Hydraulics Research
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DEVELOPMENT AND APPLICATION OF A 3-D DAP NUMERICAL MODEL OF ESTUARIES

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SUMMARY

A three-dimensional numerical model of water flow and transport of one quantity (heat, salt, mud or pollution) has been developed for estuaries or coastal waters that uses the ICL DAP. This model incorporates explicit finite differences within each model layer (all the points in a layer are updated simultaneously) but implicit differences in computing the vertical flow structure (the calculation is carried out in all of the water columns simultaneously). A simple mixing length theory, with turbulence suppression due to stratification is used to model the vertical variations.

The model is applied to simulate the distribution of salt and the flow patterns in the Severn Estuary. It has been found that the gravitational circulation velocities are very small. The residual gravitational circulation during the tide also has small values compared to the pattern of horizontal residual circulations due to tidal action. This circulation is similar to that observed. If the effect of salinity is artificially increased a strong gravitational circulation results confirming the physical validity of the model.

This model is the basic TIDEFLOW-3D option of the Hydraulics Research TIDEWAY system of numerical models for assessing the impact of engineering works on estuaries and coastal waters. The model can be readily adapted to study the movement of heat, sediment or pollution in an estuary by incorporating the appropriate physical and chemical processes. By using the ICL DAP such a 3-D model can be a cost-effective tool for making engineering judgements. The thermal version HEATFLOW-3D has been applied to a power station cooling water plume to predict the primary recirculation.

CONTENTS

FIGURES:

1 INTRODUCTION

The acquisition by Hydraulics Research Limited of an ICL DAP (Distributed Array Processor) has made 3-D modelling of estuaries a more practical tool than hitherto. Gravitational circulation, wind induced flows and buoyant plumes can be simulated in this way. The DAP can carry out effectively the very large number of calculations required because it can perform up to 4096 arithmetical operations simultaneously. Advantage is taken of this in a 3-D model by updating all of the points in a horizontal layer at once and then moving on to another layer.

A DAP Fortran version of the 3-D model described in Ref 1 has been developed that works in this way. The effect of vertical stratification on turbulent mixing is included so that two-layer situations (such as buoyant surface plumes) can be modelled.

An application to the Severn Estuary is described. The gravitational circulation due to freshwater inflow from the River Severn is modelled. An example of the effect of the wind is also given.

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The thermal version called HEATFLOW-3D has been applied to a buoyant surface plume. The development of the plume during the tide is simulated in order to predict how the recirculation temperature varies.

2 DEVELOPMENT OF DAP TREATMENT OF 3-D NUMERICAL MODEL

The 3-D numerical model described in Ref 1 was developed for use on a serial computer. This involved some clearly non-parallel calculations. For example, the non-linear advection terms uu_x etc are calculated using angled derivatives (which cannot be used on the DAP) and the sweep through the vertical is carried out from bed to surface and back for salinity (and vice versa for momentum) in each water column. The treatment of the uu_x term in a 2-D DAP numerical model is described in Ref 2 and the same treatment is used here. This means again that some diffusion must be included in the model to ensure that it does not blow up.

2.1 The finite difference scheme used in the vertical

Each layer of the 3-D model is mapped on to the DAP as a set of 64 by 64 matrices. So when the horizontal differencing is carried out the computation proceeds simultaneously at all the cells in a model layer. However, when vertical fluxes are computed the different layers are updated one after another. For this an implicit scheme is used and it is possible to have a double sweep from surface to bed and back (or vice versa) as this calculation is not carried out in all of the layers simultaneously. A complication is that due to the bed topography different water columns contain different numbers of cells. The technique to deal with this is illustrated in Fig 1. The sweep from surface to bed is carried out in all of the water columns simultaneously. In the body of the water the coefficients in the tridiagonal implicit equation f_{up} and f_{down} are both calculated. If a water column has fewer cells than the total number of layers then the bed friction is computed when the sweep reaches the bed layer instead of f_{down} and as the sweep proceeds downwards that column is not further affected (because of the use of a logical mask - see Ref 2). When the upward return sweep occurs the calculation in the water column of interest resumes when the sweep gets to the level of the bed cell and the return to the surface is then as usual. In this way the sweep can be carried out in all of the water columns simultaneously despite their containing different numbers of cells.

2.2 The treatment of the surface moving through the grid

In cases where the flow is stratified near to the surface and the flow in the lower part of the water column is nearly uniform (for example when modelling a buoyant plume) it may be useful to put several model layers close to the surface with one or more thicker layers below. However, this causes a problem if the surface moves up and down with the tide so that it moves through the model grid. The treatment of this aspect is shown in Fig 2.

The boundary elevation is used to decide which should be the surface layer in the model. The surface layer is taken to be the same everywhere so that if there is a large surface gradient in the model this treatment will not work well. If the surface is rising so that the model surface layer becomes very thick it is necessary to split the surface layer into two thinner layers. The velocities and concentrations in the two layers are taken to be the same as in the original one layer. The model will then relax to a vertical profile with different concentrations in the top two layers. In order not to use too many layers at high water (and then to waste them at low water), when the top layer is split into two the bottom layer is also assumed to absorb the next layer up. The concentration in the resulting thicker bed layer is the weighted mean of the original two bottom layers. If the vertical discretisation is carefully chosen the two bottom layers may have nearly the same concentration before they are mixed together (if the thermal plume is confined to the top few layers). When the water surface falls the two top layers will merge and the bottom layer split in two. This method has been found successful in simulating a buoyant surface plume.

3 PRELIMINARY SIMULATION OF THE SEVERN ESTUARY

In order to obtain initial conditions on flow and salt distribution for a 3-D model of the Severn estuary, 2-D models were run first to a repeating state. As there is very little vertical stratification (about 0.1‰ salinity difference between bed and surface) in the Severn Estuary the 2-D flow model should give a good representation of the depth integrated flow and horizontal residual circulation on top of which must be added the gravitational circulation due to freshwater inflow. This circulation should take a standard pattern of an inflow in the lower part of the water column and an outflow in the upper part. The circulations generated usually have a discharge which is an order of magnitude larger than the freshwater flow that brings them into existence. This means that one can estimate the expected effect, although it may be larger in very well mixed situations such as the Severn Estuary. With a total freshwater inflow of 400 cumecs the expected discharge in the gravitational circulation would be of the order of 4000 cumecs. If this is distributed over an estuary width of 50km in the upper 10m of the water the expected residual velocity is of the order of 0.01m/s. The residual velocity may be larger if it is confined to only a part of the width of the estuary. However, previous studies of depth integrated flow in the Severn Estuary and Bristol Channel (Ref 3) show residual velocities of the order of 0.05m/s which is an order of magnitude larger than the expected gravitational circulation. This means that even patterns of tide averaged residual flow in the surface and other layers through the depth will not show clearly the gravitational circulation required. In order to highlight the effect of gravitational circulation, a run has also been carried out with a larger than actual density of salt.

3.1 Initial conditions

The 2-D flow model used was that described in Ref 2. This model is the TIDEFLOW-2D option of the TIDEWAY system . The tide used was a mean tide with boundary elevations taken from the mathematical model of the Severn Estuary and Bristol Channel (Ref 4). The model included 400 cumecs freshwater inflow at the landward end (assumed to be coming from the River Severn). The gridsize of the model is 1500m and a timestep of 43 secs was used. The model was run for several tides until a repeating flow was established. The resulting residual flow pattern is shown in Fig 3. The residual velocities agree to order of magnitude with those in Ref 3. The residual current pattern is extremely complicated because of the shape and topography of the estuary. Residual gyres appear near to sharp bends in the coastline and others are associated with changes in bed shape, corners in channels, etc.

The discharges and levels from the repeating tide were stored so that a DAP 2-D salt transport model (Ref 2) could be run using the results. At this stage, clearly, the effect of the salt distribution on the estuary flow is ignored. The salt transport model was run starting from fully saline conditions throughout the estuary and 400 cumecs of freshwater coming from the River Severn. Upstream differencing was used and it was found that the flushing time of the estuary was very long. A repeating pattern of salinities was established after about 300 tides (Fig 4). As upstream differences were used it is known that they add numerical dampening to the true solution (Ref 5). The resulting salt distribution is advected to and fro with the tide, the isohalines move about 20km with the tidal excursion. At the seaward end a constant salinity was assumed, this is clearly wrong in view of the results obtained (Fig 4) as a sizeable area of constant salinity appears at high water. The salinity gradient in the estuary is however in reasonable agreement with that found observationally (Ref 6).

This salinity gradient should be able to generate a realistic gravitational circulation pattern within the estuary when used as an initial condition for a three-dimensional model simulation.

3.2 3-D model simulation

The starting condition for the 3-D simulation is taken to be that the elevation is as in the end file of the 2-D flow model, the velocities are also taken from the end file, but for the 3-D model they are taken initially to be independent of depth (a velocity profile very soon develops). The initial condition was taken from the 2-D transport model and again the starting condition has salinity independent of depth. The boundary conditions at the seaward end of the 3-D model are as before, the imposed elevation values and a constant salinity in all of the layers.

The model has five layers and a constant layer depth of 5m (except for the bottom layer). This means that in the top part of the estuary there is still only one layer but over much of the estuary there are five layers.

Fig 5 shows the tidal residual velocities in the top, middle and bottom layers of the model. The circulation is still dominated by the motions shown in Fig 3 but some effect of a gravitational circulation can be seen with landward velocities becoming larger in the lower layers while the seaward velocities decrease.

The residual circulation is found to be consistent with the results of Uncles and Jordan (Ref 8) at their stations A and B (marked on Fig 5). They found a seaward flow at all depths except very near the bed at position A with a maximum residual velocity of about 20 cm/s. At B the flow is landward at all depths increasing downwards, the maximum residual speed being about 6 cm/s.

The water levels in the upper part of the estuary are also about 10 cm higher at high water than in the depth intergrated model where the salinity gradient is ignored. This does not perturb the salt distribution very greatly (shown in Fig 6 after one tide of the 3-D simulation).

In order to see the gravitational circulation more clearly the model was also run with an effective density of salt five times greater than the correct value. This enhances the gravitational circulation as can be seen in the residual velocities in Fig 7. In this case also there is a larger salinity difference between the model layers as the Richardson number is increased.

When the correct density of salt is included as in Fig 5 the weaker gravitational circulation is difficult to see because of the strong residual currents resulting from tidal action.

3.3 Test including the effect of a wind

The 3-D Severn Estuary model was also run with a wind of 15m/s from the West. The resulting residual velocities are shown in Fig 8. Again the pattern of horizontal residual circulations due to tidal action is important but superimposed on this is a horizontal pattern of eddies due to the wind. These eddies are caused by the same process as those shown in Ref 1, i.e. the wind has a greater effect where the water is shallow than where it is deep so a flow starts down wind in the shallow areas and returning in the deeper areas. This is on top of the vertical circulation (downwind at the surface, return current near to the bed).

4 APPLICATION TO A THERMAL PLUME

The 3-D DAP model has been applied to a thermal plume from a proposed power station (Ref 7). In this application it was found (see Fig 8) that the plume remains always close to the surface as is observed in plumes from operating power stations.

A test was also carried out with a much increased vertical mixing (such as would be typical of a non-buoyant flow) and this had a great effect on the plume both causing it to mix through the depth and preventing it from moving very far offshore.

The plume was found to agree well with a simple existing steady stage integral jet model at maximum current (when the plume becomes nearly steady). However, in the application it was possible to model the plume development in time with an unsteady tidal current and also in the presence of an onshore wind.

5 CONCLUSIONS

A DAP version of the 3-D numerical model of flow in estuaries has been developed. It has been applied to the Severn Estuary where it has been found that residual velocities due to gravitational circulation are very small. Because of this the model was also run with an artificially increased density of salt in order to obtain a stronger residual circulation. A stronger stratification was also found in this case.

The three dimensional numerical model preliminarily applied here to the Severn Estuary has been shown to be capable of reproducing the three dimensional flow associated with the salinity distribution and in particular the residual gravitational circulation. This is a very important effect as it influences the movement of mud in the estuary. As mud also affects the density of the water that carries it a 3-D model incorporating both salt and mud should be developed.

This 3-D numerical model can be used effectively in practical cases because of the possibility of doing many simultaneous calculations. The Severn Estuary model took about 60ms per timestep per layer so that a whole tide was computed in just 5½ minutes. This represents a great increase in speed relative to a serial computation.

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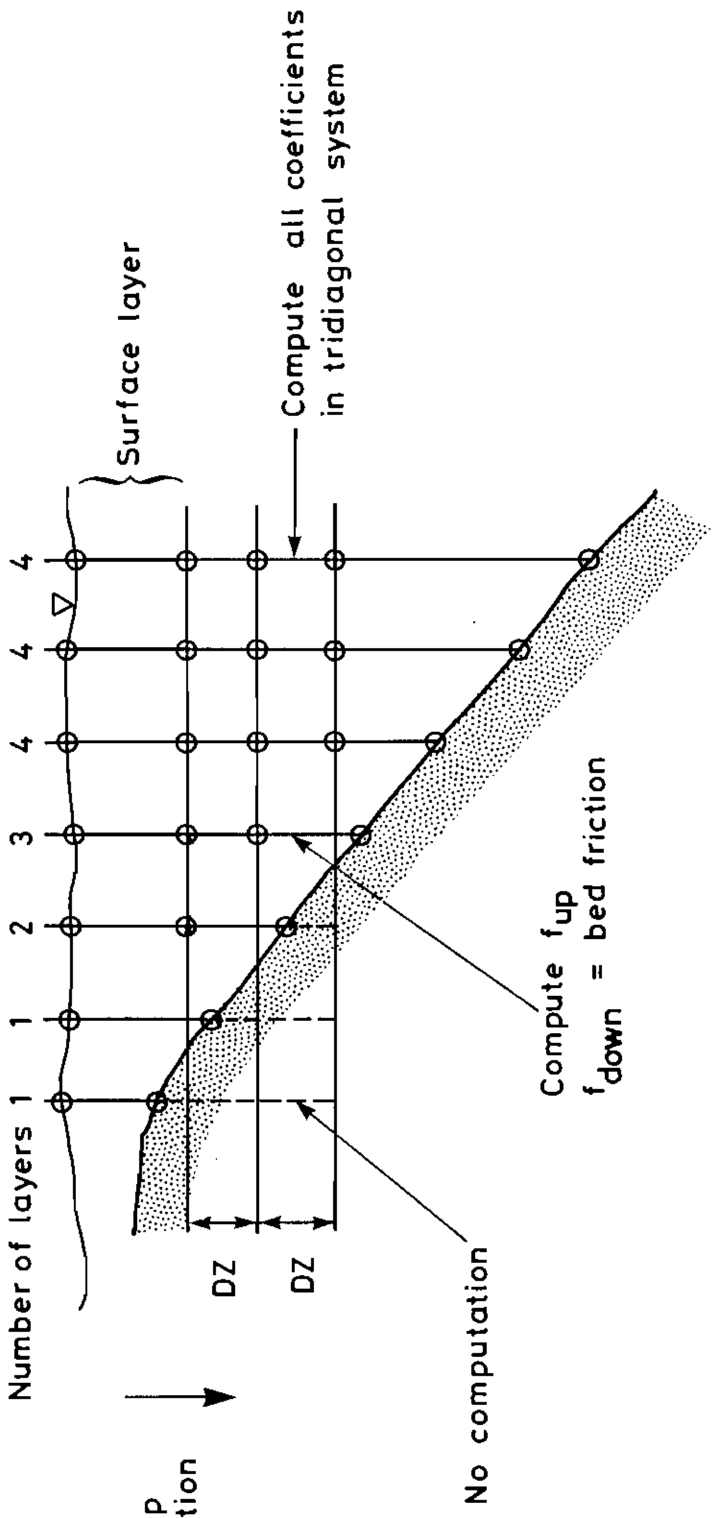


Fig 1 3-D model vertical sweep

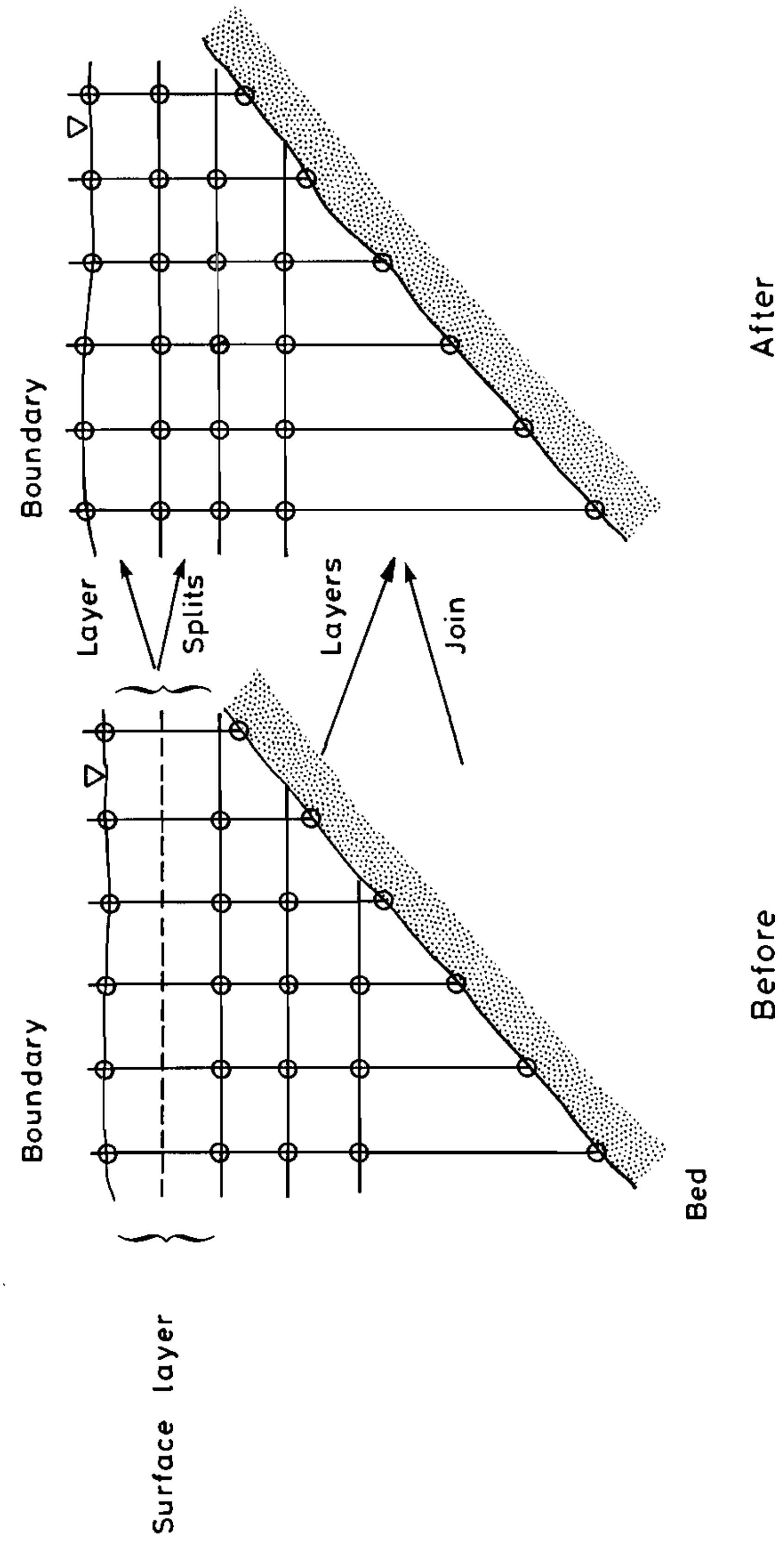


Fig 2 3-D model - surface moving through the grid (rising surface)

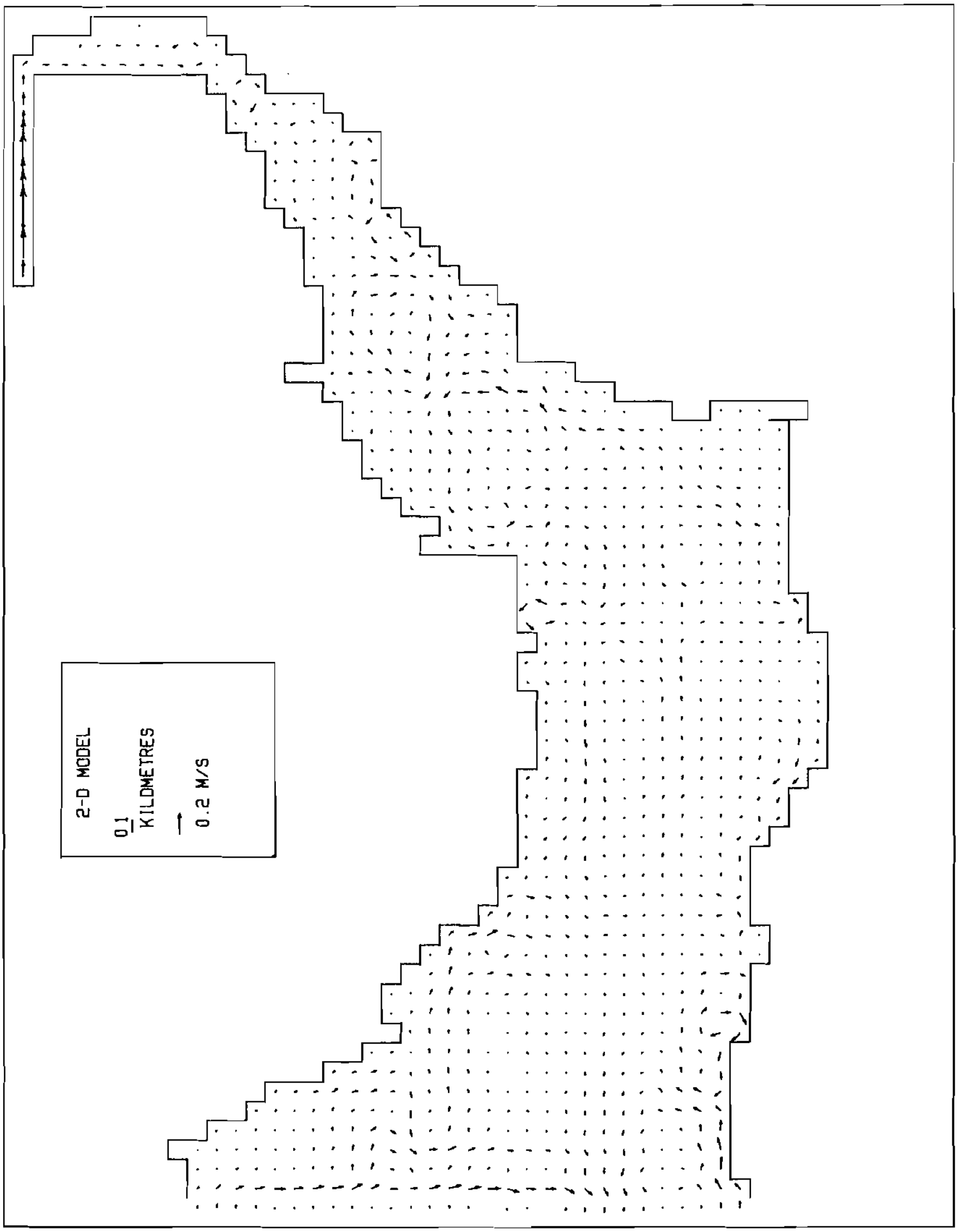


FIG 3 Residual velocities 2-D model

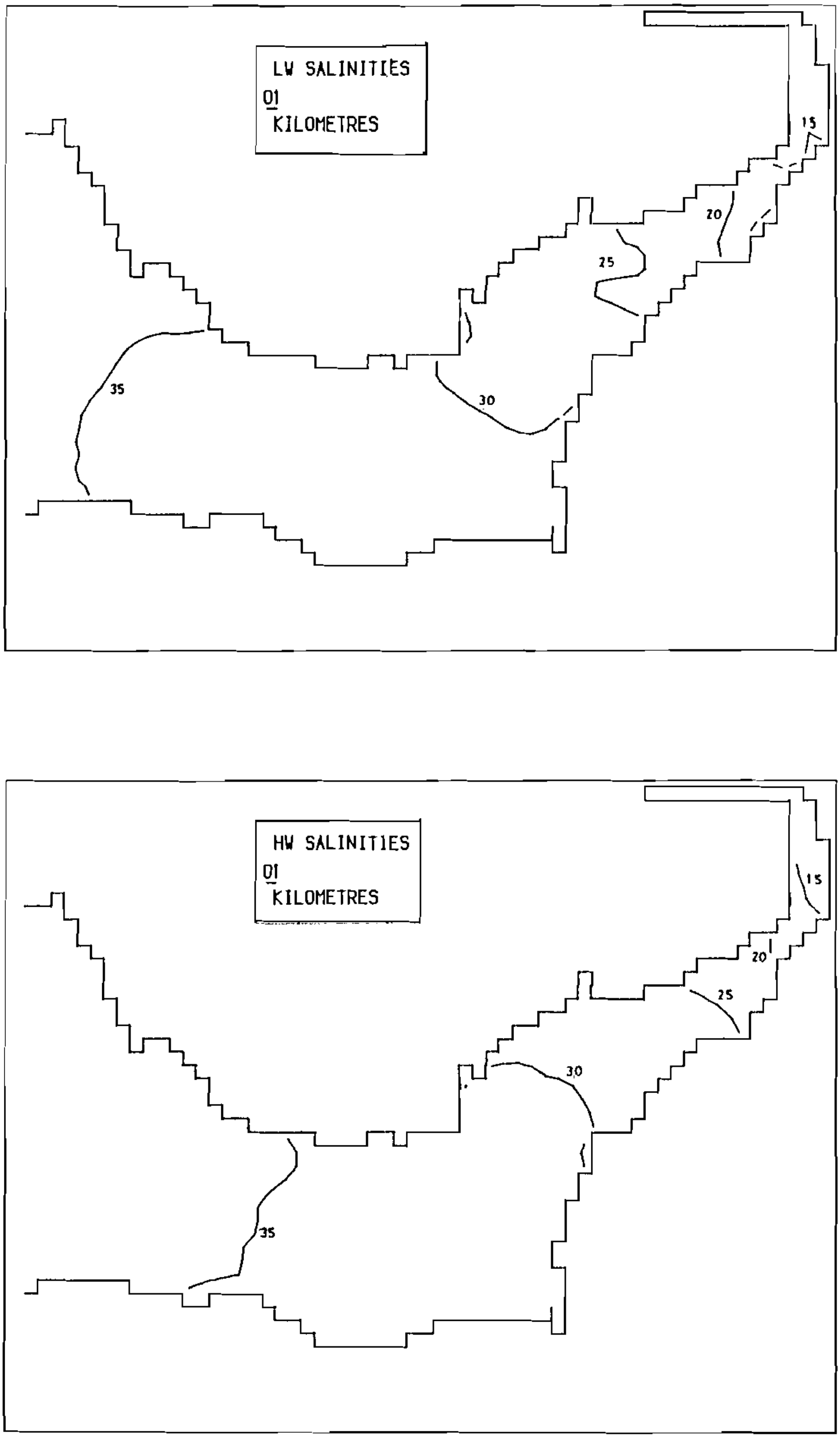


FIG 4 Salinities 2-D model

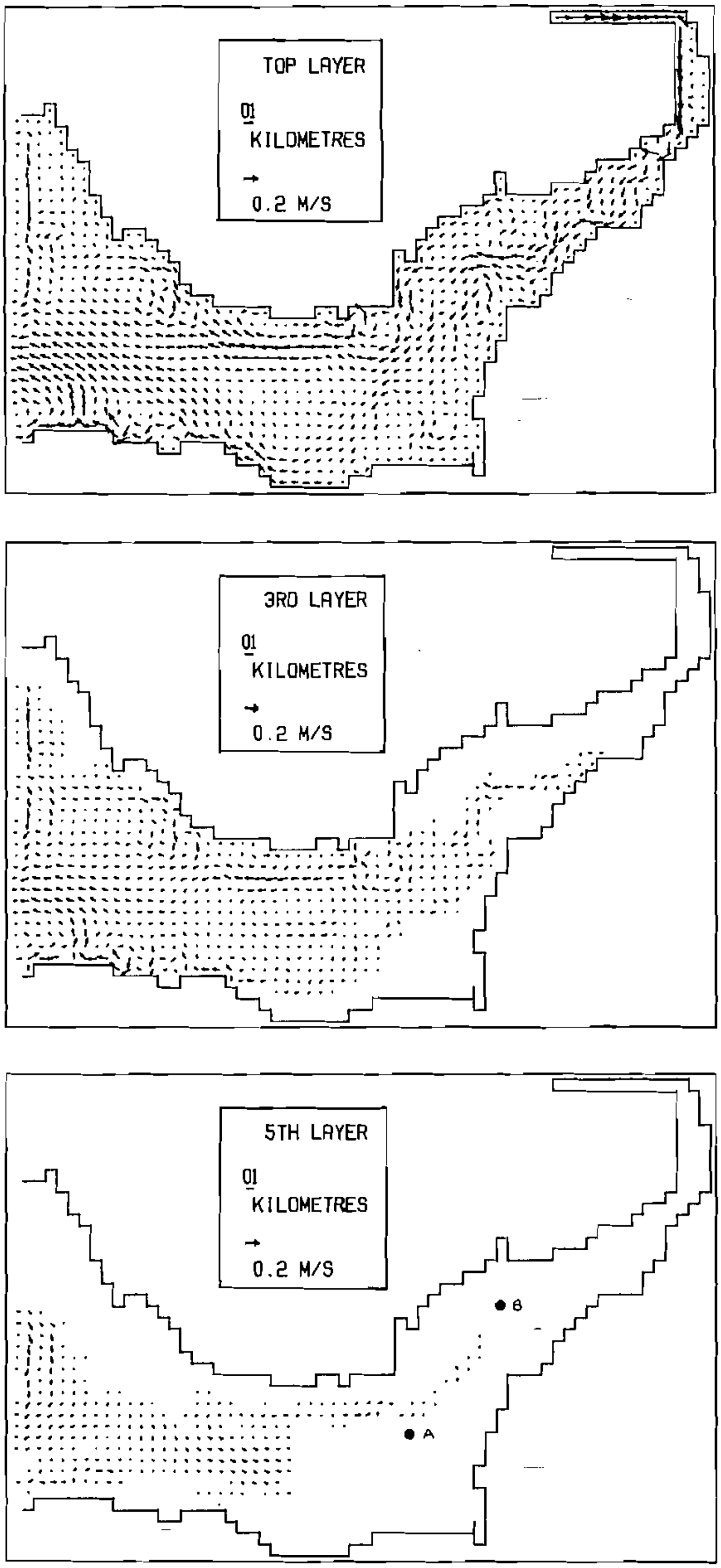


FIG 5 Residual velocities 3-D model

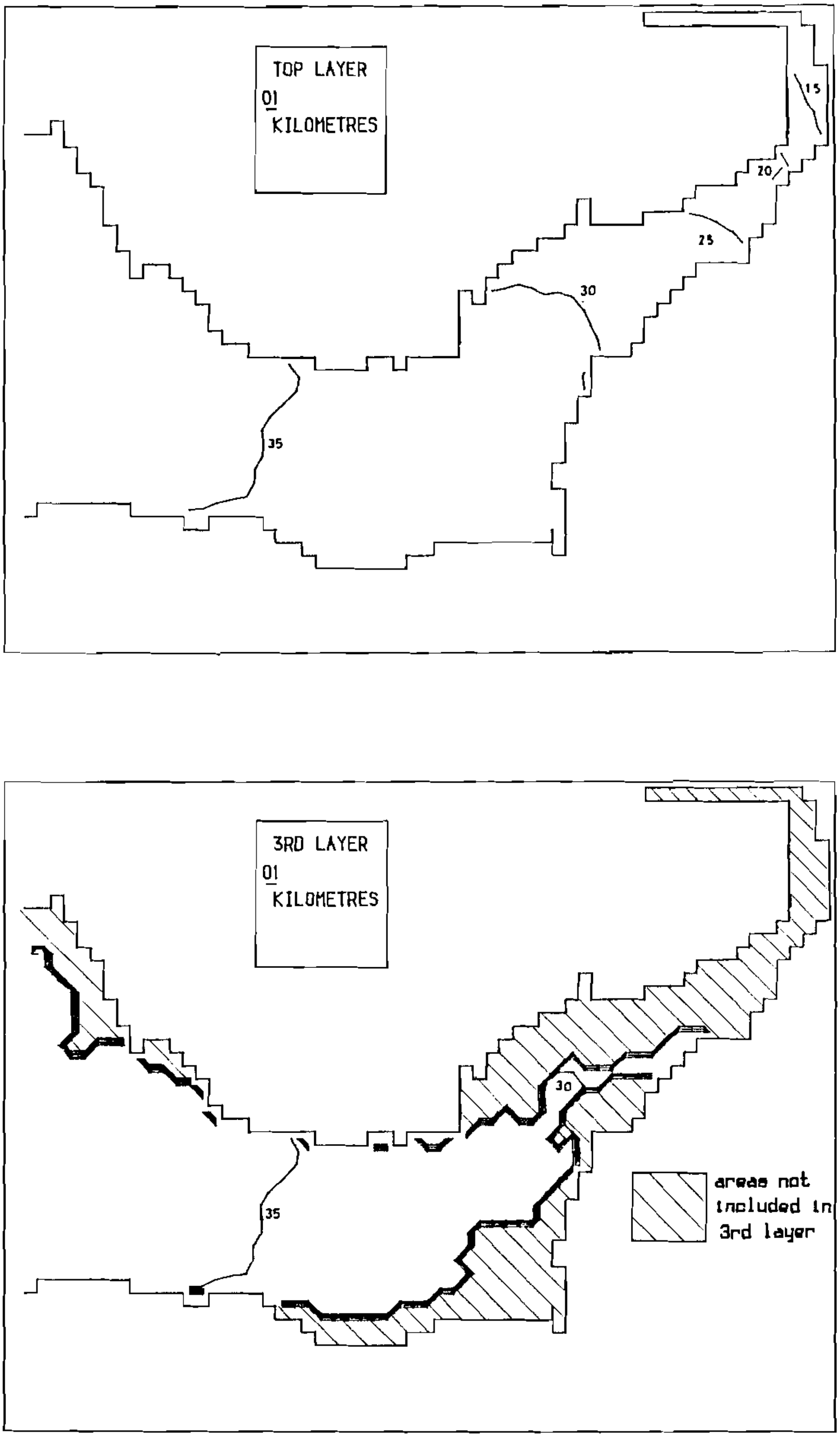


FIG 6 HW Salinities 3-D model

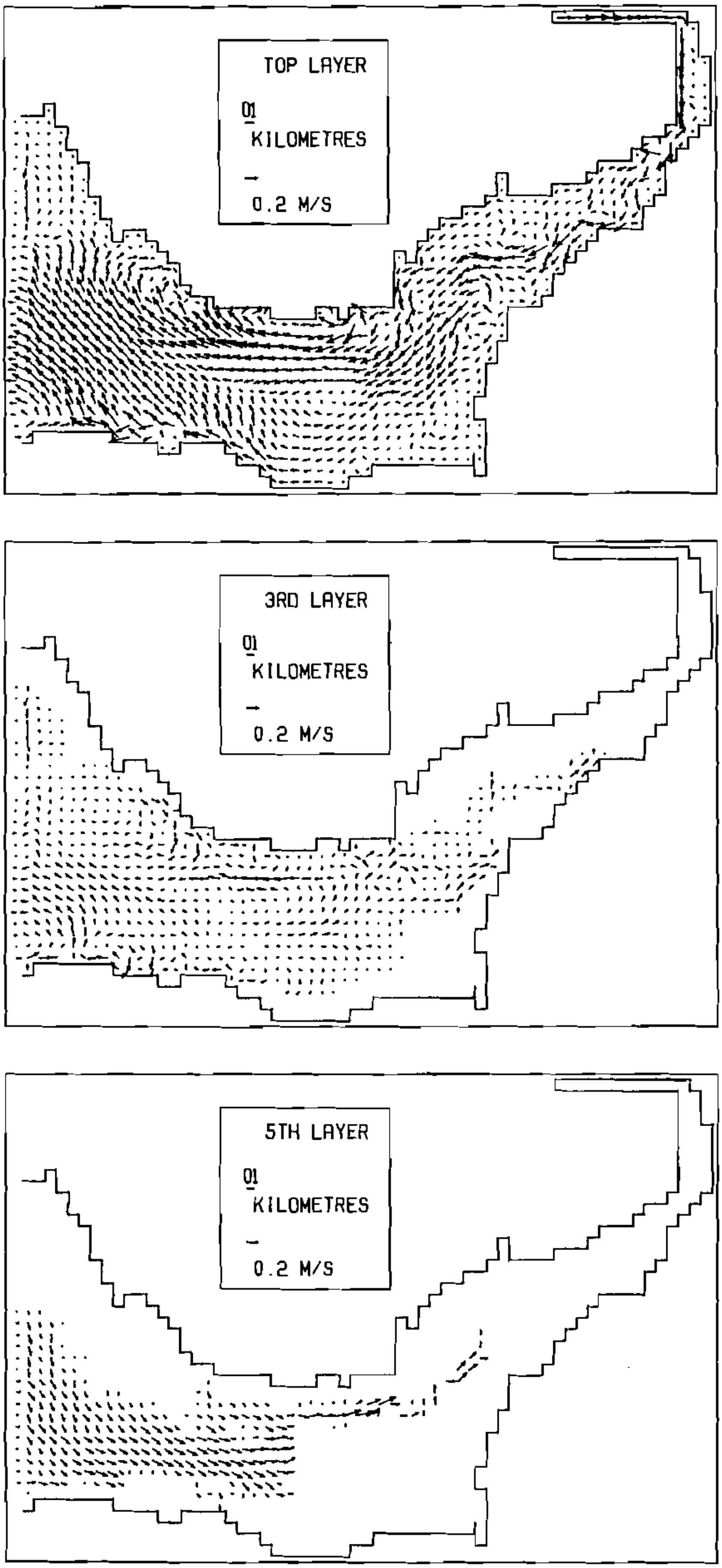
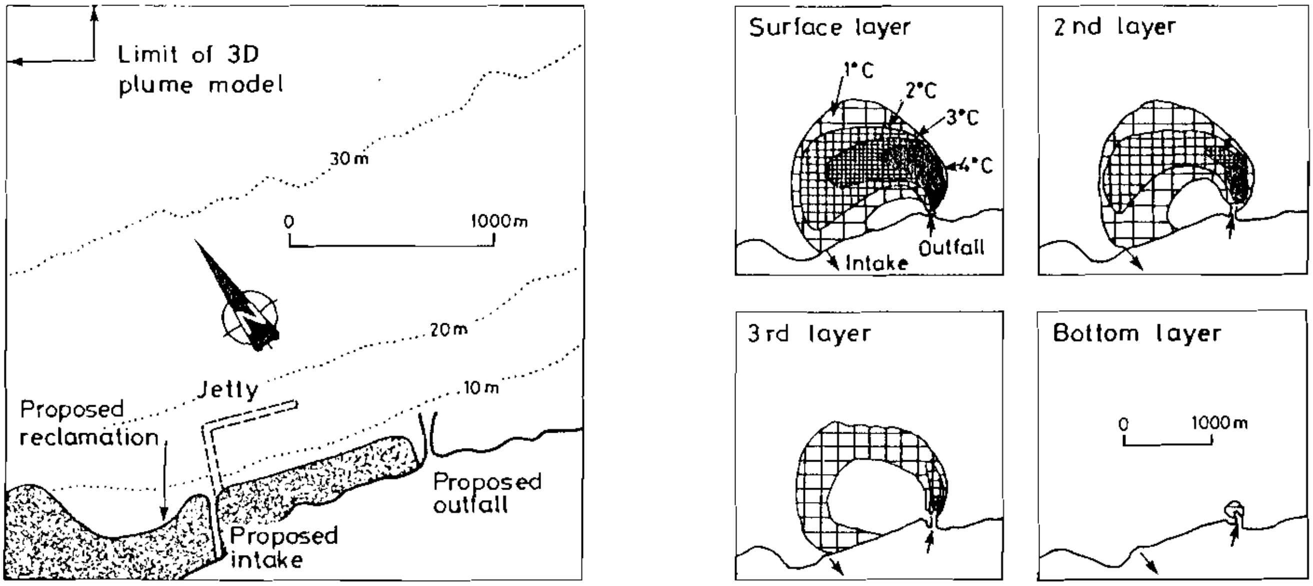
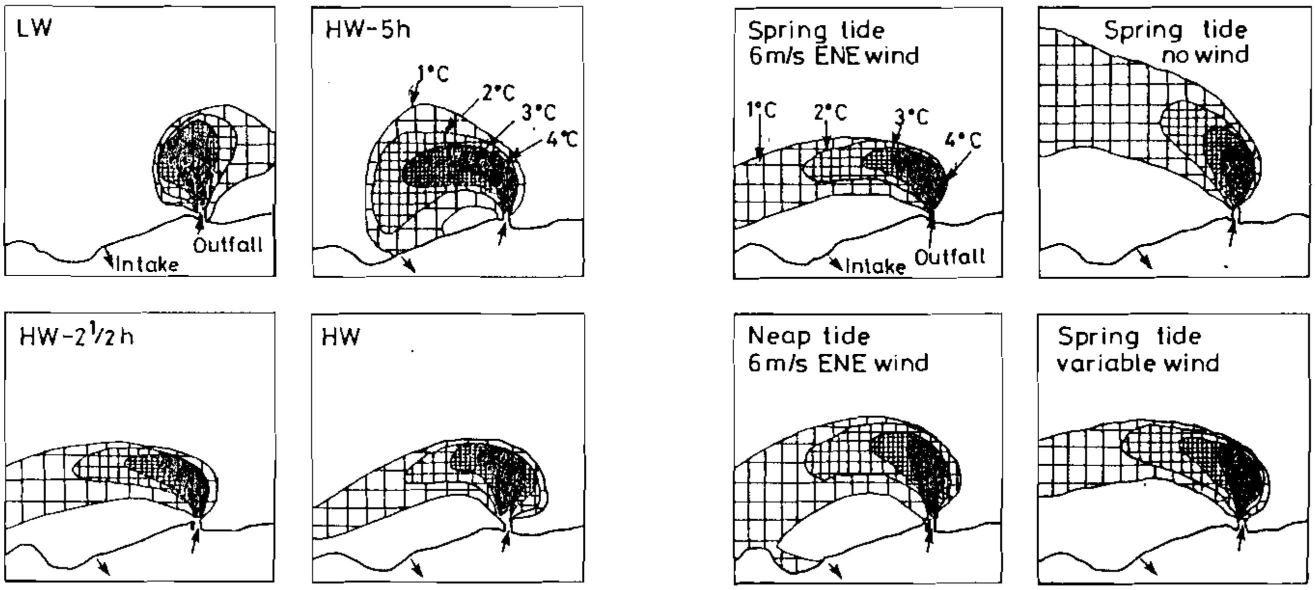


FIG 7 Residual velocities with enhanced salinity effect



(a) Area of model

(b) Isotherms in four model layers



(c) Variations during tide

(d) Various conditions

Three dimensional model results

FIG 8 Thermal plume

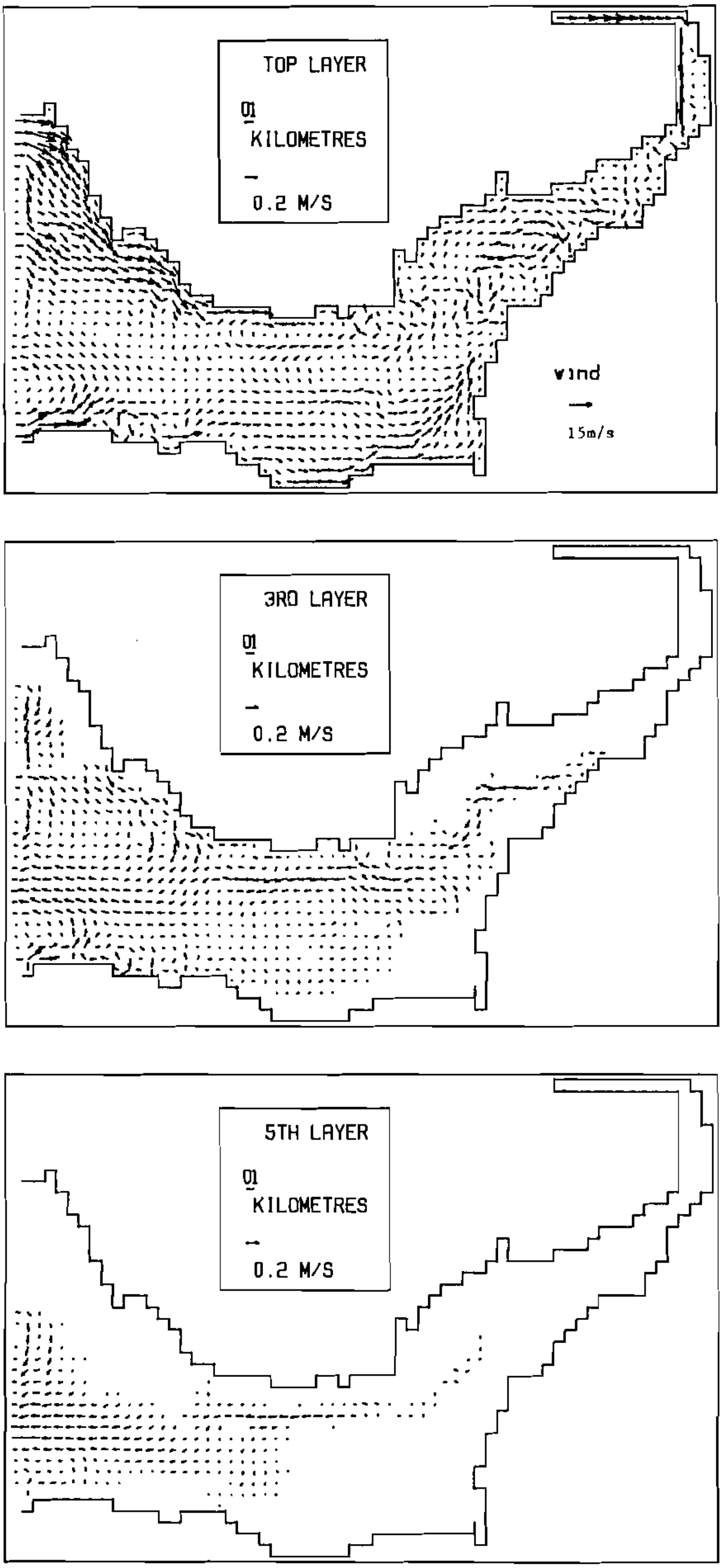


FIG 9 Residual velocities including the effect of a wind