National Rivers Authority
Broads Authority
English Nature

# Setting Up A Hydraulic Model of the Thurne Broads

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## 1. Introduction

### Study Context

1.1 The National Rivers Authority (NRA) acting in association with the Broads Authority and English Nature commissioned Binnie & Partners in January 1993 to develop a hydraulic model of the Thurne Broads system. The specification for this model is included as Appendix A.

1.2 Development of a hydraulic model was seen as one means of improving the understanding of the factors which control the water quality of Hickling Broad and Horsey Mere. This understanding could then be utilised by NRA, The Broads Authority and English Nature in the development of a catchment management plan for the Thurne Broads.

1.3 The present knowledge of the factors which control the water quality of Hickling Broad and Horsey Mere is summarised in the background information contained in the specification (Appendix A). This specification also summarises the main objective of this study as being to identify the relative importance of the different sources of water which contribute to the overall water quality of each of these broads. The model was restricted to water flow and salinity as salinity is one of the distinctive features of the water quality of both Broads.

1.4 The source of the nutrients which have led to these Broads becoming eutrophic was not the subject of this study, though its conclusions may well provide indications of the most likely source of the nutrients which enter Horsey Mere and Hickling Broad. The MIKE II model system that has been used may be extended to model nutrient processes.

### Earlier studies

1.5 The water and salt balance of the Thurne Broads was studied by Watson (Ref.1) as part of a wider study of the limnology of these broads. As part of his study he carried out bathymetric surveys of these Broads and made regular measurements of their water level and salinity. He also measured the volume and salinity of inflows to the Thurne Broads from the surrounding drainage network. He used these measurements to develop a simple model of water and salt exchange between the Thurne Broads and

the remainder of the Bure Broads system.

1.6 Watson's measurements are of particular interest as they cover the years 1975 and 1976 which was a period of unusually low rainfall. The period April to December 1976 has been selected as the period to be represented in the model, making use of Watson's data.

1.7 The development of a flood defence model of water levels and salinity for the whole of Broadland (Ref 2) has provided an opportunity to review and reassess how the waters of the Thurne Broads mix with the rest of the Broadland system. The flood defence model of Broadland was primarily designed to assess flood defence levels and the related issue of saline intrusion during North Sea surges. In the flood defence model the Thurne Broads system including Hickling and Martham broads, Horsey Mere and Heigham Sound was simplified to a single water body at the upstream end of the Thurne. The flood defence model therefore required expansion to include the Thurne Broads in greater detail.

1.8 Figure 1.1 shows the location of the Thurne Broads and the pumps which drain into the river Thurne catchment.

## 2 Input Data

### River and Broads Topography

2.1 The layout and topography of the Broadland river system was taken from the data used for the in-bank model used for the flood defence studies (Ref 2). The total number of cross-sections in the rivers Yare and Waveney was reduced from 114 to 62, though both rivers are still modelled for the same length up to Norwich on the Yare and Ellingham Mill on the Waveney. The reduction in number of sections reduced model run times and storage requirements with minimal impact on predicted water levels in the river Bure system.

2.2 Tests with the simplified model of the Yare and Waveney showed that water levels at Potter Heigham changed by less than 0.01m.

2.3 The 6 surveyed cross sections in the flood defence model of the river Thurne were augmented by cross sections surveyed by Watson (Ref.1) of the Thurne, Meadow Dyke, Candle Dyke and Whiteslea. The volumes of Hickling Broad, Horsey Mere and Heigham Sound were calculated using the MOSS digital terrain model to analyse Watson's bathymetric survey of these Broads. The surface area of these broads was also calculated using the MOSS digital terrain model to analyse tracings of aerial photographs of the broads prepared by Watson (Ref.1).

2.4 The area of reed bed around the Thurne Broads was calculated from 1990 satellite imagery of land use, supplemented by information from the Broads Authority and the wardens of local nature reserves.

2.5 Reedbed was assumed to be at a level of -20 to +10cm (Hickling Datum). Larger areas were modelled as separate channels allowing salt to pass up and down the dykes without necessarily mixing with the waters in the reedbeds. To ensure stable salinity results, these reedbeds were not allowed to dry out in the model.

2.6 Despite the wealth of topographic data available, there was still need to estimate the size of some of the smaller channels included in the model. Details of these channels are discussed in Appendix A.

2.7 The estimated volume and surface areas of the broads and river channels in the river Thurne system are given in Table 2.1. The volumes and areas have been calculated using the topographic data entered into the MIKE-11 and MOSS data bases. The majority of these data were surveyed in the mid 1970s.

2.8 The overall layout of the Thurne Broads MIKE-11 model is shown on Figure 2.1. The detailed layout of the Thurne Broads themselves is shown on Figure 2.2. In this model the broads were sub-divided as indicated to allow the model to reproduce any salinity gradients that might be set up within the broads themselves.

**Survey Datum**

2.9 The surveys used for the original MIKE-11 model of Broadland were all reduced to Ordnance Datum Newlyn. The data surveyed by Watson (Ref.1) was reduced to a local Hickling Datum which corresponded to the water level in Hickling Broad on a particular occasion. This level had never been rigorously checked against Ordnance Datum, though Hickling Datum was believed to be +0.4m ODN. This conversion between Hickling and Ordnance datum was used initially to convert all Watson's survey data to Ordnance datum for use in the Thurne Broads model.

2.10 Preliminary tests using the model which are discussed later suggest that a more appropriate level for Hickling Datum may be at +0.30m ODN. In later model runs, the data originally reduced to Hickling Datum were lowered 0.1m to correspond to the revised relationship with Ordnance Datum.

**Sea levels**

2.11 Measured water levels at Great Yarmouth for 1976 are not now available so the model has been driven primarily from calculated water levels at Great Yarmouth. An algorithm based on the method recommended in Admiralty Tide Tables (Ref.3) to calculate sea levels at any time of day has been developed to calculate water levels at Great Yarmouth from the predicted timing and levels of successive high and low tides. The shape of the basic tide at Great Yarmouth is shown in Figure 2.3. This shape is similar to the Lowestoft tide shape in Ref.3 but modified for the more pronounced high water stand at Great Yarmouth.

2.12 During the Broadland flood alleviation study (Ref.2), hourly surge residual levels were obtained for Lowestoft from the Proudman Oceanographic laboratory (POL). These hourly surge levels indicate the difference between observed and predicted water levels at Lowestoft each hour. These data were available for 1976 and were used to modify the calculated predicted water level for Great Yarmouth on the assumption that the surge residuals at Great Yarmouth and Lowestoft were identical.

2.13 The larger surges that occurred in 1976 are listed in Table 2.2. This list includes all those occasions when sea levels were more than 0.5m above or below the predicted level. The calculated tide levels used to drive the hydrodynamic model were adjusted to account for those occasions when surges raised sea levels more than 0.5m above the predicted level as these events could cause saline intrusion into the Thurne Broads system. ?

**TABLE 2.1 VOLUME AND SURFACE AREA OF THURNE BROADS**

| | Surface area ha | Volume $1000m^3$ |
|---|---|---|
| Hickling Broad | 152.1 | 1 630 |
| Horsey Mere | 35.6 | 580 |
| Heigham Sound | 25.3 | 174 |
| Martham Broads | 16.8 | 235 |
| White Slea | 7.9 | 48 |
| Candle and Meadow Dykes | 4.0 | 50 |
| River Thurne | 27.8 | 427 |
| **Total** | 269.5 | 3 143 |

Note: Levels and volumes at Hickling Datum level (+0.30m OD)

**TABLE 2.2 SURGES AT LOWESTOFT IN 1976**

| POSITIVE SURGES | | | NEGATIVE SURGES | | |
|---|---|---|---|---|---|
| Raise sea level | | | Lower Sea Level | | |
| Date | Magnitude m | Duration overall (>0.5m) hours | Date | Magnitude m | Duration overall (<0.5m) hours |
| 1 Jan. | 0.58 | 25 (4) | 3 Jan. | -0.94 | 16 (10) |
| 3 Jan. | 2.03 | 27 (24) | 4 Jan. | -1.00 | 24 (13) |
| 5 Jan. | 1.05 | 19 (8) | 10 Jan. | -0.54 | 21 (3) |
| 11 Jan. | 0.96 | 20 (12) | | | |
| 14 Jan. | 0.79 | 19 (9) | | | |
| 21 Jan. | 1.36 | 35 (25) | | | |
| 22 Jan. | 1.23 | 17 (12) | | | |
| 23 Jan. | 0.66 | 68 (10) | 28 Jan. | -0.71 | 79 (32) |
| | | | 9 Feb. | -0.61 | 23 (6) |
| 10 Feb. | 0.87 | 17 (9) | | | |
| 13 Feb. | 0.77 | 28 (8) | 23 Feb. | -0.55 | 54 (1) |
| 25 Feb. | 0.52 | 14 (2) | | | |
| 1 Mar. | 0.89 | 26 (13) | 6 Mar. | -0.51 | 138 (5) |
| | | | 21 Mar | -0.66 | 111 (13) |
| | | | 24 Mar. | -0.59 | 25 (3) |
| 6 April | 0.66 | 33 (10) | | | |
| 13 May | 0.53 | 24 (1) | | | |
| 1 Sept. | 0.53 | 75 (1) | | | |
| 10 Sept. | 0.94 | 37 (13) | 6 Oct. | -0.56 | 27 (3) |
| 7 Oct. | 0.55 | 38 (6) | 5 Nov. | -0.54 | 31 (2) |
| | | | 16 Nov. | -0.60 | 62 (7) |
| 22 Nov. | 0.54 | 57 (3) | 28 Nov. | -1.00 | 20 (12) |
| 1 Dec. | 0.61 | 152 (9) | 6 Dec. | -0.76 | 29 (6) |
| 26 Dec. | 0.70 | 19 (5) | 30 Dec. | -0.96 | 71 (18) |
| TOTAL 20 | | 750 (184) | TOTAL 15 | | 731 (134) |

2.14 The overall frequency of occurrence of positive surges at Lowestoft between 1970 and 1990 is shown in Figure 2.4. All surges of +1.2m or more occurred between September and April and 95% of surges of +0.5m or more occurred in these same months.

2.15 The salinity of seawater entering the Broads system at Great Yarmouth was assumed constant at 34g/l.

**River Flow data**

2.16 Daily gauged river flow data for 1975/6 held on the NRA data archive has formed the basis of the river flows used in the Thurne Broads model. The flows at the model limits have been scaled up to account for ungauged catchment between the gauging station and the model limits. The mean monthly flows for 1976 are listed in Table 2.3.

2.17 There are no flow gauges in the River Thurne catchment. Flows in the River Ant are measured at Honing Lock and have been increased by a factor of 1.87 to give the flow at Wayford Bridge, the model limit. The flows in the River Bure are measured at Horstead Mill. These flows have been increased by a factor of 1.26 to give estimated flows at Wroxham Bridge, the model limit. The effects of the Suffolk Water Company abstractions from the river Bure at Belaugh and Horning have been included by subtracting the quantity abstracted from the total Bure flow. The amount subtracted was calculated from NRA records of the abstraction.

2.18 These scaling factors based on catchment area ratios were used to estimate the likely river flows at the model limits during floods, as this was the purpose of the original Broadland model. At times of low flow such as the spring and summer of 1976, the contribution from the ungauged catchment between the gauge site and the model boundary could have been overestimated. This is likely unless these lowland parts of the catchment contribute a similar run off per unit area as the upper parts. There is a possibility therefore that low summer river flows have been overestimated in the model. This could affect the freshwater flow available to make up evaporation losses and combat saline intrusion from the sea.

2.19 The water entering the Broads rivers at the model limits was assumed to be fresh and have zero salinity.

## TABLE 2.3 MEAN MONTHLY RIVER FLOWS IN 1976

| | River Bure $m^3/s$ | | River Ant $m^3/s$ | |
|---|---|---|---|---|
| | Horstead Mill | Wroxham Bridge[1] | Honing Lock | Wayford Bridge[2] |
| April | 1.46 | 1.54 | 0.23 | 0.43 |
| May | 1.29 | 1.33 | 0.21 | 0.39 |
| June | 0.84 | 0.77 | 0.13 | 0.24 |
| July | 0.73 | 0.71 | 0.13 | 0.24 |
| August | 0.76 | 0.78 | 0.14 | 0.26 |
| September | 1.40 | 1.51 | 0.25 | 0.47 |
| October | 2.61 | 3.09 | 0.36 | 0.67 |
| November | 2.56 | 3.11 | 0.33 | 0.62 |
| December | 2.67 | 3.35 | 0.31 | 0.58 |

Note [1] Flow at Horstead Mill x 1.26 minus Suffolk Water abstraction at Belaugh and Horning.

[2] Flow at Honing Lock x 1.87

**Drainage pump flow and salinity**

2.20 The flows from the many drainage pumps which pump water into the River Thurne and the adjacent broads have been estimated by Watson (Ref.1) from electricity readings. These estimates of pump flows have been used as input to the model. Sensitivity tests described in section 4 examine the impact of change in the relationship between electricity consumption and pump flow for Brograve pump. As meters were only read at intervals, it is not possible to take account of short term changes in pump flow arising from rainfall or other factors. Pump inflows have therefore been assumed to be constant between estimates. These are sufficient estimates available to identify major seasonal changes in pumped flows. The periods for which pump flows are available are shown on Table 2.4.

2.21 The chloride content of drainage pump inflows was monitored by Watson (Ref.1) during the periods shown on Table 2.4 in 1975 and 1976. In 1975, the majority of pumps were sampled. In 1976 only the pumps draining to Hickling Broad, Horsey Mere and Heigham Sound were sampled. Samples were obtained approximately monthly from the drainage channels leading into each pump. For the modelling study we have interpolated between successive samples to give a continuous estimate of the chloride content of the drainage water pumped into the River Thurne or its tributaries. The salinity of the pump discharges was estimated by multiplying the chloride concentration by 1.65 to be consistent with the estimate of seawater salinity used at Great Yarmouth of 34g/l, or 20600mg/l chloride. ?

2.22 The limitation on sampling frequency prevents any estimate being made of any short term changes in salinity that might be associated with heavy rainfall or seepage through the river banks. The samples are, however, adequate to indicate the seasonal changes in water quality associated with each drainage pump.

**Rainfall and evaporation**

2.23 Rainfall and evaporation have been modelled as "lateral inflows" into the model at cells which have a significant area, generally in the Broads and reedbed. Rainfall and evaporation directly to or from the river channels has been considered negligible in comparison. Watson's (Ref.1) rainfall data have been used to determine this inflow. Rainfall and evaporation effects were only considered in the Thurne Broads system.

## TABLE 2.4 DATA AVAILABILITY

| | | Start Date | 1974 1975 1976 1977<br>JFMAMJJASONDJFMAMJJASONDJFMAMJJASONDJFMAMJJASOND | Finish Date |
|---|---|---|---|---|
| Predicted Tides | | 1972 | ********** | 1993 |
| Surge Residuals | | 1970 | ********** | 1991 |
| Rivers Flow Data | | 1960's | ********** | 1991 |
| SWC Abstractions | | 1968 | ********** | 1988 |
| Catfield | PUMP FLOWS | | ********** | |
| Horsey Mill | | | ********** | |
| Eastfield | | | ********** | |
| Stubb Old | | | ********** | |
| Stubb New | | | ********** | |
| Martham | | | ********** | |
| Potter Heigham | | | ********** | |
| Repps | | | ********** | |
| Brograve | | | ********** | |
| Thurne Pump | | | ********** | |
| West Somerton | | | ********** | |
| Martham Holmes | | | ********** | |
| Horsefen (Ludham) | | | ********** | |
| Catfield | PUMP SALINITY | | ********** | |
| Horsey Mill | | | ********** | |
| Eastfield | | | ********** | |
| Stubb Old | | | ********** | |
| Stubb New | | | ********** | |
| Martham | | | ********** | |
| Potter Heigham | | | | |
| Repps | | | | |
| Brograve | | | ********** | |
| Thurne Pump | | | | |
| West Somerton | | | ********** | |
| Martham Holmes | | | | |
| Horsefen (Ludham) | | | | |
| HICKLING BD WL | | | ********** | |
| Horsey Mill | SALINITY READINGS | | ********** | |
| Hickling Broad | | | ********** | |
| Meadow Dyke | | | ********** | |
| White Slea | | | ********** | |
| Thurne at Martham | | | ********** | |
| Candle Dyke | | | ********** | |
| Potter Heigham Br | | | ********** | |
| Womack Staithe | | | ********** | |

2.24 Evaporation rates have been derived from data from the Meteorological Office MOREC cell 121 which gives average potential grass evaporation each month from a 40 x 40km area of land. The evaporation rate for open water was taken as 1.2 times that of grass. Reedbed evaporation was taken as 1.5 times greater than that of open water. Recent work reported by UEA has suggested that reedbed evaporation may vary seasonally. These studies suggest that during the winter, reedbed has the same evaporation rate as open water, but during the May to October growing season it may be about twice the rate for open water. A comparison of the net evaporation (rainfall minus evaporation) during 1976 using the two reedbed assumptions is shown on Figure 2.5 for the Thurne Broads system.

2.25 The gain of water by rainfall or loss by evaporation is modelled by adding the appropriate flow to the cells in the model which represent the broads and larger reedbeds. These flows are added to the hydrodynamic part of the Thurne Broads model. As there is no change in salt mass as a result of rainfall or evaporation these same cells were modelled as closed boundary conditions in the salinity part of the Thurne Broads model.

2.26 The calculated loss of water by evaporation from the Thurne Broads reached 0.5 $m^3/s$ in June 1976 and was around 0.4 $m^3/s$ in July with the constant reedbed evaporation assumption as Figure 2.5 shows. Losses would be about 0.1 $m^3/s$ larger in these months using the assumed seasonal variation in reedbed evaporation. These losses are around half the assumed total freshwater input for these months from the Rivers Bure and Ant given in Table 2.3. No allowance in the modelling has been made for evaporation losses from the broads on the rivers Bure and Ant which may account for much of the remaining freshwater inflow.

**Broads water levels and salinities**

2.27 Watson (Ref 1) measured water levels in Hickling Broad, Horsey Mere and Whiteslea Sound continuously during the period April to December 1976 using chart recorders as indicated in Table 2.4. The original chart records as well as Watson's analysis of them were made available for this study. These water level records provide the main data for checking the performance of the hydrodynamic component of the Thurne Broads model.

2.28 Watson (Ref.1) sampled the waters of Hickling Broad, Horsey Mere and Whiteslea

Sound regularly during 1975 and 1976 during the period indicated in Table 2.4. The samples were originally analysed for chloride content, but have been converted to salinity by multiplying by a factor of 1.65 and are plotted on Figure 2.6. He also sampled various points in the River Thurne and other dykes but only in 1974 and 1975. The frequency of sampling varied but was normally between weekly and monthly. The measurements between April and December 1976 have been used to check the performance of the salinity component of the Thurne Broads model. The samples were originally analysed for chloride content. The chloride concentrations have been converted to salinity readings by multiplying by a factor of 1.65 which assumes the ionic composition of the sampled waters is similar to that of seawater. The sample results for the River Thurne are plotted on Figure 2.7.

2.29 There are no measured data on water levels or salinities in Martham Broad or the River Thurne during 1976 though some salinity data were obtained in 1975. Salinities within the lower River Thurne and river Bure have in recent years been monitored continuously as conductivity at Repps and Acle Bridge. These salinity data were used to help the calibration of the salinity section of the Broadland flood alleviation model. As the performance of the Thurne Broads model in the River Bure and lower river Thurne has not been altered significantly by the changes in the Thurne Broads area, the influence of the data from these recent continuous monitors is included within the overall model.

## 3. Hydrodynamic model

### Model operation

see Fig 2.2. Only 30 km²

3.1 The hydrodynamic model was set up for the Thurne Broads system and run starting with the water levels measured at the beginning of April 1976. The model was then allowed to run until December 1976. In practice this 9 months run was completed by running consecutive 3 month periods separately to limit the computer file sizes generated for future salinity tests. The model conditions at the conclusion of each 3 month run were used as initial conditions for the test of the next period.

→ 16hr run time for 3 month

see App B

3.2 The hydrodynamic model was run using a timestep of 60 seconds. This short timestep was found necessary to maintain the numerical stability of this part of the model. The water levels and discharges calculated by the model at each section were stored every hour. The frequent storage of hydrodynamic model results is needed to ensure that the effect of each individual semi diurnal tide is properly reproduced in the salinity model. The stored values are used to provide plots and printouts of the hydrodynamic model and also to provide the hydrodynamic input to the salinity model.

### Assessment of Datum level

3.3 The hydrodynamic model closely follows the changes in water level observed in Hickling Broad and Horsey Mere throughout the nine month period of testing. The model results, however, consistently predicts water levels that are 0.10m too low. This strongly suggests that the level of the Hickling Datum used by Watson should be at +0.30m ODN rather than the +0.40m ODN previously assumed.

3.4 In all subsequent model runs, and all model output shown in this report, observed water levels are shown assuming Hickling Datum is at +0.3m ODN. All levels which were related to the original level of Hickling Datum have been lowered 0.10m. This has the effect of lowering the bed level of the channels and of the Thurne Broads, but makes no significant difference to the hydrodynamic model, except for a small reduction in the already low velocities in most areas of the model. The major effect of the lower bed levels is that it increases the volume of water present in the Thurne Broads in the model at any time. This has the effect of increasing the quantity of salt held in the Thurne Broads system and reducing the proportion of the Broads volume that is exchanged as Broad levels change each fortnight.

**Water level calibration**

3.5 A comparison of predicted and observed water levels in Whiteslea Sound for June 1976 is shown as Figure 3.1. This comparison shows that the model is able to reproduce the "saw tooth" nature of the semi-diurnal tide quite accurately. The amplitude of the semi-diurnal tide in the model is around 0.035m compared with the observed amplitude of around 0.04m.

3.6 The longer term performance of the model is illustrated by Figure 3.2 which compares model predictions over the nine month period April to December 1976 with the observed maximum and minimum levels each tide. The model reproduces well the fortnightly variation in water levels which is particularly characteristic of the Thurne Broads. The model, if anything, slightly overestimates the variation in levels during each fortnight, but the agreement is close. The model correctly reproduces the significant rise in water level in late August 1976 when high spring tides and increased freshwater flows in the Rivers Bure and Ant occurred breaking the drought that had existed throughout the earlier part of the summer.

3.7 In the summer months of 1976 Watson (Ref.1) found that water levels in Whiteslea Sound varied between +0.05m and -0.20m Hickling Datum, equivalent to between +0.35 and 0.10m ODN, assuming Hickling Datum is at +0.3m OD. During the course of each fortnight, high water levels rose and fell by around 0.1m on average. The model correctly reproduces this varying water level during the summer months.

3.8 The autumn months of 1976 included above average river flows and several surges. These caused a 0.2m rise in average water level and were often marked by a larger variation in water levels each fortnight than had occurred during the summer months. In the middle of each month during the autumn, the water levels in Whiteslea Sound dropped between 0.1 and 0.3m and then rose again two weeks later. The model closely reproduces the increased average water level and the more variable conditions observed in these months.

3.9 The area and level of the reedbed in the model has had to be estimated. If the actual area affected by water level changes between +0.4 and +0.5m OD was greater than modelled, it could explain the initial 'overshoot' of water levels in the model following the rainfall and surge at the beginning of September.

**Sensitivity to friction factor**

3.10 The results from the hydrodynamic model shown in Figures 3.1 and 3.2 used a friction factor, Manning's n = 0.035. This resulted in a slight underestimate of the semi-diurnal tidal range and a small overestimate of the fortnightly variation in water level. As broads levels are partly dependent on the frictional resistance of the river channel system down to Great Yarmouth, a sensitivity test was carried out using a different value of friction factor.

3.11 The sensitivity test used a value of Manning's n = 0.020 which is lower than normal for most tidal channels. A comparison of the two model results in Figure 3.3 shows that the low value of Manning's n increases both semi-diurnal and fortnightly tidal ranges. Figure 3.3 shows that the mean water level in the broads did not change significantly as a result of the lower friction factor. Overall a value of n = 0.035 gave the better agreement with observed conditions.

3.12 If a more accurate hydrodynamic model of the Thurne Broads were needed, the present model could perhaps be improved by minor variations of friction factor along the length of the Rivers Bure and Thurne. There may also be interest in investigating whether seasonal changes in weed growth along the banks of the channels and broads has sufficient effect on the frictional resistance of the channel system to alter the levels of the Thurne Broads significantly.

**Assessment of water level calibration**

3.13 The comparison of observed and model water levels for Whiteslea Sound shows that the model is well able to reproduce most of the observed variations in the water level between April and December 1976. This period included a severe drought with very low river flows up to August 1976 and a period of higher than average river flows in the autumn months.

and flows are crudely estimated.

3.14 The model is fairly sensitive to river flows in the Ant and Bure rivers and also to tide levels, including the presence of surges at Great Yarmouth. The predicted water levels are not particularly sensitive to the choice of friction factor.

3.15 The model results strongly suggest that Hickling Datum is at +0.30m ODN as this gives water levels that are consistent throughout the Broadland system.

3.16 The water levels in Hickling Broad and Horsey Mere are dominated by the conditions at the mouth of the River Thurne which are controlled by sea tides at Great Yarmouth and flows in the Rivers Ant and Bure. Drainage inflows to the River Thurne and evaporation from the water surface and reedbeds have very little influence on the summer water levels in the Thurne Broads, though they may affect the magnitude of the water flows which sustain these levels.

**Impact of surges**

3.17 The eight large positive surges which occurred between April and December 1976 were included in the sea level calculated for Great Yarmouth as model input. Careful inspection of observed and modelled water levels on these occasions indicates their slight impact on water levels by comparison with levels on adjacent days. The model satisfactorily reproduces the water levels during these events.

3.18 The six large negative surges which occurred during the model calibration period were not included in the sea level calculations for Great Yarmouth. The changes in the water level of the Thurne Broads are not great on these dates and so the model still predicts levels that are fairly close to those observed.

## 4. Salinity model

### Model operation

4.1 The calibration of the salinity component of the Thurne Broads model used the same nine month period April to December 1976 as used for the hydrodynamic component. This was done because of the availability of salinity data for most pump inflows and also for Hickling Broad, Horsey Mere and Whiteslea Sound.

4.2 A rather more extensive set of data on drainage pump salinity were available for late 1975, but there was less information on salinity in the Board system and no information on water levels in the Thurne Broads.

4.3 Salinity data for pumps draining to the River Thurne in 1976 was not available. Initially, the salinity of the pumps at Martham, Potter Heigham and Repps were assumed to be zero. In a sensitivity test on salt inputs, the salinity of these pumps was set to 4g/l which is similar to that of Catfield pump in the summer of 1976.

4.4 The salinity readings between April and December 1976 were divided into three distinct periods when hydraulic and salinity conditions were markedly different:

1. April to August 1976. In these months pump drainage flows and river flows were unusually low and the salinity of both Hickling Broad and Horsey Mere was fairly high but stable.

2. September 1976. In September, pump drainage flows and river flows increased, which combined with some North Sea surges to cause an increase in the Broads water level of 0.25m compared with that prevailing during the previous five months. The measured salinities in the Broads during September were the highest recorded during the year.

3. October to December 1976. In these months pump drainage flows increased, but their salinity declined. River flows were above average and maintained high water levels in the Thurne Broads throughout this period, though there were some large falls and rises in level in the middle of each month. During this period the salinity of both Horsey Mere and Hickling Broad declined steadily.

4.5 The calibration of the salinity model was divided into these three periods. Each period was examined separately to see how well the model reproduced the high stable summer salinities, the peak salinity in September and the decline in salinity in the autumn months. The differences in observed behaviour and salinity content of Horsey Mere, Hickling Broad and Whiteslea Sound were also kept under review to ensure these features were reproduced.

**Sensitivity tests**

4.6 Initial salinity tests examined a range of conditions and assumptions to determine which factors were of greater importance in controlling salinity in the different parts of the Thurne Broads system. These sensitivity tests examined:

- Dispersion coefficient
- Evaporation rate
- Salt inputs
- Flow through Brograve pump

**Sensitivity to dispersion coefficient**

4.7 The results of the sensitivity tests for dispersion factor are shown on Figure 4.1 for summer conditions and Figure 4.2 for autumn conditions. In both cases the measured salinities are plotted for comparison.

4.8 In Horsey Mere during the months April to June 1976, Figure 4.1 shows that the lower dispersion coefficient maintains salinities at around 5g/l until the middle of June before they drop to 4g/l. The higher dispersion coefficient allows this drop to take place in the middle of April. The observed data suggest salinities in Horsey Mere remained between 5 and 6g/l throughout these months.

4.9 In Hickling Broad in the same period, the lower dispersion coefficient maintains salinities between 3 and 3.5g/l until early June as observed whereas the higher dispersion coefficient allows a fairly rapid decline in salinity to less than 2g/l. The lower dispersion coefficient is unable to maintain the observed salinities of about 3.5g/l throughout June.

4.10 In the autumn months, September to November 1976 shown on Figure 4.2, the choice of dispersion coefficient is of particular significance in controlling the rate of decline in salinity of Hickling Broad. The rate of decline increases with an increase in dispersion coefficient because of the greater mixing this permits with less saline waters downstream. The observed data are compatible with the choice of the lower dispersion coefficient of $25m^2/s$.

4.11 The sensitivity tests suggest that a dispersion coefficient of $25m^2/s$ is the most appropriate for use in the Thurne Broads area. This may be compared with the coefficient of $200m^2/s$ adopted for the River Bure when modelling saline intrusion as part of the flood alleviation study. The higher dispersion coefficient has been retained in the River Bure to give the correct intrusion of salt into the River Thurne during surges.

**Sensitivity to Brograve pump flow** (high salinity)

4.12 There is some uncertainty about the relationship between pump electricity consumption and the quantity of water discharged. Our work has been based on the relationships used by Watson (Ref.1). A recent reappraisal by the Internal Drainage Board suggests the volume pumped by Brograve pump may be more than twice as large as assumed previously. This change would significantly increase the quantity of salt entering the Thurne Broads system and the throughflow in Horsey Mere. The sensitivity of the model performance of the Brograve pump flow has been tested by doubling the flow volume it pumped. The salinity of the pumped discharge was not changed, which effectively doubled the salt load input to the Thurne Broads from this source.

4.13 The impact of the increased Brograve pump flow is illustrated on Figure 4.3 assuming the lower dispersion rate is appropriate. This shows that the higher Brograve pump flow causes a significant increase in the salinity of Horsey Mere, which approaches closer to the salinity of water discharged by the Brograve pump. There is a much smaller increase in the salinity of Hickling Broad which is more influenced by water returning from the lower Thurne as tide levels rise each fortnight. This returning water is a mixture from several sources and only contains a relatively small proportion of water originating from Brograve pump. The higher Brograve Pumps flows are not enough to maintain the observed salinity of Hickling Broad through the summer, or even that of Horsey Mere in July.

model underpredicts
see Fig 4.3

**Sensitivity to evaporation rate**

4.14 The net evaporation from the Thurne Broads, shown in Figure 2.5 illustrates that evaporation was much greater than rainfall from April to mid-August 1976, but that rainfall slightly exceeded evaporation in the later months of 1976. Accurate assessment of open water evaporation rates from a particular body of water is difficult as evaporation depends on many meteorological factors, not all of which are accurately assessed by evaporation pan measurements. In addition, the amount of evaporation from reedbed is uncertain. The sensitivity of the model to evaporation rate will be most marked in summer, but hardly affect conditions in other seasons, as evaporation rates are much lower and usually less than the direct rainfall. This was the case in the Thurne Broads in the autumn months of 1976.

4.15 A sensitivity test in which evaporation rates in July and August 1976 were based on the higher assumption of reedbed evaporation was carried out. The results are compared in Figure 4.4 using the lower dispersion factor and increased Brograve pump flow for both tests. This showed that for most of the time Horsey Mere salinity was hardly changed by evaporation rate. However, there were differences for short periods between June and August of up to 0.9g/l.

4.16 In Hickling Broad, Figure 4.4 shows that the increased reedbed evaporation caused the model salinity of Hickling Broad to fall faster throughout June and July. This rather paradoxical result is because the increased loss of water to evaporation drew in more water from the lower Thurne and Bure to maintain its water level. In the model, the water that was drawn in had lower salinity than the water already present in Hickling Board. As a result when these waters mixed the resultant concentration dropped faster than in the original case, even after allowing for the concentrating effect of the increased evaporation. The opposite result would have occurred if the salinity of the lower Thurne was higher. The observed salinity of Hickling Broad remained fairly stable at around 3.5g/l throughout this period.

Doubt ?

4.17 Variations in the evaporation rate are likely to affect the salinity behaviour of Hickling Broad in summer, but have less effect on Horsey Mere which has a smaller surface area and greater throughflow from the upstream drainage pumps at Brograve and Eastfield. The salinity of these lakes is unlikely to be affected significantly by changes to evaporation rate at other times of year.

**Sensitivity to salt inputs**

4.18 A final sensitivity test examined the impact of changes to the salinity of the pumped drainage water discharging to the River Thurne principally through Martham or Potter Heigham pumps. These salinities had not been measured in 1976 so there were no data available on conditions in 1976.

4.19 The results of the sensitivity tests which used the higher dispersion coefficient of 200m$^2$/s, the lower Brograve Pump flows and constant (lower) evaporation rate are shown in Figure 4.5. These results indicate the great sensitivity of Hickling Broad in particular to the presence of salt inputs in the lower Thurne. In summer, the addition of some salt in this area was the only method found which could in the model maintain the salinity of Hickling Broad at the observed 3.5g/l from April to July 1976. In autumn higher salinity in the lower Thurne pump discharges had a similar impact to the reduction in dispersion coefficient from 200 to 25m$^2$/s.

4.20 An alternative source of salt input could arise if saline groundwater were able to seep into Hickling Broad. The impact of such a seep would be very similar to that of an increased salinity of the lower Thurne pumps. Groundwater seeps into Hickling Broad seem unlikely as local groundwater levels are reported as being lower than the water level of the Broad. This level difference would encourage the seepage of water out of Hickling Broad rather than the other way round.

**Assessment of salinity calibration: general**

4.21 The various sensitivity tests show that changes in salinity in the Thurne Broads system could arise for a number of reasons. In our assessment we have worked from the assumption that all significant salt inputs have been identified unless there is no other more plausible explanation for the observed behaviour of the system. We have generally assumed that if the observed results can be obtained by selecting realistic values for coefficients which are difficult to measure quantitatively, such values are more likely to be correct than an alternative explanation which casts doubt on available data or existing understanding. There is no way of proving conclusively that such a choice is the correct one on any particular occasion.

**Assessment of salinity calibration: autumn 1976**

4.22 The results from the modelling studies show that the salinity of both Hickling Broad and Horsey Mere in the autumn months of 1976 can be explained by the correct choice of dispersion coefficient and do not require any additional sources of salt.

**Assessment of salinity calibration: summer 1976**

4.23 In the summer months of 1976, the choice of a low dispersion coefficient is not sufficient to maintain model salinities in Hickling Broad at their observed values. The use of a dispersion coefficient of $25m^2/s$ in the River Thurne and its tributaries, compared with a value of $200m^2/s$ in the remainder of the River Bure system seems rather surprising. The high dispersion coefficient adopted in the remainder of the Bure system was selected during the flood alleviation strategy which was primarily concerned with events lasting a few days at most. Sensitivity tests for that study showed that in the lower reaches of the Rivers Bure and Thurne, where data were available, a high value of dispersion coefficient was more appropriate. During surges, stratification is marked, with freshwater overlying saline water in much of the River Bure system. This causes rapid intrusion of the saline water into the River Bure. A high dispersion coefficient was needed to reproduce this advance in the model which made no direct allowance for the effects of stratification. In the Thurne Broads, the waters are reported to be well mixed vertically and with the much longer timescales considered in this study, results are much more sensitive to the chosen value of dispersion coefficient. NB.

4.24 The observed salinities in Horsey Mere are better reproduced in the model by using the larger Brograve pump flows calculated by the IDB. The choice of evaporation rate or presence of additional salt inputs are relatively unimportant in Horsey Mere.

4.25 The sensitivity tests showed that during the summer of 1976, the presence of additional salt inputs were necessary to maintain the observed salinity of the Broad. The quantity of extra salt that needs to be added depends on the dispersion coefficient and the evaporation rate assumed. With additional salt entering the lower Thurne, the model sensitivity to evaporation rate shown in Figure 4.4 could well be reversed because the water flowing into Hickling Broad will contain more salt and so may cause an increase in the salinity of the Broad.

4.26 In practice, the required salinity of the Thurne pumps will be significantly lower than

the 4g/l assumed in the sensitivity testing because of the effect of the suggested lower dispersion coefficient. Overall salt from the Lower Thurne pumps seems unlikely to be the source of salt required in the summer of 1976. Experience over the past few years has suggested that the salinity of the soke dyke closely mirrors the adjacent river. The ditches draining land further from the river are also likely to be fresh as the catchment is much further inland than the areas where saline groundwater has been found. There is no need for additional salt from this source during the autumn of 1976, suggesting this source of salt is only present during major droughts.

4.27 An alternative source of salt could arise if saline intrusion in the model has been underestimated. This would happen if the freshwater flow in the River Bure at its confluence with the River Thurne were overestimated. No account has been taken of the evaporative loss of freshwater from the Bure and Ant broads upstream of the River Thurne. This will cause freshwater flow at the River Thurne confluence to be overestimated in the model and permit salt to move further upstream and perhaps allow it to contaminate the River Thurne. In addition the contribution of freshwater from the ungauged catchment during the summer of 1976 may have been overestimated.

Why not carry out sensitivity tests

**Assessment of salinity calibration September 1976**

4.28 The observed rise in salinity during late August and September is not reproduced within the model and requires additional explanation.

4.29 Watson (Ref.1) has suggested that the rise in salinity in September 1976 was due to salt being washed off dried out reedbeds which flooded as water levels rose in late August and early September. He assumed these reedbeds had been dry during the summer when water levels were low. This salt could have been deposited on the reedbeds several months earlier, as water levels had remained low for some time. In the model, no extra input of salt occurred in the model in late August and early September, so it predicts declining salinities, as more fresh water enters the system with the rise in water levels in late August.

4.30 Reedbeds drying out cannot be modelled in the current version of the salinity model, as infinite concentrations of salt in a dry cell would cause the model to become numerically unstable. Adding a suitable mass of salt to the system in September could, however, reproduce the effects of accumulated salt being washed from the reedbeds

into the broads they surround. Within the model the presence of water in the reedbeds at all times causes greater mixing as the water levels rise and fall each month and limits the amount of salt which can accumulate in the reedbeds. If this process did not occur in the model, any accumulation of salt in the reedbeds would cause the model salinity of Hickling Broad to be lower. A small change in evaporation rate or lower Thurne salt input would probably be sufficient to offset this effect and still maintain a reservoir of salt large enough to cause the observed rise in salinity in September 1976.

4.31 Another factor contributing to the high salinities recorded at all stations in September could be that the drainage pumps pumped a larger volume in response to the rain that fell in late August and early September. This drainage volume could have been more salty than normal if salt had accumulated on the land or in stagnant ditches as a result of evaporation earlier in the summer. Unfortunately, there are no flow or salinity measurements available to indicate how the drainage system responded to the rainfall.

available now needed ?

4.32 Another factor may be that the rise in water levels in early September may have caused more seepage through the banks into the soke dykes as the salinity of the soke dykes closely matches that of the adjacent river. In the lower Thurne, the seepage of salt into the soke dykes at the time of the surge on 1/9/93 could have raised their salinity, which would be reflected in the quality of water discharged by the drainage pumps during September.

?

4.33 Some or all of the factors discussed above may have contributed to the increase in the recorded salinity at all monitoring sites in the Thurne Broads in September 1976. In the absence of more refined data the relative importance of each factor cannot be judged.

**Impact of surges**

4.34 The salinity modelling of the Thurne Broads does not seem sensitive to the presence of surges which occurred in 1976. The salinity profile along the River Thurne shown in Figure 4.6 suggests salinity effects of the surge in early September 1976 hardly reached the confluence of the River Thurne with Candle Dyke. In the lower part of the River Thurne, the impact of this surge is very evident as shown on Figure 4.7 in the model at Potter Heigham.

4.35 An interesting feature apparent on Figure 4.7 is that at the time of all the positive surges listed in Table 2 except that of 1 September there was a short-lived but significant reduction in salinity at Potter Heigham. In the model this seems to be because as the surge travels up the River Bure, it pushes freshwater ahead of it. As a result, the first water quality indication of a surge in the model is often a decline in salinity. If the surge is large or prolonged, and freshwater flows are low this initial period of low salinity may be replaced by a period of high salinity as saline water passes the monitoring site. This appears to have happened after both the 6 April 1976 surge and 1 September 1976 surge. The high river flows at the time of the other autumn surges prevented brackish water intruding as far as Potter Heigham. The stratification which occurs in nature in the River Bure system during surges will probably alter the way surges push freshwater ahead of them into the Thurne Broads.

## 5. Conclusions and Recommendations

### Water level predictions

5.1 The model of the Thurne Broads satisfactorily reproduces the daily, fortnightly and seasonal changes in broads water levels that occurred during 1976. The modelling suggests that Hickling Datum is probably at +0.30m OD. but see Fig 3.1 Whitesloe sound.

### Salinity Predictions

5.2 The model of the Thurne Broads is able to reproduce many of the observed changes in salinity during 1976. The model results are sensitive to the choice of dispersion coefficient and to the presence of any salt input to the system in Hickling Broad or downstream of the Broad.

5.3 The results from the model suggest that there needs to be an extra source of salt during the summer of 1976 to enable the observed salinity of Hickling Broad to be reproduced. This source appears to have ceased contributing salt during the autumn of 1976. This source could be salt from groundwater entering Hickling Broad directly, or causing the Lower Thurne pumps to discharge brackish water. There is no other evidence that either of these sources are present. An alternative source could be greater saline intrusion in the Bure because freshwater flows were lower than assumed. The present model has made no allowance for evaporation losses from the Bure and Ant broads and there is uncertainty about the freshwater flow at the limit of the model in the River Bure and Ant. Both these factors may mean that saline intrusion penetrated further up the River Bure than the model currently assumes.

5.4 If the presence of such a summer salt source is assumed, the model is able to reproduce observed salinity changes from April to December 1976 apart from a rise in salinity during September which may be due to the wash off of salt that had accumulated in the reedbeds or drains earlier in the summer.

### Recommended further work

5.5 Further investigations of the effect of evaporative loss from the Bure and Ant broads should be carried out to confirm whether saline intrusion is the unidentified source of salt required to reproduce the observed salinity of Hickling Broad in the summer of

1976. The sensitivity of saline intrusion to the assumed freshwater flow in the Rivers Bure and Ant at their tidal limits should also be examined as evaporative losses from the broads may equal or exceed the minimum river flow.

5.6 The understanding of conditions in the Thurne Broads would benefit from measurements of the flow and salinity of pumps discharging to the River Thurne. The model suggests that Hickling Broad is sensitive to the salinity of these pumps. Any other data ?

5.7 Once a satisfactory model has been developed of conditions during 1976, there would be benefit in extending the database for the model so that it can be tested using conditions experienced in another year. If successful such a test would help validate the model and confirm that the relative importance of the different factors affecting the salinity of the Thurne Broads were correctly incorporated into the model. If not, companion of the results for the two years would also improve the understanding of the whole system. recent drought

**Recommendations for model use**

5.8 The model of the Thurne broads is able to examine the effect of changes in the flow or salinity of pumps discharging to the system. The results from any study should be checked for their sensitivity to dispersion coefficient lower Thurne pump salinity or freshwater inflow in the rivers Bure and Ant, until such time as the source of salt affecting Hickling Broad has been confirmed.

5.9 Once confidence has been gained that the model correctly reproduces the salinity behaviour of the Thrune Broads, attempts could be made to reproduce the nutrient balances which affect the trophic status of these Broads. The combination of salinity and nutrient models will provide a powerful mechanism for establishing the best way of managing the Thurne Broads catchment to ensure their continued nature conservation interest.

5.10 As with any model, the results obtained depend totally on the data and assumptions used. All results should be reviewed to determine which factors are most significant in controlling the behaviour of the system and how well the behaviour of such factors is understood.

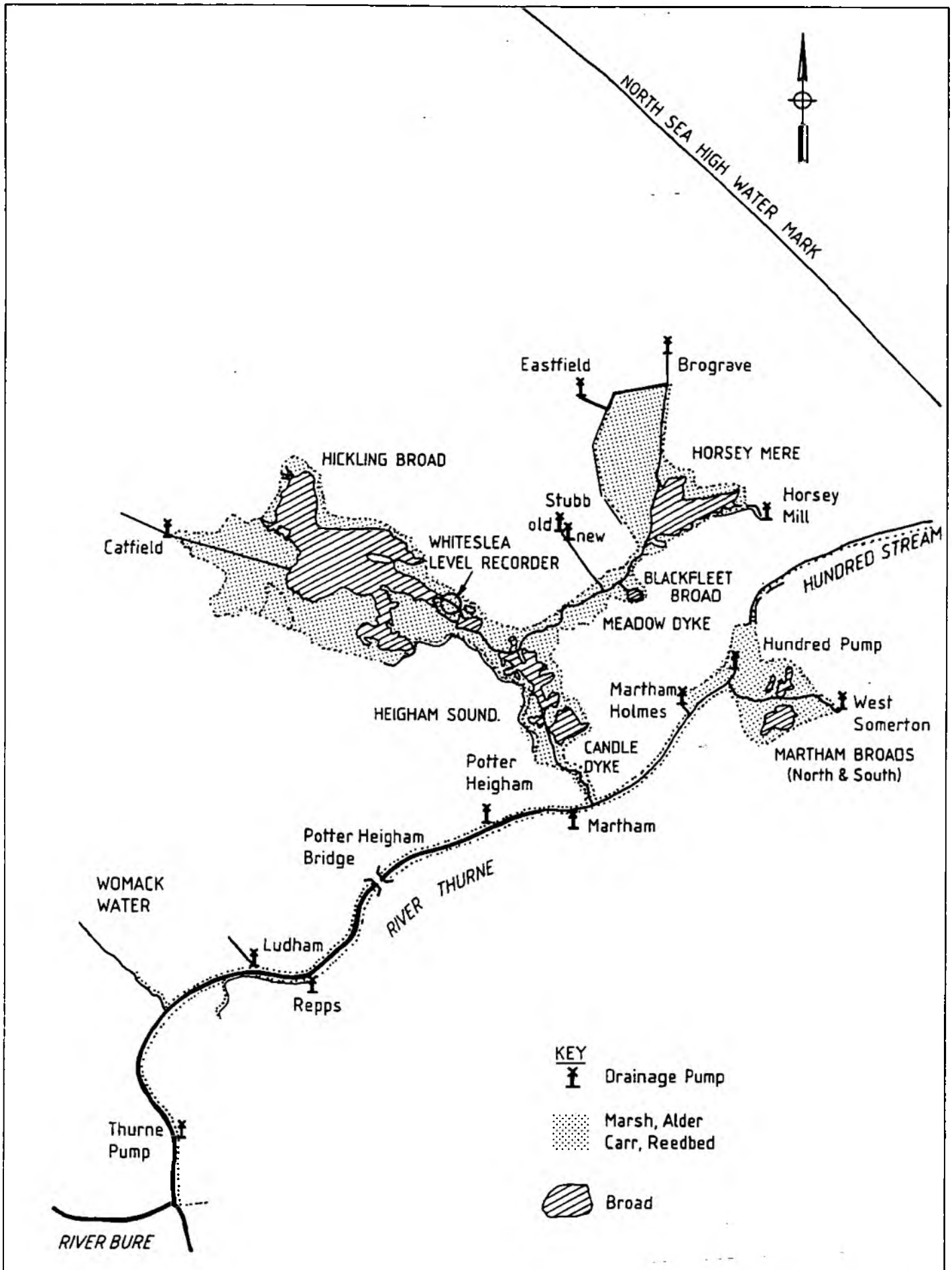
More data needed ?

## 6. References

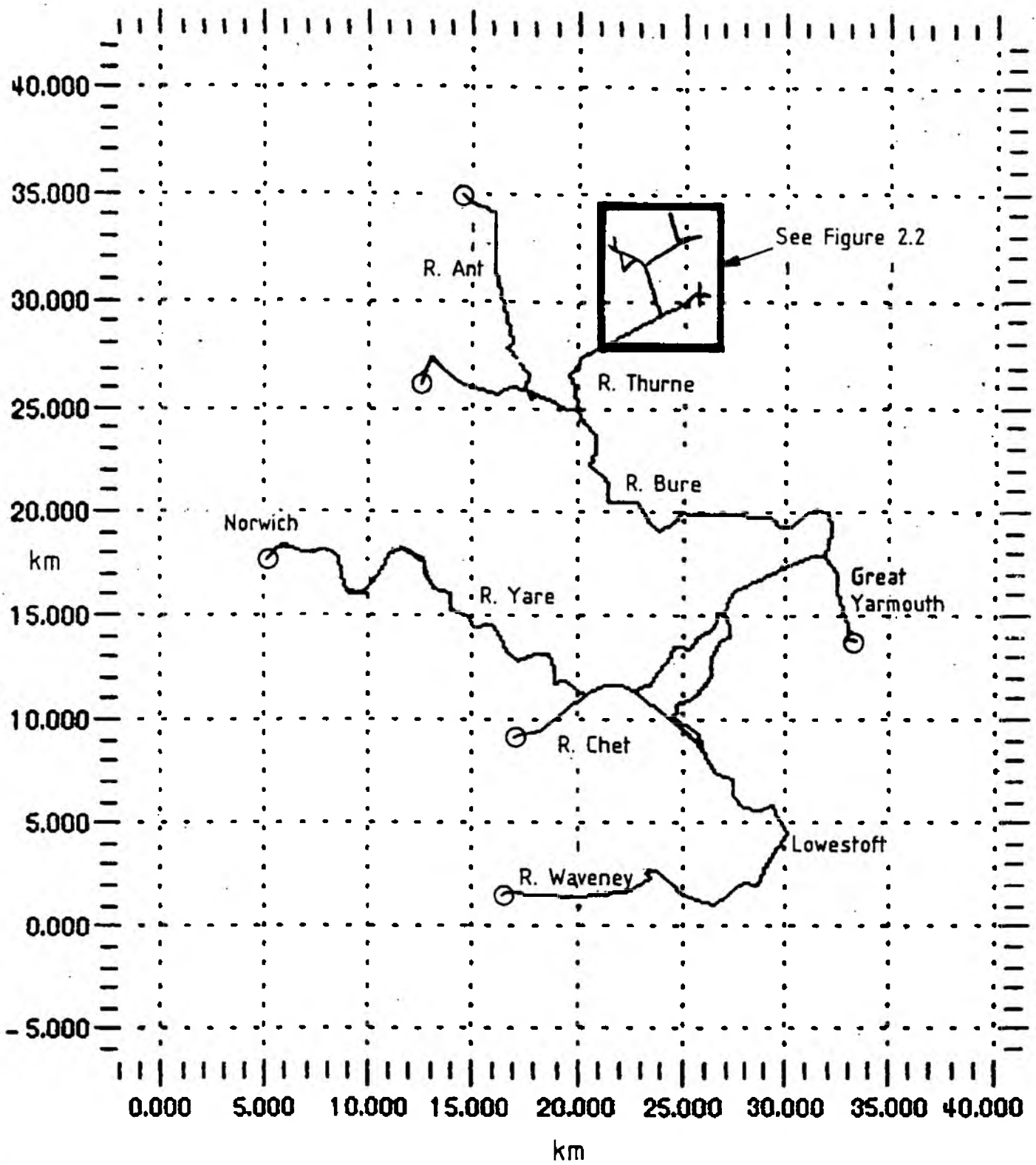

1. Watson R.A. The limnology of the Thurne Broads with particular reference to algal nutrients. Vols 1&2; Thesis submitted to University of East Anglia for the degree of Ph.D, Norwich 1981.

2. Binnie & Partners: Flood Alleviation Strategy for Broadland; Annex 1: Model Studies. Report to NRA November 1993.

3. Hydrographer of the Navy: Admiralty Tide Tables 1993.



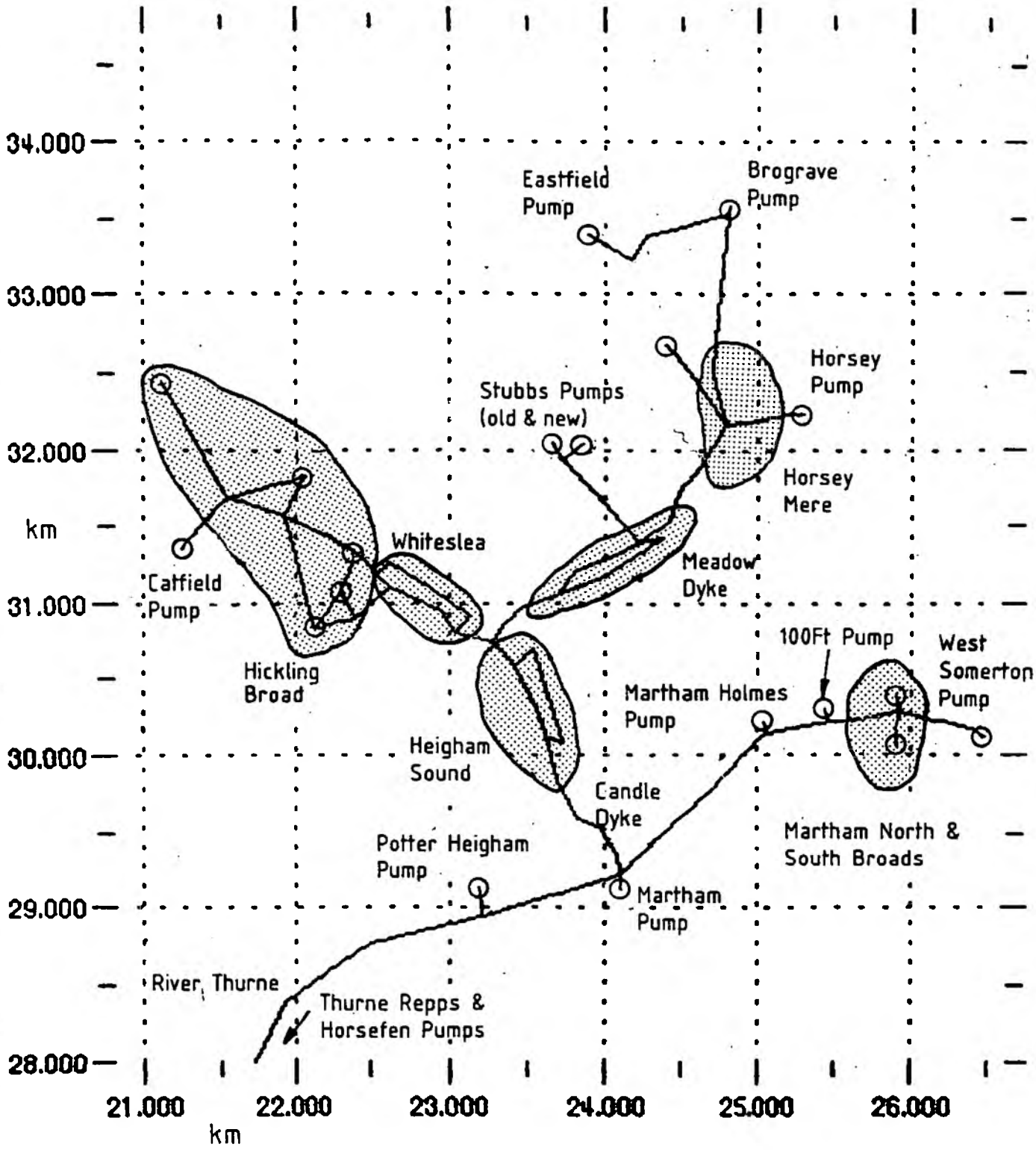

THURNE BROADS
LOCATION PLAN
Figure 1.1




BROADLAND MODEL LAYOUT

Boundary Condition Locations :- O

OVERALL LAYOUT OF
THURNE BROADS MODEL
Figure 2.1

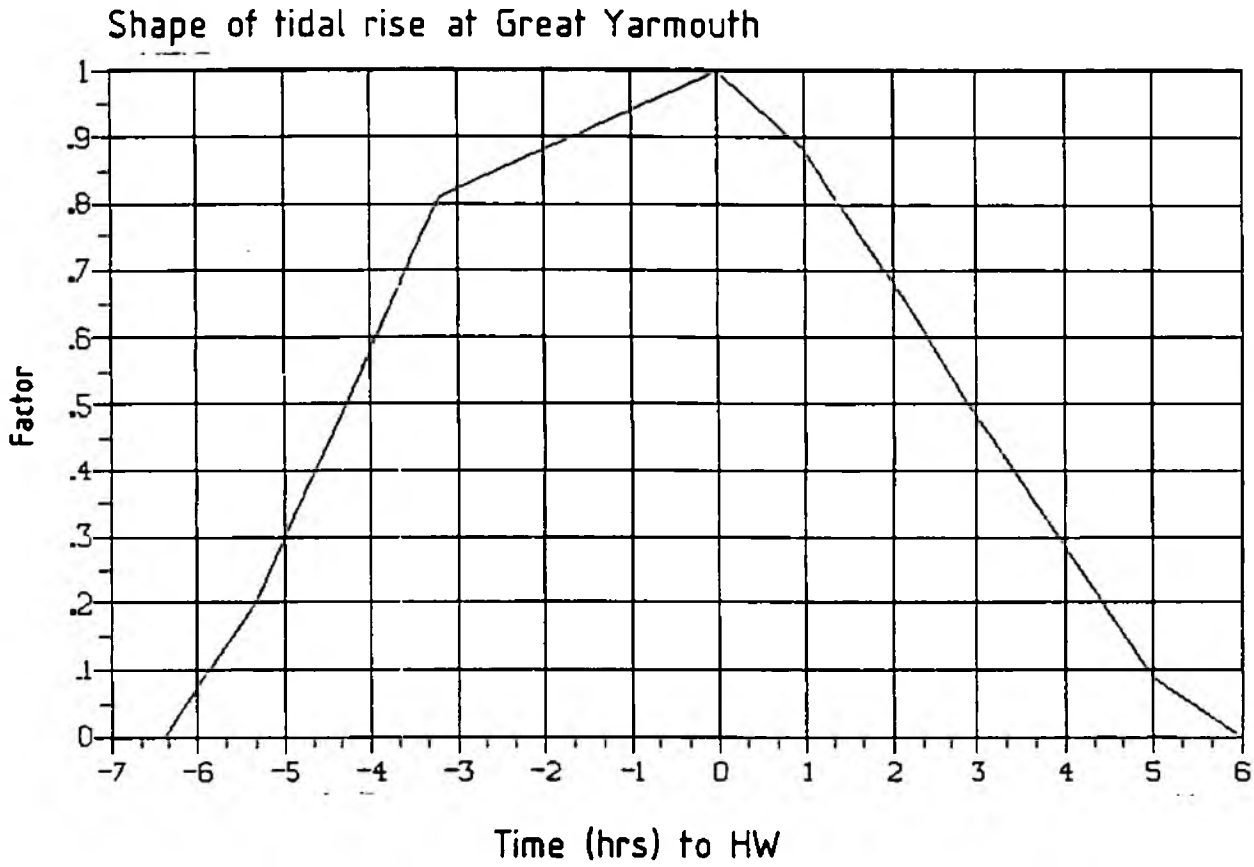



THURNE BROADS MODEL LAYOUT

Boundary Conditions Locations :- ○

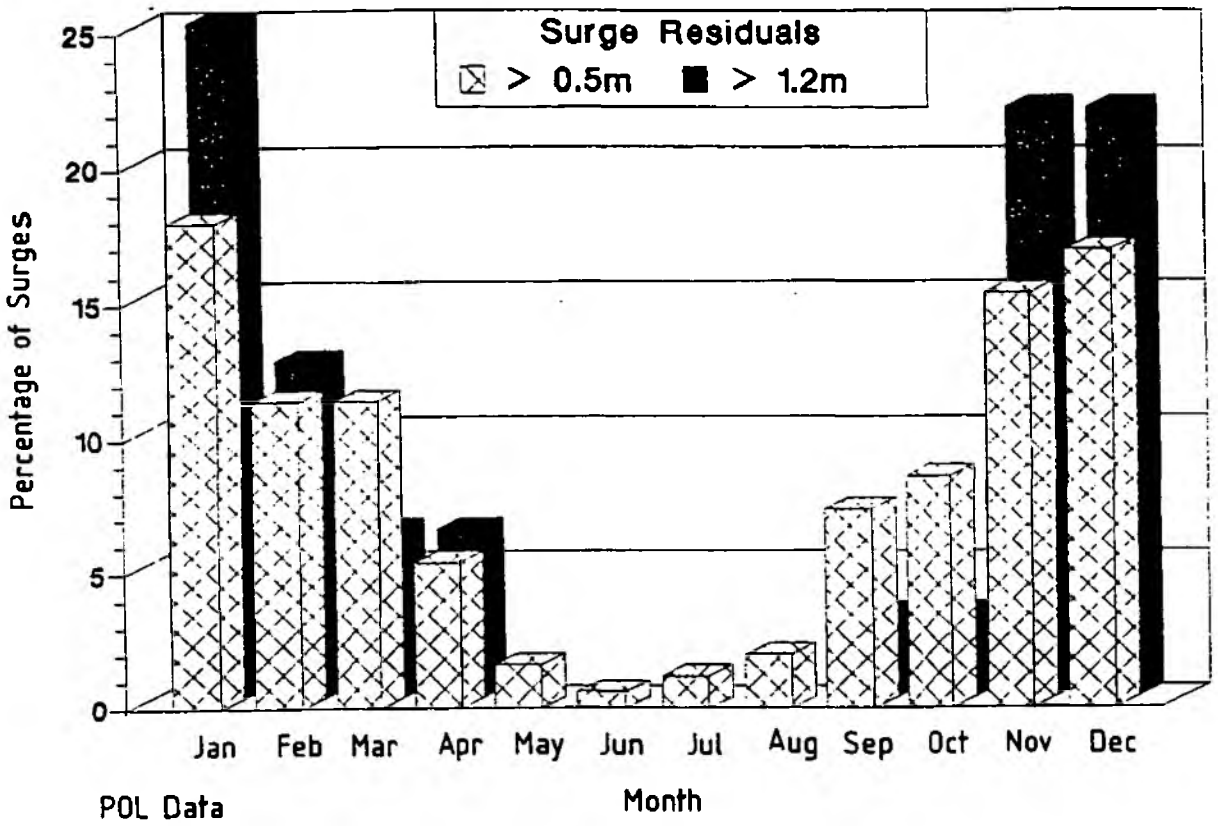
Broads (diagrammatic) :-

DETAILED LAYOUT OF MODEL OF THURNE BROADS AREA
Figure 2.2

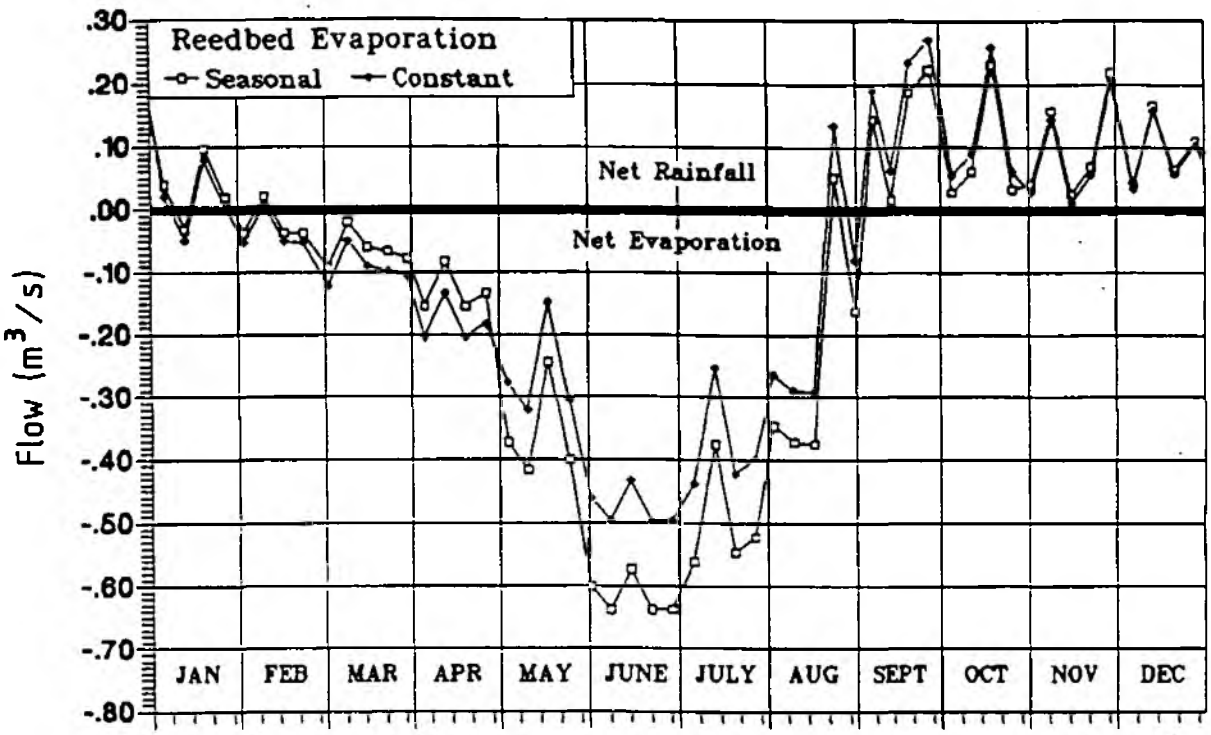



This curve has been fitted between the times and heights of predicted tides to give an estimated sea level (without surges)

GREAT YARMOUTH
TIDE SHAPE
Figure 2.3




LOWESTOFT SURGE RESIDUALS
MONTHLY DISTRIBUTION
Figure 2.4

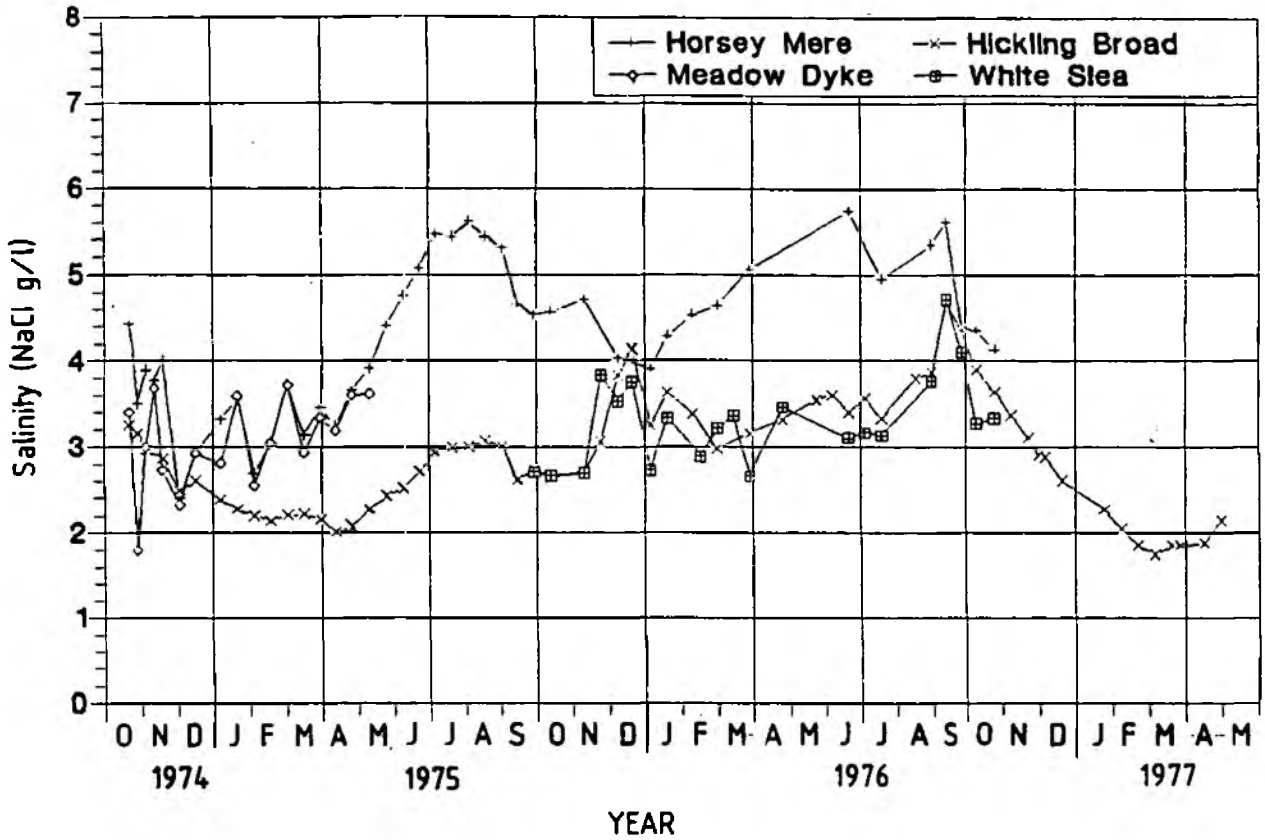



1976

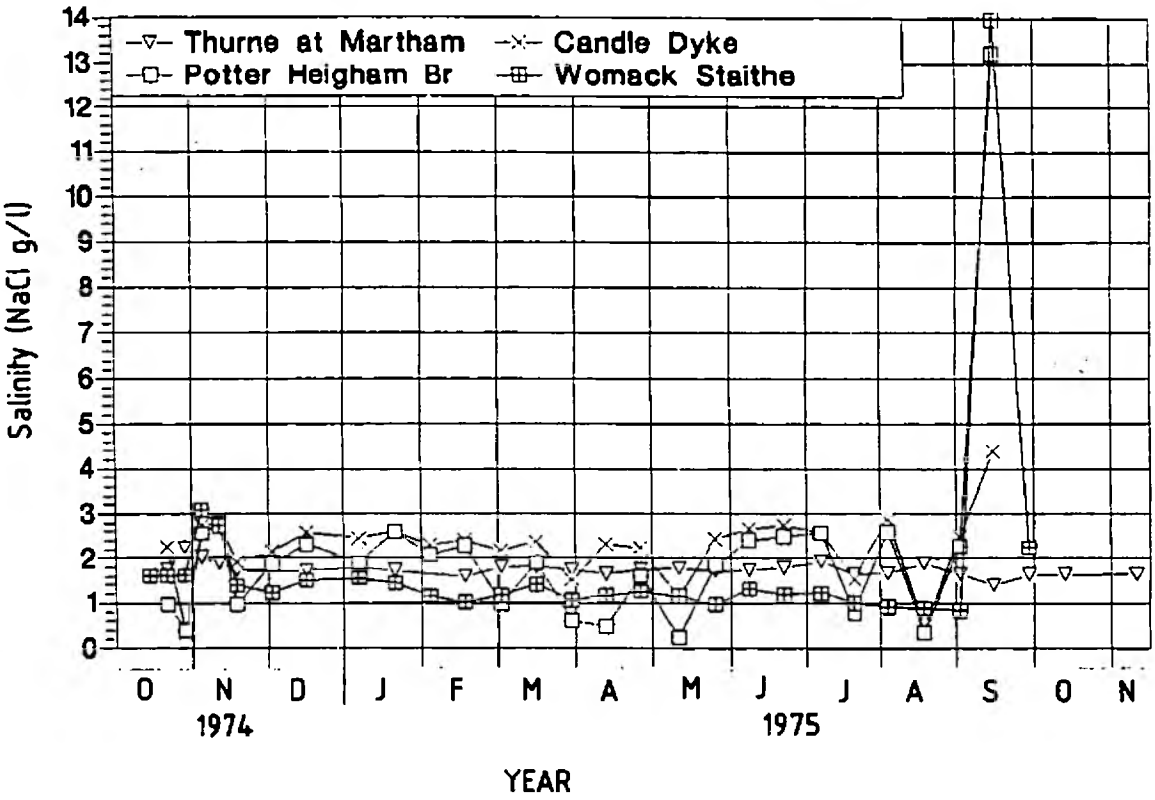
Rainfall positive - Evaporation negative
Reedbed evaporation is 1.8 * Open Water (constant) or 1.2, 2.5 (seasonal)

Note:-
Rainfall and evaporation are applied to the 229.8ha area of the Thurne Broads (excluding rivers) and 322.8ha of reedbed and woodland

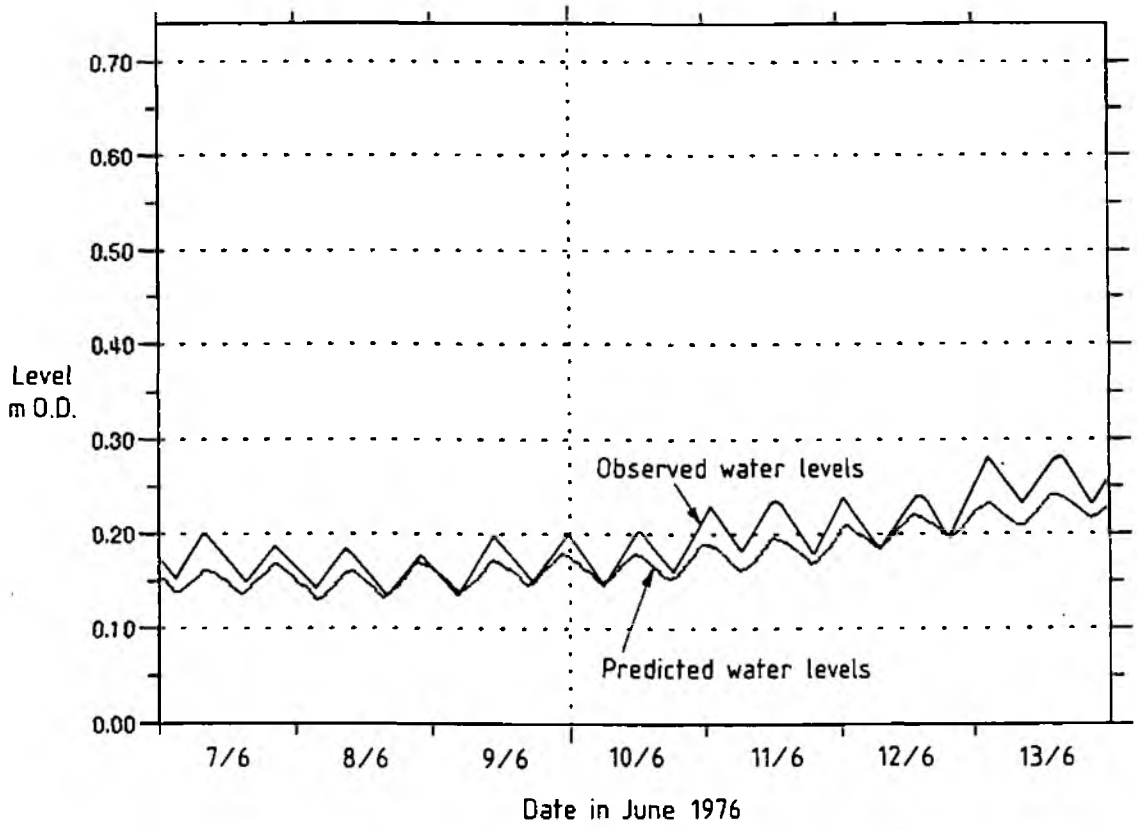
RAINFALL AND EVAPORATION
RATES FOR 1976
Figure 2.5




SALINITY READINGS IN
THURNE BROADS 1974 - 77
Figure 2.6



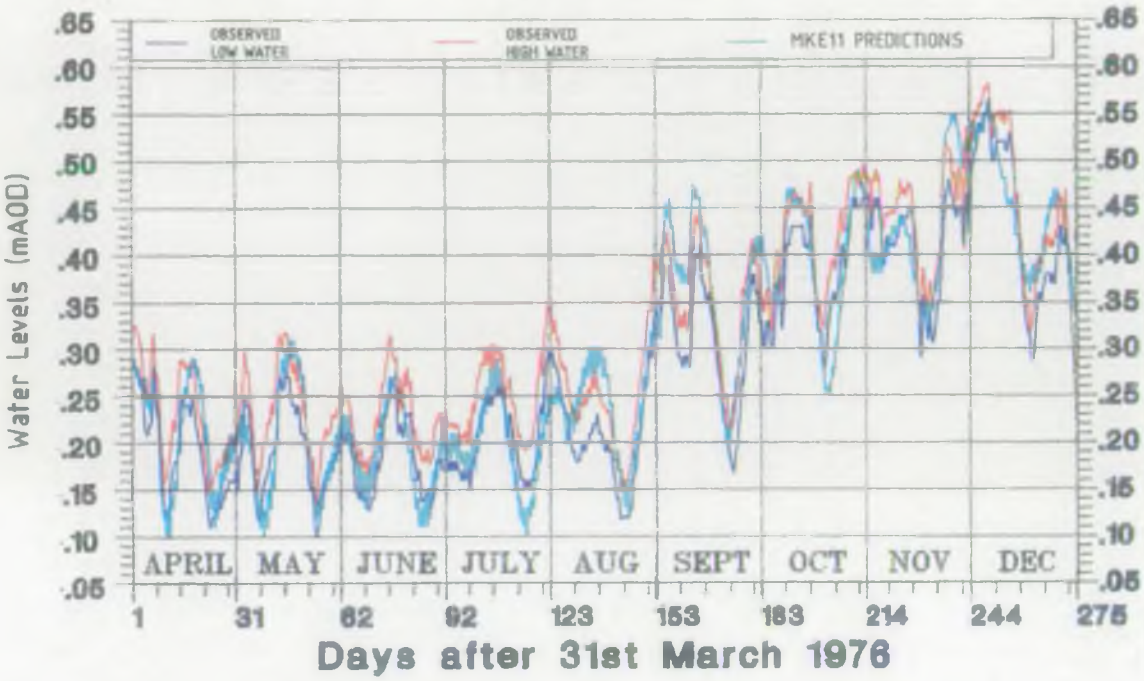

SALINITY READINGS IN
RIVER THURNE 1974/5
Figure 2.7



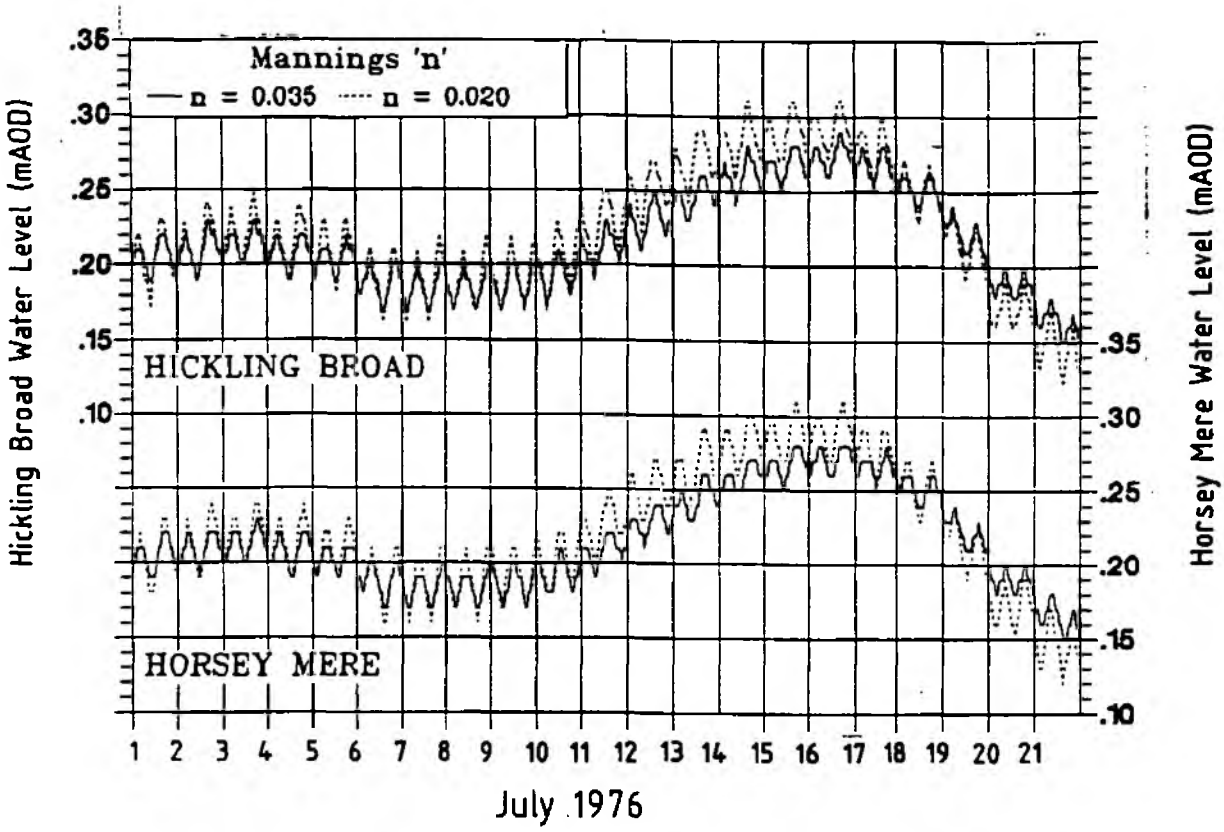

Scaling
Accuracy required ?

WHITESLEA SOUND.

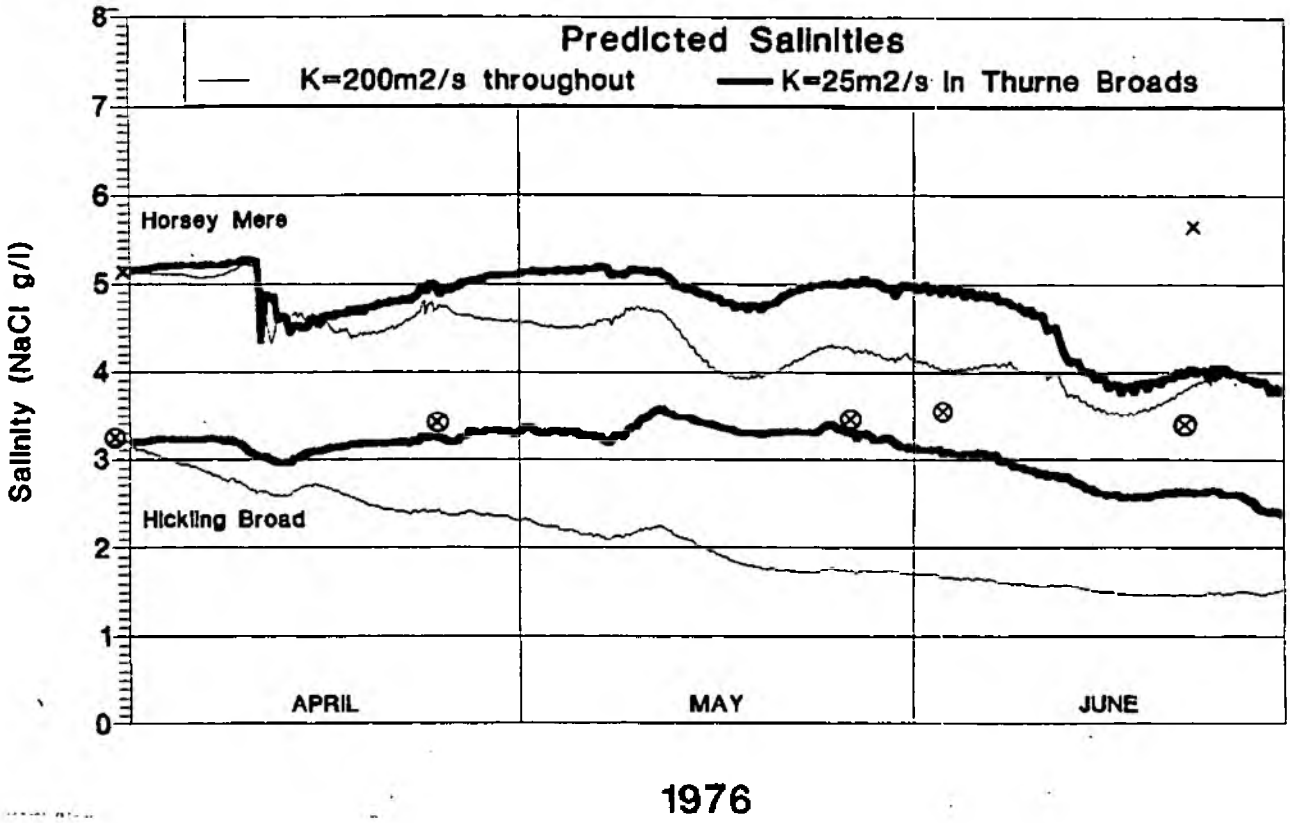
COMPARISON OF MODEL AND
OBSERVED WATER LEVELS
FOR JUNE 1976
Figure 3.1




COMPARISON OF MODEL AND
OBSERVED WATER LEVELS FOR
APRIL TO DECEMBER 1976
Figure 3.2




SENSIVITY OF HYDRODYNAMIC
MODEL TO FRICTION FACTOR
Figure 3.3

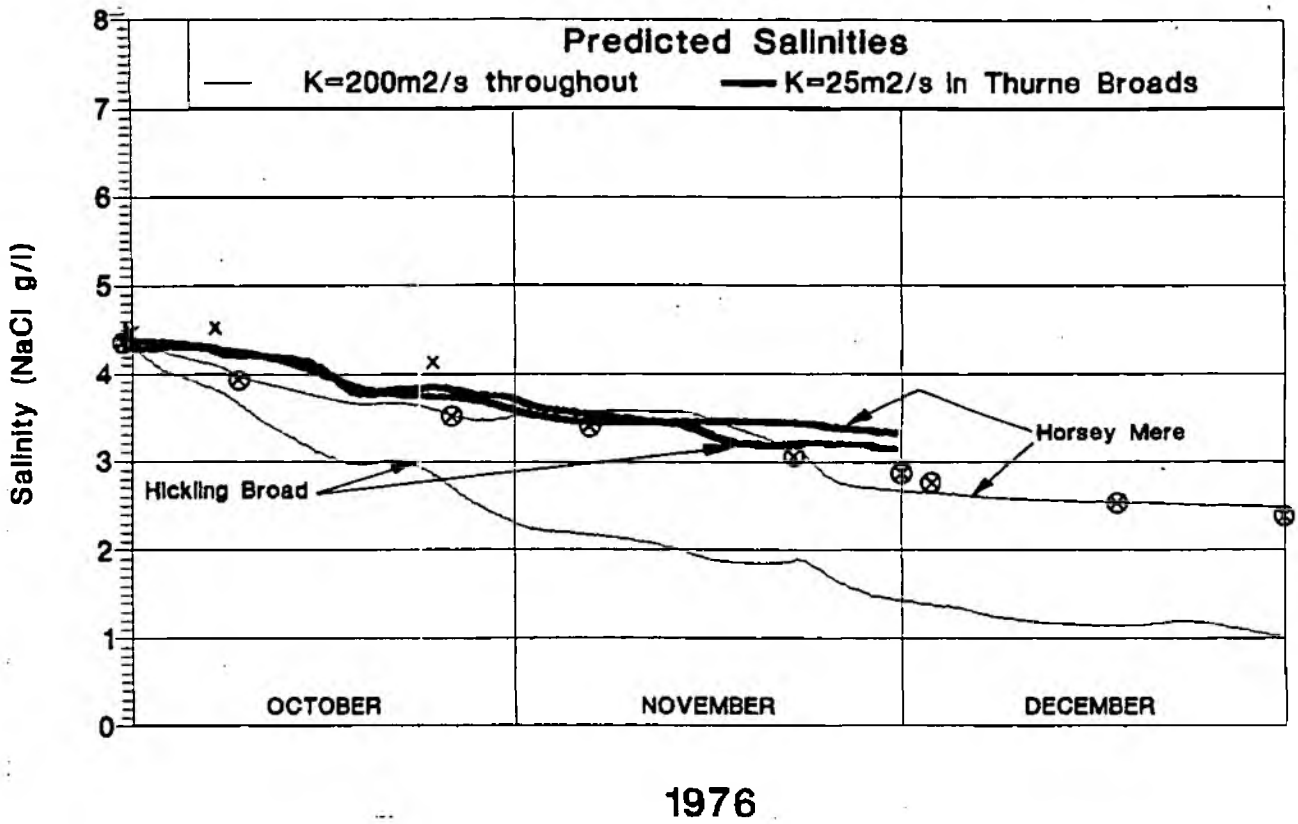



OBSERVED SALINITY

× Horsey Mere

⊗ Hickling Broad

SENSITIVITY OF SALINITY MODEL
TO DISPERSION: SUMMER 1976
Figure 4.1

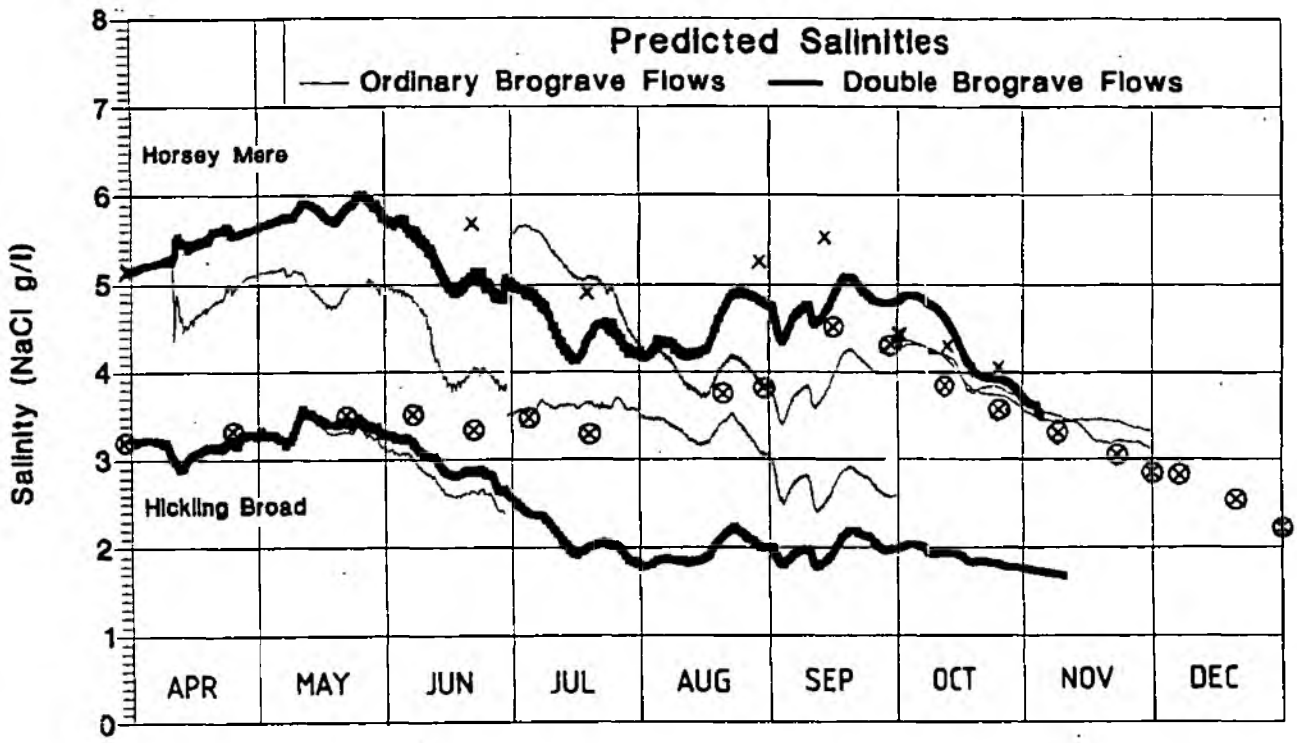



OBSERVED SALINITY

× Horsey Mere

⊗ Hickling Broad

SENSITIVITY OF SALINITY MODEL
TO DISPERSION: AUTUMN 1976
Figure 4.2




1976

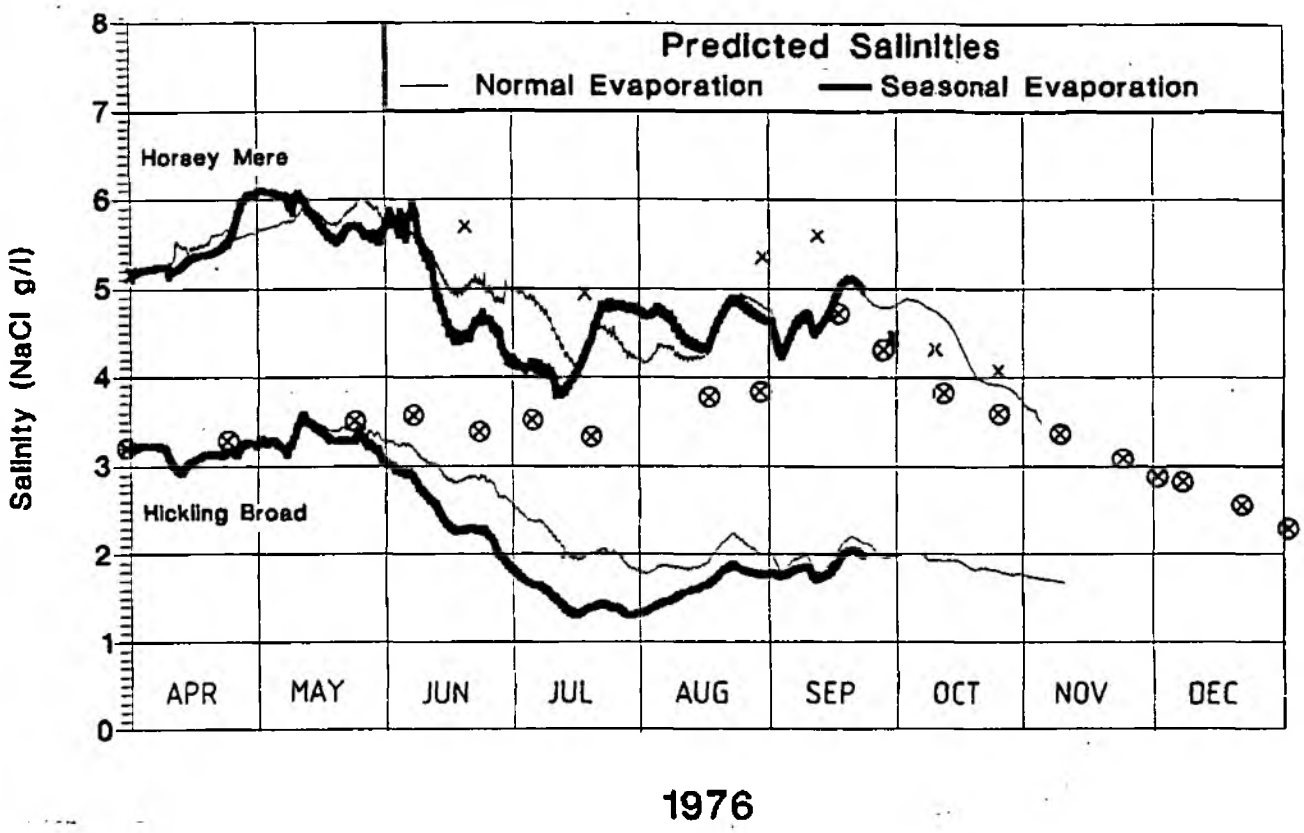
OBSERVED SALINITY

× Horsey Mere

⊗ Hickling Broad

Note:-
Broads salinity for 'ordinary' Brograve Pump run reset to observed values on 1/7/76 and 1/10/76

SENSITIVITY OF SALINITY MODEL
TO BROGRAVE PUMP FLOW
Figure 4.3

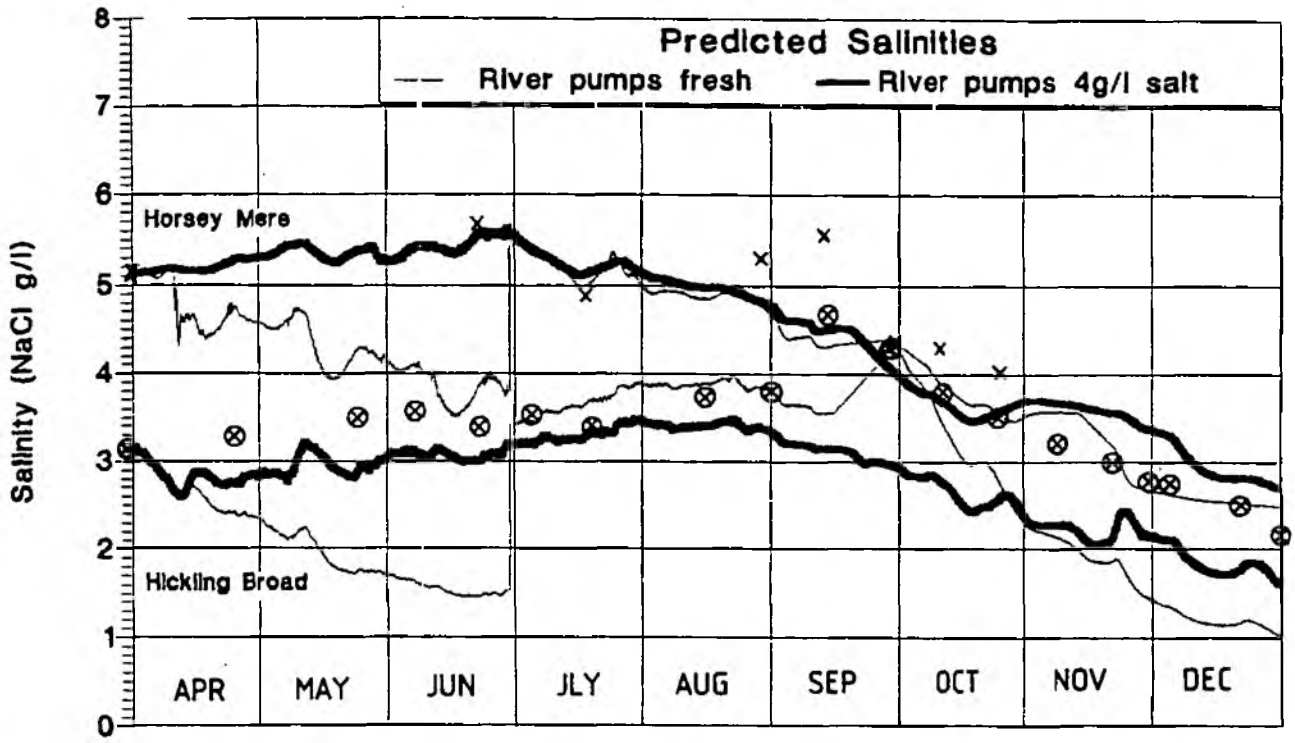



OBSERVED SALINITY

× Horsey Mere

⊗ Hickling Broad

SENSITIVITY OF SALINITY MODEL
TO EVAPORATION RATE
Figure 4.4




1976

OBSERVED SALINITY

× Horsey Mere

⊗ Hickling Broad

Note:-

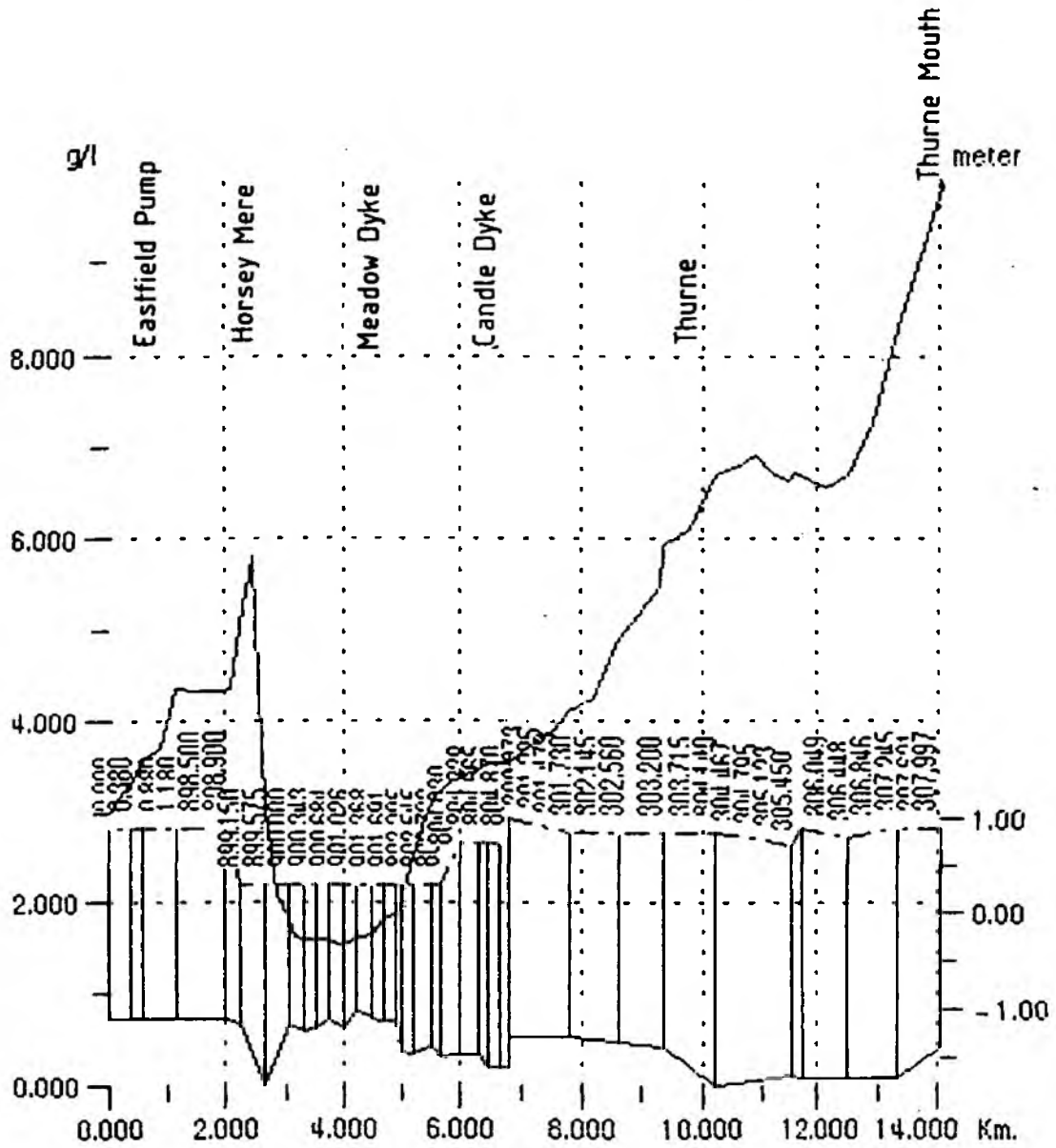
Broads salinity in 'River Pumps Fresh' run reset to observed value on 1/7/76 and 1/10/78

SENSITIVITY OF SALINITY MODEL
TO THURNE PUMP SALINITY
Figure 4.5

PEAK OF 3RD SEPTEMBER 1976 SURGE

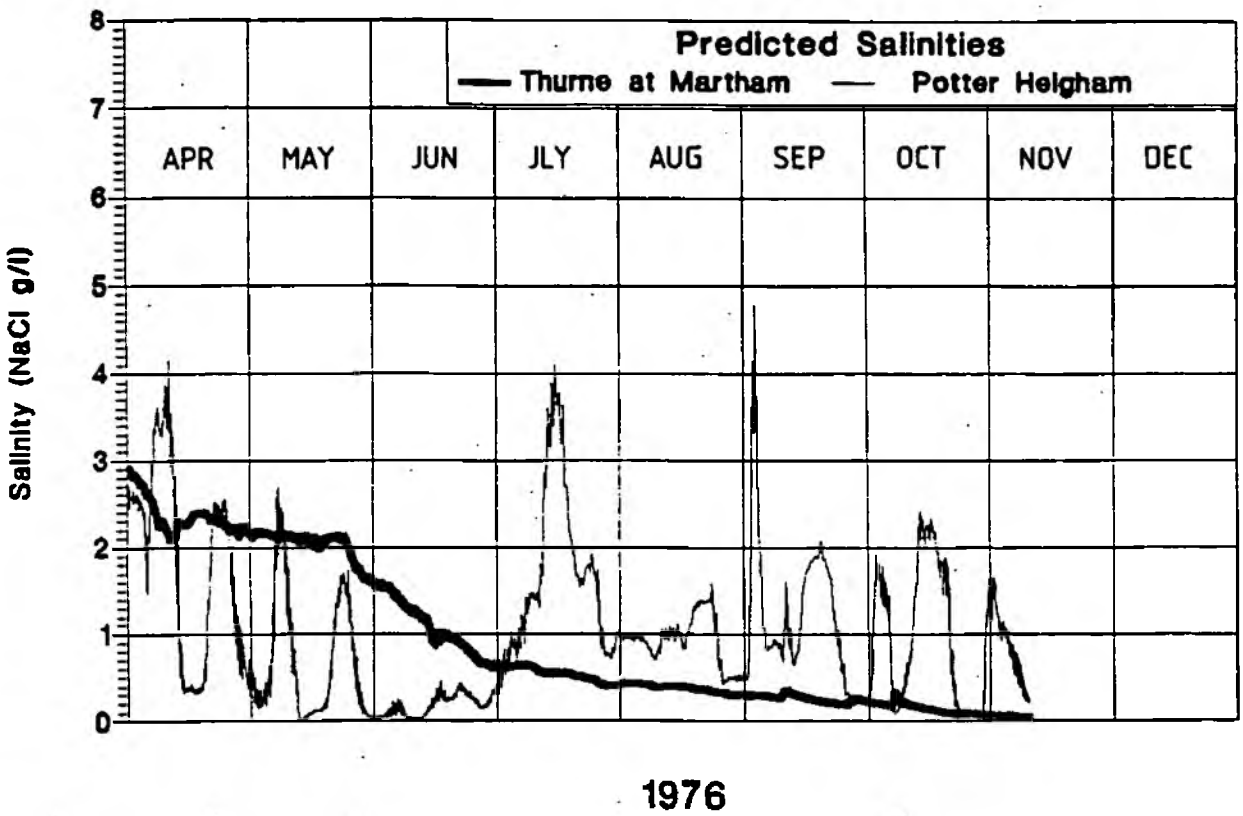
Eastfield Pump (LHS) through Horsey Mere, Heigham Sound down to Thurne Mouth (RHS)

Dispersion factor = 200 m²/s in lower rivers, 50 m²/s elsewhere.




| HOUR 1544 | |
|---|---|
| PARAMETER : SALT, 3-SEP-1976, 08:00<br>DATA FILE : THURN-1X.RBOUNDARY FILE : THUR4CLQ.BSF<br>RESULT FILE : THUR776H.TICALCULATED : 7-MAY-1993, 14:5 | MIKE 11<br>Dwg no.: |

RIVER THURNE SALINITY
PROFILE SEPTEMBER 1976
Figure 4.6




Predictions for Martham at Martham Broad

PREDICTED MARTHAM AND POTTER HEIGHAM
SALINITIES FOR APRIL TO DECEMBER 1976
Figure 4.7

# APPENDIX A

# SPECIFICATION

# Hydraulic Model of the Thurne Broads

## Specification

### Background

The limnology of the Thurne Broads was the subject of Dr R A Watson's thesis at the University of East Anglia in 1981. It had particular reference to the subject of algal nutrients. Beside this work the NRA (and its predecessor authority) have subsequently augmented the database of information in terms of water quality analysis and land drainage pump records. The NRA, together with the Broads Authority and English Nature need to formulate a catchment management plan for the Thurne Broads.

The Thurne Broads receive their water from direct rainfall and from land drainage pumps, in particular the Brograve Pump which is influenced by coastal saline seepage. The water throughflow is reduced by evapotranspiration losses and impeded by tidal backflow from the River Bure. The majority of the water flows through Horsey Mere, by-passing Hickling Broad and the extent of tidal mixing between these two sites has not been adequately quantified.

Both Hickling Broad and Horsey Mere have become eutrophic, although the source of nutrients responsible is still uncertain. Roosting gulls on Hickling Broad were likely to have been a major source of nutrients, but enriched water from the lower River Thurne and the River Bure may now be important sources due to tidal inputs. Phytoplankton populations are influenced by water residence time and the salinity of these broads can cause *Prymensium parvum* (an alga that produces a fish toxin) to occur.

To improve water quality it would be desirable to reduce the salinity and the nutrient status of these broads. However to achieve this more information is required regarding the source of water to these broads. In particular the influx of water from the River Bure and lower Thurne and the relative effects of land drainage pumps and tidal action, on tidal mixing and chloride concentrations need to be determined.

The development of a flood defence model for Broadland using MIKE 11 provides an ideal opportunity to model water movement in the Thurne Broads by taking part of the flood defence model and increasing the detail in the Thurne area.

### Requirements

1) A single dimensional flow model (MIKE 11) to predict

   Water level height at Hickling Broad (for verification)

   Chloride concentrations at the following stations in the Thurne river and broads.

   Horsey Mere
   Hickling Broad
   Heigham Sound

R Thurne at Martham Broad
R Thurne downstream of Candle Dyke

2) Model predictions to simulate chloride concentrations at 2 weekly intervals over a period of 3-6 months.

3) Model to be driven from

Tide level records at Acle Bridge
Fluvial Flow in the R Bure (Horstead Gauging Station)
Pumped water inputs from land drainage pumps

Boundary conditions to include the salinity at Acle Bridge.

4) An allowance will need to be made within the model for water loss by evaporation from both the water surface and from evapotranspiration from reedswamp vegetation.

**Phasing of modelling**

Initial model testing

The model will be tested initially using data collected by R Watson (1976/77). Initial calibration to be carried out using 3 months of this data, followed by verification with the following 3 months.

The model will then be used to model the following tidal sequences.

Typical winter conditions.

Typical summer conditions

Low rainfall summer conditions (1989-1990)

**Data Availability**

Channel cross-sections (Watson's data, Copies attached)

| | |
|---|---|
| Meadow Dyke | 8 sections |
| Candle Dyke | 3 sections |
| R. Thurne | 9 sections |

Bathymetric maps (contours at 10cm intervals)

Hickling Broad
Horsey Mere
Heigham Sound (no longer accurate)

Water levels

Hickling Broad (not levelled to OD)

Charts March 76- July 77, Tidal heights tabulated for each tide (Watson's data)

Data logger from July 1992

Acle Bridge

charts from 1976 (NRA data)

Water area

Channels, Broads and estimate of flooded area for Hickling Broad. from Watson's thesis

More recent data to be obtained following recommendations from consultants by Broads Authority.

Pump volumes

Monthly estimates of volume from electricity consumption

Water quality

Chloride concentrations from all pump inlets (monthly)

Chloride concentrations from lakes/rivers at 2 weekly intervals

Ideally the model should provide data regarding the volume of water entering and leaving Hickling Broad, (and other model compartments) in order that both average water residence time and phosphorus budgets could be computed. It is anticipated that this may require additional model development beyond this 1st stage of model development.

**Outputs**

Brief report summarising

data sources
model type
model parameters
calibration accuracy
graphical output of results
conclusions
recommendations for further work

Model for use on NRA computer

Instructions and training for use of model

# APPENDIX B

# MODEL LAYOUT AND BOUNDARIES

## Appendix B

## Model Layout and Boundaries

### B1. Model Set-up

B1.1 The Thurne Broads have been modelled by adding appropriate channels and storage areas to the MIKE-11 model that was used for the Broadland Flood Alleviation Study (see Figures B1 and B2) Recorded sea levels and river flows can therefore be used to drive the hydrodynamic model. Where ?

B1.2 The number of cross-sections in the Rivers Yare and Waveney has been greatly reduced from what was used in the Broadland model, although the rivers are still modelled up as far as Norwich and Ellingham Mill respectively. These upstream reaches have little effect on the Thurne Broads and this simplification reduces the time required to run the model and the size of the output files produced.

B1.3 Cross-sections have had to be estimated in a number of different places around the system as more detailed information was not available. These include the channels around Rush Drain, Blackfleet Broad, and between Martham Broads and the River Thurne. In the Upper Thurne the cross-sections have been copied from the most upstream section used in the Flood alleviation model, which was taken near Candle Dyke. Potter Heigham Bridge has been modelled as a 6m wide culvert with an invert at -1.4 mOD and a soffit at +2.0 mOD.

B1.4 Cross-sections in Meadow Dyke have been spaced out evenly as their precise locations were not known.

B1.5 Most drainage pumps have been connected to the system via their own small channels, typically 1 or 2 m wide and 5m long. This enables them to be modelled as separate boundary conditions in MIKE-11. With some pumps the channels had to be lengthened to 100m to prevent model instabilities.

B1.6 Eastfield and Stubb pumps have been connected via longer channels, 1100 and 700 metres long. Eastfield pump's channel loops around the north of Brayden Marshes.

B1.7 The Thurne Broads and reedbeds were divided into a number of calculation cells, the dimensions of each were calculated by MOSS. Salinity in each cell is assumed to be totally mixed, i.e. no stratification occurs.

B1.8 Only reedbed east of the road around the west of Hickling Broad has been included.

B1.9 The connection between Martham Broad (North) and the River Thurne is 200m wide, as indicated on the aerial photograph tracings. A channel 10m wide has been used to connect Martham Broad South to the Thurne. Although no connection is visible on the tracings, seepage is likely to occur through the reedbeds and a channel must be present if the Broad is included in the model. Like other Broads, they were estimated to be about 1.5m deep.

## B2. Boundary Conditions (Hydrodynamic Runs)

B2.1 These are needed in the model wherever water enters or leaves the system, as shown in the table below:-

| Boundary Name | MIKE11 database | Representing | Model reach | Chainage |
|---|---|---|---|---|
| Sea Level 76 | Pumps | Sea Levels | Yare | 55.95 |
| Yare 74 | Pumps | River Yare Flow | Yare | 10.00 |
| Waveney 74 | Pumps | River Waveney Flow | Waveney | 201.30 |
| Ant 74 | Pumps | River Ant Flow | Ant | 400.00 |
| Burered | Pumps | R.Bure Flow (reduced) | Bure | 103.50 |
| Chet 74 | Pumps | River Chet Flow | Chet | 0.00 |
| Brograve | Pumps | Estimated Pump Inflows | Meadow | 898.0 |
| Eastfield | Pumps | Estimated Pump Inflows | Eastfield | 0.0 |
| Horsey | Pumps | Estimated Pump Inflows | Horsey | 0.0 |
| Stubb Old | Pumps | Estimated Pump Inflows | Stubb | 0.0 |
| Stubb New | Pumps | Estimated Pump Inflows | Stubb New | 0.0 |
| Catfield | Pumps | Estimated Pump Inflows | Catfield | 0.0 |
| W Somerton | Pumps | Estimated Pump Inflows | Thurne | 297.49 |
| Martham Holmes | Pumps | Estimated Pump Inflows | Holmes | 0.0 |
| Martham | Pumps | Estimated Pump Inflows | Pumpmartham | 0.0 |
| Potter Heigham | Pumps | Estimated Pump Inflows | PotterH | 0.0 |
| Repps | Pumps | Estimated Pump Inflows | Repps | 0.0 |
| Horsefen | Pumps | Estimated Pump Inflows | Horsefen | 0.0 |
| Thurne | Pumps | Estimated Pump Inflows | Thurne Pump | 0.0 |
| Evap** | Evap | Evaporation & Rainfall | Evap** | 0.0 |

B2.2 Repps and Horsefen Pumps have been amalgamated but could be separated if required. The model includes the facility to add the new 100ft pump when required.

B2.3 Water abstractions from the Bure have been modelled by reducing the flow input to the river at Wroxham.

B2.4 In most cases evaporation and rainfall to/from the Broads has been modelled by a lateral inflow to the relevant channel. These can be seen in THUR*76*.BSF files, in MIKE-11 menu B.5.

B2.5 At a channel junction or at a boundary, no extra lateral inflows are allowed in MIKE-11. At four cells in Hickling Broad (HC, HF, A, I) an extra (imaginary) channel has been added to enable extra flow in or out of the model to occur. These cells are shown on Figure B2.

## B3. Boundary Conditions (Salinity Runs)

B3.1 These are needed in the model wherever salt enters or leaves the system, as shown in the table below:-

| Boundary Name | MIKE11 database | Representing | Model reach | Chainage |
|---|---|---|---|---|
| Sal = 34 | Salinity | North Sea Salinity | Yare | 55.95 |
| Sal = 0 | Salinity | River Salinity | Yare<br>Waveney<br>Bure<br>Ant | 10.00<br>201.30<br>103.50<br>400.00 |
| WSomerton_Cl | Pumps | West Somerton Salinity | Thurne | 297.49 |
| Martham_Cl | Pumps | Martham Pump Salinity | Ant | 0.0 |
| Horsey_Cl | Pumps | Horsey Mill Salinity | Horsey | 0.0 |
| Brograve_Cl | Pumps | Brograve Pump Salinity | Meadow | 898.0 |
| Eastfield_Cl | Pumps | Eastfield Pump Salinity | Eastfield | 0.0 |
| Stubbold_Cl | Pumps | Stubb Old Pump Salinity | Stubb | 0.0 |
| Stubbnew_Cl | Pumps | Stubb New Pump Salinity | StubbNew | 0.0 |
| Catfield_Cl | Pumps | Catfield Pump Salinity | Lings Mill | 0.0 |
| Closed Boundaries | Menu G.5.5 | All other hydrodynamic boundary locations. | | |

B3.2 Some river boundaries have also been modelled as "Closed Boundaries" to reduce the size of salinity boundary (*.BSF) files.

B3.3 Evaporation / rainfall to cells involves no salt transfer so all these boundaries have been modelled as closed salinity boundaries.

## B4. Model Run Times and Output Files

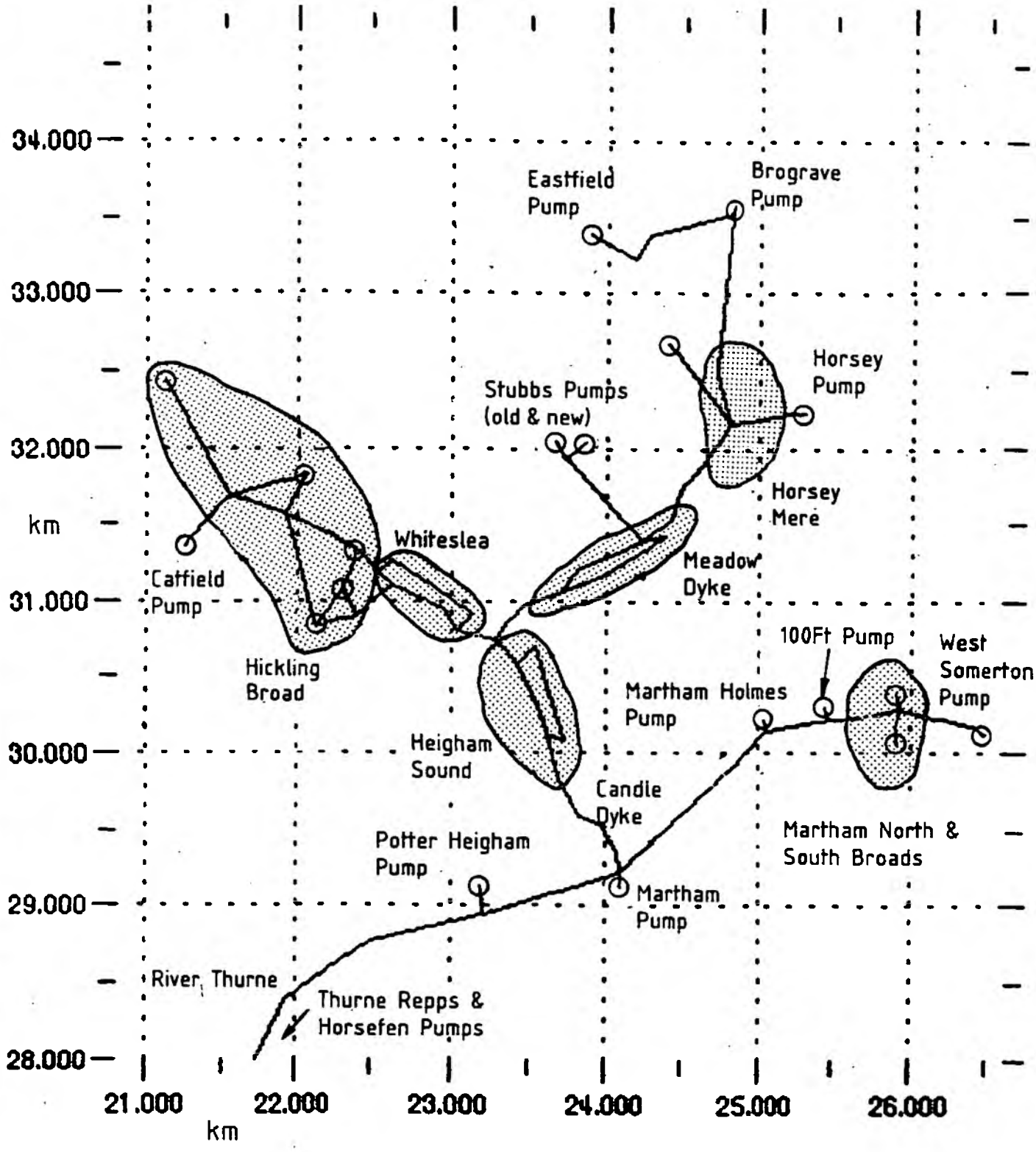
B4.1 The model run time depends on the time step, the period of simulation and the speed of the computer. For the hydrodynamic model, a 60 second time step is essential for numerical stability. With a 33MHz 486DX IBM compatible PC computer, 3 month hydrodynamic simulations could be completed overnight in around 16 hours.

B4.2 The results from the hydrodynamic model are stored every hour to provide the hydrodynamic data required by the salinity model. The storage interval is a compromise between the need to retain details of tidal flow and level variations for the salinity model and the rapid increase in file size as the storage interval reduces. Storage of hydrodynamic model output data at hourly intervals from a single 3 month run generated a 10Mb computer file.

B4.3 The salinity model in theory required a similar time step to the hydrodynamic model. In practice longer time steps could be used as the resultant instabilities which mainly arose in the Great Yarmouth area did not noticeably affect results in the Thurne Broads section of the model. This allowed 3 month salinity model tests to be completed in as little as 2 hours on occasions.

B4.4 The output from the salinity model is only required for presentation of model results. The frequency of output is thus dictated by the purpose of the test. If salinity variations during the course of a tide are significant results may need to be stored every hour. In other area where salinities change more slowly, model output two or three times a day may be sufficient. The frequency of storage of model results controls the size of the salinity output file. If interest is centred on areas where salinity changes slowly, the salinity output file may only require 2 or 2.5 Mb of storage.

B4.5 The availability of appropriate methods for storage of the large output data files that are generated by this application of MIKE-11 are an important requirement for a study using this model.




THURNE BROADS MODEL LAYOUT

Boundary Conditions Locations :- ○

Broads (diagrammatic) :-

DETAILED LAYOUT OF MODEL OF THURNE BROADS AREA

Figure B2

# APPENDIX C

# AREAS AND VOLUMES OF THE THURNE BROADS

## Appendix C

### Areas and Volumes of the Thurne Broads

| Replacement Volumes | Open Water Area, (HD) (1000m2) | Volume (HD) (1000m³) | Reedbed & Woodland (1000m2) | Total Area, HD (1000m2) | Salt Water Out (1000m³) |
|---|---|---|---|---|---|
| Hickling Broad | 1521 | 1630 | 1218 | 2333 | **467** |
| Horsey Mere | 356 | 580 | 785 | 879 | **176** |
| Meadow Dyke | 21 | 21 | 255 | 191 | **38** |
| White Slea | 79 | 48 | 177 | 197 | **39** |
| Heigham Sound | 253 | 87+87 | 215 | 396 | 79 |
| Martham Broads | 168 | 235 | 578 | 553 | 111 |
| Thurne (u/s) | 74 | 100 | 0 | 74 | 15 |
| Thurne (d/s) | 204 | 327 | 0 | 204 | 41 |
| Candle Dyke | 19 | 29 | 0 | 19 | 4 |
| Total | 2695 | 3143 | 3228 | 4847 | 969 |
| Volume of Lower Thurne, Candle Dyke and Heigham Sound Channel (1000m³) | | **443** | Volume of Salt Water leaving Broads, 20cm level drop (1000m³) | | **720** |

C1.1 The right hand column shows the volume of water released if this area drops in water level by 20cm (typical fortnightly variation.) Brackish Broads water will reach the Bure.

C1.2 The boundaries between areas are different from Raymond Watson's. Extra areas have been added to those given in previous tables to account for area between spot heights and bank levels.

C1.3 Woodland areas are also included in the reedbed column. Two thirds of the reedbed and woodland is assumed to be at or below Hickling Datum.

C1.4 Half of Heigham Sound's volume is considered to be in the channel.

C1.5 This table assumes that all the water in the dykes drains out to the Bure before any of the Broads water.

C1.6 For Hickling or Horsey water to reach each of the following points:-

| | | | |
|---|---|---|---|
| Candle Dyke | a drop of | 2.43 cm | is needed. |
| River Thurne | | 3.21 cm | |
| Potter Heigham | | 6.05 cm | |
| River Bure | | 12.3 cm | |

C1.7 If all of Heigham Sound water is replaced, to reach the Bure a 14.68 cm fall is needed.