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VALIDATION OF A 3D NUMERICAL MODEL OF A BUOYANT PLUME

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ABSTRACT

In order to model cooling water plumes from power stations into a tidal current a three dimensional unsteady model is required. This is because the complicated interaction of current oscillation with plume buoyancy produces plume shapes which are continually changing with time.

This report details the comparison of such a 3D unsteady numerical model, the HEATFLOW-3D model from the HR TIDEWAY suite, with site data for a particular power station. The plume studied is that from the Hinkley Point power station on the Severn estuary where a great deal of thermal data has been collected.

This data has been stored within a computer database which permits thermal data for a particular tide or set of tides to be extracted and processed so as to compare with the mathematical model.

The models results have been compared both with this data from in situ strings of thermistors and also with infra red aerial photogrpahs of the plume. The model has been found to predict many important features of the observed plume, its shallowness, the spreading plume at slack water, the fronts between the plume and ambient water, the division of the plume at times into two etc.

Despite this impressive agreement, which shows that all the necessary physical processes are being modelled, there are some consistent differences between model and data viz the offshore spread at slack water is less than observed, the surface temperatures tend to be too large and the plume tends to be too thin. Further work should show whether these differences spring from the neglect of the mixing effects of wind and waves, the difficulties in adequately modelling flow over the rocky foreshore or some other feature. Sensitivity tests to several of the important model parameters have been carried out to identify which are the most significant.

The model has established itself as being the preferred method for predicting the spread and dilution of cooling water plumes. The inclusion of all relevant physical processes makes other numerical modelling techniques out of date except for very simple cases (e.g. constant ambient current, very small discharges etc).

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CONTENTS

CONTENTS (CONT)

FIGURES (CONTD)

APPENDICES

1 INTRODUCTION

For the modelling of the midfield of power station cooling water plumes (that part contained within about a tidal excursion up and downstream) many methods have been used. Physical models (eg Ref 1) are very valuable but also extremely expensive as undistorted scales are necessary to reproduce stratified flows. Integral jet models (eg Ref 2) are very valuable for steady situations (eg in the absence of tides). Extensions to tidal currents (eg Ref 3) are only partially successful as extremely complex plume shapes are found. Source in stream models (eg Ref 4) are very good at giving unsteady solutions but without buoyancy effects the plume is usually much too restricted in area. Depth integrated flow models have been used for the midfield but they are usually quite inadequate as the plume should be confined close to the surface. Depth integrated models, however, are extremely valuable for farfield predictions (eg Ref 5).

In order to predict the complicated flows and buoyancy effects in the midfield a three dimensional unsteady numerical model is required. All of the relevant physical processes can be included so that superior results can be produced. Such a three dimensional model, HEATFLOW-3D, has been under development at Hydraulics Research (HR) for the last four years. The model uses the ICL DAP parallel processing computer. The model, although it has been used predictively to give advice on cold sites, has not hitherto been validated against survey data from an operating power station.

The purpose of this work is to rectify this omission. The model results are compared to survey data both from on site thermistor data and from infra red aerial photographs. The data used is for the Hinkley Point power station on the Severn estuary. Here the strong tidal currents, the flooding and exposing of a wave cut rock platform and the discharge of 70m^3/s of warm cooling water combine to give a plume of a very complicated and constantly changing form.

2 DESCRIPTION OF THE MODELS

HR chose Hinkley Point for validating the midfield plume model because of the large thermal data base available for that site. However, it was not the easiest site to use for this purpose because:

(i) tidal excursions are considerable (up to 20km for spring tides) so that it is not possible at this stage to encompass the whole midfield plume in a model;

(ii) the tidal range is very large so that the discharge behaves as a surface jet at low water being directed along a 30m wide channel, but at high water it behaves as a submerged discharge;

(iii) the rock platform at Hinkley Point has a complicated shape causing eddies at various stages of the tide.

It was not possible to study the full evolution of the midfield plume with a single model so two models with grid sizes of 100m and 40m were used during the validation exercise.

2.1 100m model

The model was aligned with the National Grid of Great Britain, covering an area about 12km along the coast and 3km offshore (Fig 1). This was convenient because the Bondi Severn Barrage model (Ref 7), from which the boundary conditions were taken, was also aligned to the National Grid. The 100m model hydrography was obtained from Admiralty Collector Chart K3641 "Watchet to Weston Bay" surveyed in 1961/62. Between 319500E and 322500E the depths greater than 6m below Ordnance Datum (Newlyn) (ODN) were obtained from the Osiris-Cesco survey. Heights on the rock platform in front of the power station came from a land survey of unknown origin supplied by CEGB. The outfall channel details came from CEGB drawing HIN 07 01 A447.

The south and east boundaries were land boundaries, the west boundary had prescribed elevations and the north boundary had prescribed velocities. Boundary data values were interpolated from results obtained from the Severn Barrage model which had a 500m grid in this area.

2.2 40m model

The 40m model geometry was created from the 100m model data base with additional detail included to improve the representation of the Hinkley Point rock platform. Due to the finer grid, the model area had to be correspondingly smaller to fit into the computer. The dimensions of the 40m model were approximately 3200m along the coast and 1800m offshore (Fig 1). The limited area of the 40m model did not inhibit the simulation of the critical stages of the midfield plume. However, it initially left out a second rocky outcrop just to the east of the model area and during validation it was found necessary to distort the model slightly to include its effect.

The north boundary of the model was treated as an impermeable boundary. For this purpose the model was oriented at about 4° relative to the National Grid to correspond approximately with the flow streamlines. The west boundary had prescribed elevations and the east boundary had prescribed velocities. Boundary data values were interpolated from results obtained from the Osiris-Cesco survey

2.3 Model details

The study was based on the TIDEFLOW-2D and HEATFLOW-3D options of the HR TIDEWAY modelling system.

TIDEFLOW-2D, which is a depth-integrated model, was run in order to check the tidal currents and to provide initial conditions for the 3D model. It is formulated on the well established tidal flow equations representing conservation of mass and momentum. The TIDEFLOW-2D model is described in Appendix 1.

The main midfield plume studies were made with the HEATFLOW-3D model. This model is based on the well established equations of conservation of mass, momentum and heat, including the important processes of vertical turbulent mixing, buoyant spreading, advection by tides and wind induced currents. Details of the model are given in Appendix 2.

The HEATFLOW-3D model was run in this case with four layers. The top three layers each had a depth of 1m and the remaining layer represented the rest of the water column. The major part of the plume was expected to occupy only the top three layers (ie, from the surface down to a depth of 3m), as shown by observations. On the eastern and western boundaries of the model the excess temperature above ambient was taken to be zero so that any heat reaching these boundaries was lost to the system. The model boundaries were chosen as far as possible away from outfall so that no serious heat loss would occur in this way.

The appropriate discharge and heat($71m^3/s$ of cooling water at 11.1K above ambient, to represent the combined A and B station discharges) were put into the bed layer of one cell at the head of the discharge channel. While this was satisfactory near to low water when the discharge was confined to the channel, at other times a better representation of the submerged outfall would have been preferable.

The cooling water was extracted from the model's lowest layer at the intake position. No account was taken of possible higher discharge temperatures resulting from thermal recirculation. This would need consideration to be given to the transit time of water through the cooling water system and to selective withdrawal.

3 HINKLEY POINT THERMAL PLUME DATABASE

In 1983 CEGB commissioned Osiris-Cesco to carry out an extensive thermal and hydraulic field investigation to gain a better understanding of the natural processes affecting the dispersion of waste heat from the Hinkley Point site (Ref 5). Measurements were made over the three month period July to September 1983, and the data recovered from the survey comprised:

(i) thermistor string data;
(ii) current meter data;
(iii) tide gauge data;
(iv) meteorological data.

Thermistor strings were deployed at the stations (L, M, N, O, P, Q, R, S) shown in Figure 2 and two other stations T and U further to the west. Each string contained 14 temperature sensors and 4 depth sensors. Data was supposed to have been recorded at 10 minute intervals but sometimes there were problems with the instruments or the loggers so there were gaps in the records. Three tide gauges and two current meters were deployed but one current meter failed to work. Data was again recorded every 10 minutes. A meteorological station was deployed which recorded the atmospheric temperature, wind speed and direction, atmospheric pressure, humidity and solar radiation.

The CEGB Central Electricity Research Laboratory also monitored intake temperatures during the same period and station output figures were also recorded to provide information about the quantity of waste heat discharged.

3.1 HR thermal plume database

The data was kindly supplied by CEGB on magnetic tape and included about 2 million temperature values and depths and several hundred thousand velocities and water levels. It was probably the largest set of this type of thermal data which had been collected up to that time.

In order to facilitate analysis of the data and to enable comparisons to be made between the Hinkley model and the observations, HR set up a computer database. The database consists of an index and blocks of thermal and tidal data.

The purpose of the index was to summarise the main features of each tide to enable particular subsets of data to be retrieved from the database. The index was created using tide data from Position M which was the station with the longest continuous operation. As no usable tide gauge data was available at the time the database was set up, (the tide and current data supplied had been previously corrupted by alternate days being overwritten by the other days), the depth sensor output at this station was used to find the times of high water. The tides thus found were indexed with the following information:

- dates and times of start and finish of each tide
- depths at start (HW), middle (LW) and end (HW) of each tide
- ebb and flood ranges of each tide
- start and end record numbers of thermal data in the database
- list of recording stations which were not working over each tide

3.2 Accessing the database

There were two principle modes of accessing the database - by individual tides and by the full length of a stored record for a specified survey station. Tides could be selected according to range, date and mean wind speed criteria specified by the user or simply by the tide index numbers input by the user.

The main plotting output facilities were:

(a) temperature-time plots of surface - bed temperatures differences for examining the primary plume.

(b) temperature-time plots of normalised bed temperatures for examining the variations of the combined natural and power station farfields. (Normalisation was done by subtracting the lowest bed temperature found in each tide included).

(c) temperature-depth profiles.

The temperature-time plots could be in the form of a long time series for a thermal record, or several selected tides of thermal data could be superimposed to exhibit variations between different cases. Surface-bed temperature differences extracted in this way were stored in the computer for subsequent use in checking the validity of a model. Other facilities were provided for examining selected tide data on the computer terminal screen including the length of tides and tides listed in order of decreasing ebb ranges. Also a filter was available. This allowed long term trends in the data to be examined or the long term trends could be subtracted from the original record to bring out the tidal variations more clearly. Filtering worked on bed temperatures or surface - bed temperature differences depending on the particular interest.

4 VALIDATION OF THE 100m MODEL

4.1 Model representation of the tide

The representation of tidal flow was examined first by running the depth-averaged TIDEFLOW-2D model for a repeating spring tide corresponding to the tide observed between 0800 and 2000h on 14 May 1980 (Ref 7). The flow and tide level boundary conditions were interpolated from the 500m Severn Barrage model results and a combined A/B station discharge of 71m^3/s was included. No special attention had been given to Hinkley Point when the barrage model was being calibrated and consequently the results were not ideal. Figure 3, taken from Reference 7, gives an indication of the accuracy which was obtained. It can be seen that while the tide was well represented with regard to range and to the time of high water, the model low water was delayed by about half an hour. The errors in the barrage model tide and corresponding errors in the tide currents would have been carried over into the new 100m model. The flow in the 100m model was, in fact, almost identical to the flow prescribed from the barrage study.

The velocities in the barrage model had been compared with CEGB data from the Hinkley area during the HR study of background temperatures at Hinkley Point (Ref 6). It was found that model particles moved in the correct direction on a spring tide but that ebb tracks tended to be too long while flood ones tended to be too short. These are the natural consequences of the tide curve distortion described earlier. In spite of these shortcomings, the barrage model had been considered adequate for modelling the farfield in Reference 5. It was also considered that the shortcomings would not seriously interfere with the validation of the plume model. Figure 4 shows the comparison between the 100m model current and the current meter data from the Osiris-Cesco survey on 11 August 1983, a day with a similar tidal range to 14 May 1980. Although the model speeds were a little slow, the directions were correct and the overall flow was considered representative, albeit of a slightly smaller tide than had been intended.

4.2 Comparison of model plume with infra red imagery

Fortuitiously CEGB had some aerial infra red (IR) images of the Hinkley plume for the period from 1155 to 1540h on 14 May 1980 which was the same spring tide for which the model was calibrated. Wind conditions on that day were described as light (Ref 8). According to Reference 8, low water on 14 May 1980 occurred at 1355 BST so the images cover about two hours either side of low water. Low water slack was easy to recognise in the images as a large plume of warm water formed at the end of the outfall channel. On subsequent images the pool could be seen to be advected away from the outfall by the flood tide, (Fig 5c).

Figures 5a - d show a direct comparison with data of model surface temperature contours hindcast by the model (for the top 1m) at the times shown and to the same scale. The model was run from high water with the established flow pattern from the depth integrated model. The agreement is good in general, the buoyant spreading of the warm water pool in particular behaves similarly both in the model and in nature. The poor resolution of the 100m grid is made clear in this comparison, any better agreement with data could hardly be expected in view of this drawback of the model.

4.3 Comparison with thermistor string data

11 August 1983 was chosen from the period of the CEGB thermal survey as having a similar tidal range to that in the model and fairly low winds (less than about 5m/s). The thermal survey station positions are shown in Figure 2 and the model temperatures in the top three model layers are shown in Figure 6 in comparison with the data for the surface - bed temperature differences.

The peaks in the model temperatures are of similar shape and size to those in the data. A slight delay at times is to be expected, bearing in mind the late time for low water discussed previously. In order to produce representative temperatures during the first half of the tide the model was run for half a tide after the first complete tide. The results in Figure 6 are therefore taken from this second tide from the first 6¼ hours and the rest are taken from the first tide.

Most of the thermistor strings were located outside the main run of the plume. This means that it is much harder to use them for validating the plume structure as a small change in plume position may make a very large difference to the termperatures recorded. Nevertheless the model did produce a similar pattern of pulses to those in the data.

4.4 Conclusions

The 100m model was found to represent qualitatively the buoyant spreading and other important physical features of the plume, thereby confirming its physical formulation. Although the model was in reasonable agreement with the data this was not considered quite good enough for claiming full validation and it was decided to carry out further tests using a model with a finer grid.

5 VALIDATION OF THE 40m MODEL

5.1 Model representation of the tide

In view of the poor quality of the local tidal flow data from the 500m barrage model it was decided to run the 40m model using boundary values obtained from the Osiris-Cesco survey. This greatly improved the agreement between model and observations (Fig 4). During the course of the validation it was found that the distribution of currents could be improved by distorting the model geometry just inside its eastern boundary to simulate the effect of the rocky outcrop which could not quite be included within the maximum possible area the computer could handle. It was also found beneficial to increase the model roughness to 0.4m to reflect more correctly the resistance of the rock platform at Hinkley Point.

5.2 Comparison of model plume with infra red imagery

The 40m grid resolved much more detail than could be achieved with the 100m model, as can be seen in Figures 8a-c which are presented at scales corresponding as closely as possible to the I/R images. Exact comparisons between model and I/R patterns were not possible because the photographs were taken at an angle so the heat patterns were distorted and also the signals were not processed to obtain the actual surface termperatures. Nevertheless, it is clear that the model was reproducing the main features of the I/R imagery, including the extensive buoyancy driven spread at low water with the characteristic sharp leading edge, and the much narrower plume which occurs at LW - 45 min with evidence of bifurcation.

5.3 Comparison of model temperatures with thermistor string data

From examination of the thermal data it was found that considerable differences could be recorded on different days with similar tide and wind conditions. The presence of a pulse in a particular record depends on whether the recording position was just inside or outside the sharply defined outer edge of the plume, and the position of the edge of the plume would have been very sensitive to local variations in the wind. Under these circumstances it was considered appropriate to compare the model against observations selected from the data base for a range of typical days so that any discrepancies could be related to the scale of the uncertainties arising from natural variations.

For this purpose, two sets of observations were selected from the database ostensibly for the same neap and spring tide ranges with low winds. Note that low winds in this context refer to low daily averages and not necessarily low winds throughout the days in question. In each case a small range of tides was prescribed to obtain a representative selection. The values so obtained are plotted in Figures 9 and 10 together with the comparable model results. The observations are plotted as surface-bed temperature differences to remove ambient and farfield variations.

Although the observations show considerable natural variations, there are, nevertheless, some well defined trends in the shapes and timing of pulses. The model reproduces many of these features. Note, in particular, how the model matches the pattern of two temperature pulses at position L during the flood tide and the intervening period without any plume showing which was a strong feature in the observations. The pulses reflect the passage of the LW slack pool and the broadening of the plume as currents slow towards the end of the flood tide. In between, the plume was swept away inshore of the instruments and consequently nothing was recorded either in the model or by the instruments.

5.4 Sensitivity tests

Sensitivity tests were carried out using the 40m model to examine the effects of a wind, of not incorporating flux corrected transport (so giving horizontal diffusion) and of changing the horizontal eddy viscosity and diffusivity. The wind speed and direction chosen were 5m/s from NW. This was a frequent occurrence during the 1983 survey. Offshore winds were extremely rare. The model was run for a neap tide for a whole tide and a third with this wind. The resulting temperature time histories and surface isotherms are shown in Figs 13 and 14. The plume is kept inshore to some extent by the onshore wind (comparing Figs 10 and 12) and there is evidence of somewhat greater vertical mixing. The 5m/s wind does not appear to cause much reduction in surface isotherm areas, a result previously reported in Ref 9.

The effect of not including flux corrected transport (ie just using upstream differencing) was investigated partly as a means to see how horizontal diffusion would affect the plume and partly in order to see how the fct algorithm was performing. The same neap tide run but without fct is shown in Figs 15 and 16. Comparing again with Figs 10 and 12 shows the temperature peaks to be generally reduced although station L is nearly unaffected. The extra mixing serves to give results in rather better agreement with data. This suggests that the model is underpredicting the turbulent mixing.

The plume offshore spread is very much as before but the detached hot spots and features in the plume are washed out by the artificial diffusion in this test. A test was carried out in which the horizontal turbulent viscosity was decreased from $5m^2/s$ to $0.1m^2/s$. The test was for a spring tide and the results are Figs 17 and 18 (compare Figs 9 and 11).

Except for small scale structures in the plume the results are generally fairly insensitive to this parameter.

A further test was carried out with a horizontal eddy diffusivity of $5m^2/s$ (the other tests do not include horizontal diffusion). The results are shown in Figures 19 and 20. Clearly the higher horizontal diffusion results in a smearing of the temperature peaks in the model. This also increases vertical mixing.

5.5 Conclusions

The 40m model was considered to be in very good agreement with the observations bearing in mind the fully three-dimensional, unsteady nature of the problem and the day to day variations seen in the observations.

6 DISCUSSION

The previous two sections have shown the comparison between the 40m model and data and between the 100m model and data. The comparisons are generally very encouraging showing that the model is simulating the essential physical processes. This section will consider the differences and similarities between the two models (which were run for the same spring tide condition). This shows the sensitivity of the model to the grid size and also shows systematic differences of the model from the data for which suggested explanations are given.

The comparison of the two models is given by Figs 6 and 7 and Figs 9 and 11. The comparison of temperature time histories shows a very similar pattern of pulses from the two models. In both cases the main peak at M is late and peaks at P and R do not occur. These results all indicate a tendency for the plume to lie too close inshore. On the neap tide the plume correctly extends further offshore than on the spring. The late flood peak at L is better represented in the 100m model than in the 40m model.

It seems likely that these differences are all to do with an inadequate representation of the current patterns over the rock platform. The 100m model runs with boundary conditions from the original Severn Barrage model and the currents in the Hinkley area are known not to be wholly correct in this model. The 40m model has an offshore impermeable boundary which the flow is forced to follow. In either case the flows over the platform may not be wholly correct.

A comparison of surface isotherms for the two models shows generally very similar results, the main discrepancies being close to high water when a rather different shape of slack water pool forms. It is possible that the momentum of the outfall is not included correctly in the model and contributes to shaping this high water pool and helping to project it offshore.

The general conclusion from this comparison is that the results of the 40m and 100m numerical models are largely very similar, that is the model is not very sensitive to gridsize.

The discrepancies of the neap tide with observations (Fig 10) in which surface temperatures are high and the plume rather too stratified are symptomatic of too little mixing. The neap tide run with no fct (Fig 15) showed how horizontal diffusion brings down peak temperatures at the surface and allows more vertical mixing to occur. It is not, therefore, clear which area is the more fundamental. In particular an increase in vertical diffusion will cause greater shear and a greater horizontal spreading of the plume.

Some further sources of possible discrepancies are,

1. neglect of turbulence generated by boulders in the outfall channel.

2. The A and B station discharges are lumped together in the model but actually they remain separate both in the outfall channel and also somewhile thereafter.

3. The model assumes equilibrium of turbulence so that at slack water there is no turbulent mixing. Actually this is a time when in the absence of shear turbulent motions will still be present as a remnant of the previous shear. This process may have an important effect on the slack water pools.

Despite these various uncertainties the agreement of model and data is adequate to undertake engineering studies for cold sites and choose preferred combinations of intake and outfall locations.

7 CONCLUSION

Both the 100m and 40m models reproduced the main features of the thermal observations. The validation has been taken further than any similar work that has been published hitherto. Some differences between model and data were also found, the model plume does not spread so far offshore and tends to occupy a thinner surface layer. These differences may indicate that some improvement to the mixing length foundation is possible or else it may be important to include wind and wave effects. This model is now being used as a productive tool having been shown in this work to simulate all the necessary physical processes.

8 ACKNOWLEDGEMENTS

I should like to thank the CEGB for providing the site data necessary to carry out this validation. The thermal database was prepared by Mr J Lawrence. Many of the runs were done by Mr G Eadie. The work was mostly done under the guidance of Dr G V Miles.

9 REFERENCES

1. Koh R C Y, Brooks N H, List E J and Wolanski E J (1974) Hydraulic Modelling of Thermal Outfall Diffusers for the San Onofre Nuclear Power Plant. W M Keck Laboratory of Hydraulics and Water Resources Tech Rep No KH-R-30, California Institute of Technology.

2. Evans-Roberts D J (1978) Integral plume model for surface discharges, HRS Report IT 186

3. Cooper A J (1980) Buoyant plume in an unsteady environment. 2nd International Symposium on Stratified Flows, Trondheim.

4. Williams J M, A numerical model of the temperature distribution in the vicinity of Sizewell Power Station outfall, Rapports et Proces-Verbaux Reun Cons int Explr Mer 167: Dec 1974, p.171.

5. Hinkley Point C Pre-application studies. Power station background, temperature and siltation studies with and without the Severn barrage. Report No EX 1254, Hydraulics Research Ltd, 1985.

6. CEGB Generation, development and construction division. Hinkley Point 'C' Power Station. Hydrographic 1983 survey, Osiris-Cesco Ltd.

7 Severn Tidal Power. Two dimensional water movement model study, Report No EX 985, Hydraulics Research Station, 1981.

8. The Severn Estuary - recording of tidal levels in 1980. Report EX 943, Hydraulics Research Station, September 1980.

9.. Wind - induced mixing of bouyant plumes. Report No SR78, Hydraulics Research Ltd, 1986.

FIGURES.

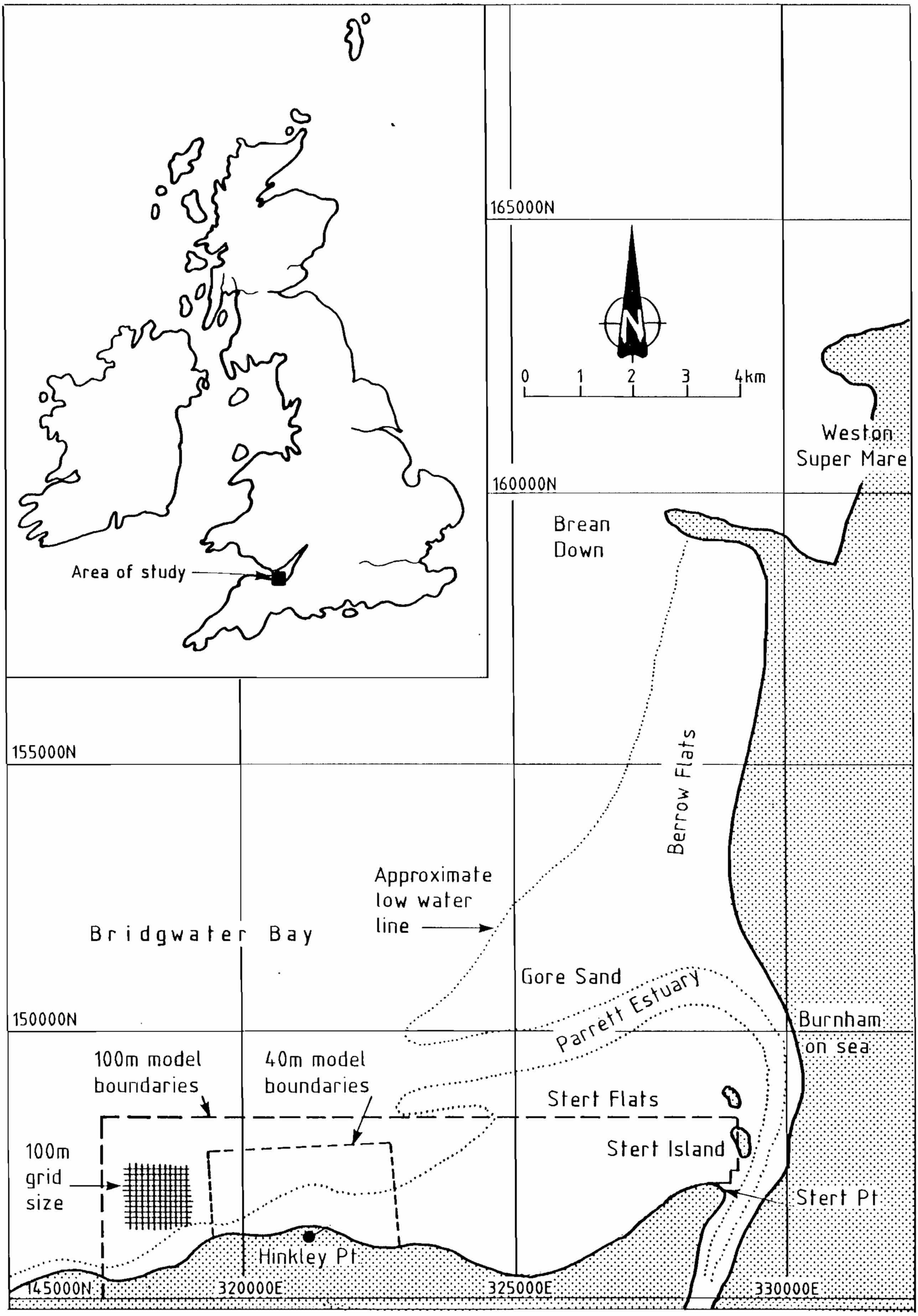
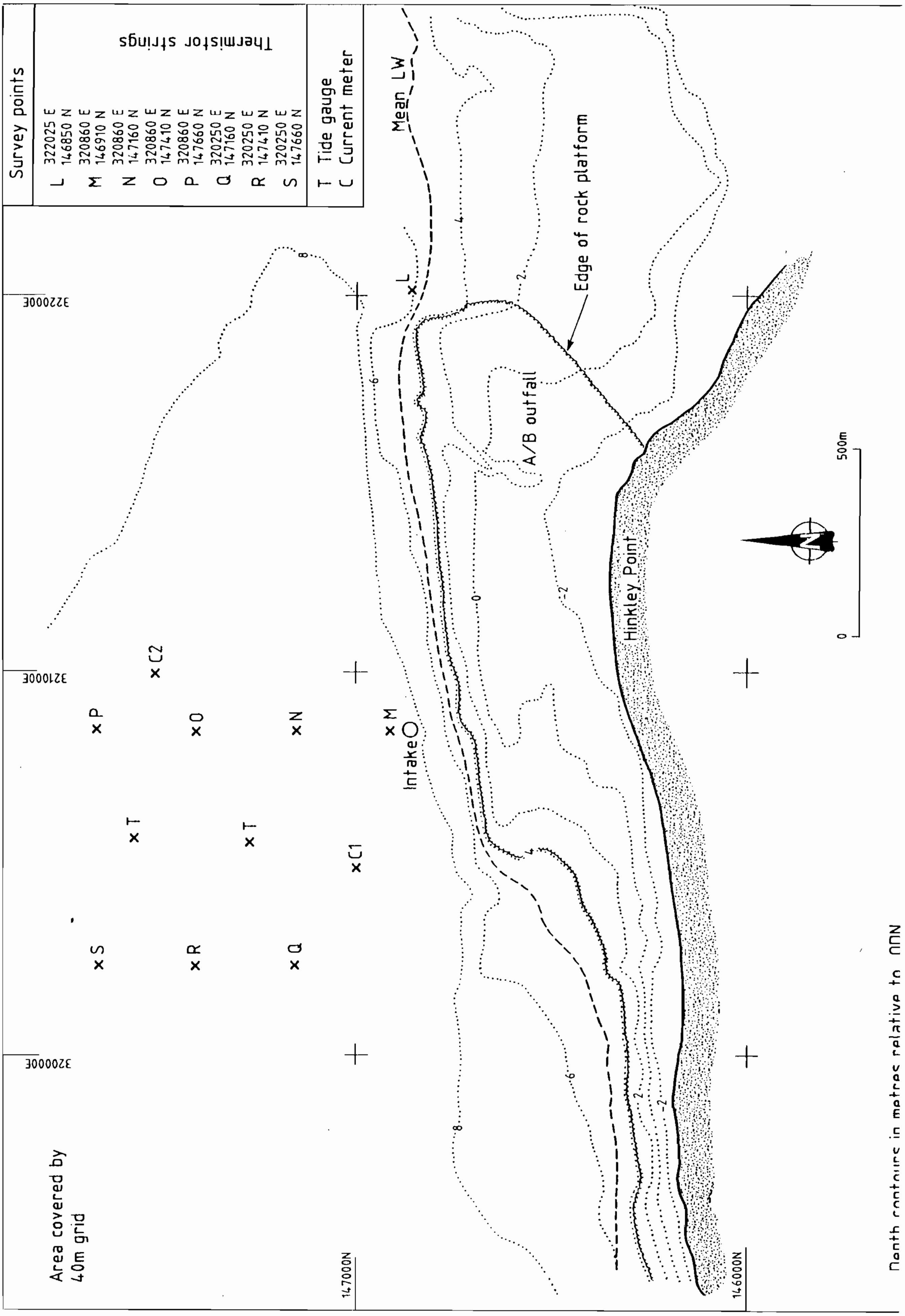


Fig 1 Hinkley midfield model location map



Survey points	
L	322025 E 146850 N
M	320860 E 146910 N
N	320860 E 147160 N
O	320860 E 147410 N
P	320860 E 147660 N
Q	320250 E 147160 N
R	320250 E 147410 N
S	320250 E 147660 N
T	Tide gauge
C	Current meter

Fig 2 Positions of survey observation points

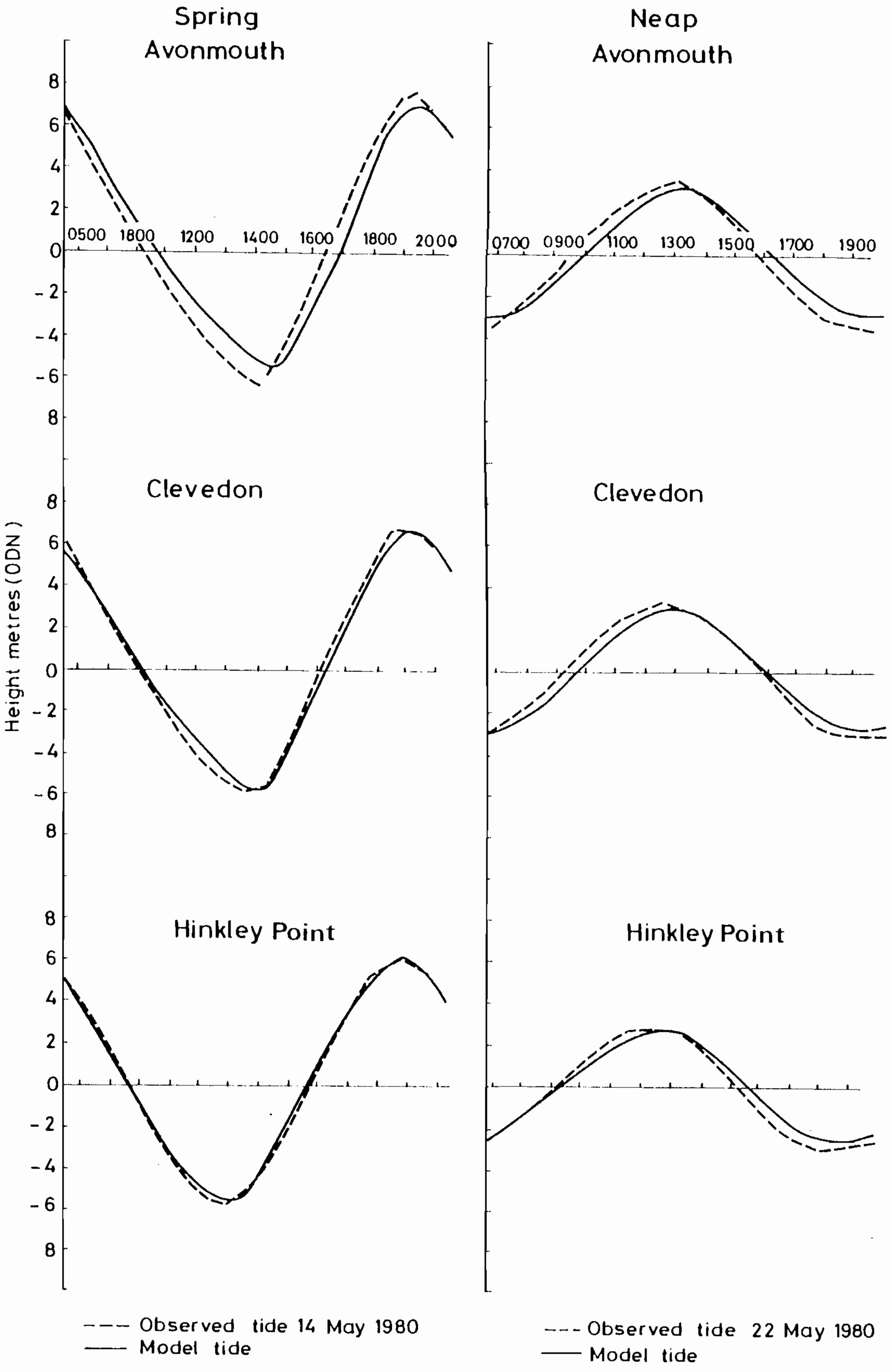


Fig 3 Tidal elevations from Severn Barrage model (existing conditions)

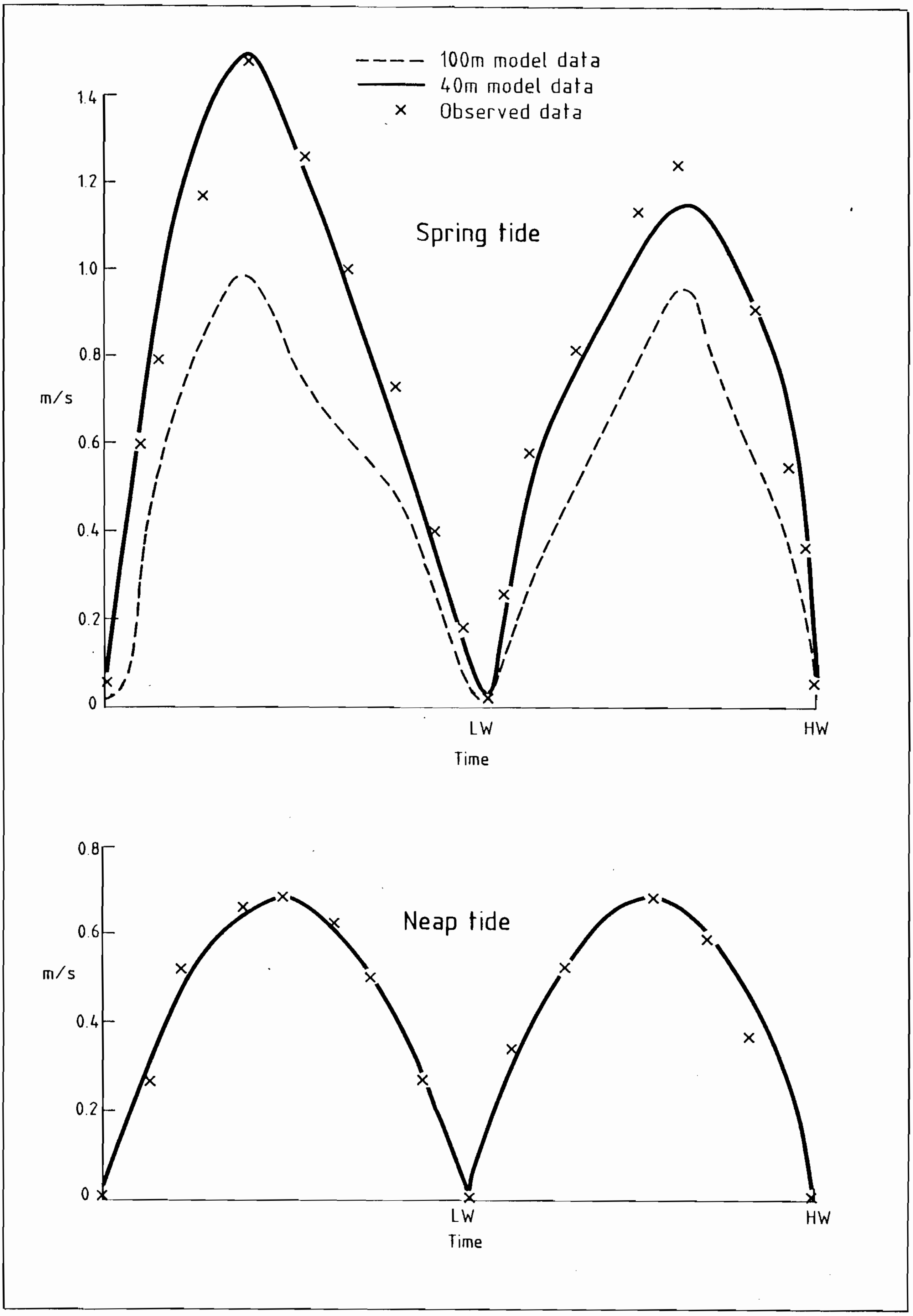


Fig 4 Representation of tidal currents

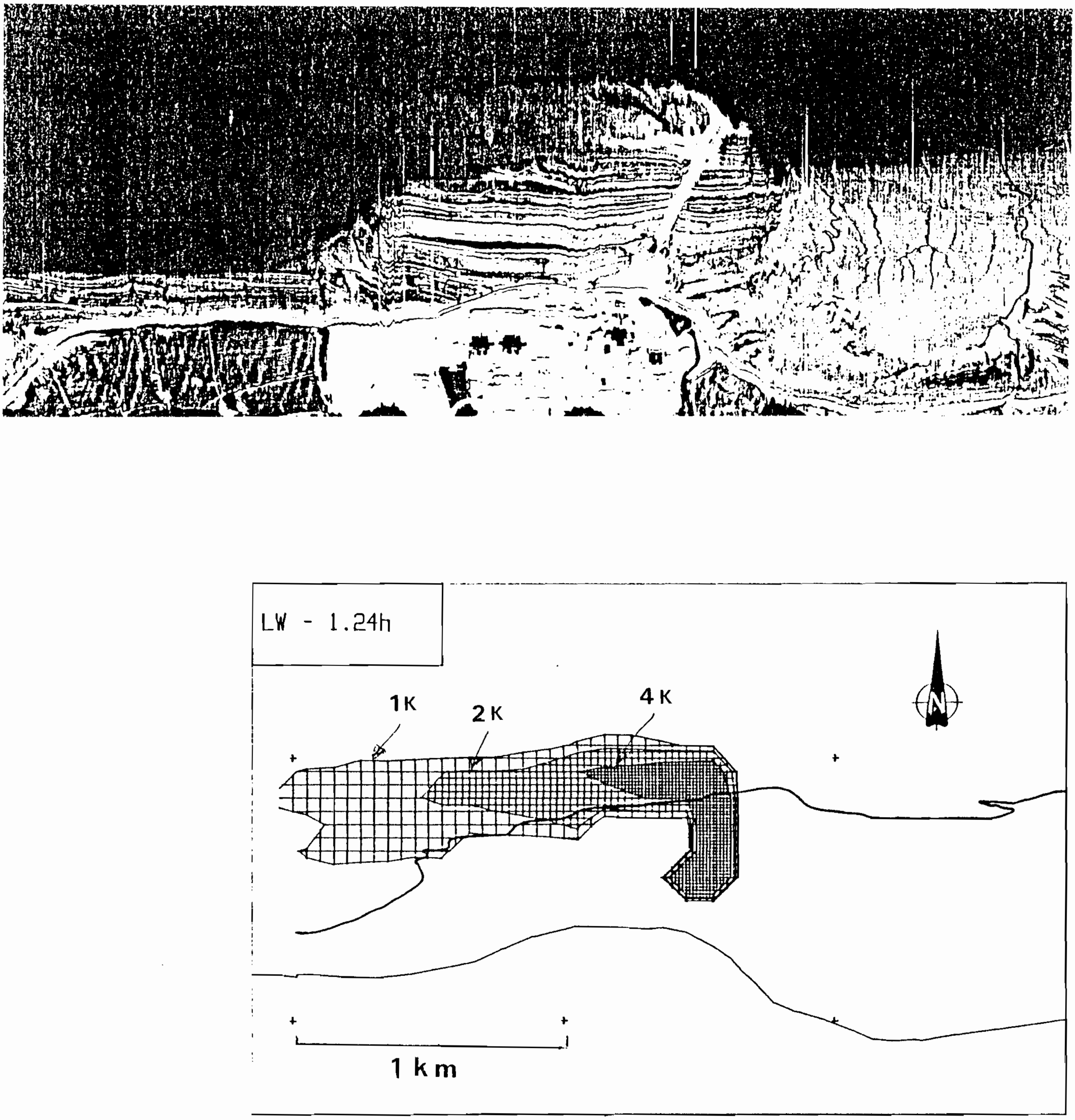


Fig 5a Surface isotherms from infrared imagery and 100m model

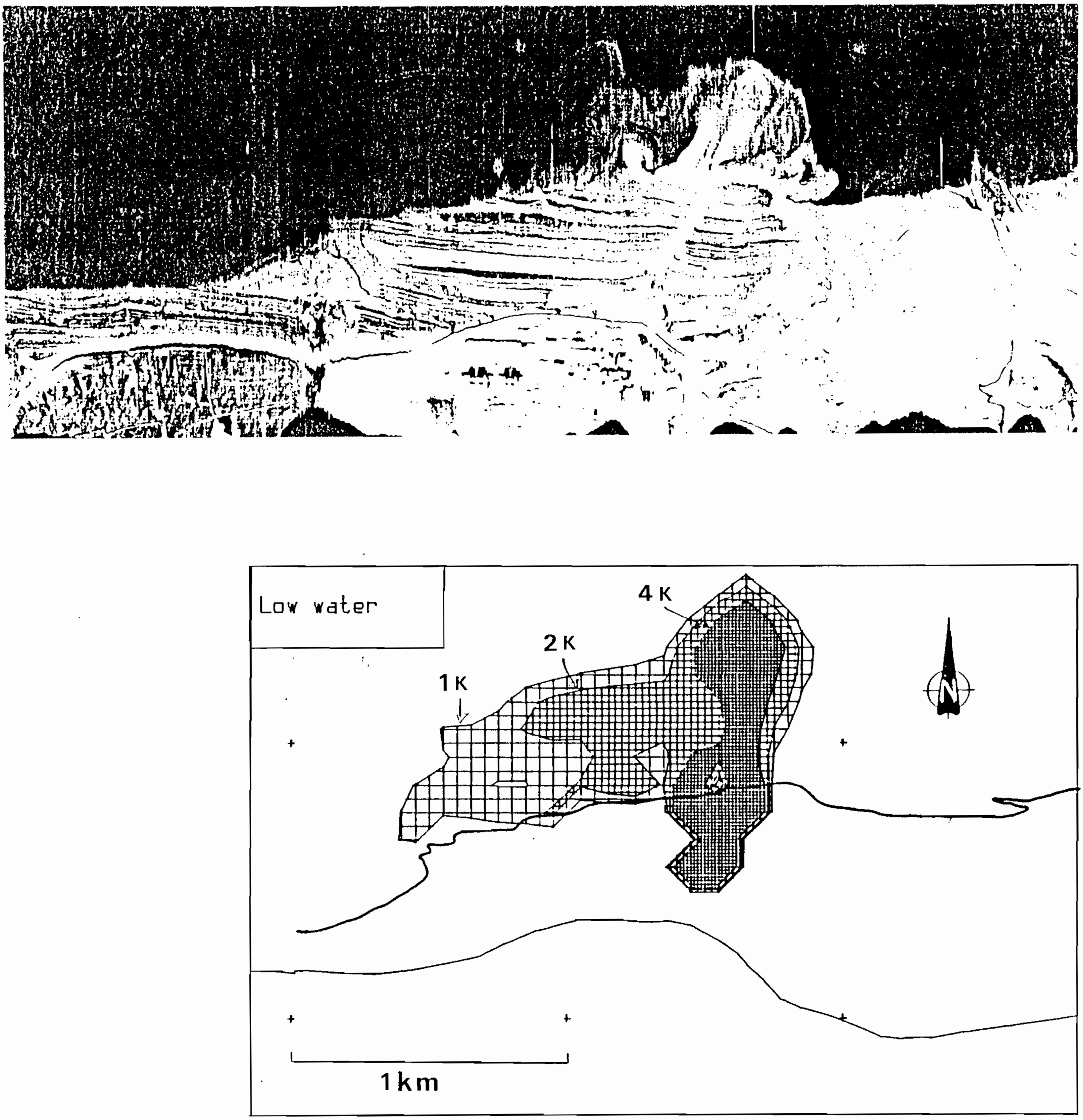


Fig 5b Surface isotherms from infrared imagery and 100m model

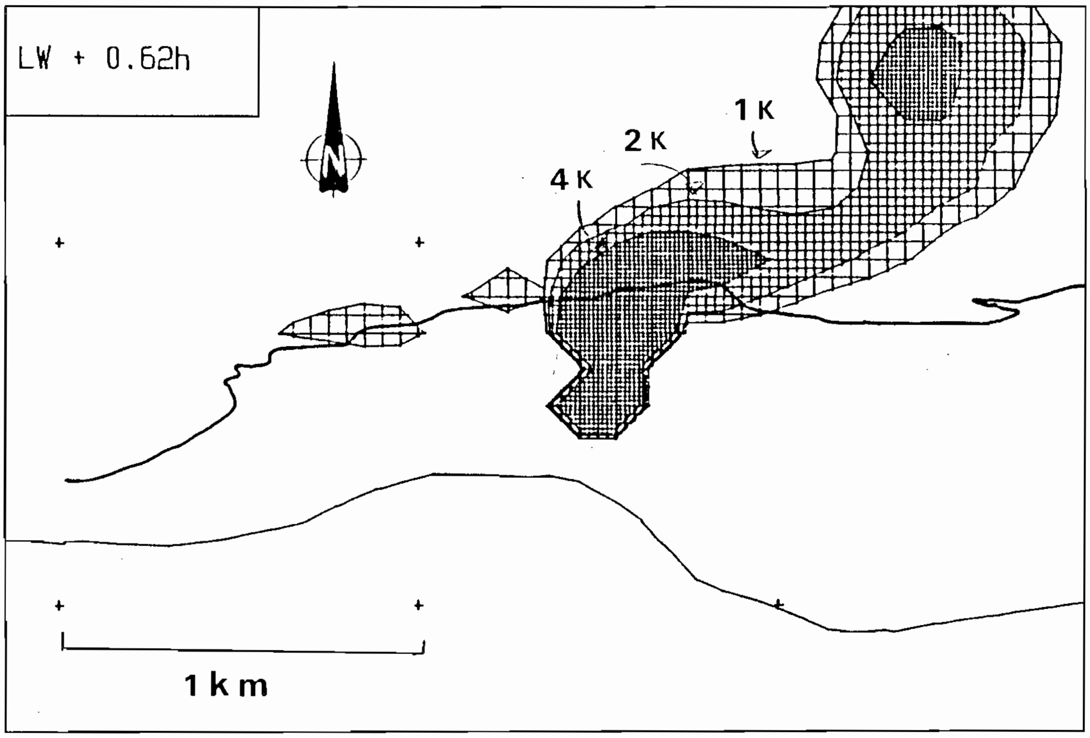


Fig 5c Surface isotherms from infrared imagery and 100m model

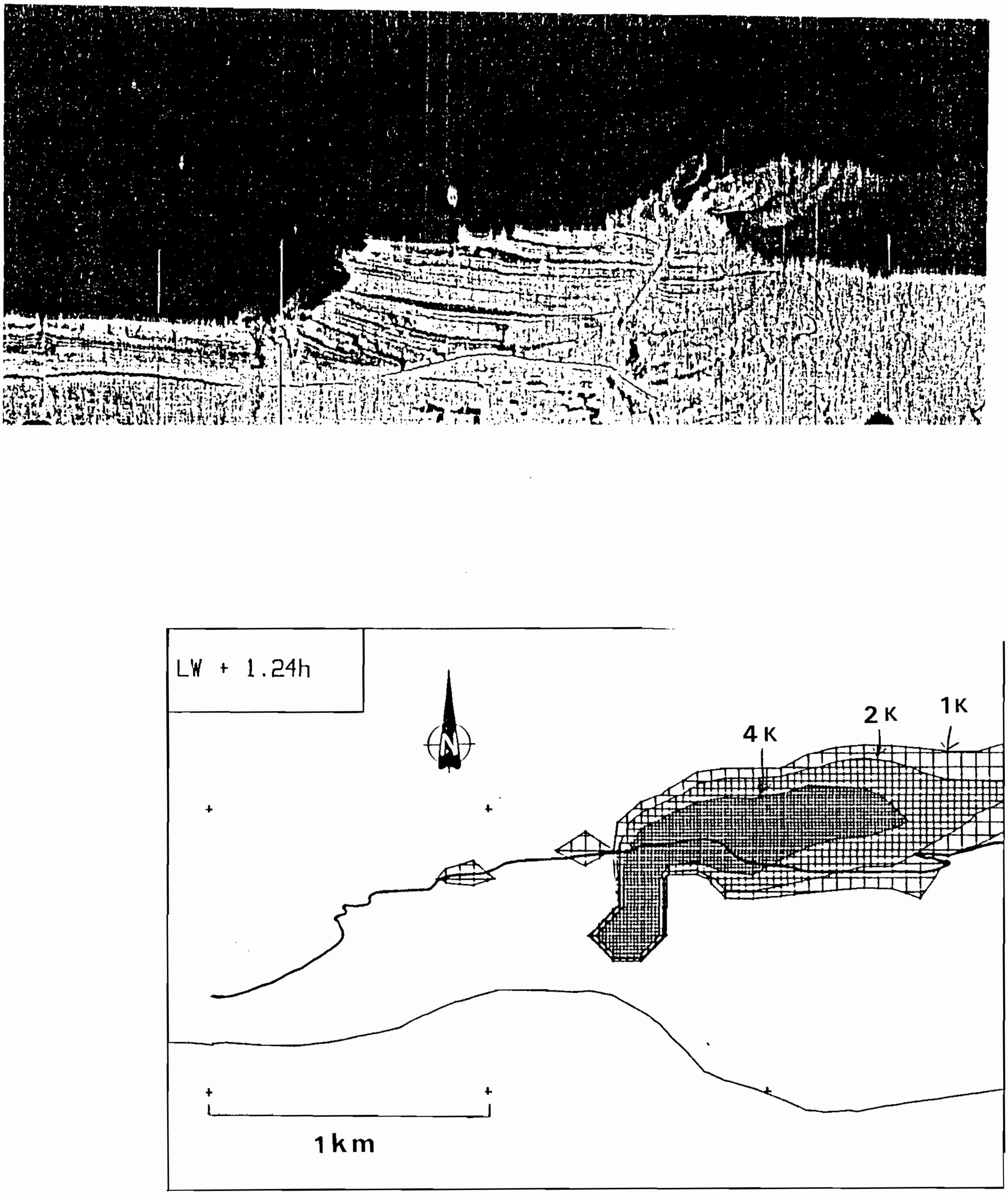


Fig 5d   Surface isotherms from infrared imagery and 100m model

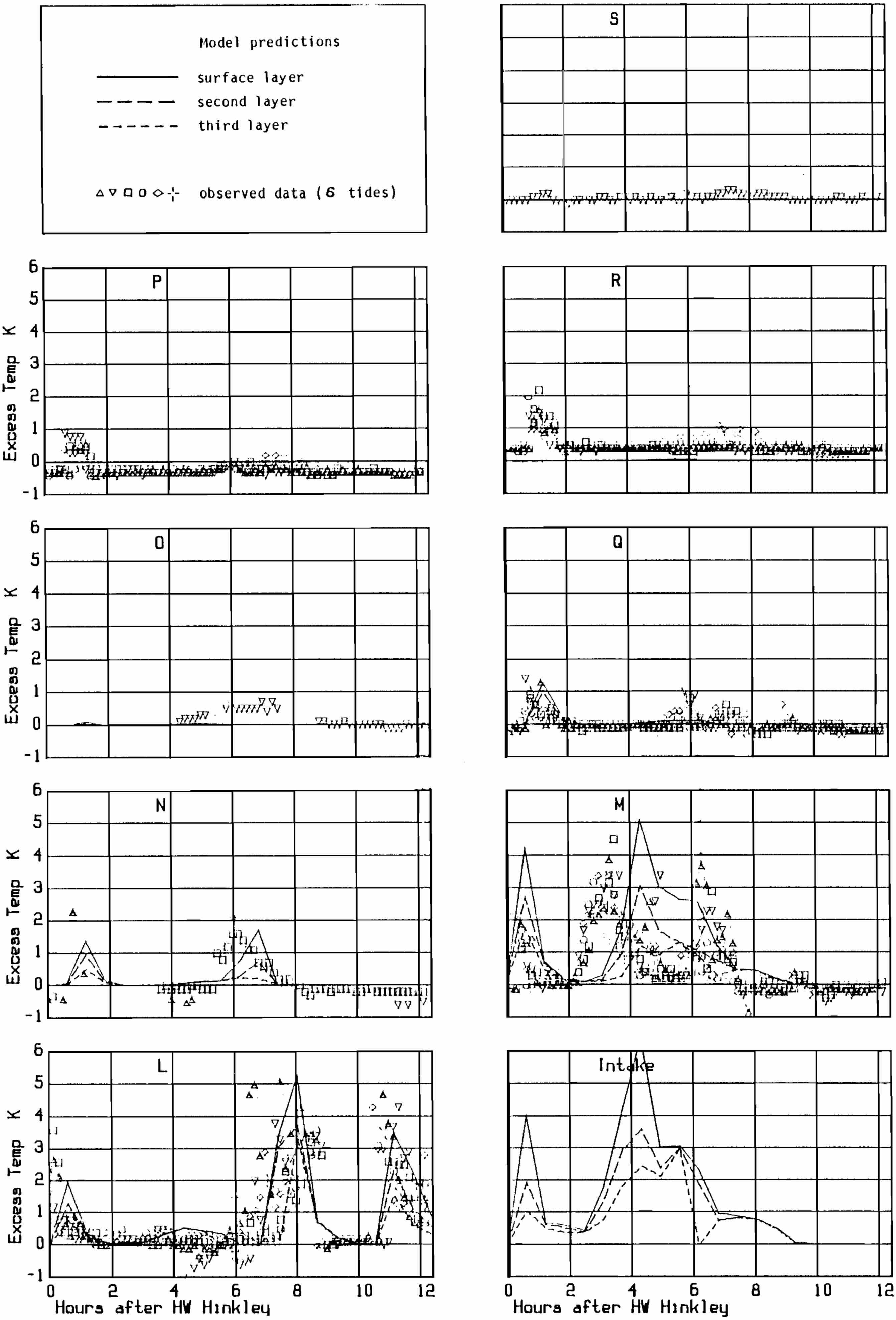


Fig 6 Simulated temperatures in 100m model
Spring tide

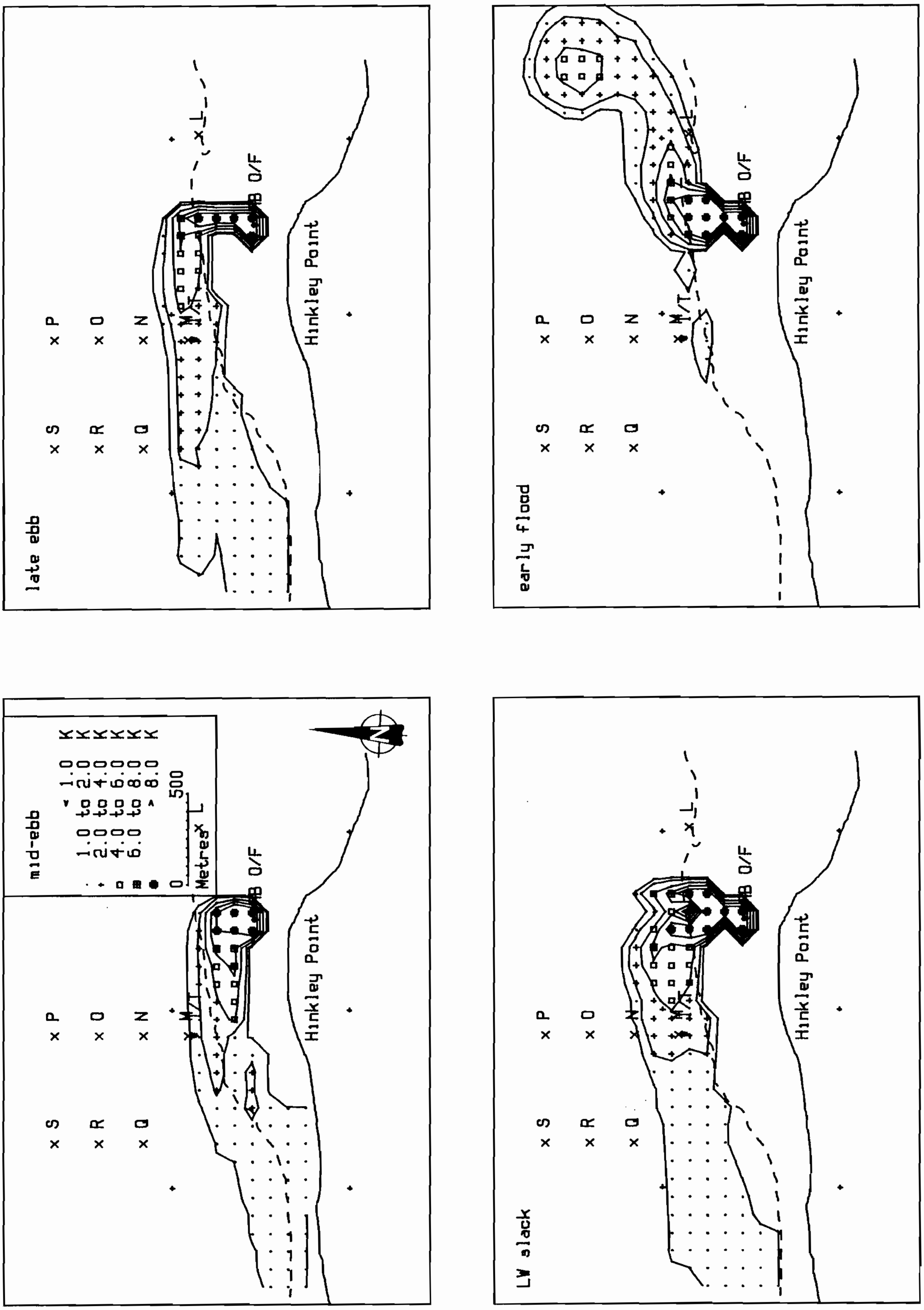


Fig 7a Surface isotherms 100m model
Spring tide

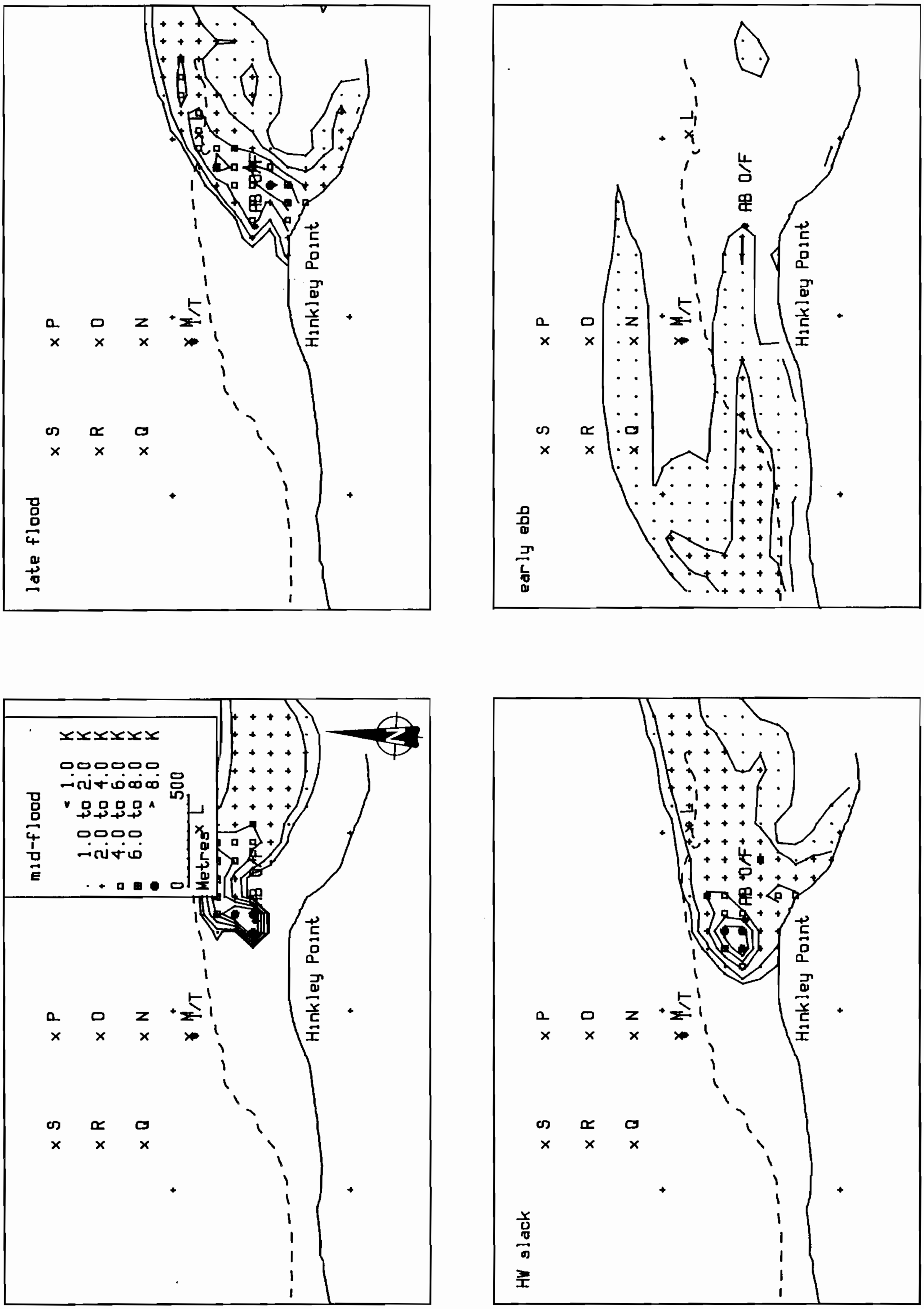


Fig 7b Surface isotherms 100m model
Spring tide

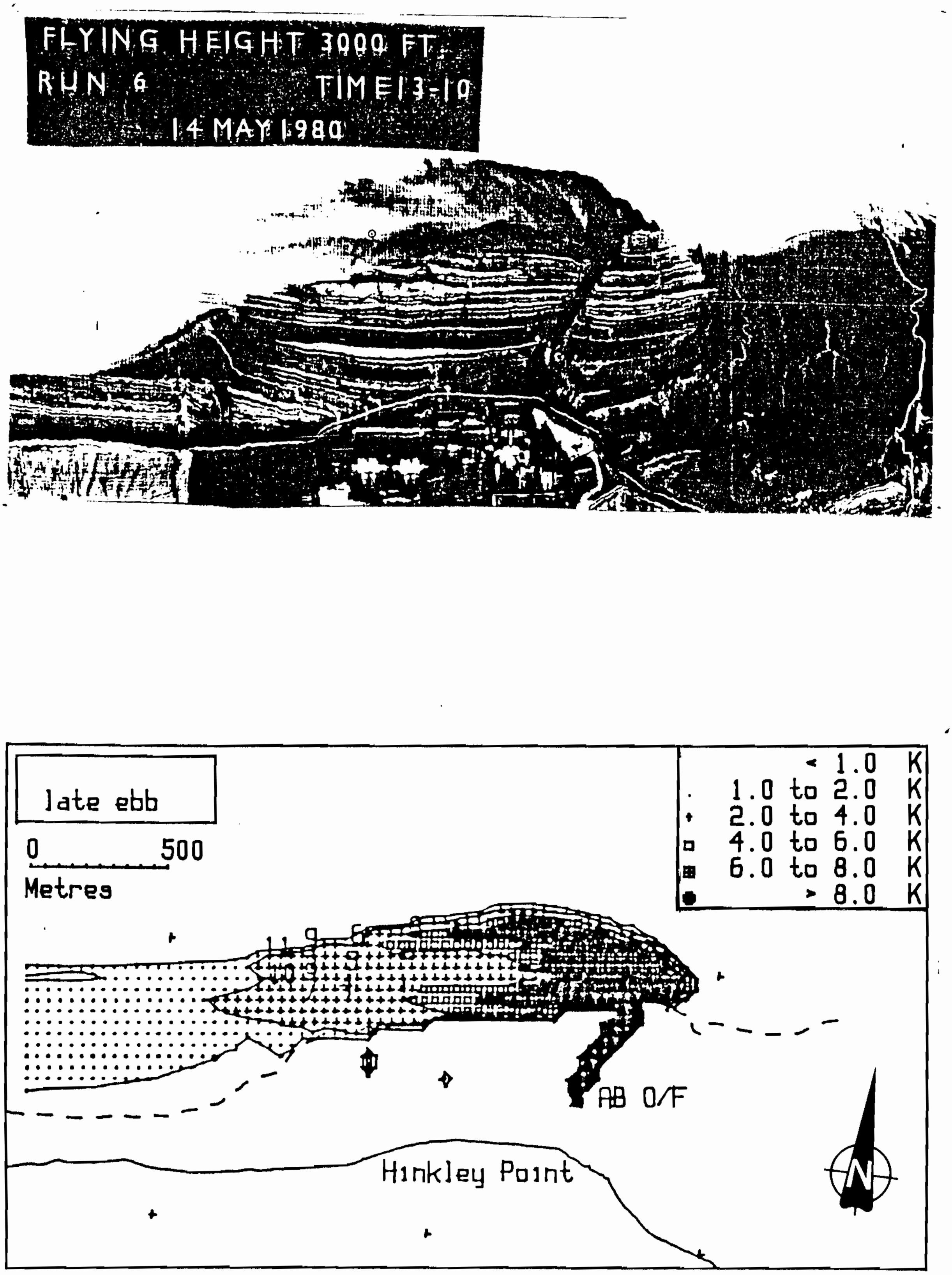


Fig 8a Surface isotherms from infra-red imagery and 40m model

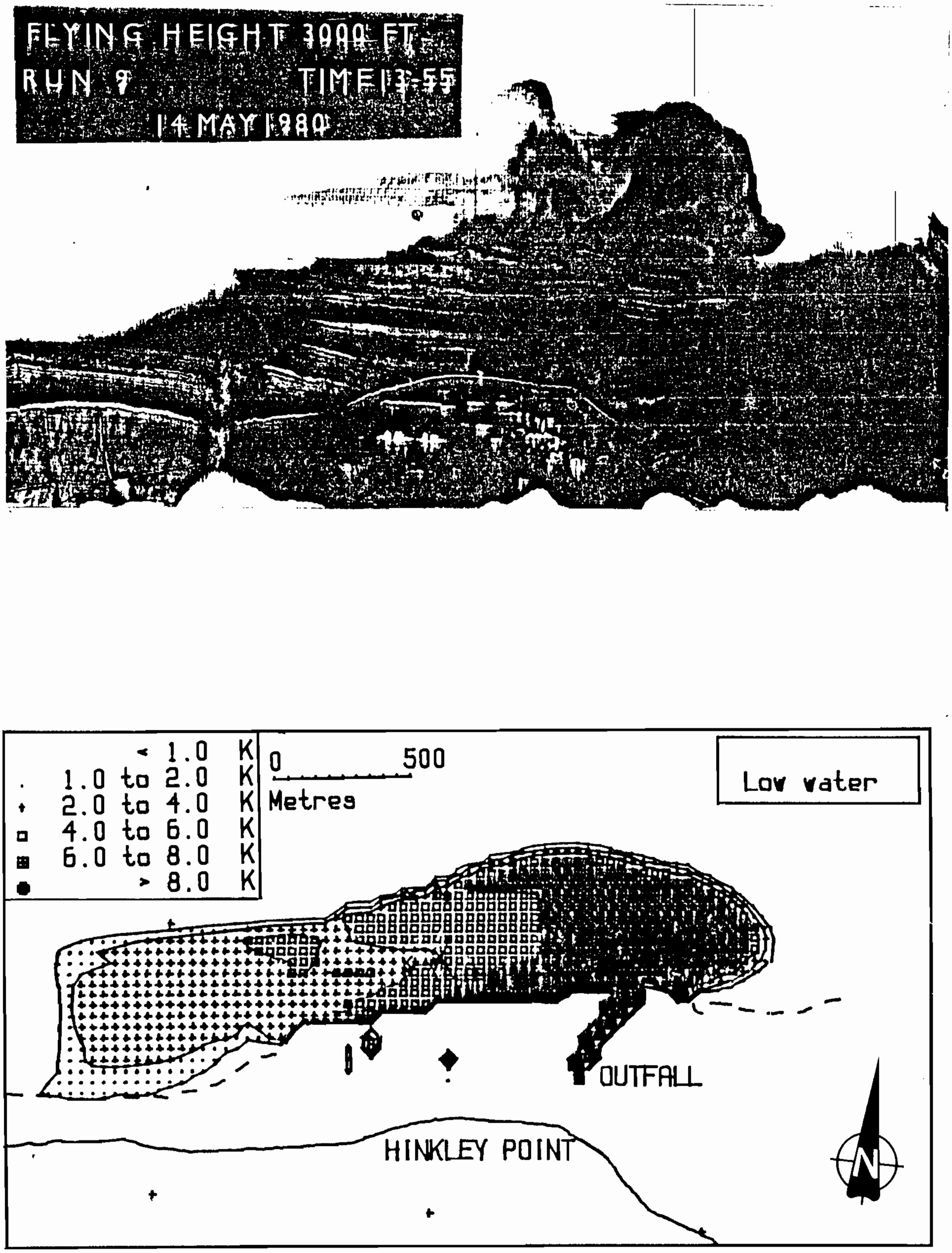


Fig 8b Surface isotherms from infra-red imagery and 40m model

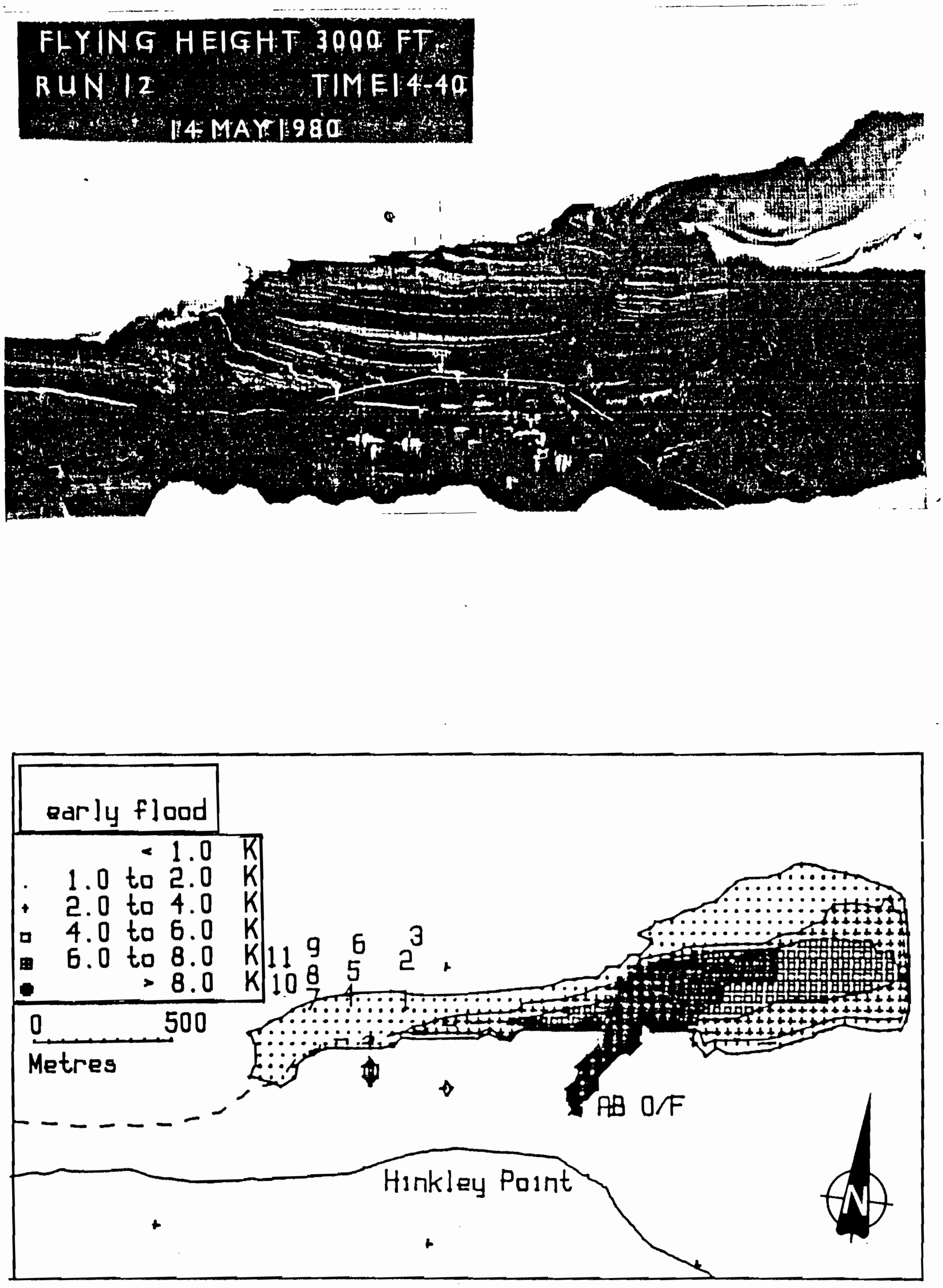


Fig 8c Surface isotherms from infra-red imagery and 40m model

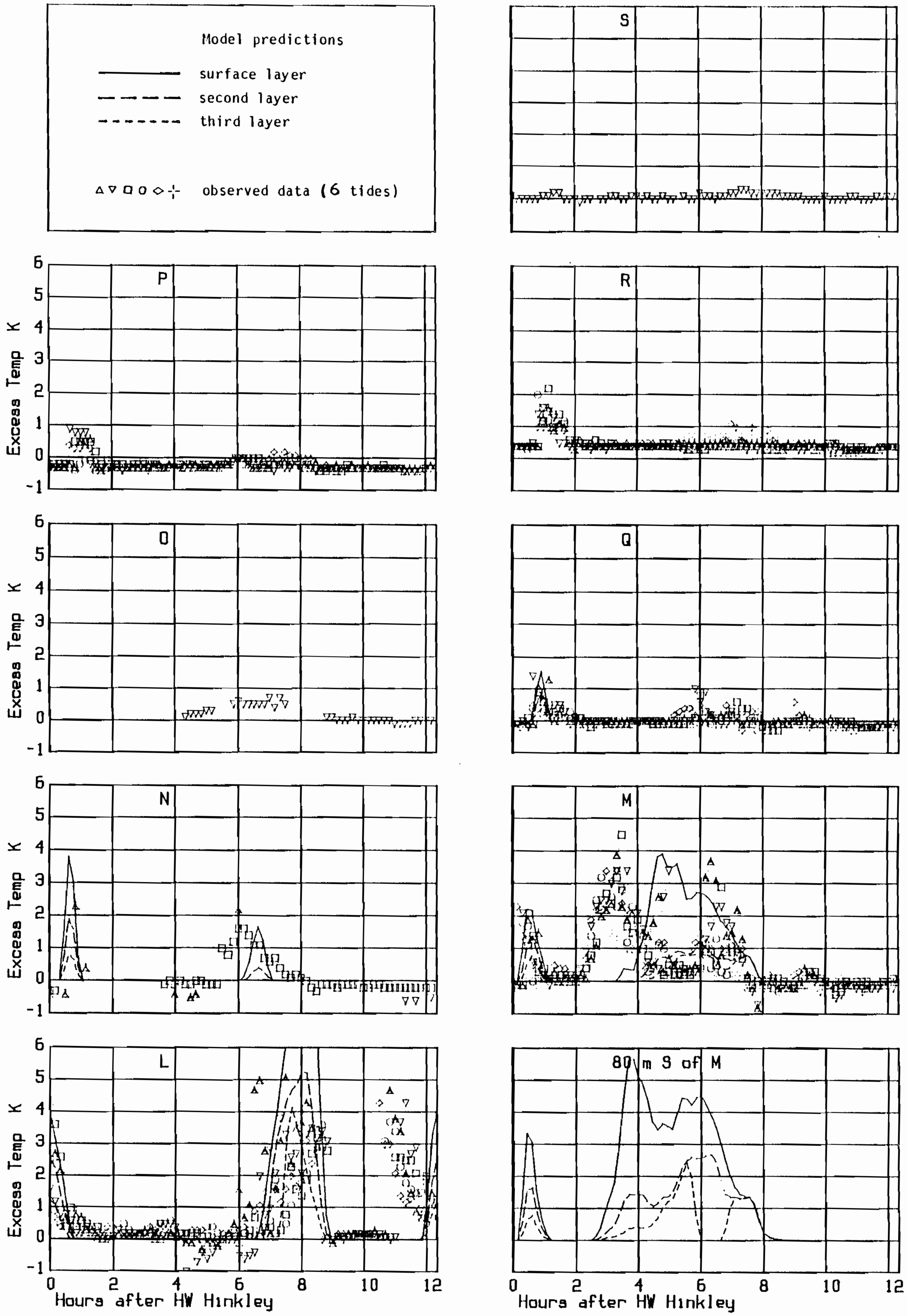


Fig 9 Simulated temperatures in 40m model
Spring tide

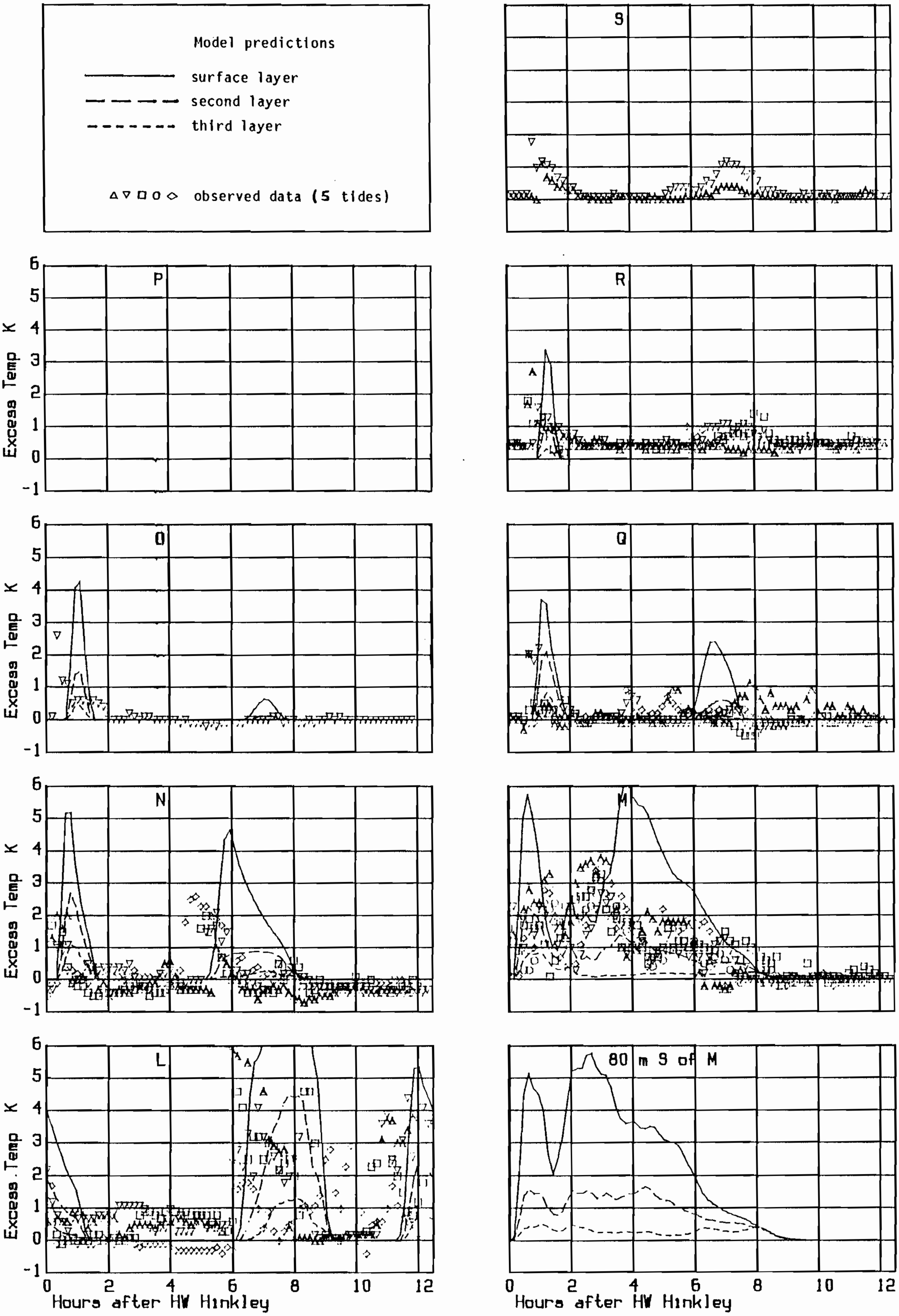


Fig 10 Simulated temperatures in 40 m model
Neap tide

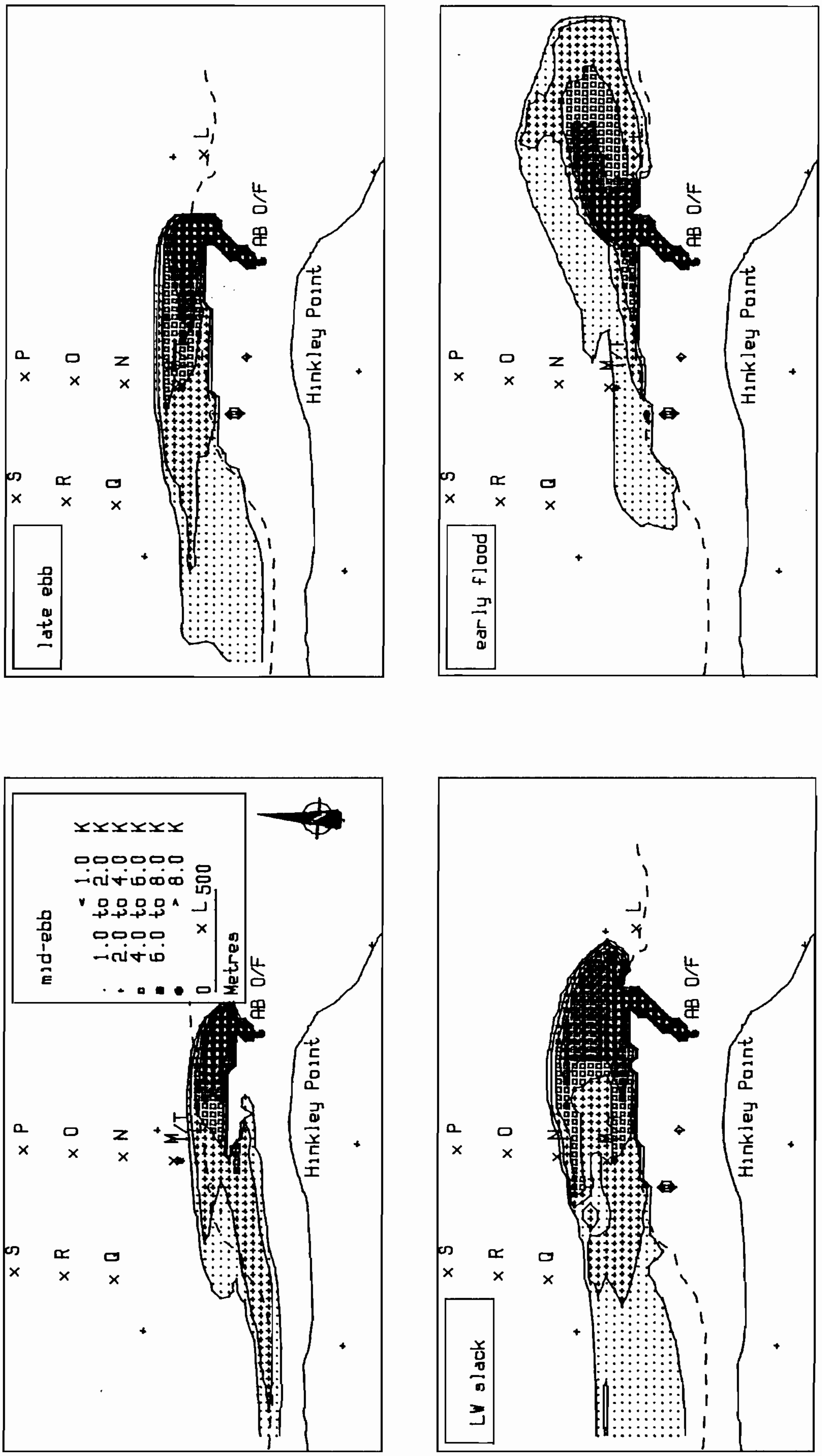


Fig 11a Surface isotherms Spring tide
Existing condition

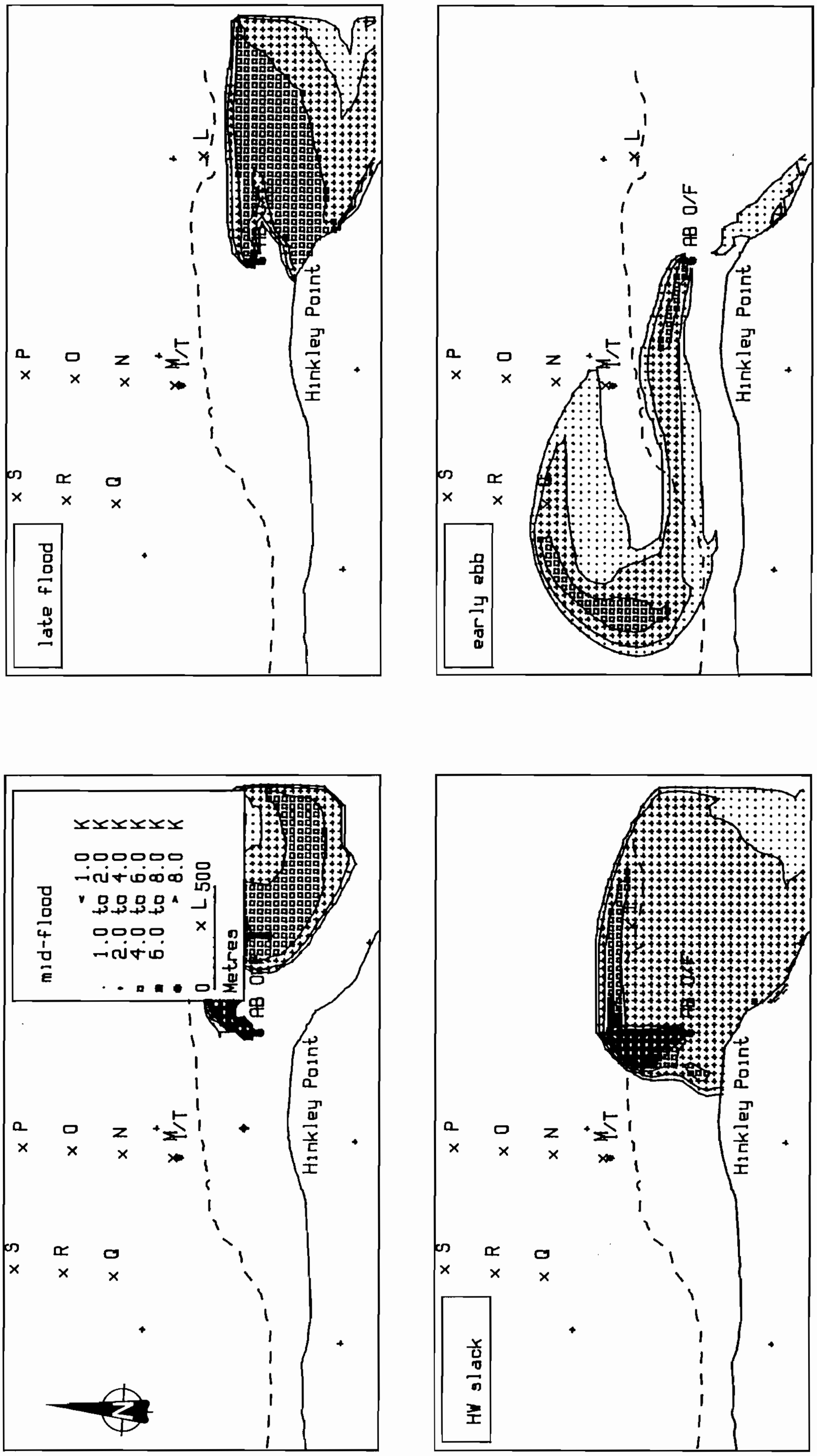


Fig 11b Surface isotherms Spring tide
Existing condition

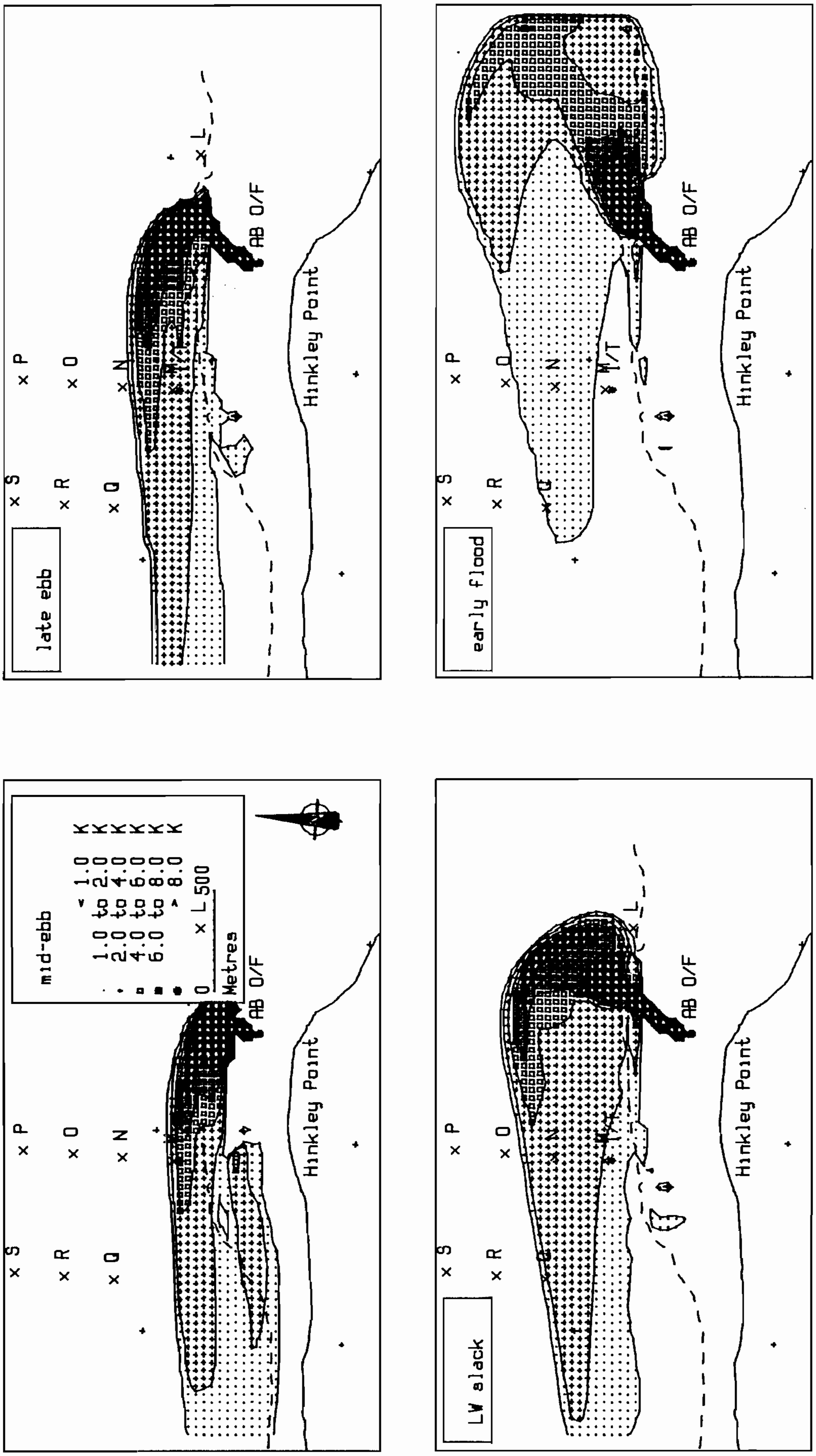


Fig 12a Surface isotherms Neap tide
Existing conditions

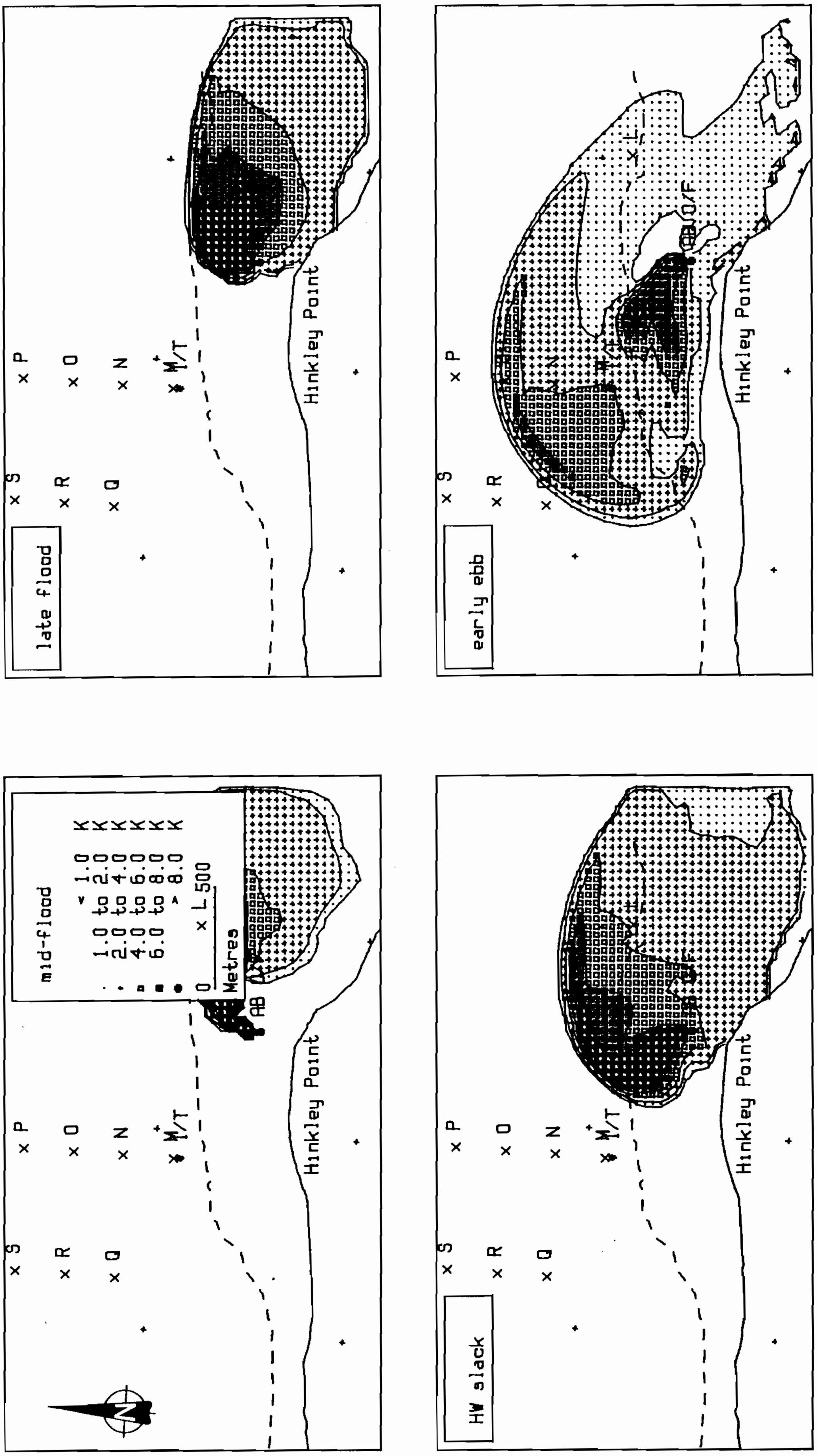


Fig 12b Surface isotherms Neap tide
Existing conditions

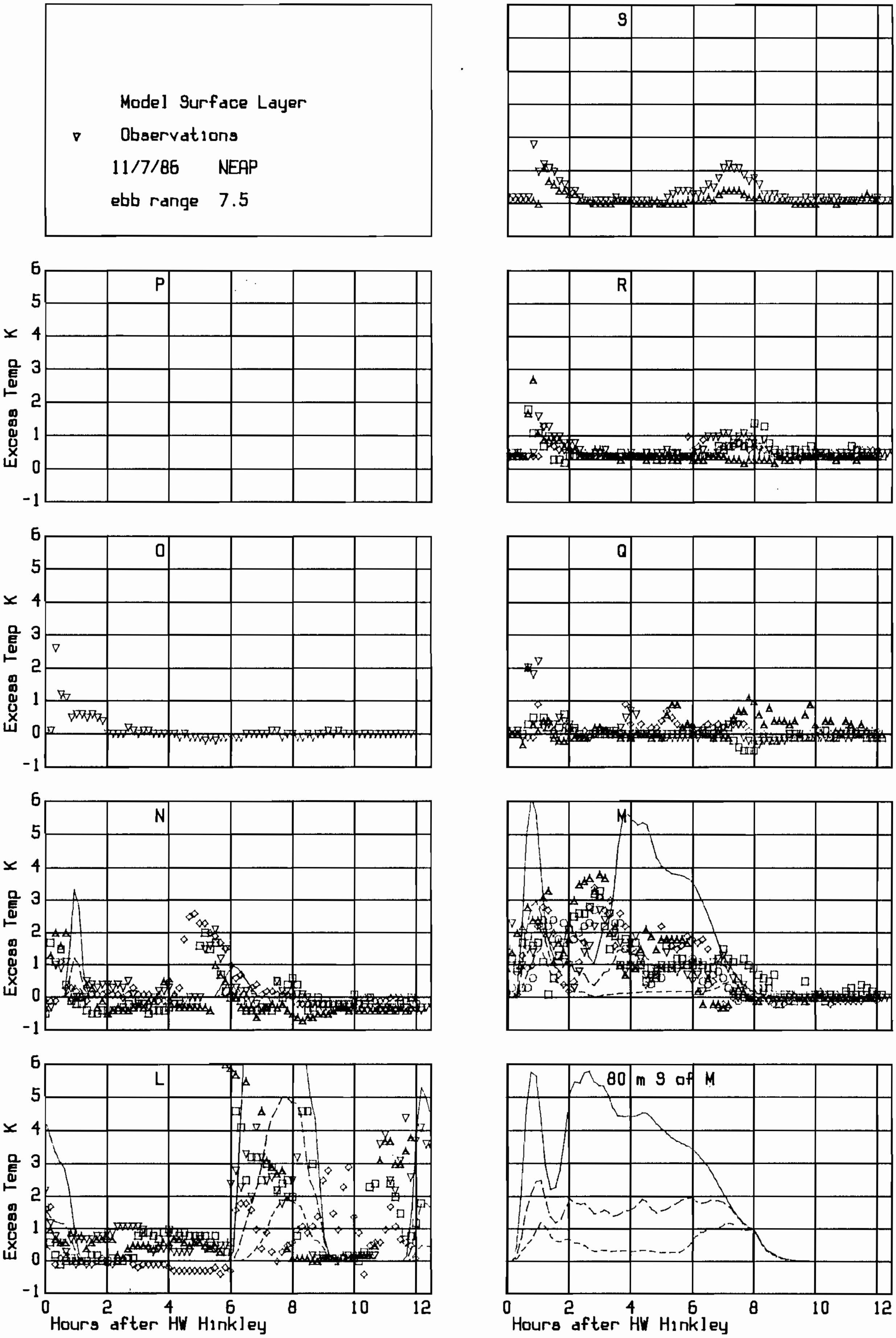


Fig 13 Neap tide with 5 m/s NW wind
40m model

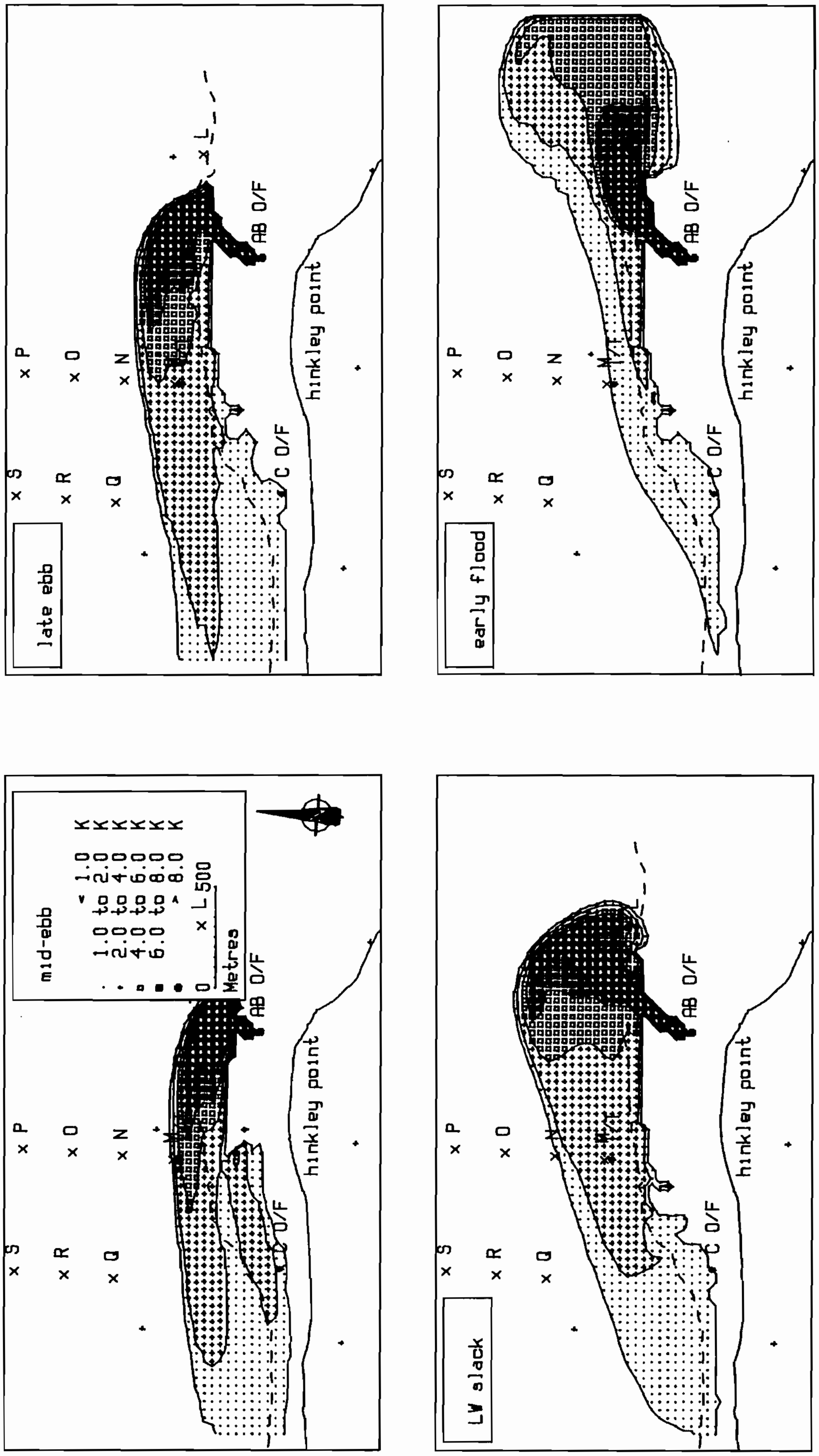


Fig 14a Surface isotherms Neap tide
5 m/s NW wind

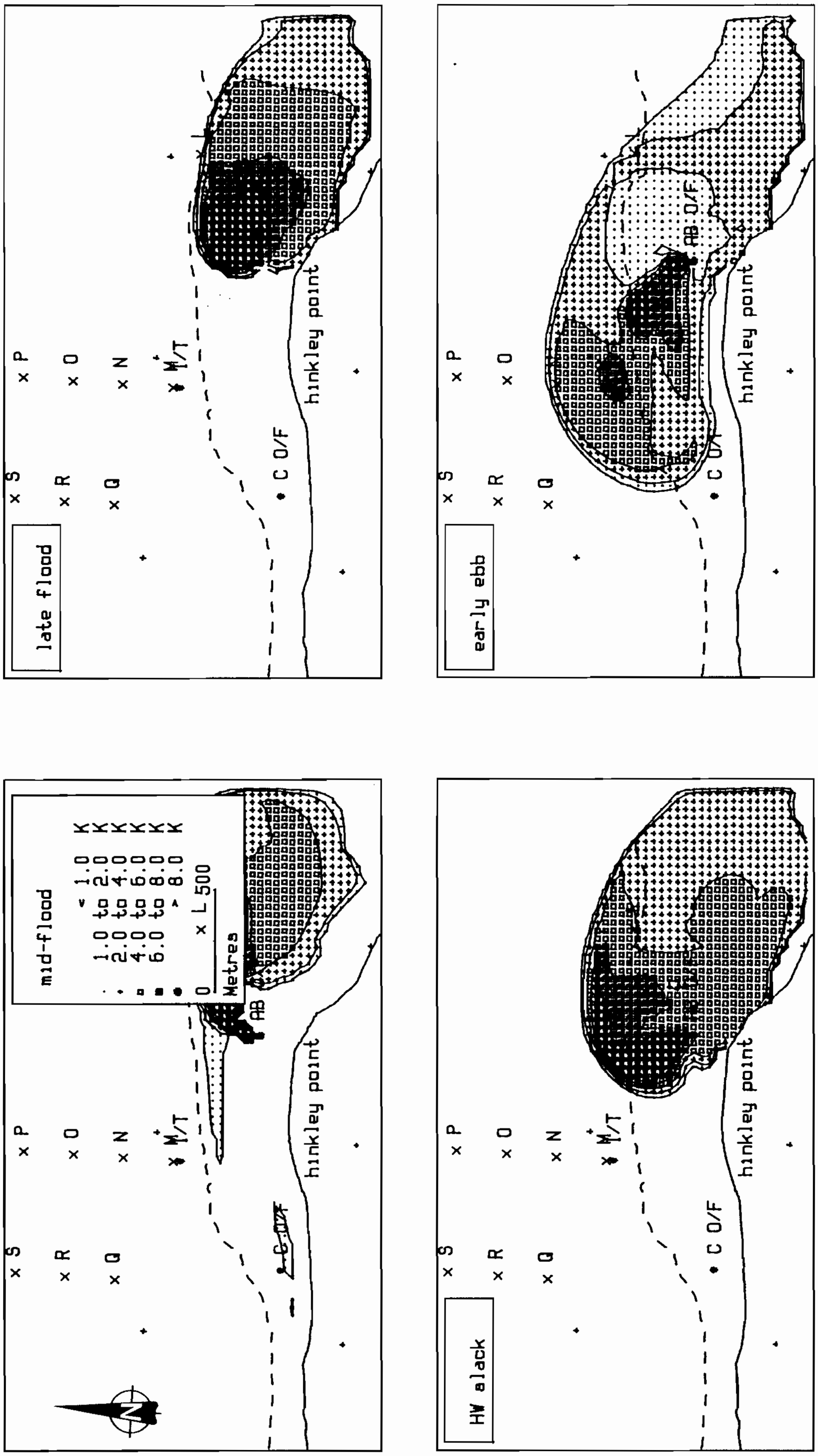


Fig 14b Surface isotherms Neap tide
5 m/s NW wind

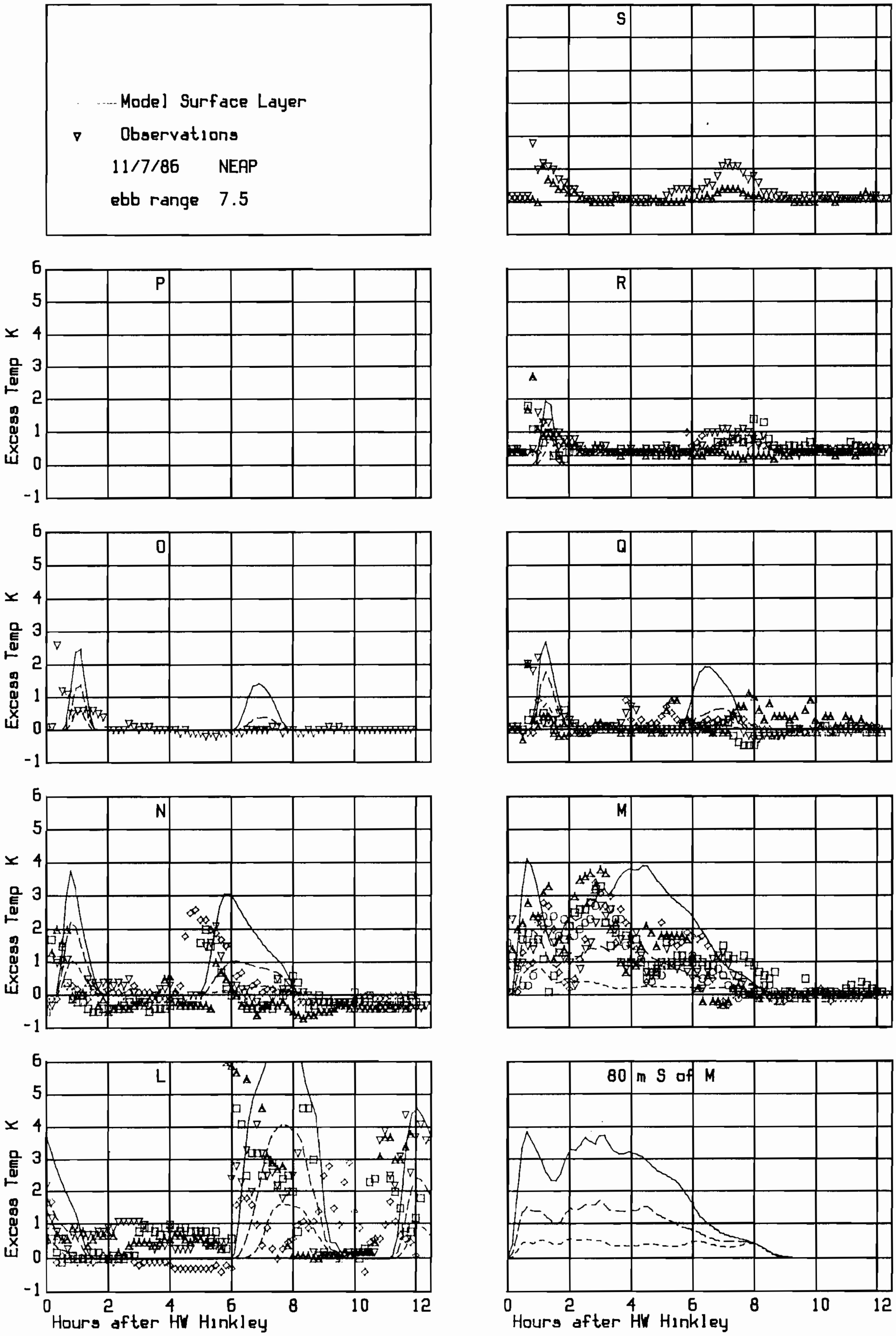


Fig 15 Neap tide with no FCT
40m model

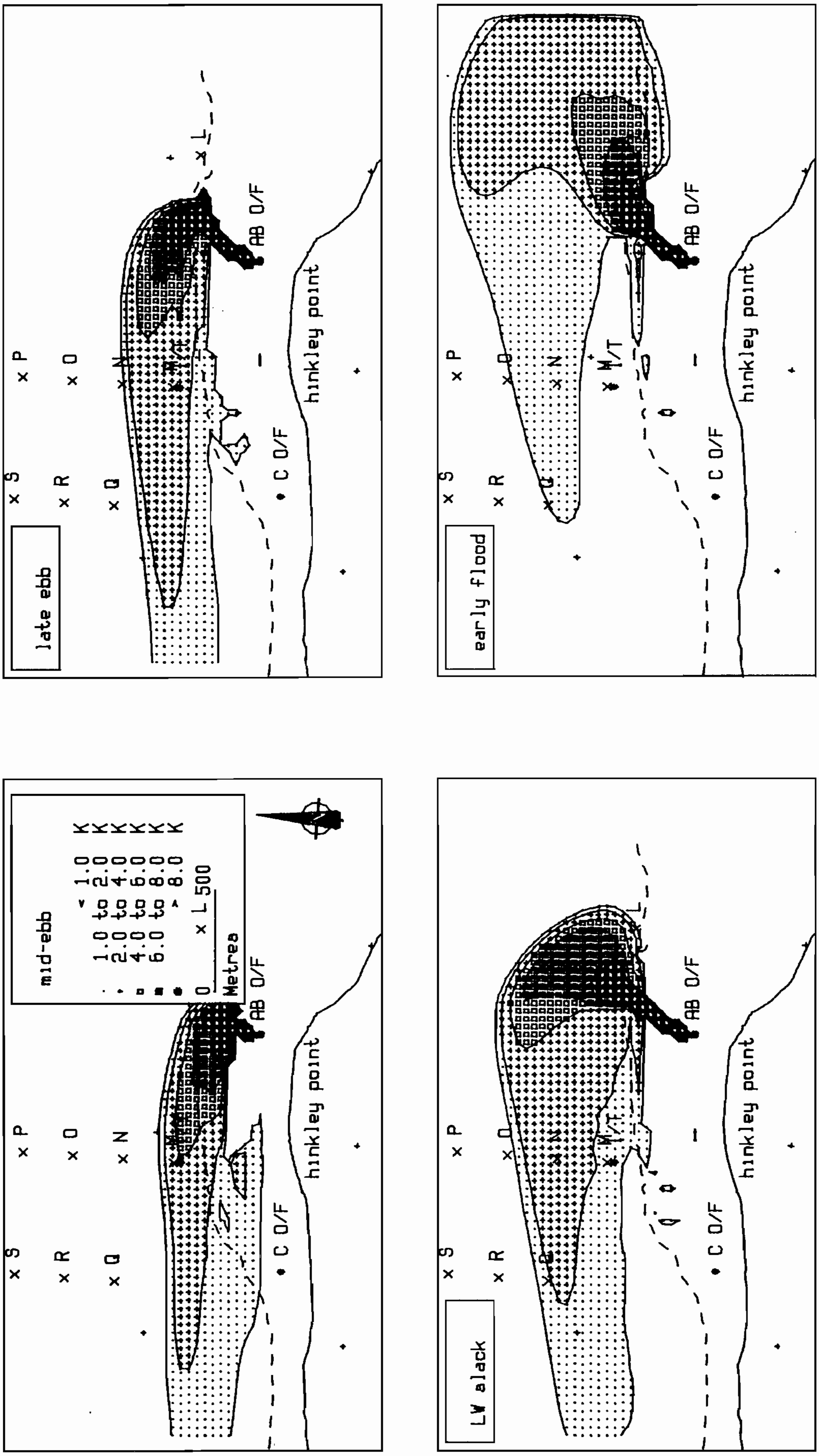


Fig 16a Surface isotherms Neap tide
no FCT

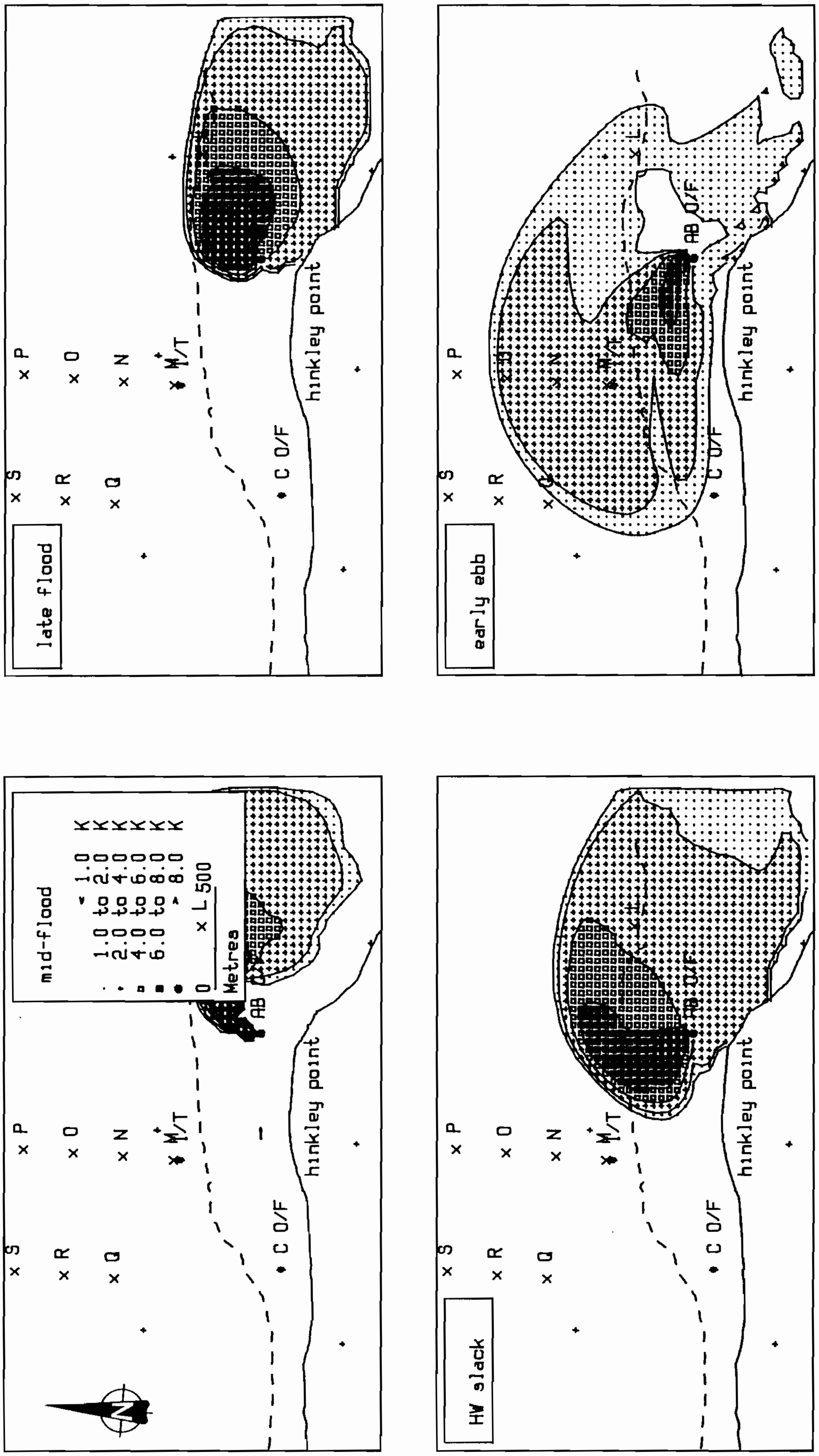


Fig 16b Surface isotherms Neap tide
no FCT

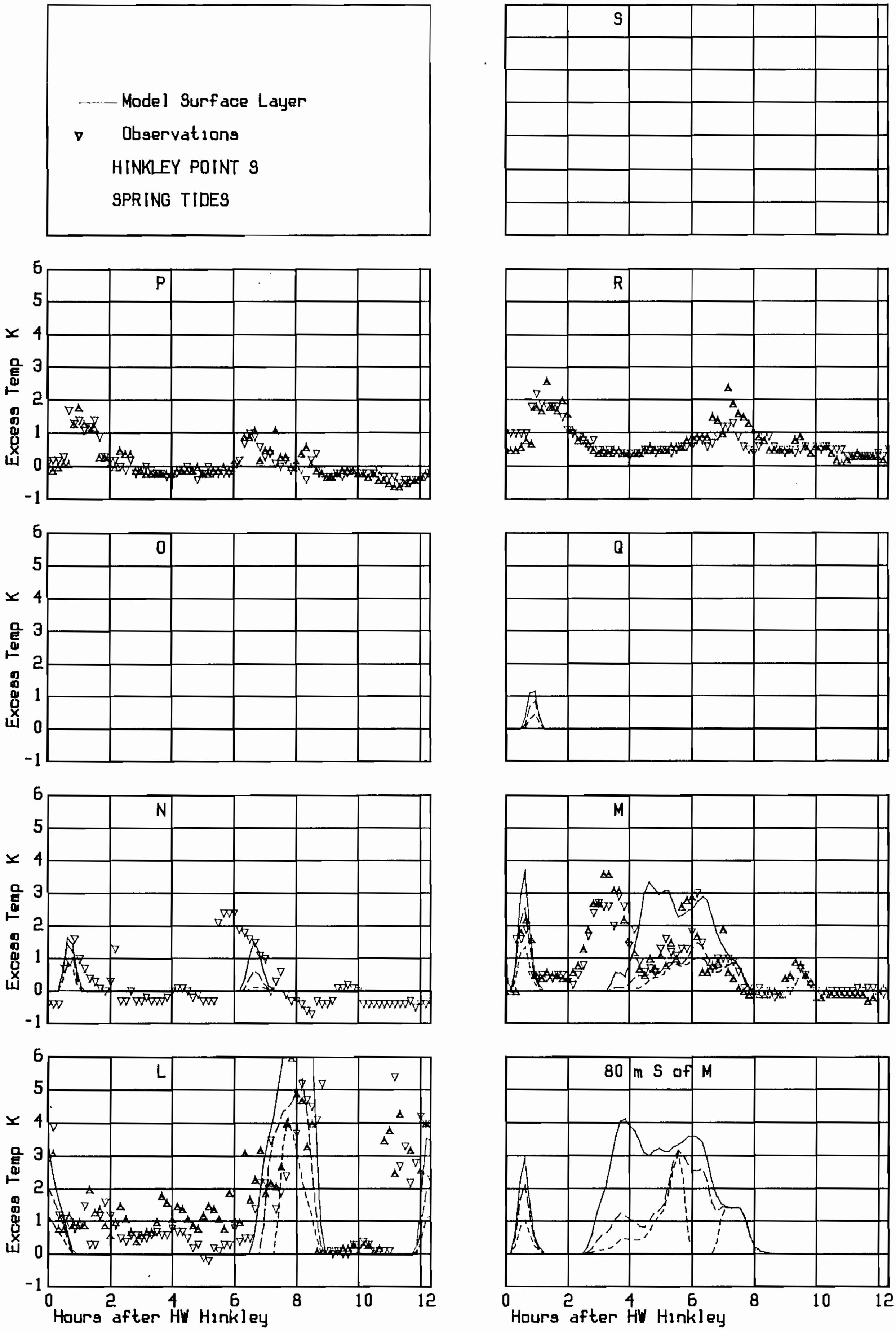


Fig 17 Spring tide viscosity = 0.1 m**2/s
40m model

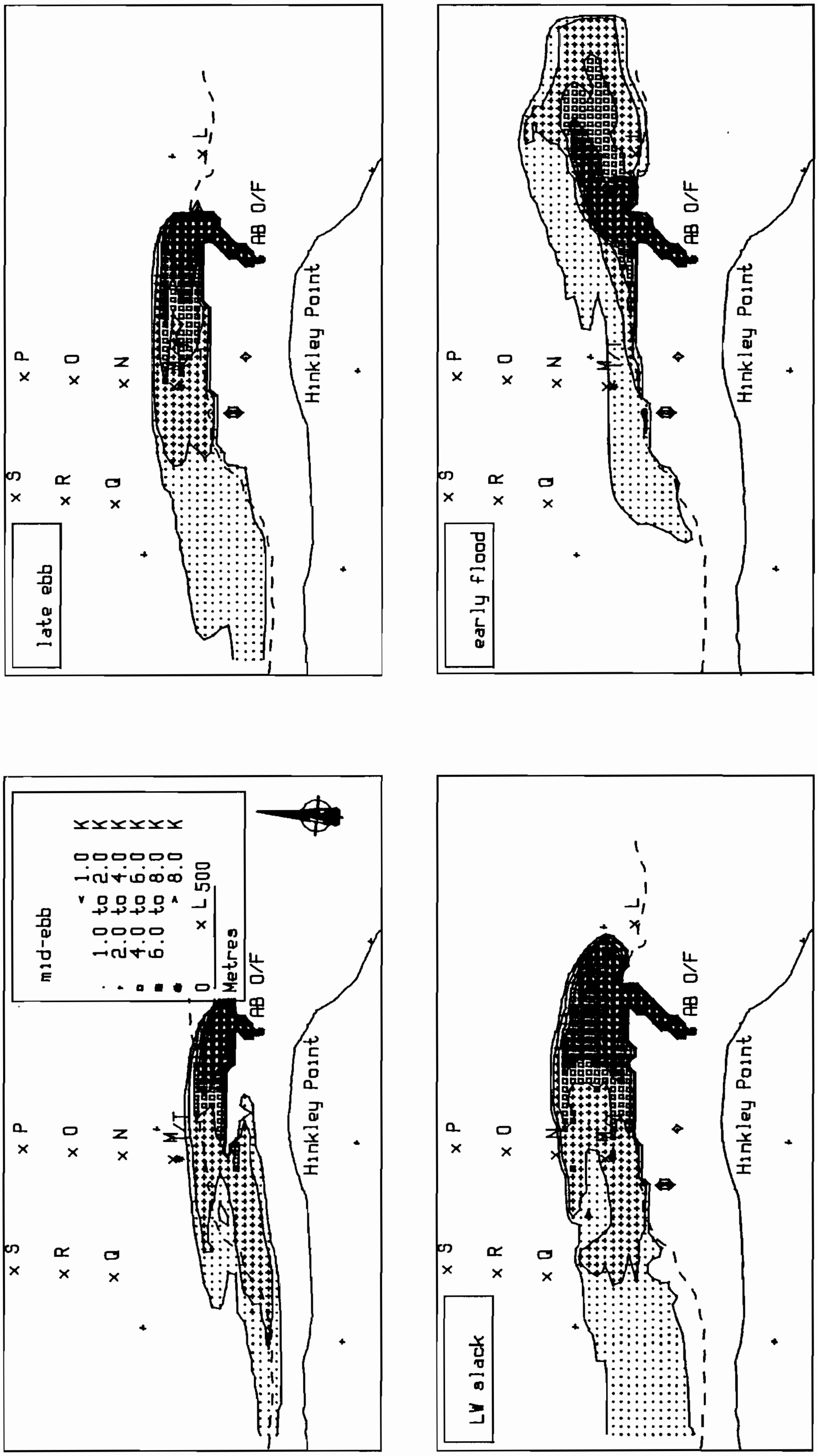


Fig 18a Surface isotherms Spring tide
viscosity = 0.1 m**2/s

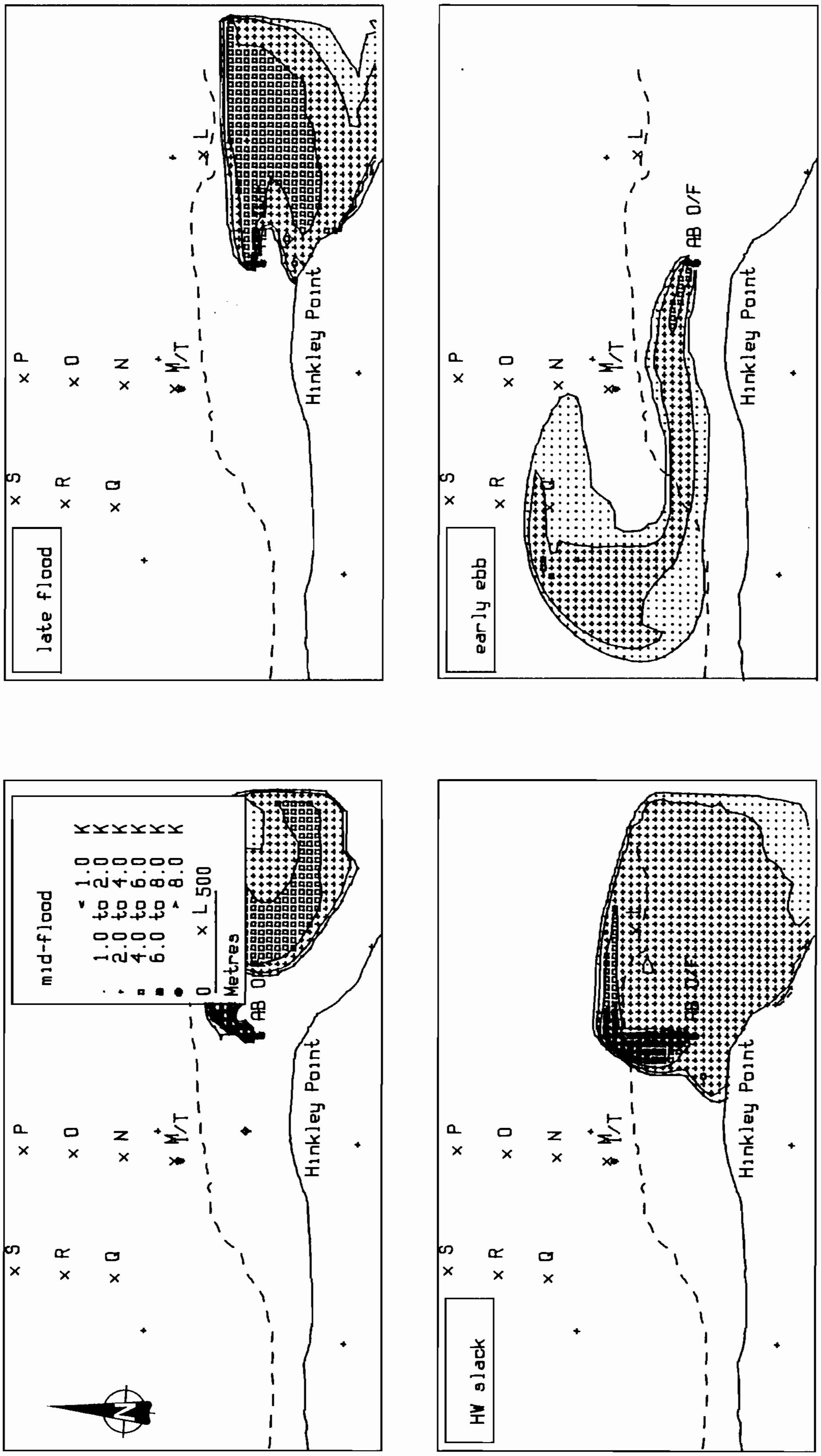


Fig 18b Surface isotherms Spring tide
viscosity = 0.1 m**2/s

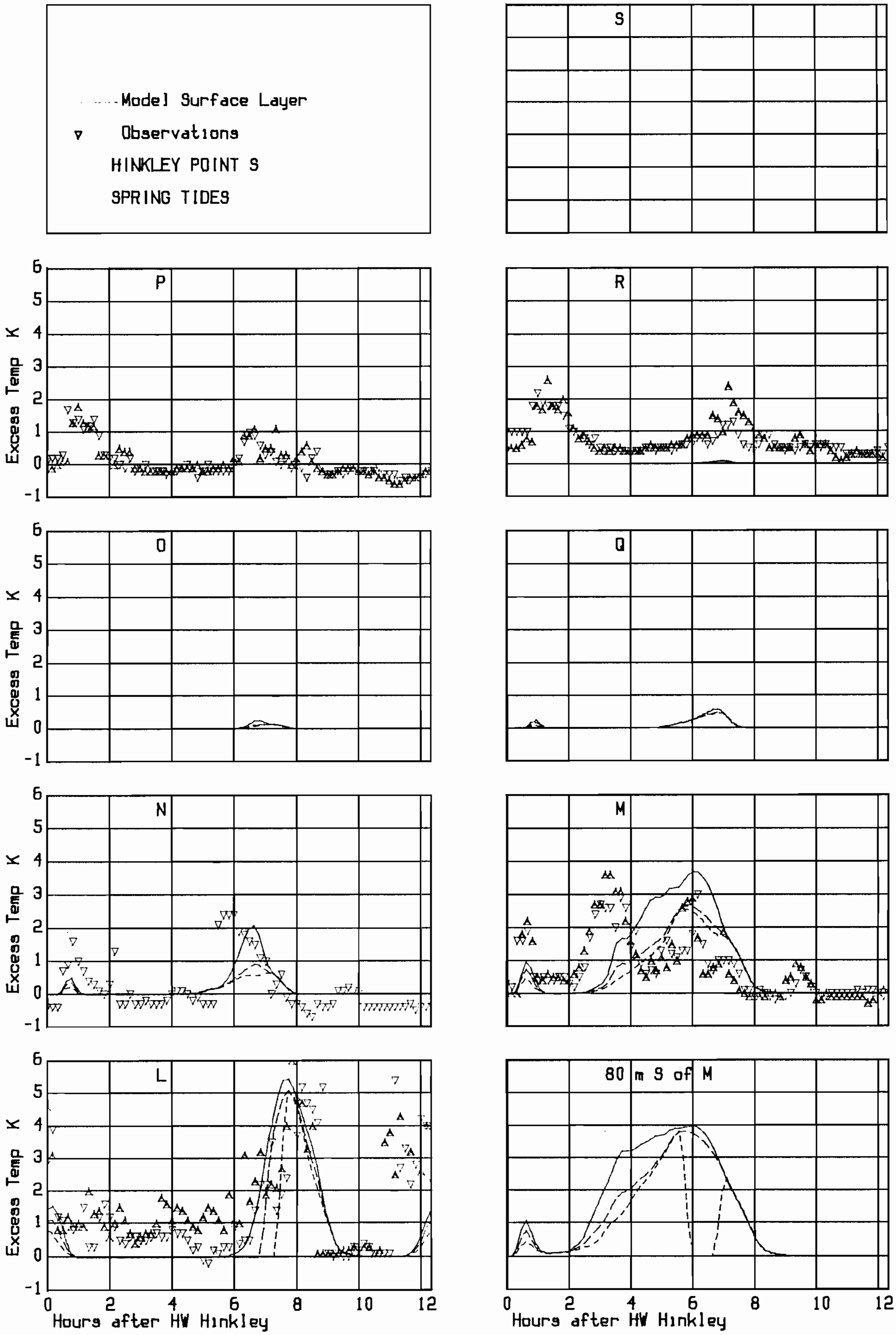


Fig 19 Spring tide diffusion =5 m**2/s
40m model

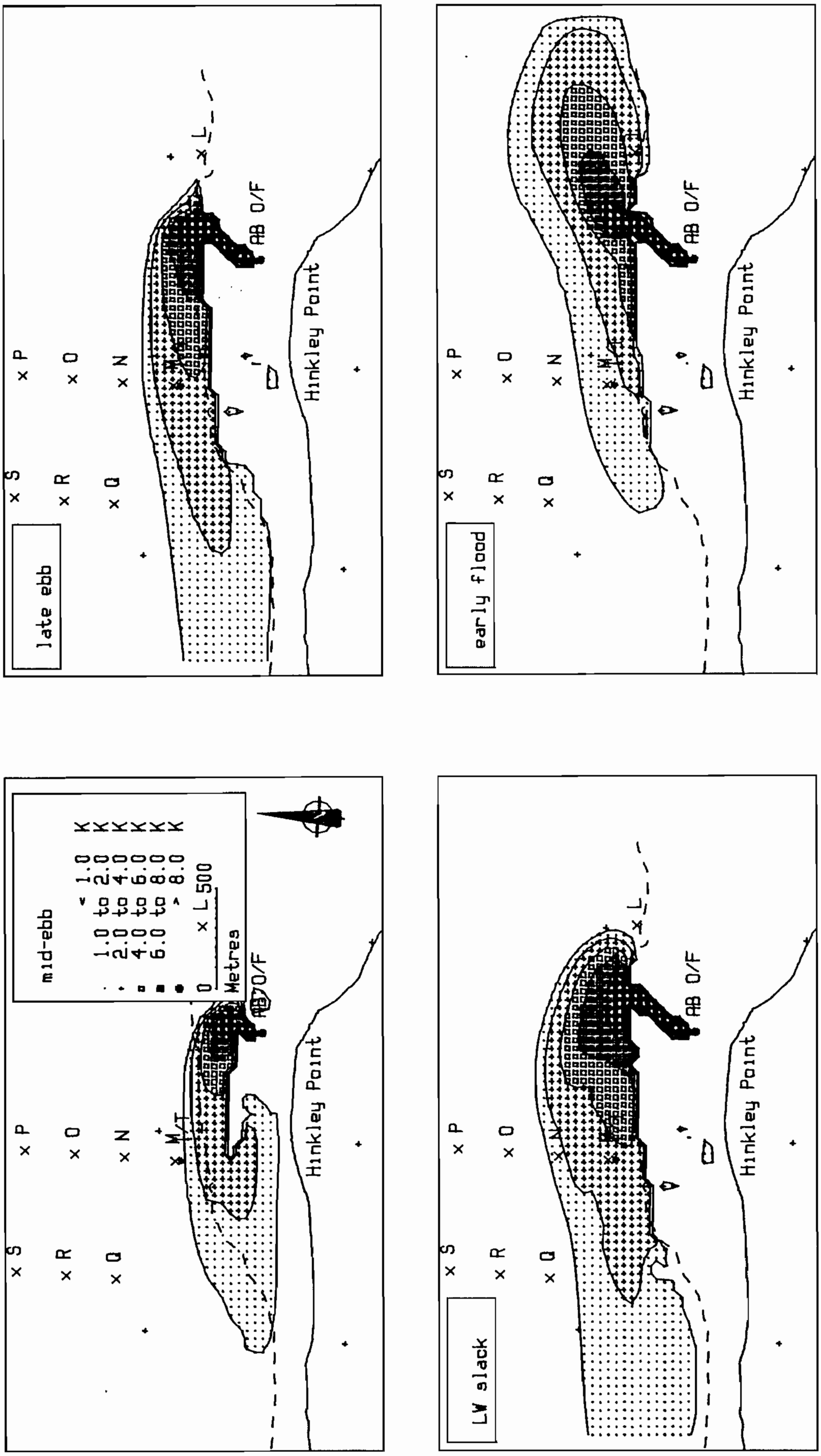


Fig 20a Surface isotherms Spring tide
diffusion = 5 m**2/s

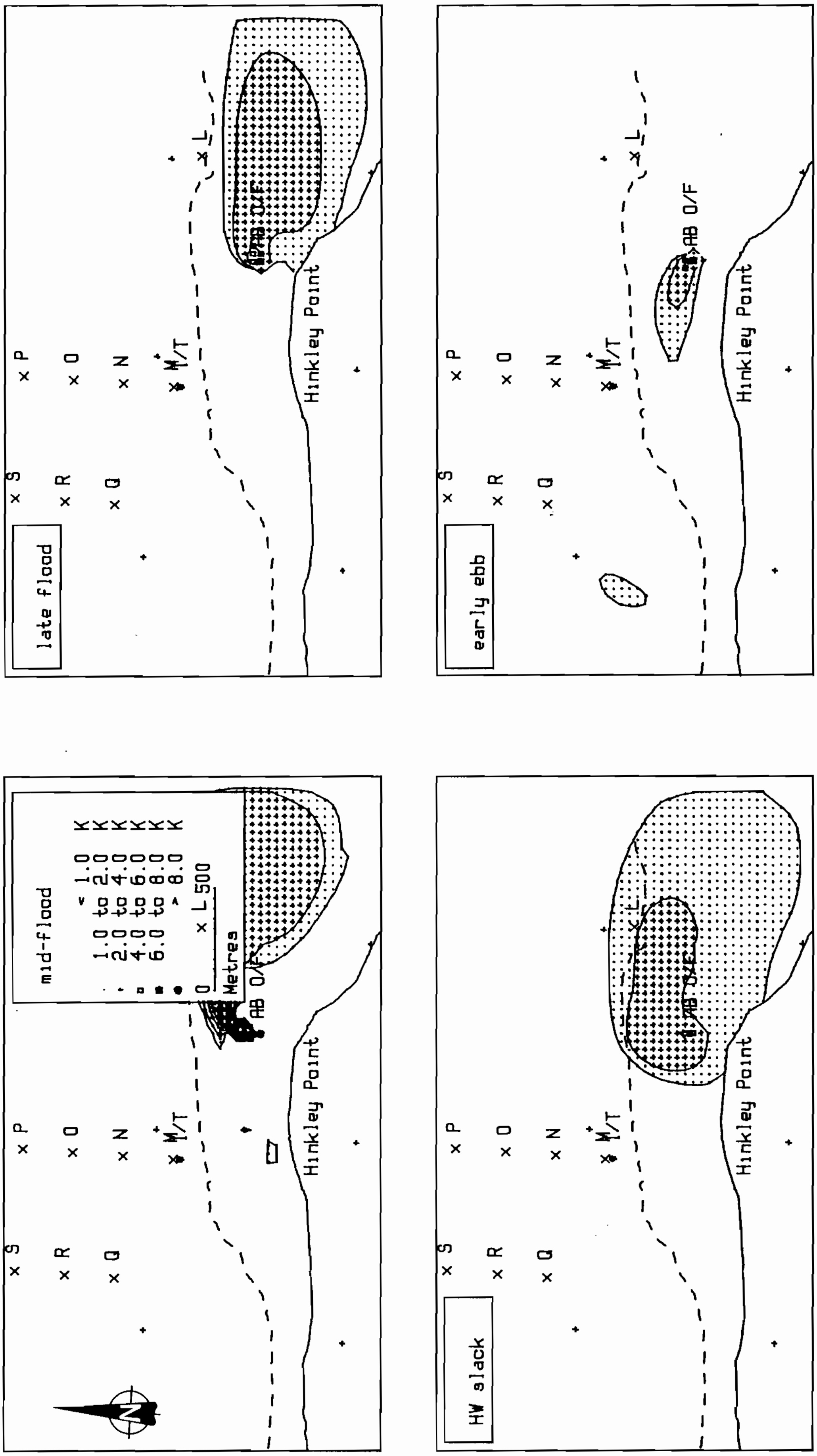


Fig 20b Surface isotherms Spring tide diffusion = 5 m**2/s

APPENDICES.

APPENDIX 1

TIDEFLOW-2D MODEL DETAILS

The HR TIDEFLOW-2D model is two-dimensional: the computed velocities being depth-averaged.

The model utilises finite difference techniques to solve the following equations which represent the physical concept of conservation of mass and Newton's Laws of Motion:

Conservation of mass:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial}{\partial x}(ud) + \frac{\partial}{\partial y}(vd) = 0$$

Conservation of momentum:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = - g\frac{\partial \zeta}{\partial x} + \Omega v - fuq/d + D\nabla^2 u + \tau_{sx}/\rho d$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = - g\frac{\partial \zeta}{\partial y} - \Omega u - fvq/d + D\nabla^2 v + \tau_{sy}/\rho d$$

where:

ζ	is the water surface elevation relative to mean sea level (m)
h	is the bed level relative to the same datum (m)
d	is the total water depth $\zeta + h$ (m)
u,v	are the depth averaged velocity components (m/s) referred to Cartesian co-ordinates x and y
t	is time (sec)
g	is the acceleration due to gravity (m/s^2)
f	is the friction factor
Ω	is the Coriolis parameter (t^{-1})
D	is the horizontal eddy viscosity coefficient (m^2/s)
q	is the water speed $(u^2 + v^2)^{\frac{1}{2}}$ (m/s)
∇^2	is $\partial^2/\partial x^2 + \partial^2/\partial y^2$ (m^{-2})
τ_{sx} and τ_{sy}	are x and y components of surface windstress

The equations incorporate the assumptions that the flow is incompressible and well mixed, that vertical accelerations are negligible (hydrostatic pressure assumption), and that a quadratic friction law is valid.

The friction factor f is defined using the rough channel law,

$$(8f)^{-\frac{1}{2}} = 2\log_{10}(14.8d/k_s)$$

The roughness length, k_s, is related to the size of the protuberances on the bed, either directly in the form of particle sizes (especially in the case of shingle and stones etc) or indirectly in the form of ripple lengths (in the case of fine particles, ripple lengths are about 1000 times median grain size (see for example Yalin*)).

The formula for the eddy viscosity coefficient, D is not well determined: Fischer* discusses various formulae. Fortunately the solutions to the equations are not in general critically dependent on D and an initial estimate based on Fisher's discussion, can be taken as:

$D = O(u^*d)$

where u^* is a typical shear velocity.

The size of D does have an effect on the size of tidal eddies and so, by comparing model eddy sizes with observations, the value of D used could be roughly confirmed as being reasonable.

Output from a model run consists of tide levels and the two components of the current for each model cell. These are stored in the computer at frequent intervals during the tide and subsequently processed to yield computer plots of model flow patterns and particle tracks and curves of tide level and current speed and directions during the tide.

The stored results are also available if required for use as input to other elements of the TIDEWAY system to study sediment transport and the dispersion of cooling water and pollution.

* Yalin, M.S. Mechanics of sediment transport Pergamon Press, Oxford 1972.

* Fischer, M.B. Mixing and dispersion in estuaries. Ann Rev Fluid Mech 8 pp 107-133. 1976.

APPENDIX 2

HEATFLOW-3D MODEL DETAILS

A standard 2D depth integrated model is inadequate to represent the flow including stratification which occurs near to the cooling water discharge from a power station. For this reason, HR has devised the HEATFLOW-3D model of flow and heat transport.

If a depth integrated model were used to represent the surface plume close to the outfall the plume would be assumed to be mixed through the total depth of water although the true plume thickness is no more than about 3m. This would result in a great underestimate of the plume temperatures. The buoyant plume spreading can also not be effectively accounted for in this kind of model.

The HEATFLOW-3D model has a similar horizontal grid to a 2D flow model but has several layers on top of one another. The flow equations given below are very similar to those for a 2D flow model in each layer but wind stress and bed friction apply to the top and bottom layers respectively and turbulent transport between the layers is modelled to extend these effects through the body of water.

The transport of heat is modelled using explicit upstream differences horizontally but vertically an implicit finite difference scheme is used to handle the vertical turbulent diffusion with unconditional stability. The reduction of vertical mixing by the temperature gradient is an essential element included in the model without which the plume would mix rapidly through the water column unlike what is found in practice. A flux corrected transport algorithm may be used to limit the numerical diffusion that results from using upstream differences in the two horizontal directions.

The governing equations are:

Conservation of water volume

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \qquad (1)$$

Conservation of momentum in the x and y directions

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} + \frac{1}{\rho}\frac{\partial p}{\partial x} =$$

$$\Omega v + \nu_H \nabla^2 u + \frac{1}{\rho}\frac{\partial T_x}{\partial z} \qquad (2)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} + \frac{1}{\rho}\frac{\partial p}{\partial y} =$$

$$-\Omega u + \nu_H \nabla^2 v + \frac{1}{\rho}\frac{\partial T_y}{\partial z} \qquad (3)$$

where the hydrostatic pressure is

$$p = -g\int_z^\eta \rho dz \qquad (4)$$

Conservation of heat

$$\frac{\partial T}{\partial t} + \frac{\partial}{\partial x}(uT) + \frac{\partial}{\partial y}(vT) + \frac{\partial}{\partial z}(wT)$$

$$= k_H \nabla^2 T + \frac{\partial f_{sz}}{\partial z} \qquad (5)$$

where

x, y, z	are Cartesian co-ordinates, z vertically upwards (m)
u,v,w	are the corresponding velocity components (m/s)
t	is time (s)
ρ	is density (kg/m ^{3})
p	is pressure (N/m ^{2})
Ω	is the Coriolis parameter (s $^{-1}$)
∇^2	is $\partial^2/\partial x^2 + \partial^2/\partial y^2$ (m $^{-2}$)
η	is the value of z at the free surface (m)
ν_H	is horizontal eddy viscosity (m ^{2}/s)
T_x, T_y	are horizontal components of vertical turbulent momentum transport (N/m ^{2})
T	is temperature excess above ambient (K)
k_H	is horizontal eddy diffusivity (m ^{2}/s)
f_{sz}	is vertical turbulent flux of heat (K/m/s)

The density ρ is supposed to be a linear function of the excess temperature T, a typical value of the coefficient of proportionality (expansion coefficient) would be -.00025. The model uses a mixing-length description of the turbulence which takes account of different size eddies dominating the turbulent diffusion at different levels in the water column. The form of the mixing length used and the reduction in vertical turbulent exchange by stable stratification are derived from Odd and Rodger*.

The form of the heat field predicted by the model is usually dominated by the combined action of the turbulent suppression due to the vertical stratification and the gravitational circulation due to the horizontal temperature gradients. These tend to generate a surface plume initially. If discharged down an open channel the plume usually has forward momentum which tends to carry it out to sea, but it entrains some of the slow moving ambient water causing it to slow down and to bend it.

In order to resolve just the top of the water column while the water surface rises and falls with the tide the datum changes at each step and a regridding takes place. This does tend to introduce some vertical mixing but the effect seems to be small compared to the physical diffusion and the plume is not smeared out by the process.

The effect of a windstress on the surface can be included in the model. This produces surface flow in the direction of the wind and an undercurrent in the opposite direction. The effect on the plume is thus the sum of the direct windstress on the plume and the wind induced ambient current tending to bend the plume. Research is being undertaken to estimate the effect of windstress on the vertical mixing in the plume; this effect is currently neglected.

Output from the model is stored in data files which can be accessed to produce plots of temperature at different levels as a function of time at specified stations or isotherm contour plots of the model layers at specified times.

* Odd N V M and Rodger J G. Vertical mixing in stratified tidal flows, Journal of the Hydraulics Division, American Society of Civil Engineers (ASCE), Vol 104, No HY3, March 1978.