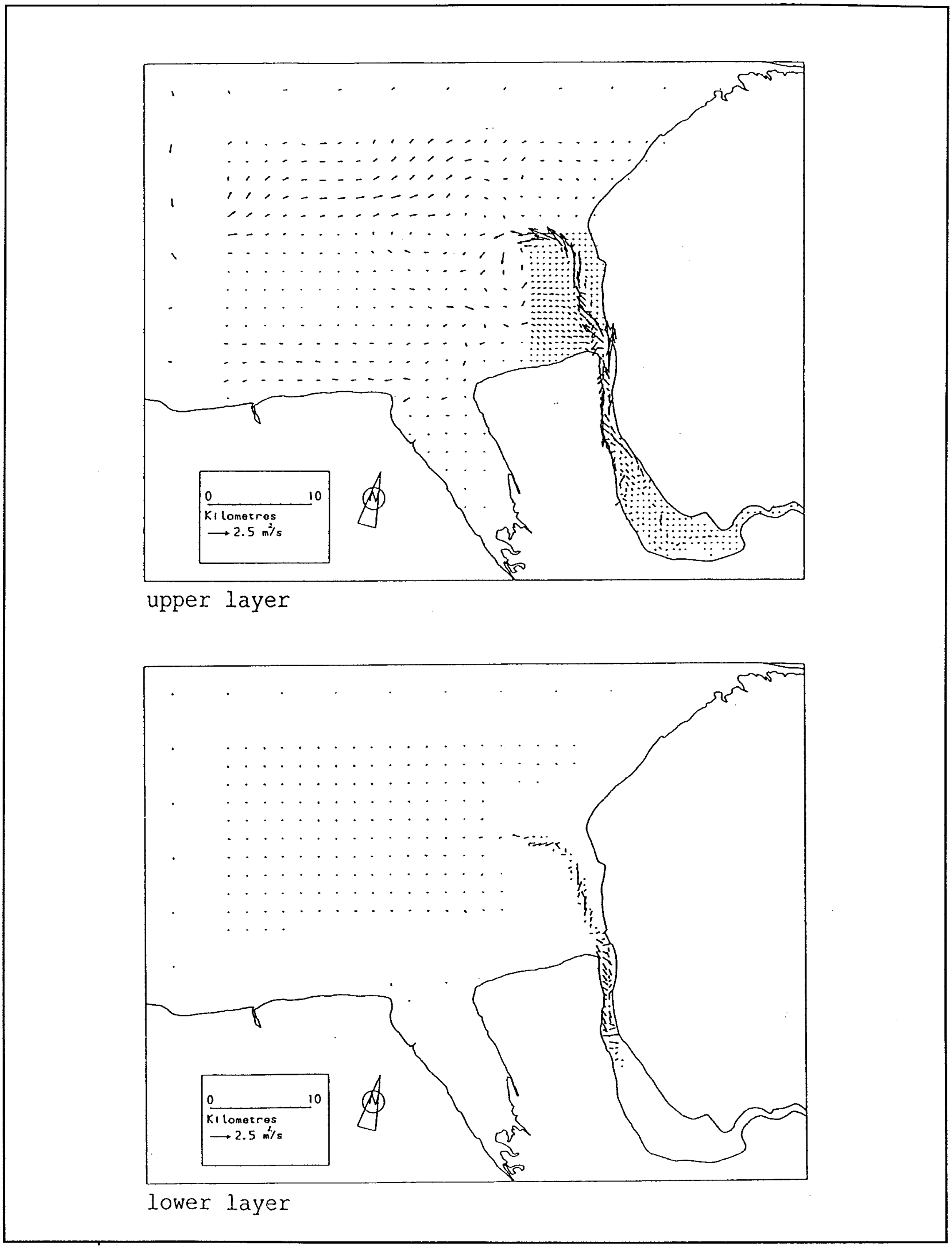


Figure 14 Mersey TIDEFLOW2D2L model residual currents

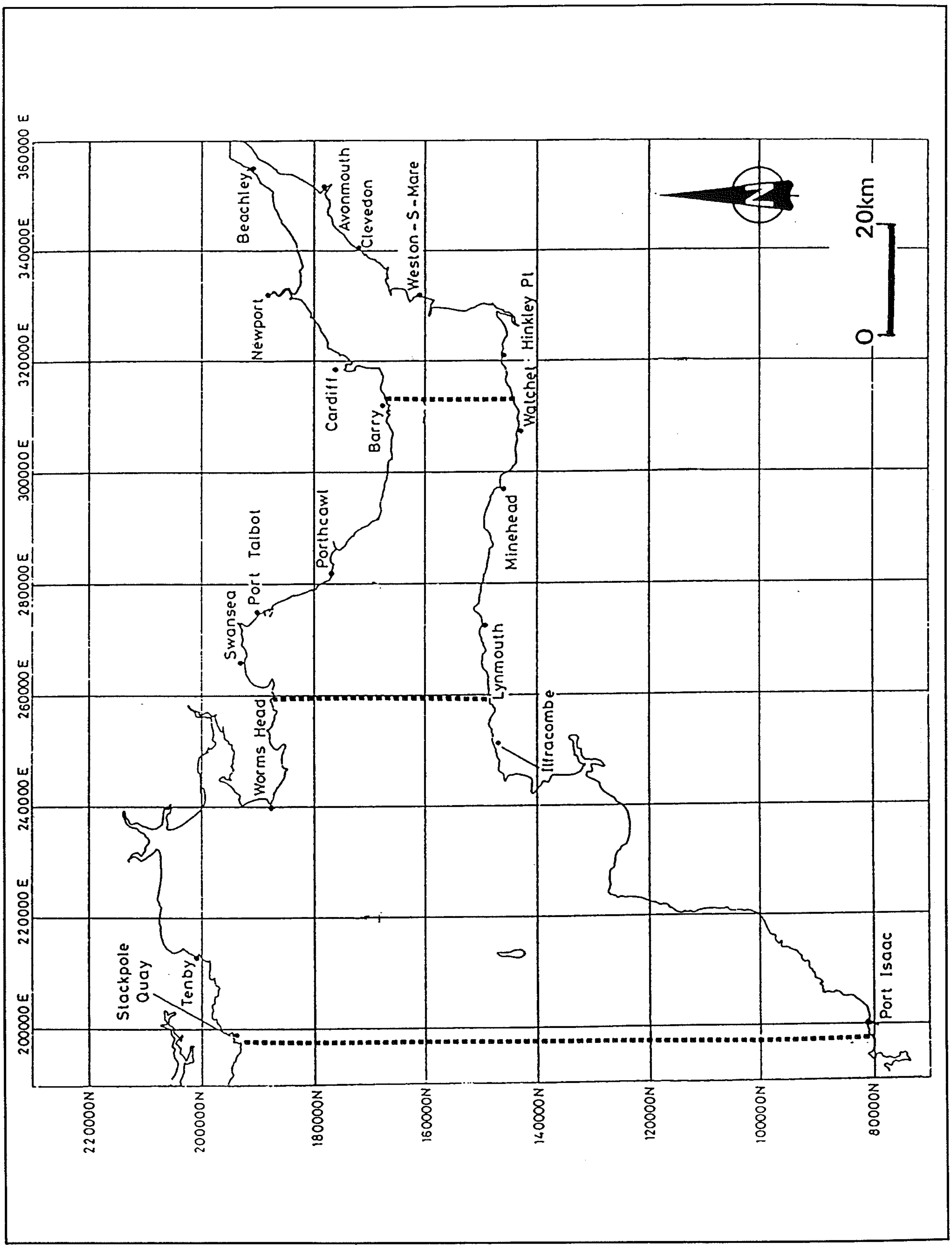


Figure 15 Bristol Channel and Severn estuary, plan

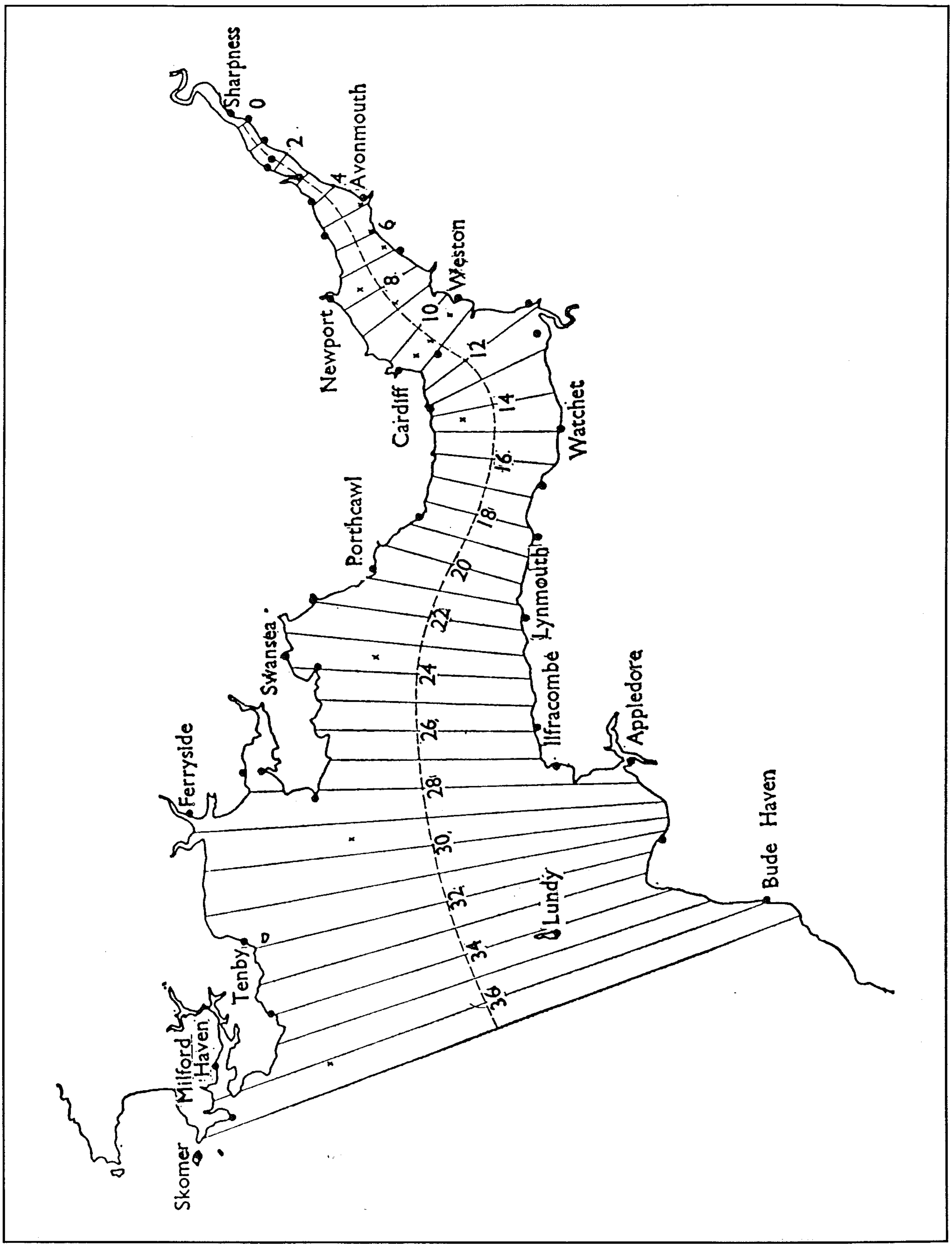


Figure 16 Severn estuary Heaps 1D model

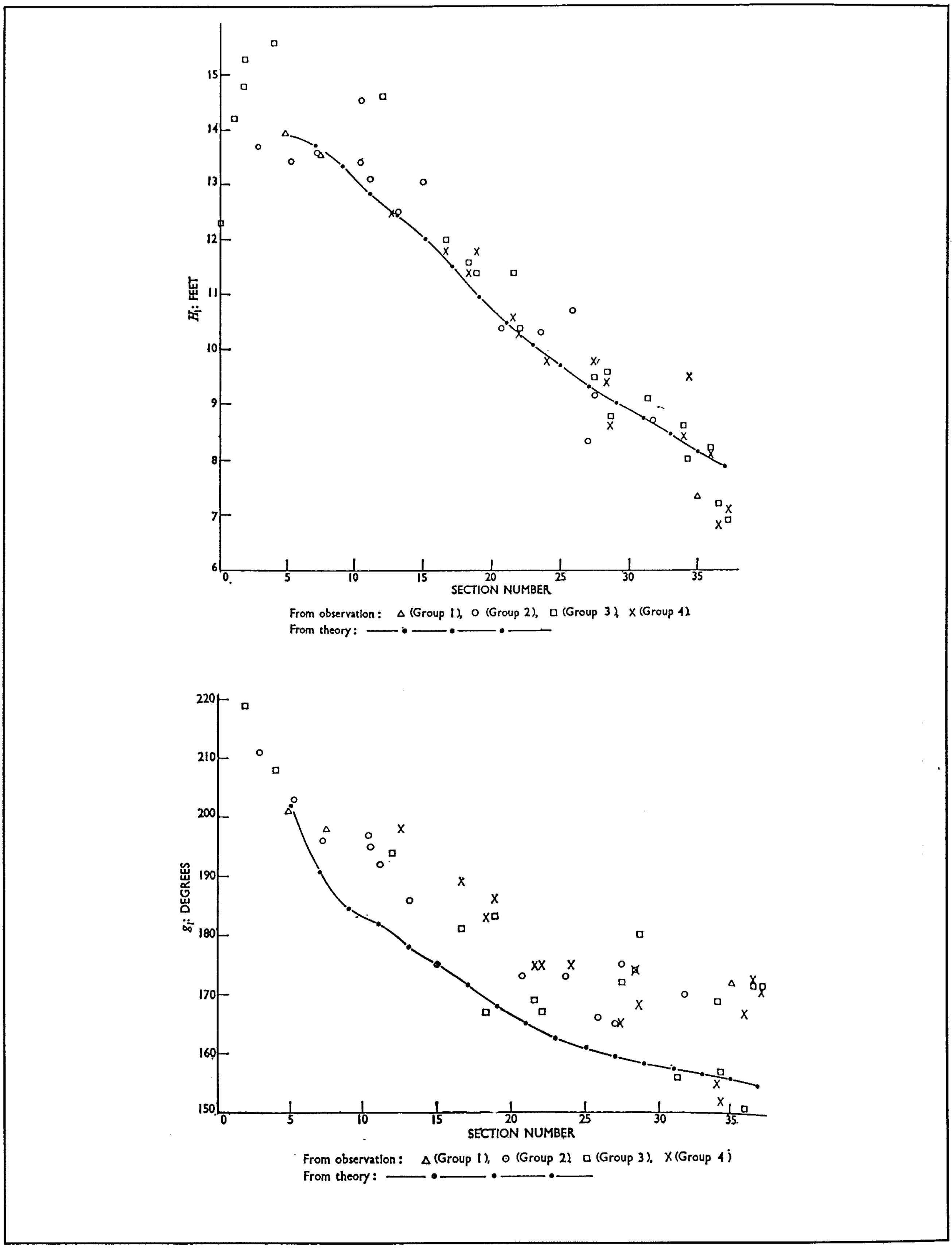


Figure 17 Severn estuary Heaps 1D model, M2 amplitude and phase

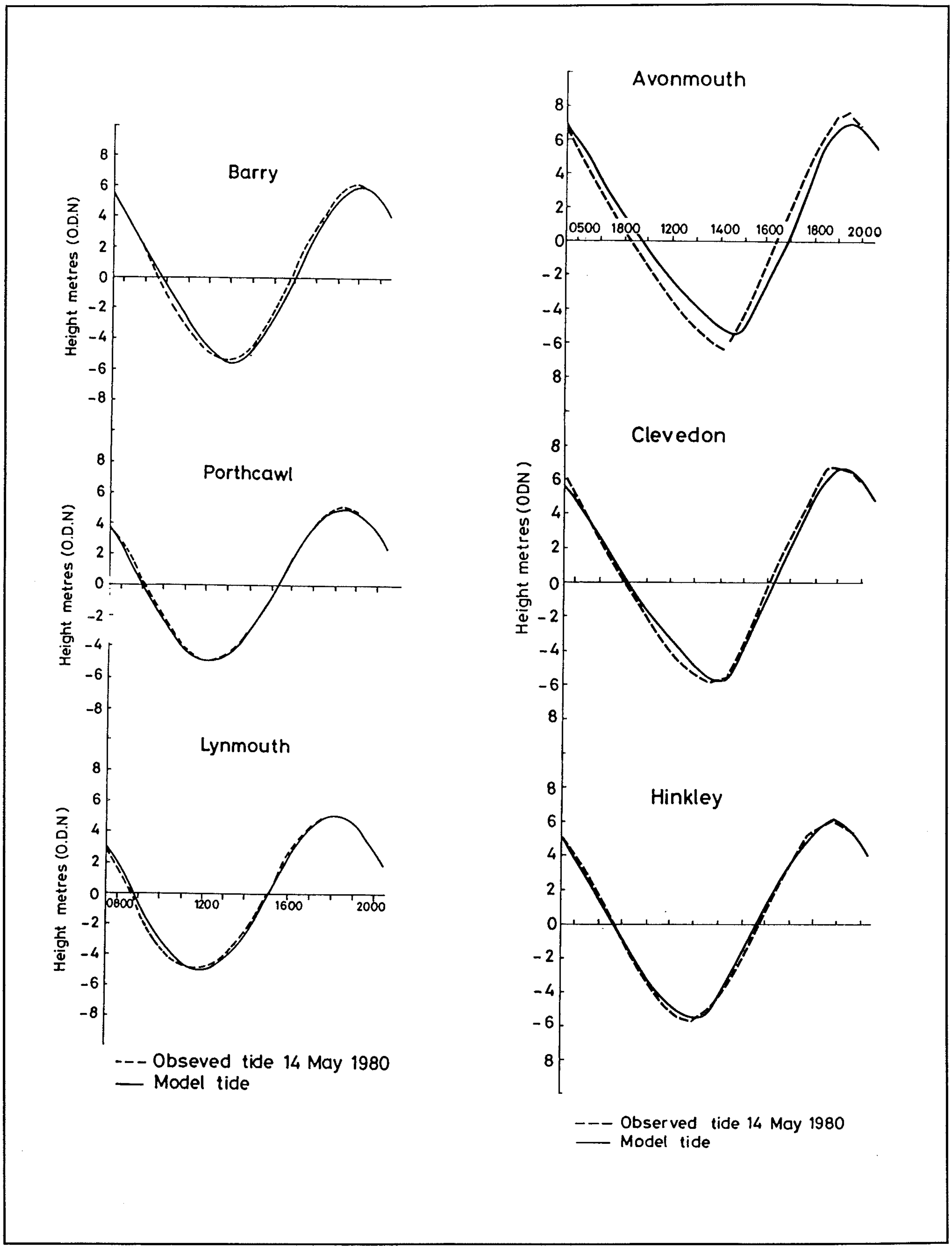


Figure 18 TIDEFLOW2D Bondi model tidal propagation

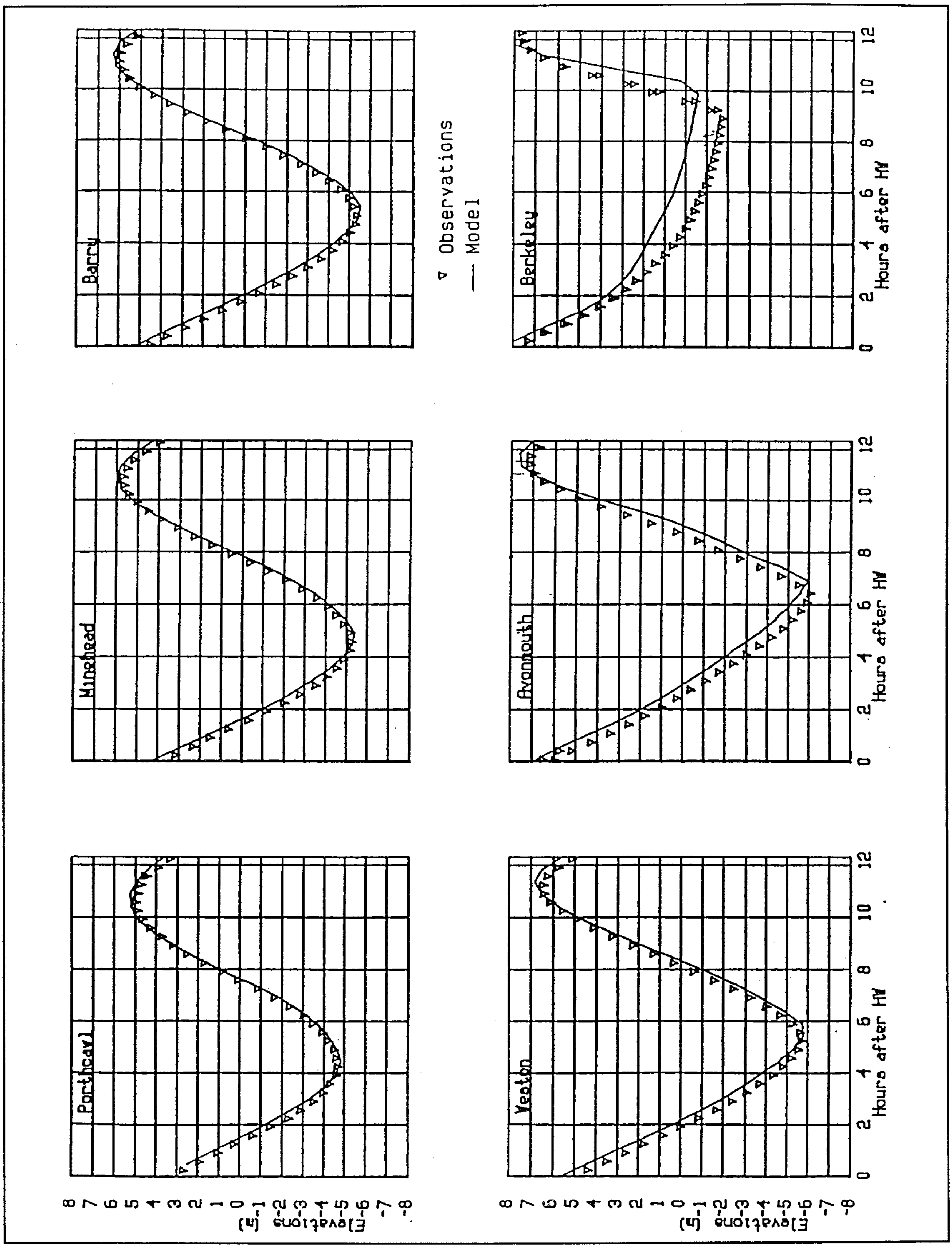


Figure 19 TIDEFLOW2D finer model tidal propagation

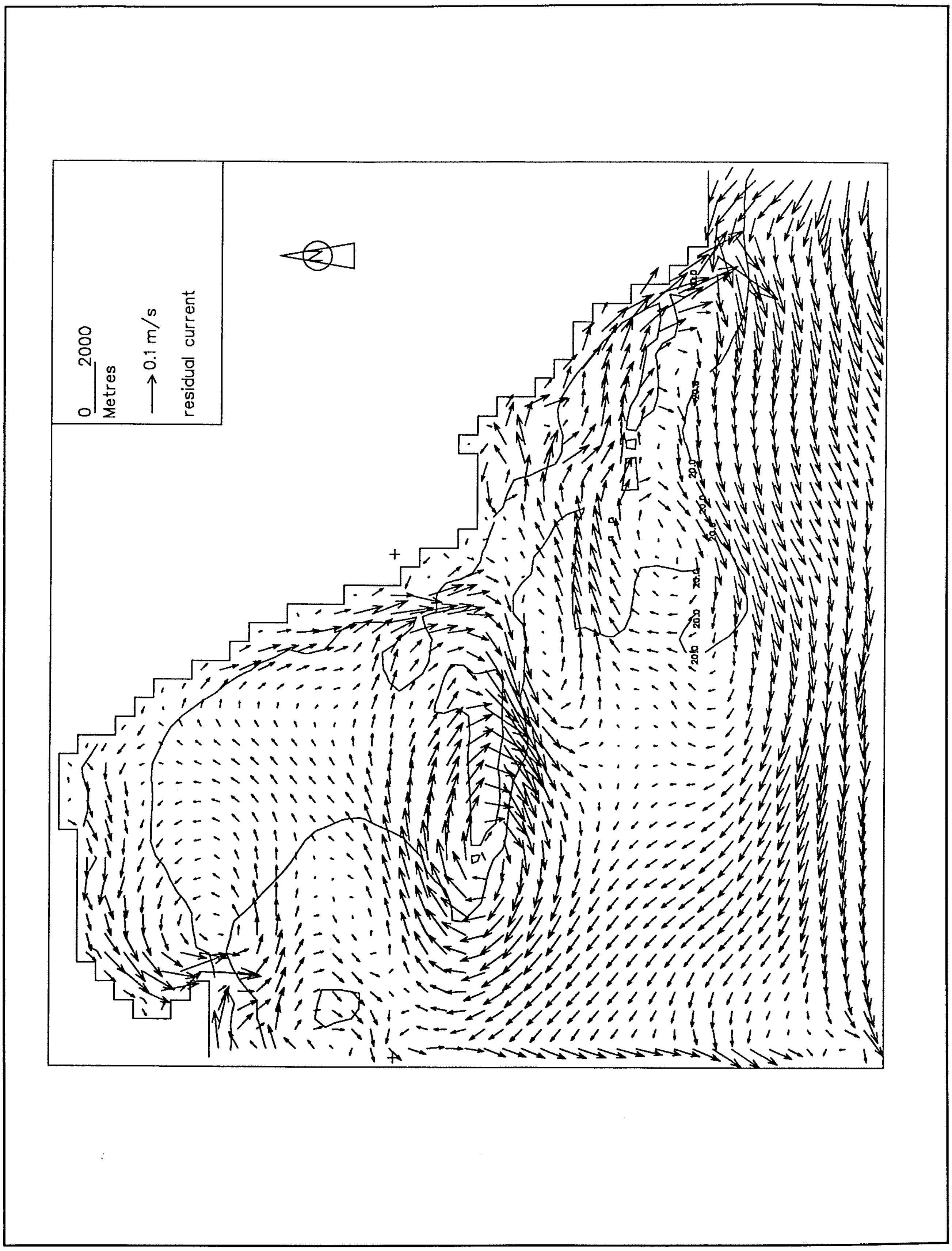


Figure 20 Severn estuary residual flows in TIDEFLOW model

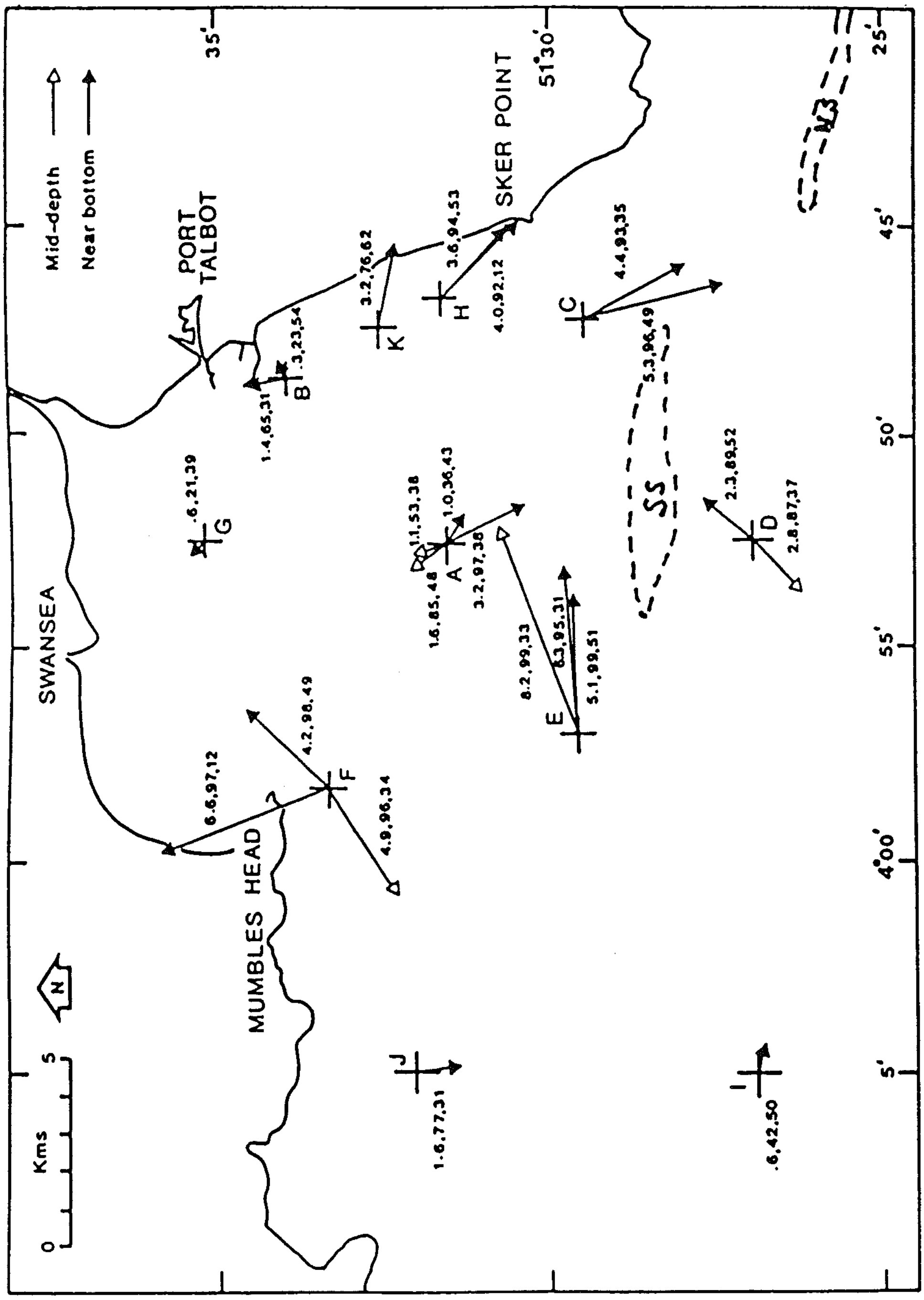


Figure 21 Observed residuals at Nash Bank

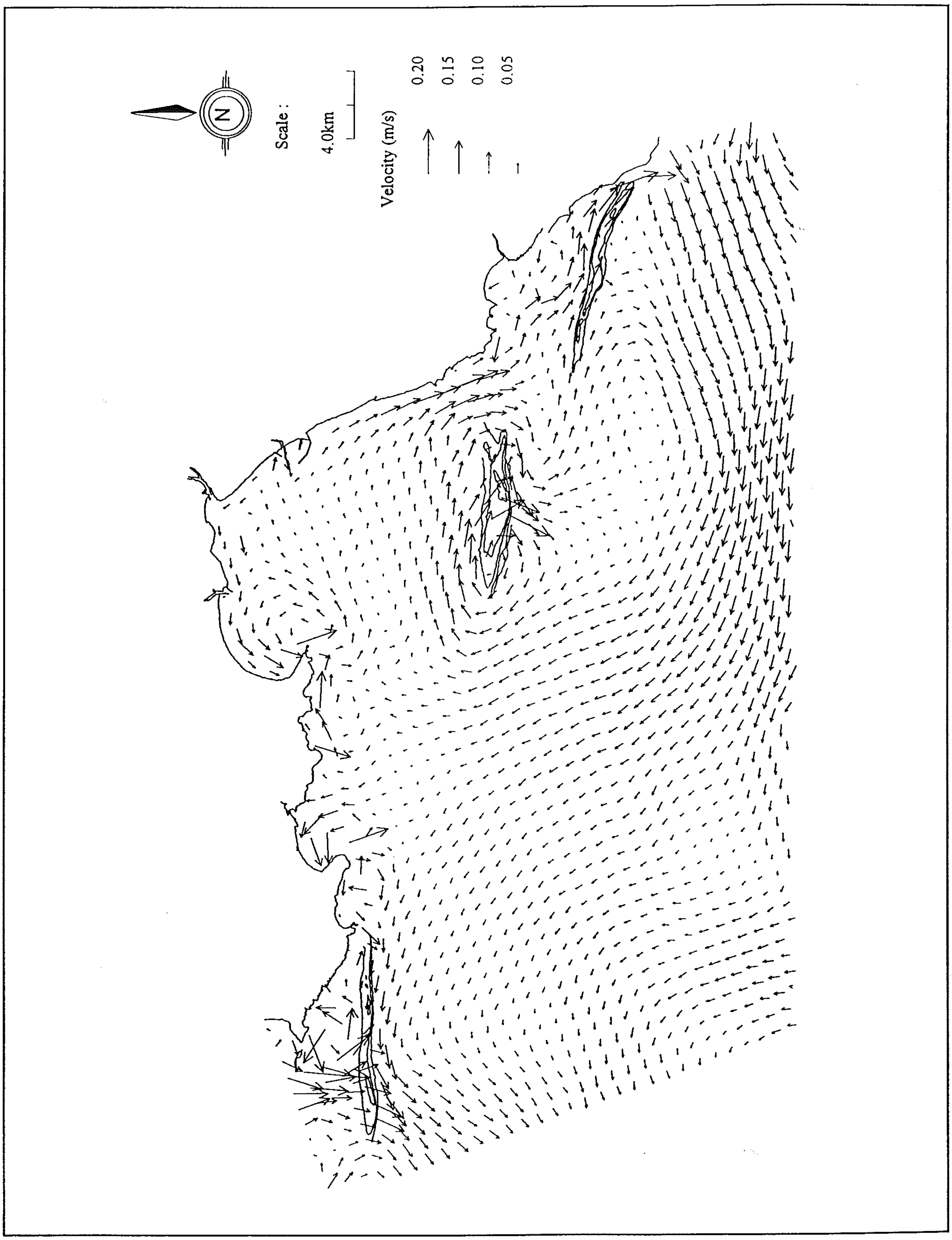


Figure 22 **Severn estuary residual currents DIVAST model**

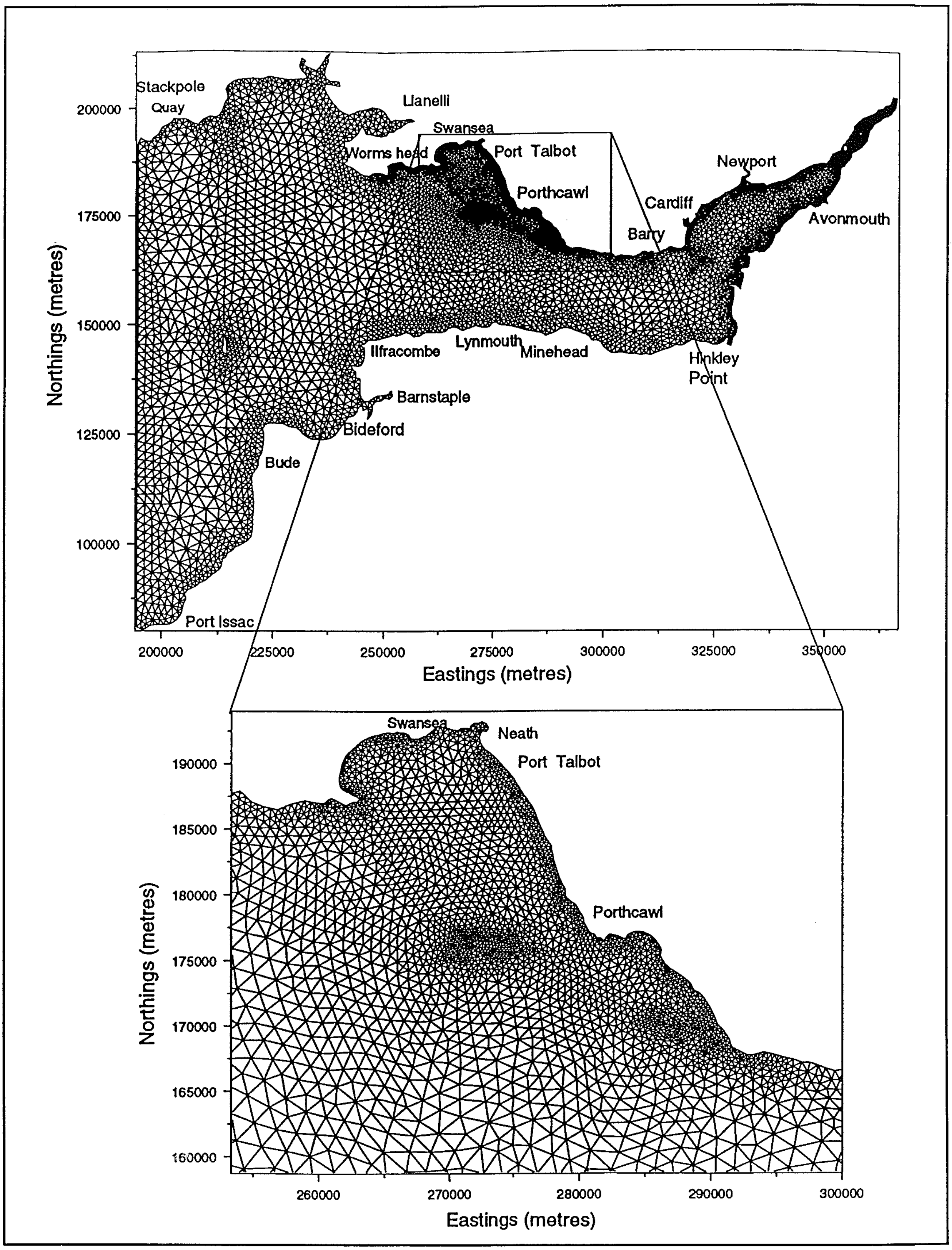


Figure 23 Severn estuary - TELEMAC model grid

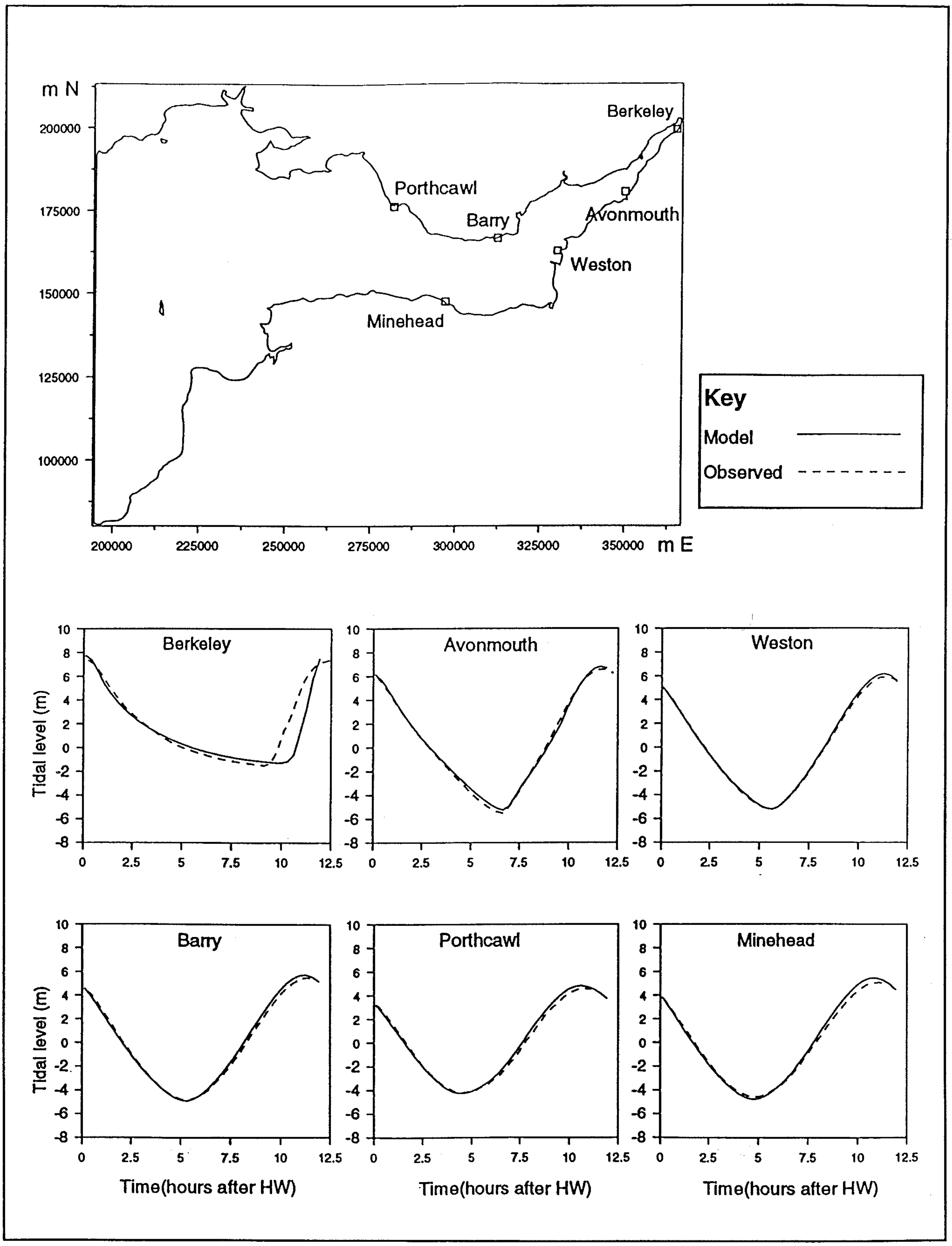


Figure 24 Severn estuary TELEMAC model tidal propagation

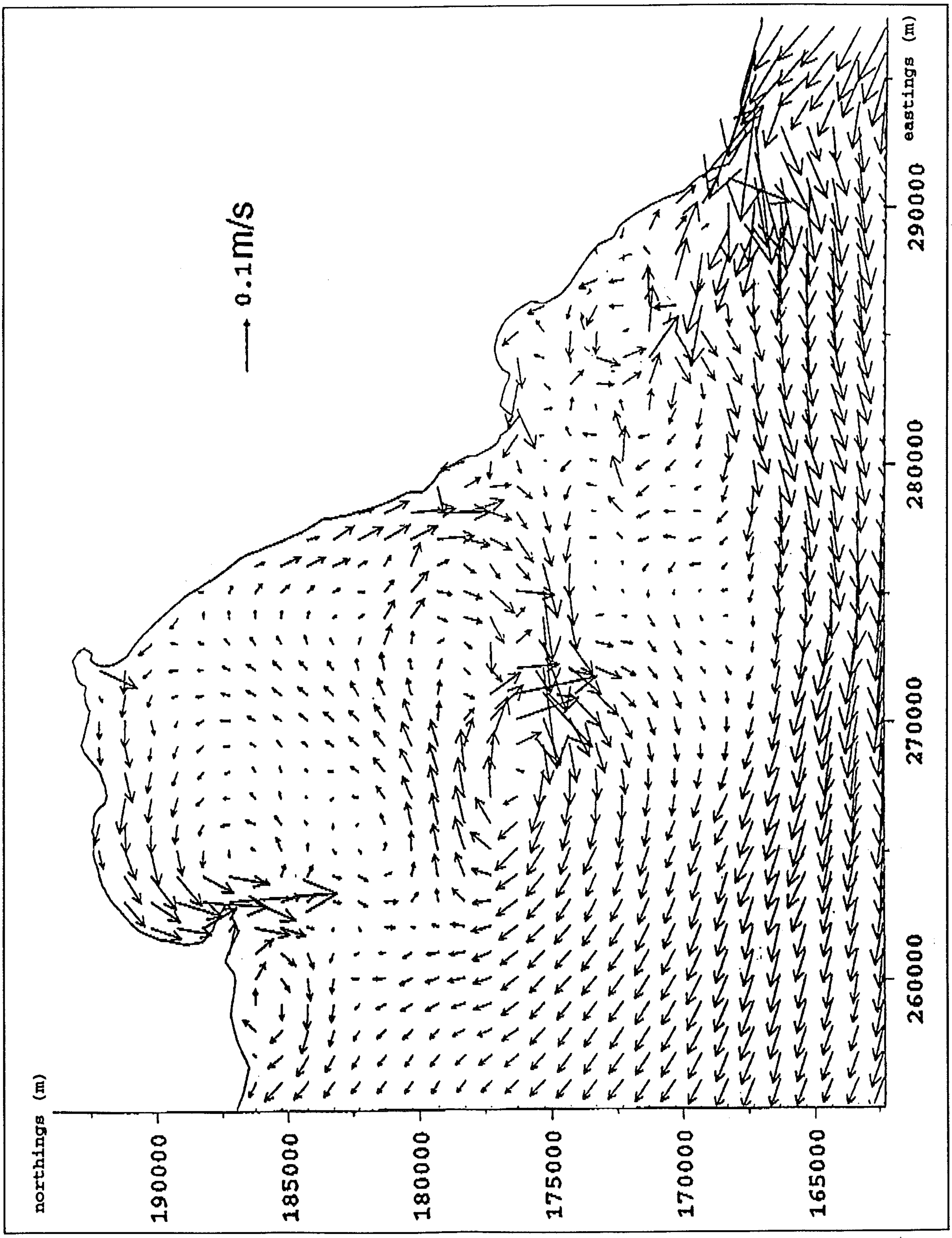
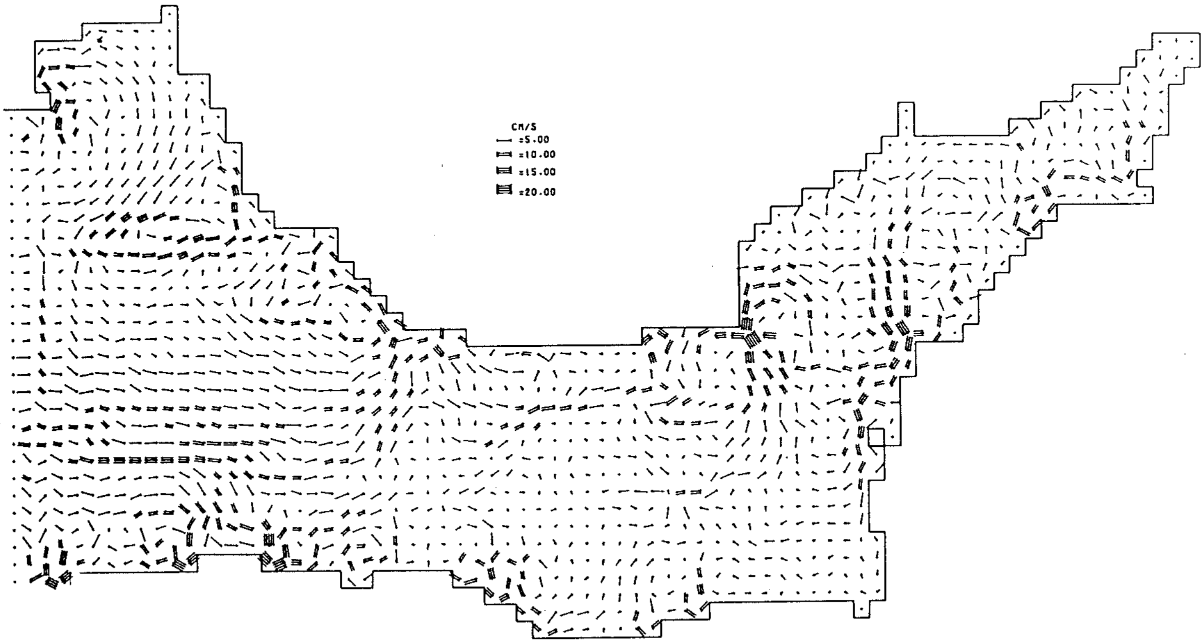
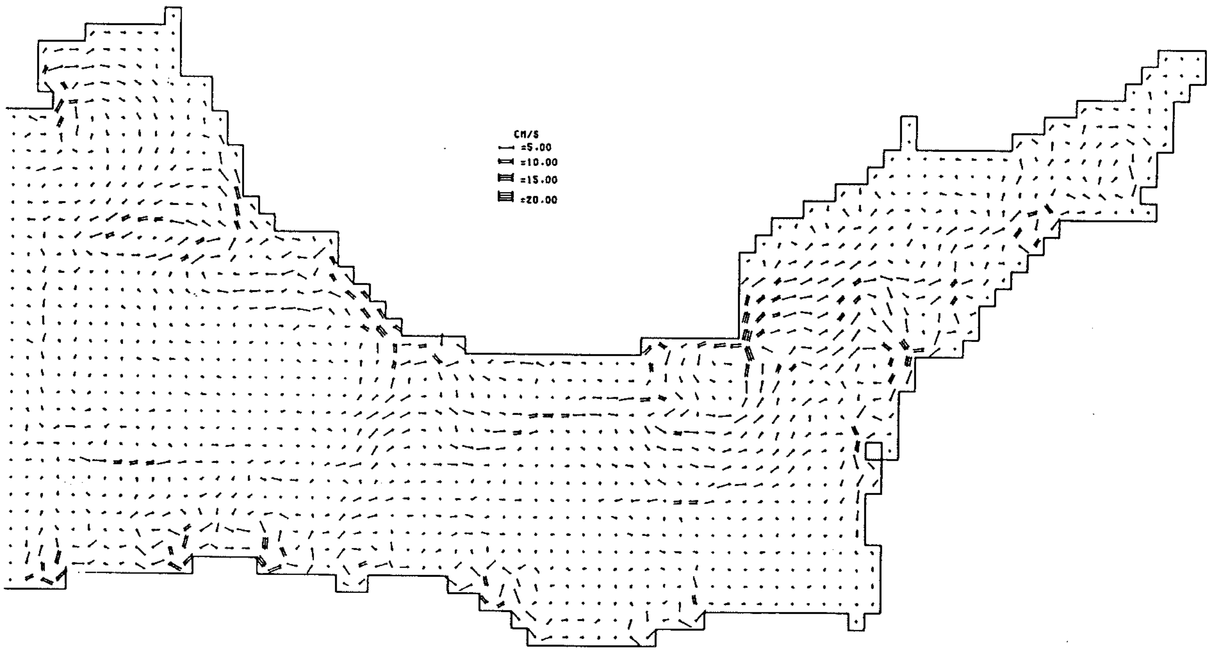


Figure 25 **TELEMAC model residual currents**



Surface residuals.



Bottom residuals.

Figure 26 Severn estuary 3D flow model residuals

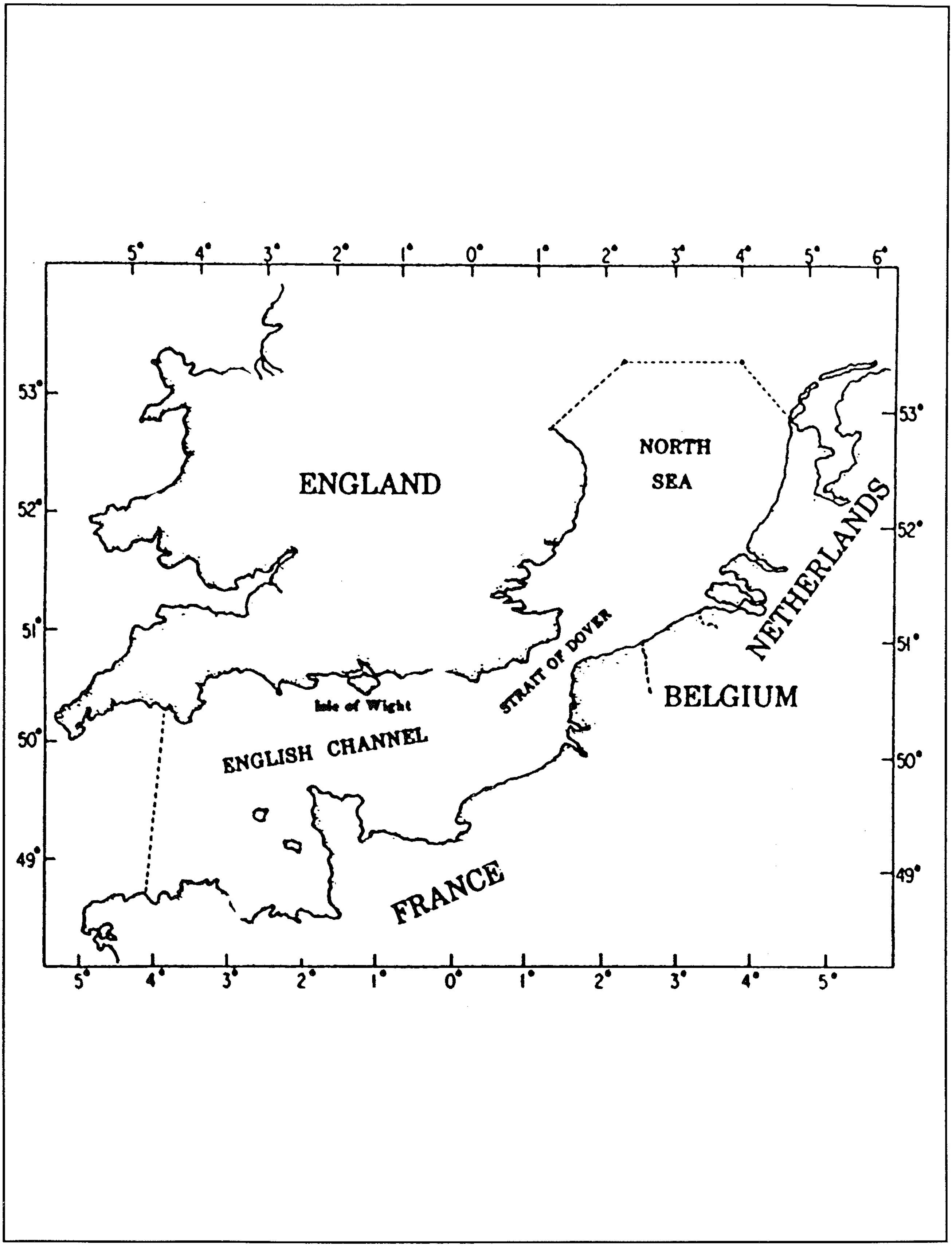


Figure 27 North sea, plan

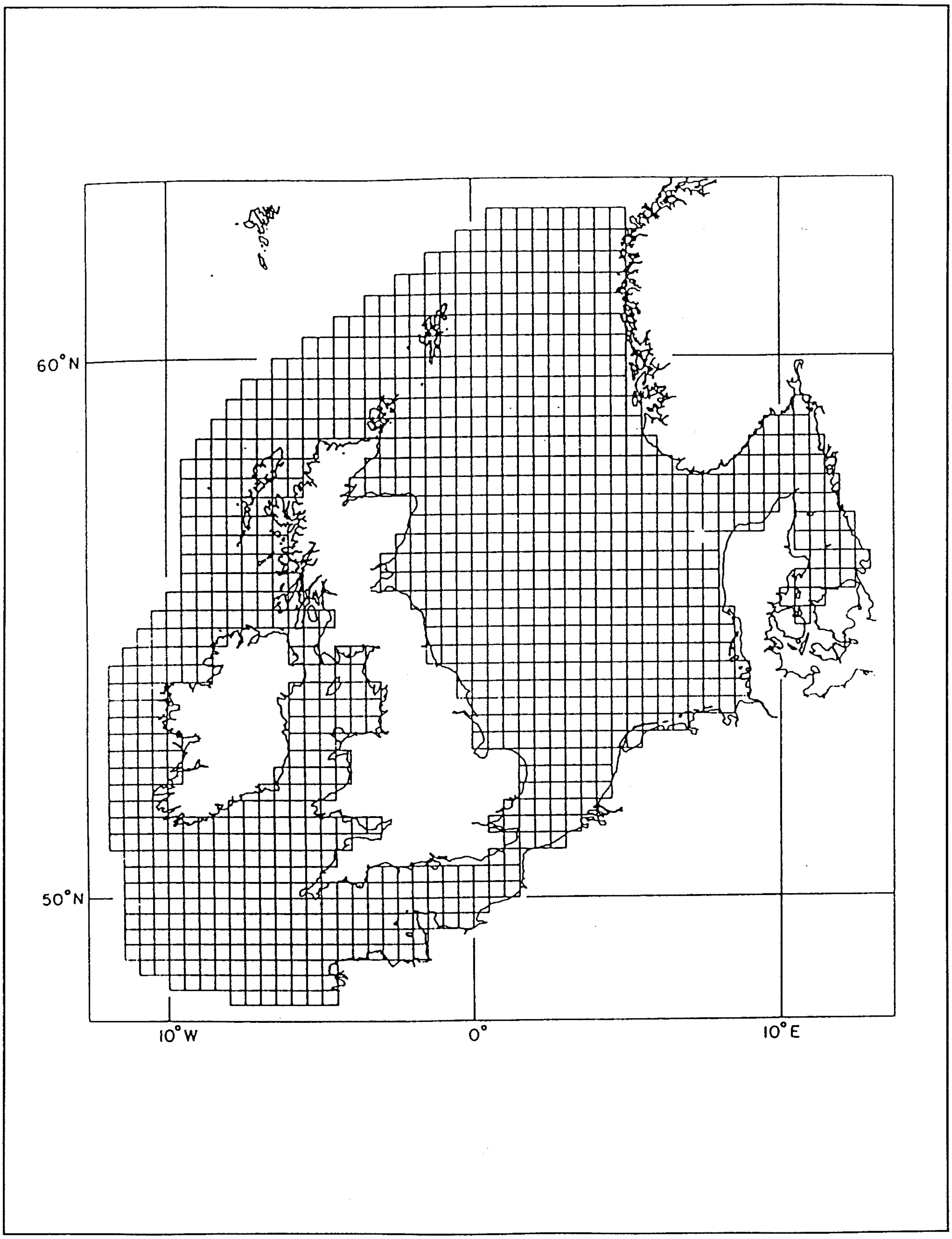


Figure 28 **Model area Davies' model**

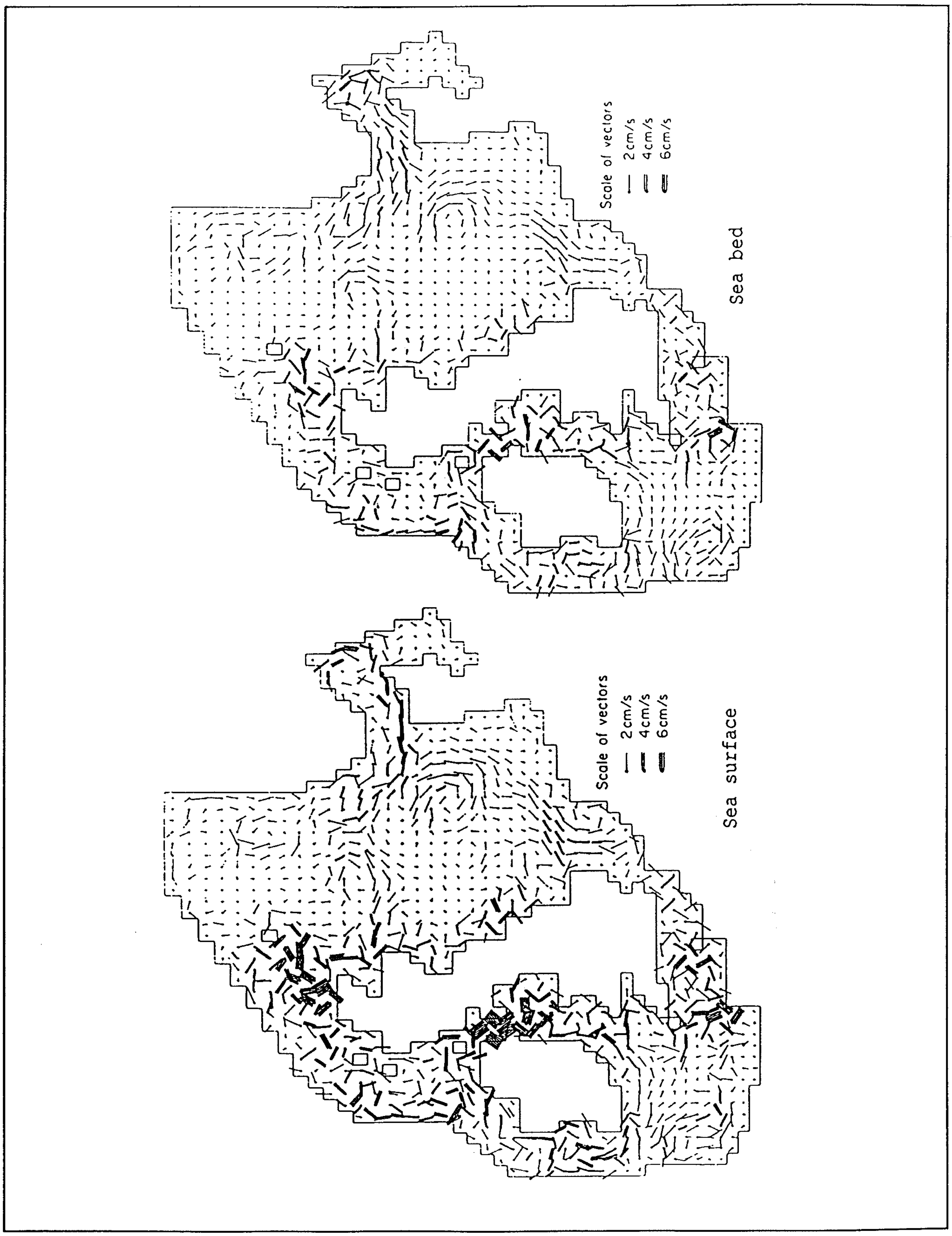


Figure 29 Residual currents without wind Davies' model

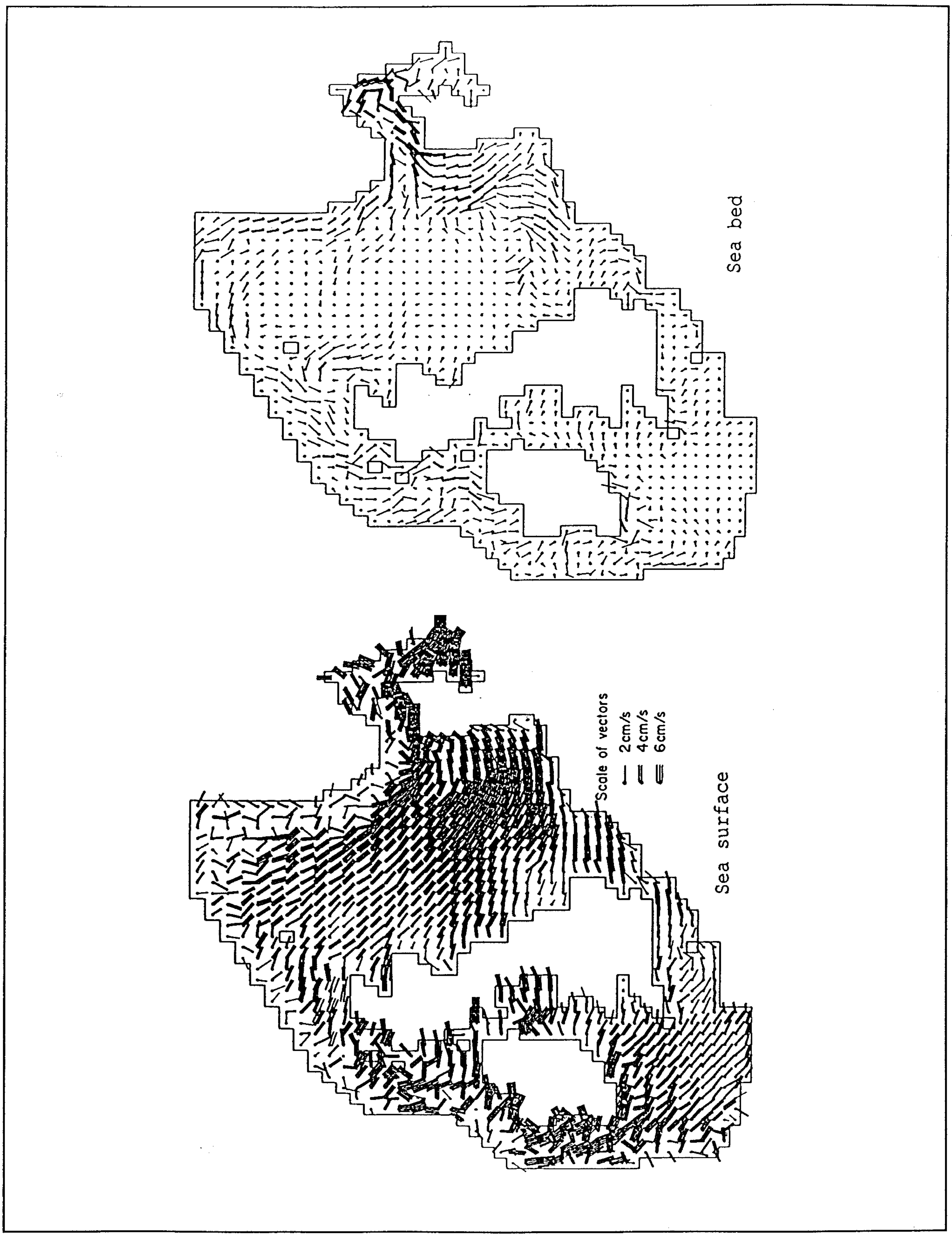


Figure 30 Residual currents with wind Davies' model

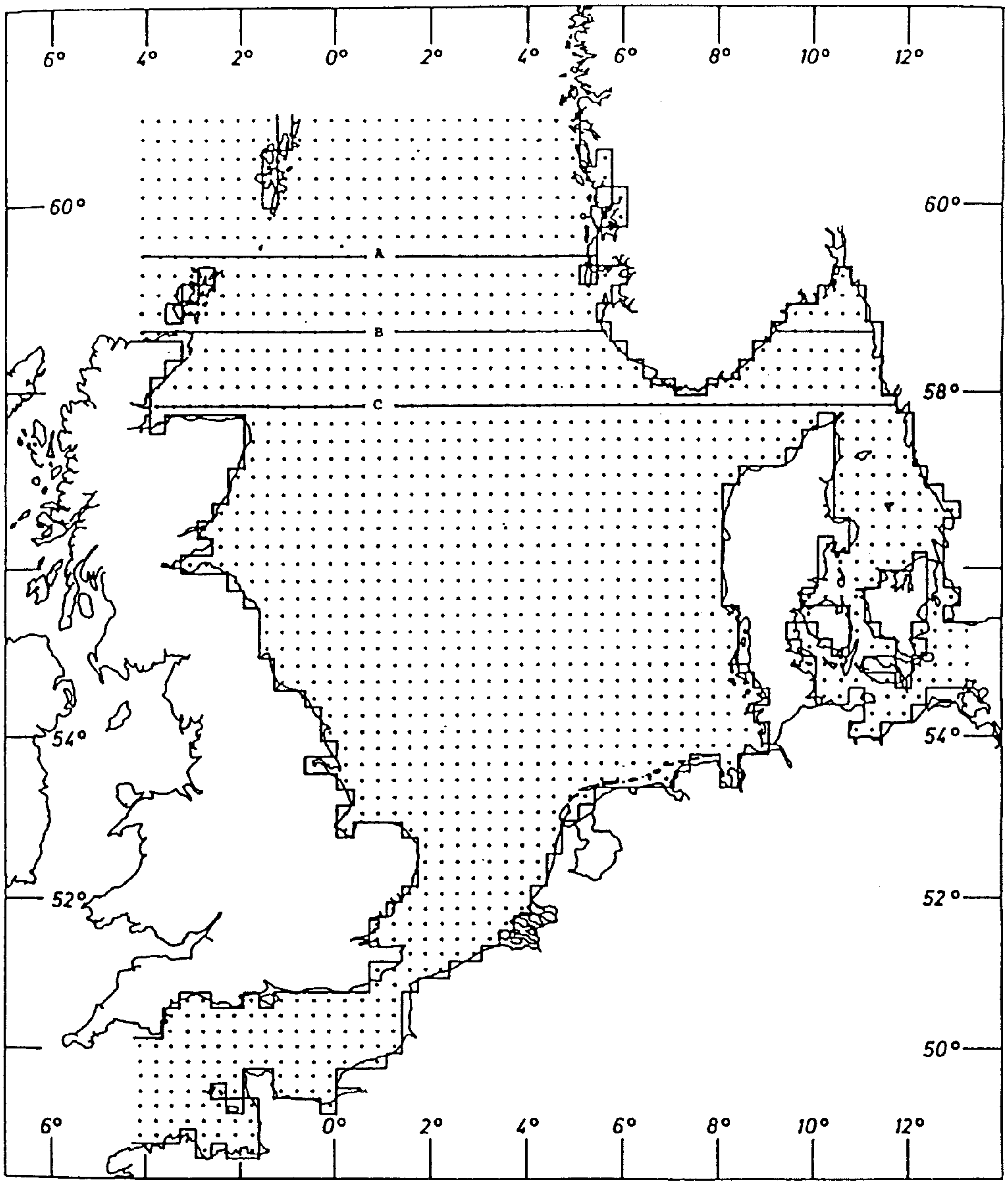


Figure 31 Model area Backhaus' model

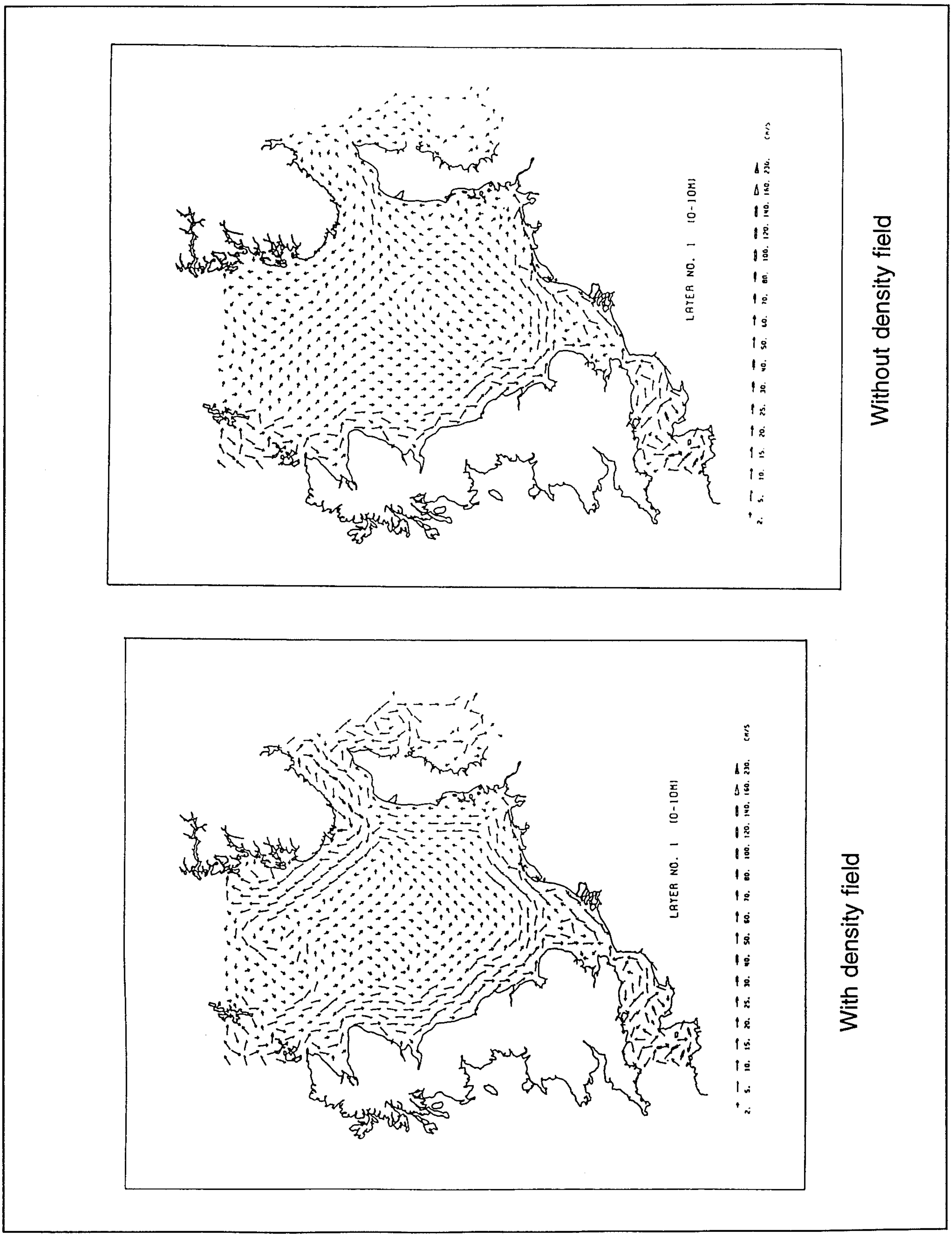


Figure 32 **Backhaus' model residual flows with and without density field**

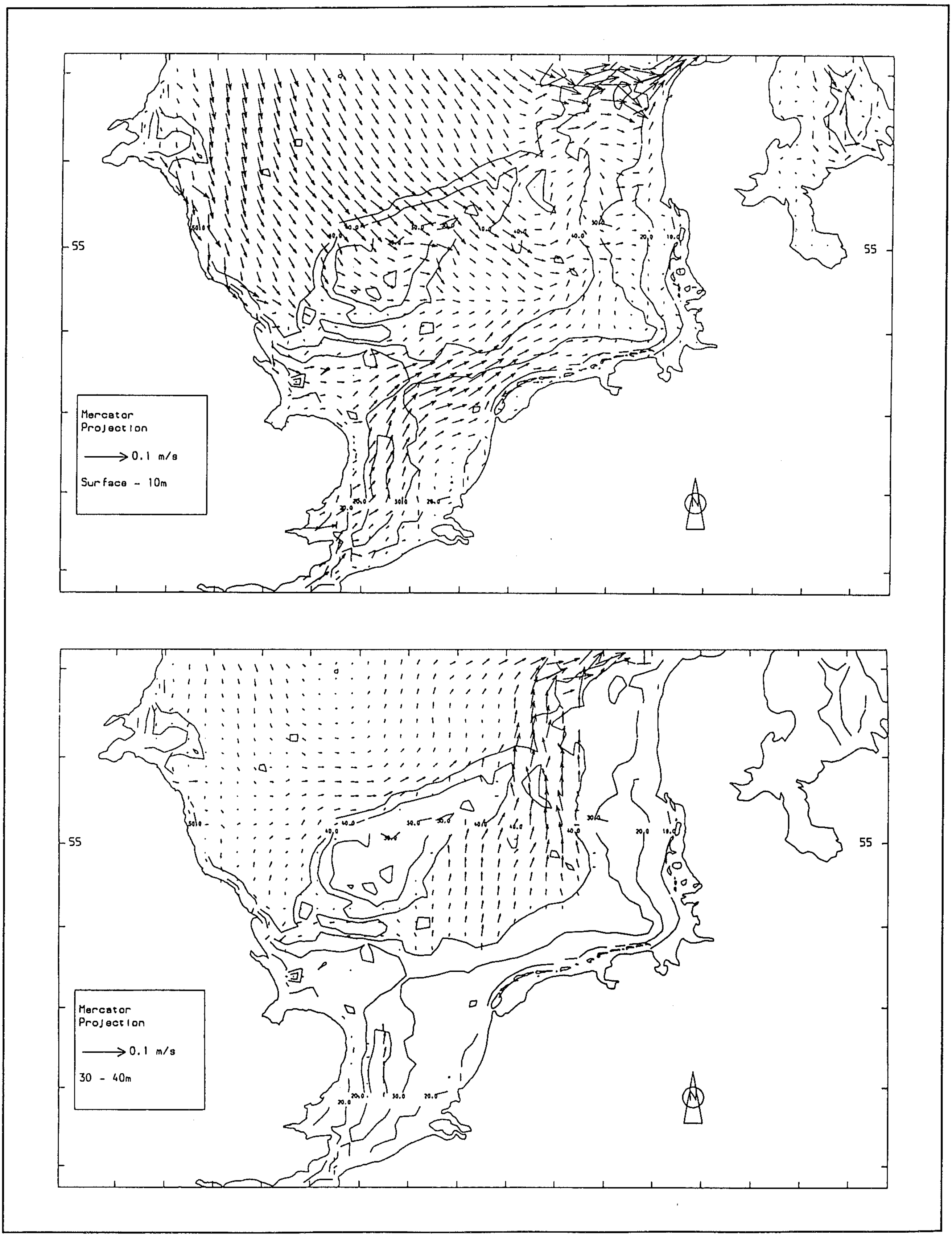


Figure 33 TIDEFLOW3D model residual flows, summer period

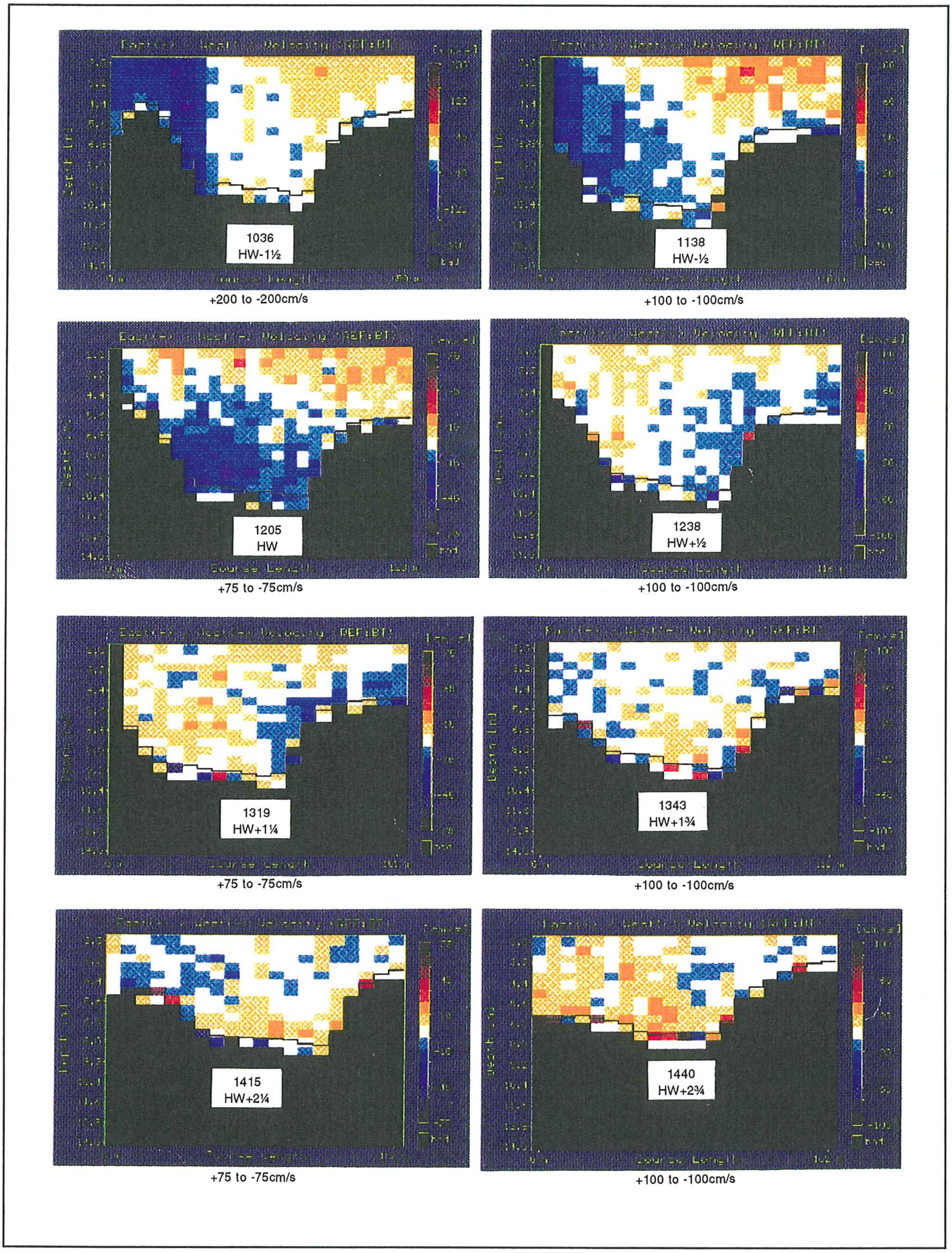


Figure 34 Conwy marina ADCP cross sections

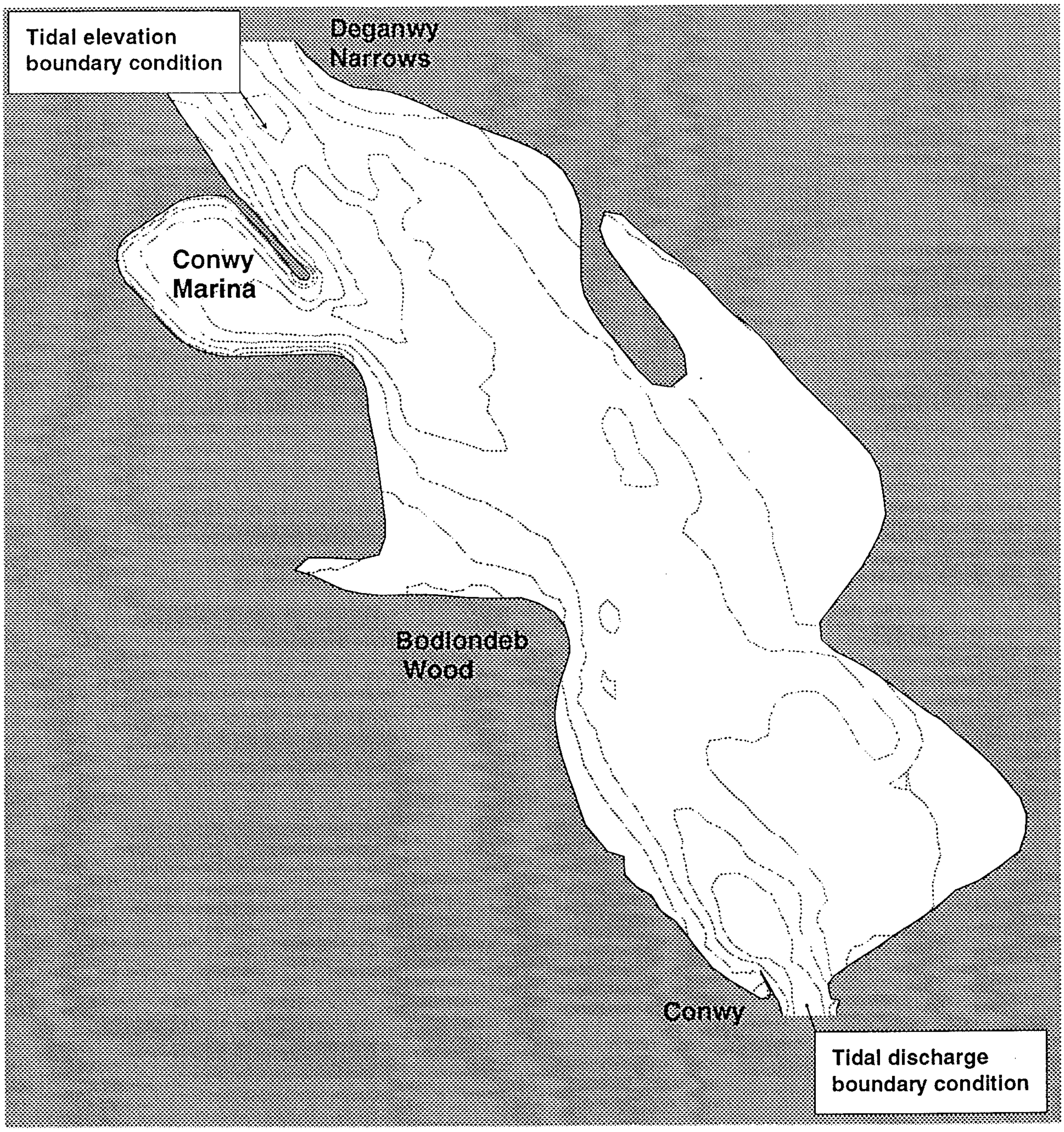


Figure 35 Conwy marina model area and boundary conditions

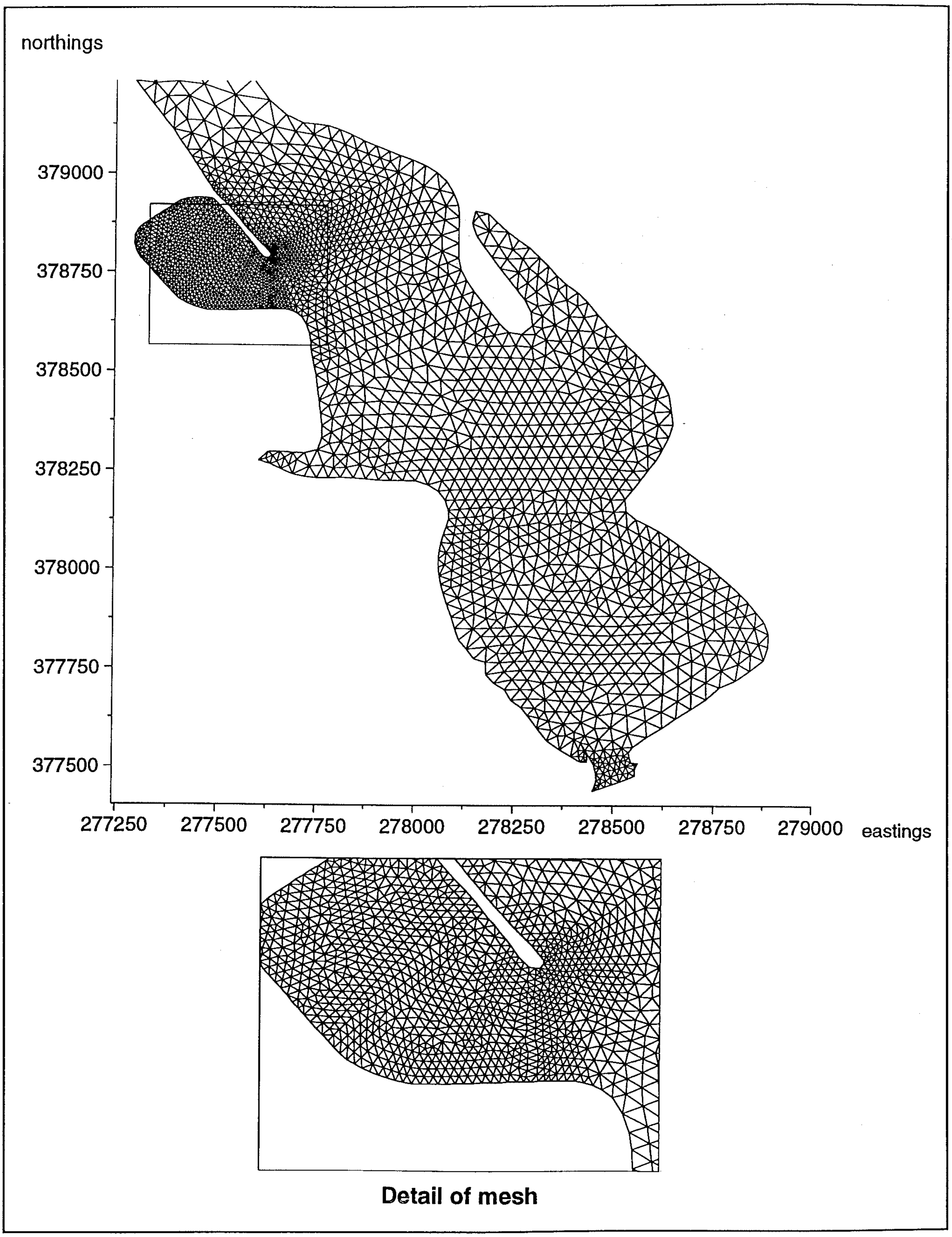


Figure 36 **Conwy Marina TELEMAC model grid**

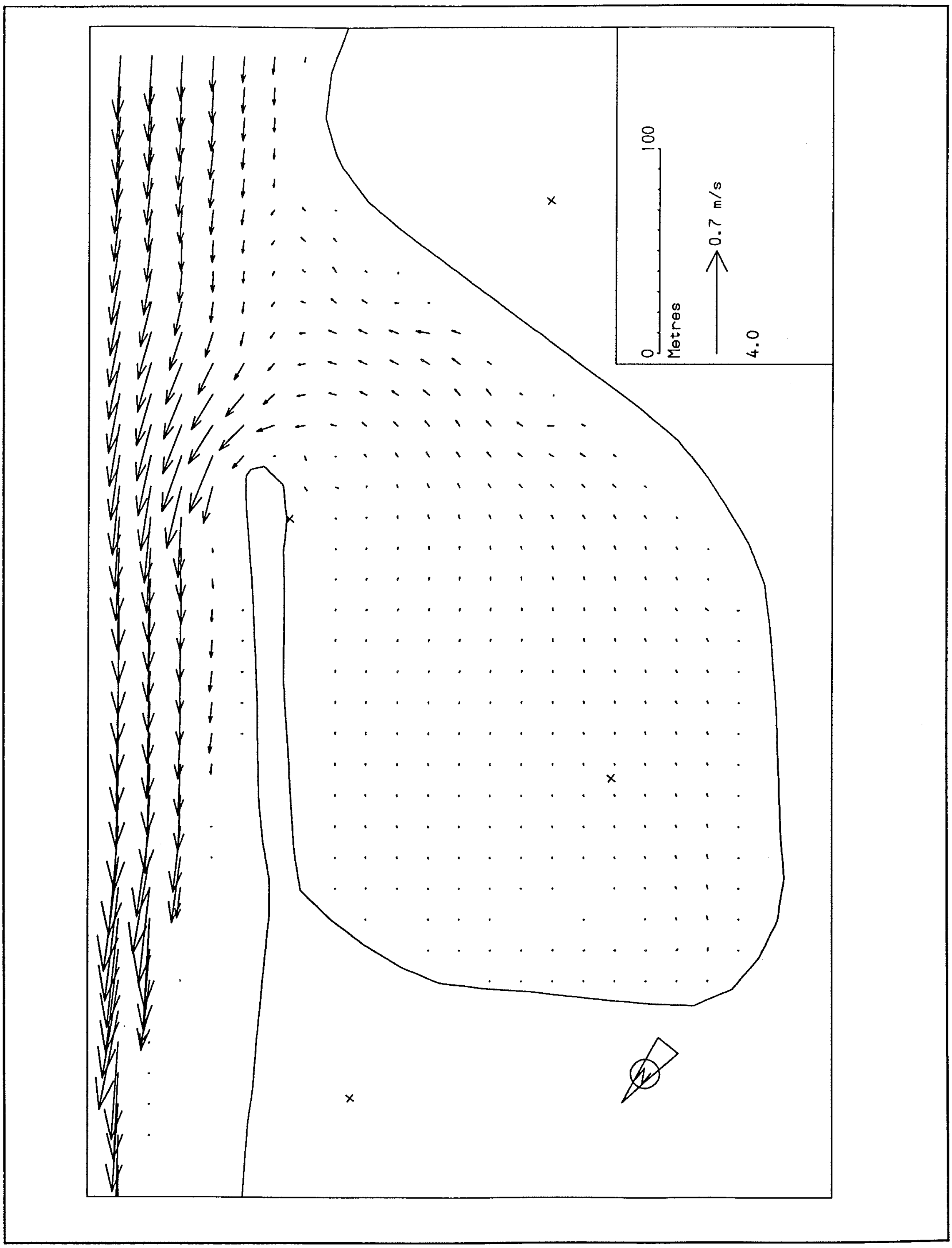


Figure 37 Conwy Marina TIDEFLOW model currents HW+4hours ebb

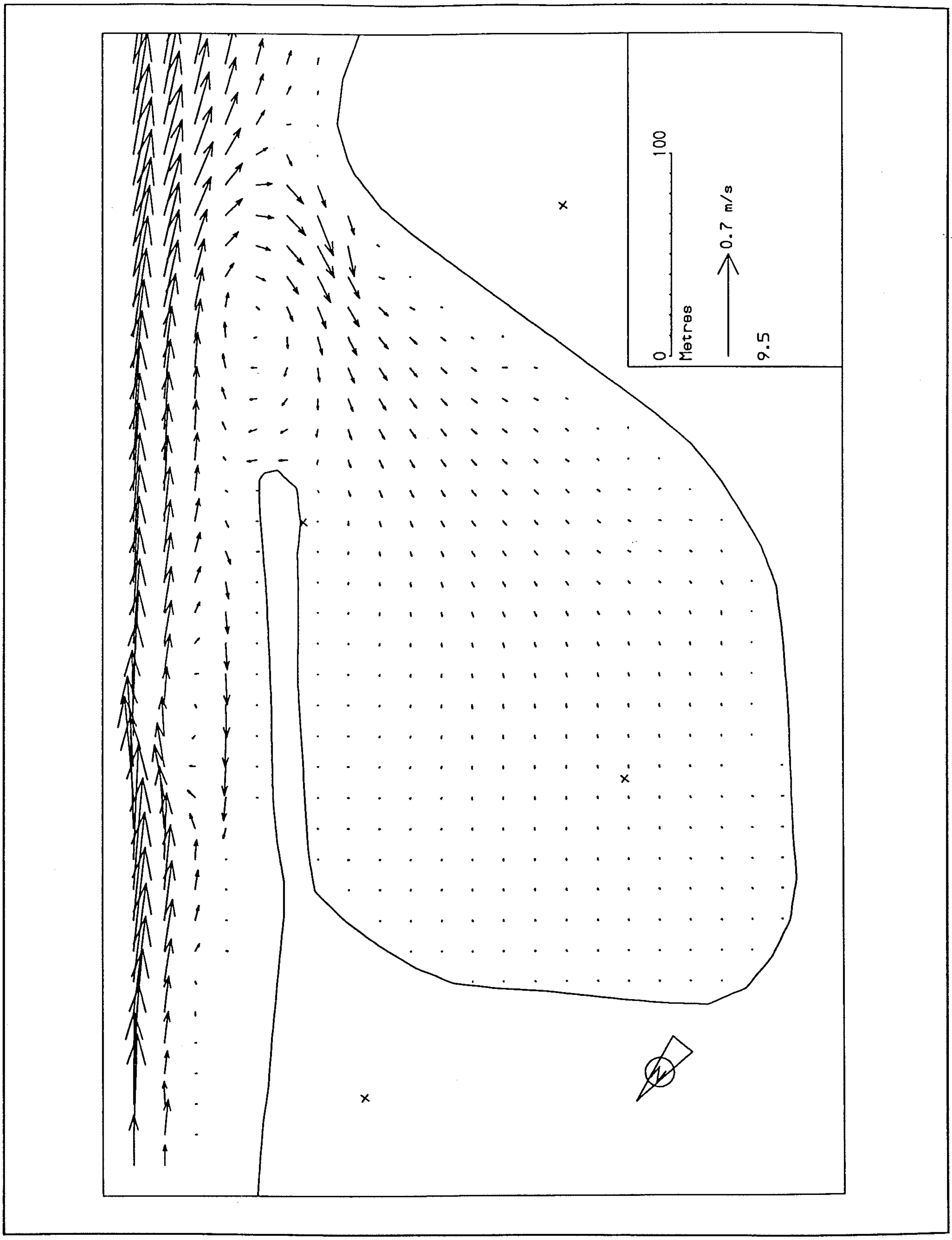


Figure 38 Conwy Marina TIDEFLOW model currents HW+9.5hours flood

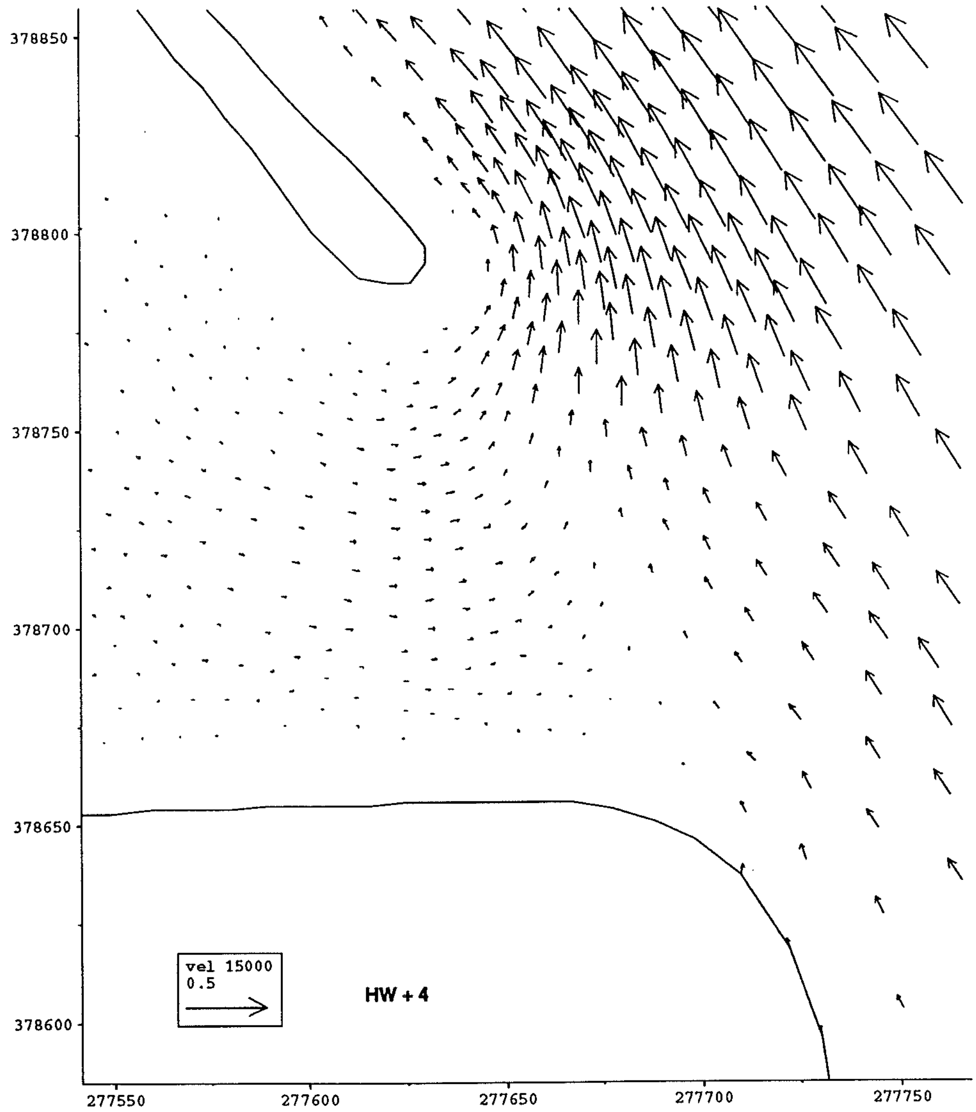


Figure 39   Conwy Marina TELEMAC currents ebb

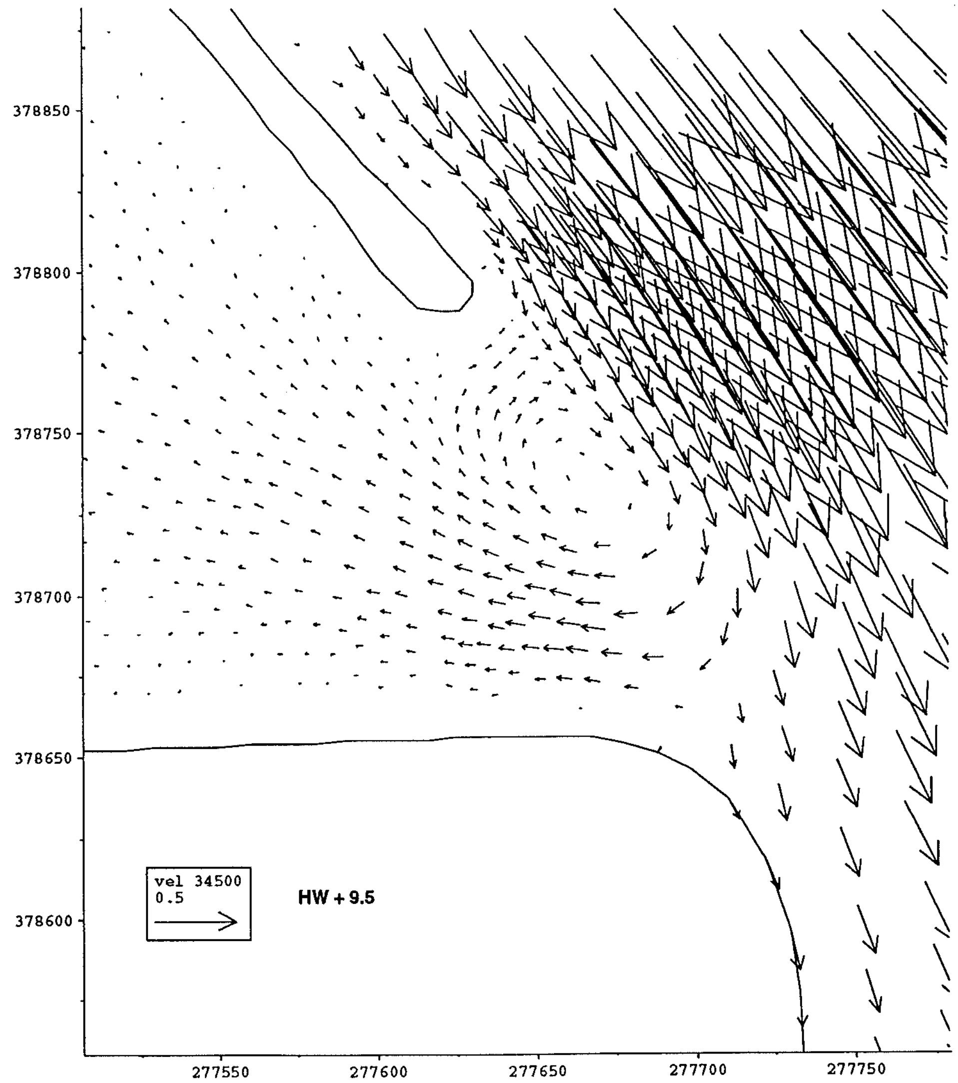


Figure 40 Conwy Marina TELEMAC currents flood

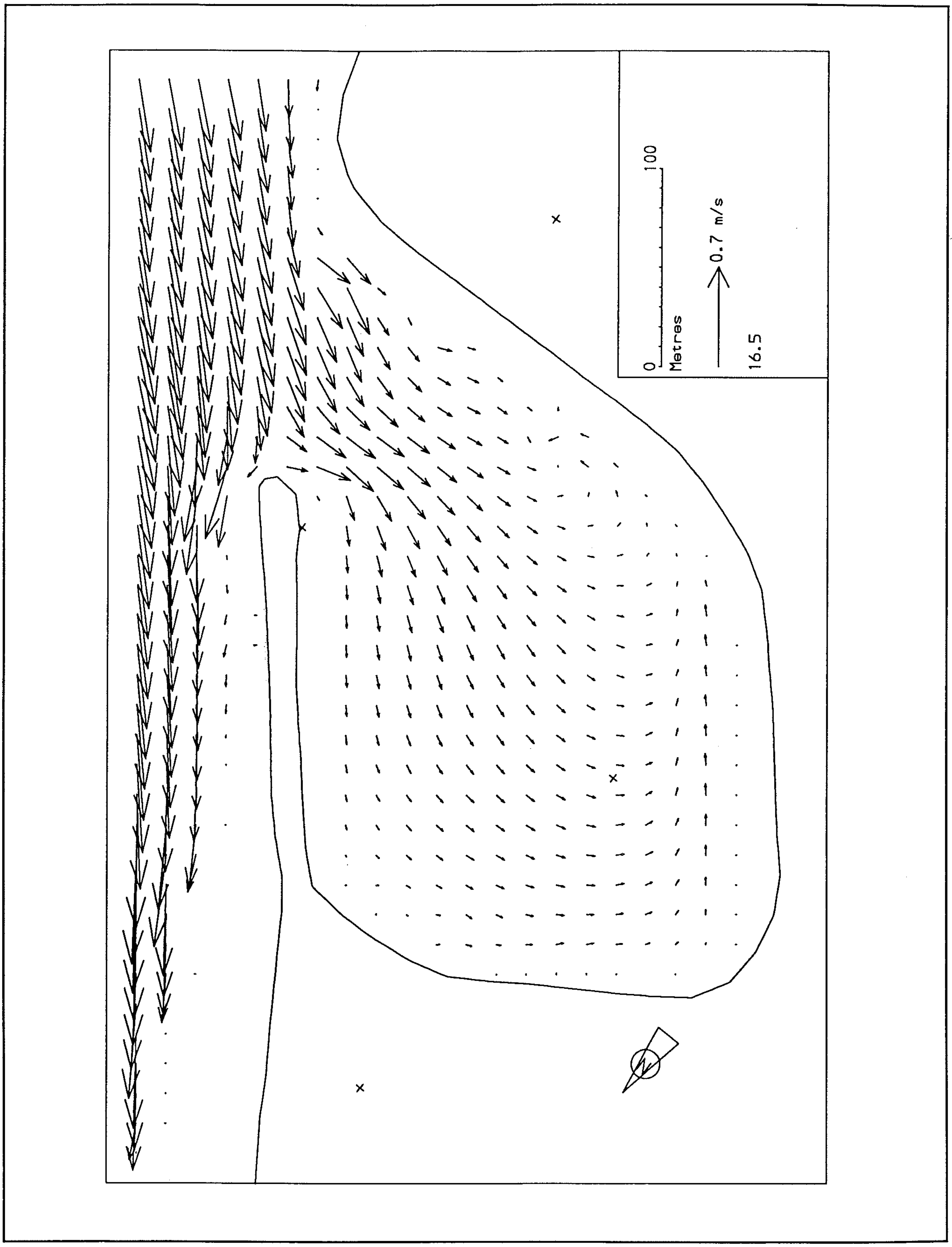


Figure 41 TIDEFLOW3D current ebb, surface

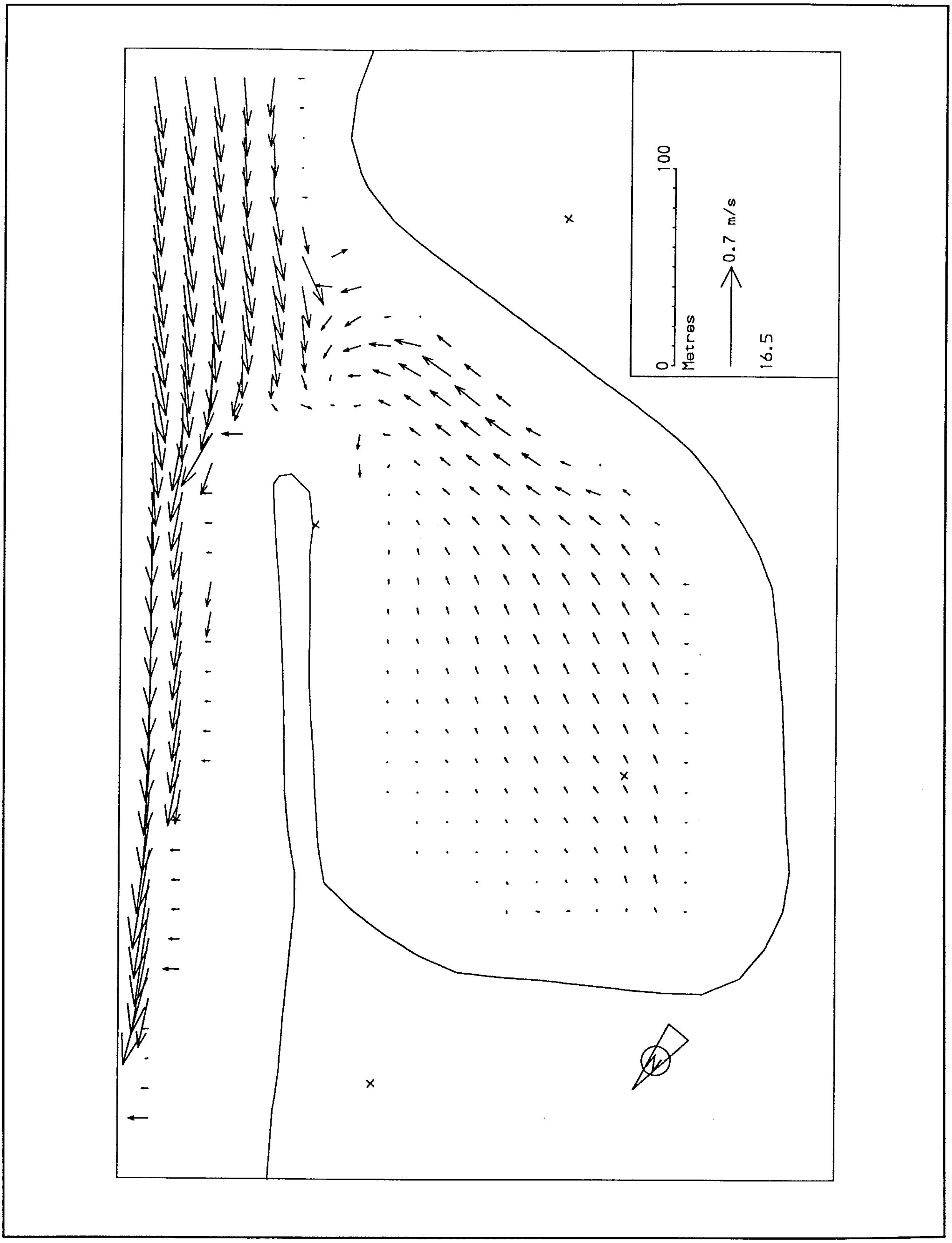


Figure 42 TIDEFLOW3D current ebb, bed