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Title	Modelling nutrient and chlorophyll_a dynamics in an Irish brackish waterbody
Author(s)	Hartnett, Michael; Nash, Stephen
Publication Date	2004-01
Publication Information	Hartnett, A,Nash, S (2004) 'Modelling nutrient and chlorophyll_a dynamics in an Irish brackish waterbody'. Environmental Modelling & Software, 19 :47-56.
Publisher	Elsevier
Link to publisher's version	http://dx.doi.org/10.1016/S1364-8152(03)00109-9
Item record	http://hdl.handle.net/10379/3974
DOI	http://dx.doi.org/DOI 10.1016/S1364-8152(03)00109-9

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MODELLING NUTRIENT AND CHLOROPHYLL_A DYNAMICS IN AN IRISH BRACKISH WATERBODY

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Abstract

This paper presents aspects of a research investigation into nutrient fluxes into and out of an important Irish estuary, Wexford Harbour, located in the southeast of Ireland. Details of the methodology applied, the data collection and analysis and the models used are outlined. In particular, the paper addresses modelling of chlorophyll_a production in the brackish waterbody and its dependency on light attenuation.

There are three distinct stages to the research carried out: (i) collection, collation and analysis of physical, chemical and biological water quality variables; (ii) development, validation and application of a chlorophyll_a production model; (iii) development of a Geographic Information System.

The nutrient and chlorophyll_a production model simulates nine interactive water quality parameters; during the first stage above these parameters were measured to provide initial conditions for the model and for calibration purposes. From measurements, relationships were derived between the water quality variables and salinity, which were used to specify initial spatially varied values of the parameters to the model at different seasons. A relationship was also developed between light intensity, turbidity and concentrations of chlorophyll_a, based on field measurements. This relationship was incorporated into the model. The paper presents chlorophyll_a predictions using this relationship and illustrates how the enhanced model can be used as an accurate modelling tool for managing coastal ecosystems. The water quality model was incorporated into the ArcView GIS system providing an easy-to-use graphical user interface to run simulations and interrogate results.

Keywords

Modelling, Chlorophyll_a, Nutrient Cycles, Light Attenuation, Water Quality Management

Introduction

Brackish waters are commonly characterised by high productivity due to frequent inputs of nutrients from both freshwater and marine sources. These nutrients promote the growth of phytoplankton leading to the potential occurrence of algal blooms. Algal blooms can produce toxins which stress or kill aquatic life, contaminate shellfish and limit the value of the water body for public and recreational use. Toxic blooms in freshwater are correlated with nutrient enrichment, (Petersen et al., 1999) and such pollution may also have a role in marine and estuarine toxic algal blooms. Such high productivity, combined with alternating salinity and temperature conditions, can result in fluctuating oxygen levels. These disturbances often result in estuaries and brackish waters being characterised by a low biodiversity.

Disturbed ecosystem conditions and low biodiversity in brackish waters often occur naturally and are not a management problem. However, if eutrophic conditions develop then benthic and/or planktonic algal blooms, and loss of species of economic importance can be a problem (Caddy, 1993). Algal blooms can be unsightly, and can die en-masse causing severe local anoxic conditions with hydrogen sulphide emissions.

Problems in estuarine management are receiving increasing regulatory attention through European Union directives, the Oslo and Paris Commission, and through other environmental legislation (e.g. Birds and Habitats Directives). International research programmes, notably the EU, Estuarine Land-Ocean Interactions Studies (ELOISE) and its global counterpart Land-Ocean Interactions in the Coastal Zone (LOICZ) specialise in modelling nutrient dynamics in coastal and estuarine waters.

Nutrient budgets have been published for two marine inlets in Ireland, Killary Harbour (Rodhouse et al., 1985, Rodhouse and Roden, 1987, Roden et al., 1987) and Lough Hyne (Johnson et al., 1995). The first major study of water quality in Wexford Harbour was carried out in 1980 in connection with the proposed main drainage scheme for Wexford Town (An Foras Forbatha, 1980). Surveys were then conducted on behalf of Wexford

County Council in 1982, 1984 and 1986 (Regional Water Laboratory, 1982, 1986, An Foras Forbatha, 1984). The water quality in the estuary has deteriorated since 1993 and the leve1 of nitrate in the River Slaney has doubled between 1985 and 1996 (Neill, 1997). In 1996, a coastal bloom of the planktonic alga *Phaeocystis* sp. affected the Harbour, leading to concerns about the possible contribution role of estuarine inputs to such blooms (Neill, 1997). This research presents a methodology for the assessment of phytoplankton production in Wexford Harbour. It takes a quantitative approach to assessing and predicting the state of the ecosystem of the estuary. Such ecosystem modelling is very complex but essential to gain a balanced perspective on significant causes of pollution, and any remedial measures necessary. Previous such models of estuarine and coastal systems have taken similar hydrographic and nutrient modelling approaches to that proposed here (e.g. Mensguen and Hoch, 1997). However, the spatial and temporal resolutions were not as high as in the present study which results in improved predictions of chlorophyll_a production. In most models the population of phytoplankton is estimated by considering the total phytoplankton biomass. In practice the most common method of measuring phytoplankton biomass is to measure a characteristic of all phytoplankton, for example, chlorophyll_a, and use this as the aggregate variable. This modelling study, therefore, simulates the production of phytoplankton as the production of chlorophyll_a and the two terms may be substituted for each other throughout this paper.

In this project the ArcView Geographical Information System (GIS) was used to develop a user-friendly water quality management tool. The authors are aware of only one previous published study that has used GIS to prepare data for input to the model and present the results of the model calculations, (Runca et al., 1996). GIS applications appear to be quite limited in such studies.

Description of Slaney Estuary and Wexford Harbour

The River Slaney is the main river flowing into Wexford Harbour, see Figure (1). Two smaller rivers, the Sow and the Assaly, flow in at the north of the inner Harbour, near Castlebridge, and at the south of Wexford Town respectively. The Slaney Estuary is a long, narrow estuary, which extends for a distance of 26 km from Enniscorthy Town to Wexford Town. The estuary widens considerably at the confluence of the River Sow becoming relatively narrow again near Wexford Town; downstream of Wexford Town it spreads out into a broad, shallow estuary and harbour. Due to the shallowness of the harbour, dilution and transparency values are low (Neill, 1997). In the area below Wexford Town vertical mixing is high and it was, therefore, found that it would be best to release waste into this area (Carlow County Council et al., 1986). In contrast, intermixing of waters from the southern part of the harbour with the main channel is a relatively slow process. The mean tidal range in Wexford Harbour is 1.5m for spring tides and 0.9m for neap tides. Extensive areas of mudflats become exposed within the study area at low water particularly in the southern and outer harbour areas. In the main harbour area, stretching from Wexford Town to Raven Point, the plan area of the water at low water is *c.*78% of the high water plan area. These areas of mudflats increase the difficulty of modelling the hydrodynamic patterns within the harbour.

Many of the areas in Wexford Harbour and the Slaney Estuary are important for birds. The entire estuary and harbour is designated as a proposed National Heritage Area (NHA). The North Slob is also designated a National Nature Reserve (NNR), a Special Protection Area (SPA) and a Ramsar Convention Site (RAM). Twenty percent of the Slob is protected as the Wexford Wildfowl Reserve and is internationally important for wintering waterfowl. There are extensive salt marshes in Wexford Harbour and at the South Slob. Raven Point supports an important sand dune system, which acts as a vital roosting area for migratory waterfowl and is designated as a NNR, SPA and RAM. Wexford Harbour is designated as a proposed

SPA.

The harbour and the estuary are an important passage for salmon and other migratory fish. Wexford is also the main site for on-bottom mussel cultivation in Ireland, where the annual production is in the region of 5,400 tonnes.

Methodology

The development of a methodology for the prediction of chlorophyll_a production involved a structured interdisciplinary approach which incorporated three distinct stages: (a) data collection and analysis, (b) primary production modelling and (c) GIS development. Each of these stages is discussed below.

(a) Data Collection and Analysis

Water samples were collected at a number of locations throughout the study area. The sampling stations were based on pre-existing Irish EPA sampling sites to allow comparison with previously recorded data. Sampling was undertaken over a tidal cycle, at high and low tide, on all sampling dates and sampling locations were fixed using GPS. Table (1) lists the sampling dates and the number of samples collected on each date while Figure (2) shows the locations of the sampling stations used for the study. Samples were collected throughout a full year to take account of seasonal variation. A more detailed survey was undertaken over a lunar cycle for Wexford Harbour during the autumn of 1998. Wexford Harbour is predominantly shallow and unstratified, thus, surface samples were adequate for most stations. Additional samples were taken where significant salinity and temperature changes with depth were found.

Samples were collected in 2 litre plastic bottles, which were acid-washed and pre-rinsed in seawater at each site. The following additional information was also recorded: date, hour, exact location, weather conditions, temperature (water and air), water depth, depth of water sample and level of tide, transparency (secchi disc), dissolved oxygen concentration and salinity (using a salinity meter). Samples were kept in darkness at a low temperature (ca. 4 ^{o}C) following collection in order to minimize biological activity. Samples were analysed within 24 hours of collection to ascertain levels of: total nitrogen, total ammoniacal nitrogen, total oxidised nitrogen, total phosphorous, orthophosphate, chlorophyll_a, BOD and suspended solids. All laboratory water analyses were conducted by the Aquatic Services Unit, University College Cork, Ireland. The salinity meter used when sampling was calibrated against 10 psu and 35 psu standard seawater from IOS in Godalming in Surrey. The methods used during water analysis are documented in Costello et al. (2001).

An extensive study of available information on freshwater, industrial and domestic discharges into the Harbour was carried out to ascertain nutrient input levels. The inputs were derived from previous studies undertaken by the local authorities, licensed companies, and the EPA. Discharges upstream of the estuarine area were considered to have been accounted for by measurements of nutrients in freshwater and where actual monitoring data was not available for sewage discharges, the OSPARCOM method was used to estimate water flow and waste loads from population data provided by Wexford County Council.

(b) Chlorophyll_a Production Modelling

The water quality model used in this study was the Depth Integrated Velocity and Solute Transport model, DIVAST. The primary production module included in the model is based on the USA EPA formulations included in the QUAL2E model (Brown and Barnwell, 1987). Readers are referred to Brown and Barnwell (1987) for further details. This model incorporates the following nine water quality parameters and their interactions: salinity, BOD, organic, ammoniacal and nitrate nitrogen, dissolved oxygen, chlorophyll_a, organic phosphorous and orthophosphate. Since the formulations incorporate the full phytoplankton-phosphorous-nitrogen-dissolved oxygen cycles and interactions, this is one of the most comprehensive modelling studies undertaken in Irish coastal waters; previous studies have utilised mainly simplified nitrogen models and nitrogen-phytoplankton interactions (Dowley and Qiang, 1991, Petit & Co., 1992).

DIVAST is a comprehensive and versatile model which is applicable to shallow, well-mixed coastal and estuarine water bodies. The model was originally developed by Professor R.A. Falconer at the University of Bradford, UK. It is a 2-D, finite difference model which can be used to simulate time-scales of minutes as well as days and months. As stated previously, existing data indicated that most of Wexford Harbour is well-mixed and does not exhibit large-scale vertical stratification, thus, it was considered suitable to model the area using a 2-D, depth-integrated approach.

DIVAST comprises two linked components: a hydrodynamic module and a water quality and solute transport module. The hydrodynamic module computes water currents and elevations throughout the study area at time intervals of about one minute. It is based on the solution of the depth integrated Navier-Stokes equations and includes the effects of local and advective accelerations, the rotation of the earth, barotropic and free surface pressure gradients, wind action, bed resistance and a simple mixing length turbulence model. For the water quality and solute transport module, the general depth integrated advection-diffusion equations are solved, which include local and advective effects, turbulent dispersion and diffusion, wind effects, source and sink inputs and decay and kinetic transformation processes. Thus, the growth, decay and transport of chlorophyll_a, nutrients and dissolved oxygen are computed based on the hydrodynamics and the interactions between the various water quality parameters.

The Wexford Harbour Model extended from Edermine Bridge on the River Slaney to Rosslare Harbour. This comprised a total of approximately 413,100 grid points covering a plan area of 16.6 × 22.4 km at a 30m grid spacing. The preparation of the bathymetric data is dealt with in the following section. At the open sea boundaries of the model, detailed information on the prevailing tidal regimes was specified. Seasonal flow data for all major freshwater sources discharging to the estuaries was also input to the hydrodynamic model. All of the required hydrodynamic data concerning bathymetry, tidal data, and freshwater flows were integrated in the GIS system and transferred into the hydrodynamic model via a specially constructed interface. Similarly, all industrial and domestic discharges in to the primary production model were specified through the GIS interface.

(c) GIS Development

A GIS system was developed to support the preparation, analysis and display of a disparate range of datasets developed during the course of this research. The system was developed using the ArcView system and is compatible with the GIS strategy of the Irish EPA. The system uses the basic functionality of ArcView and the additional module ‘Spatial Analyst’ to perform grid or raster cell manipulations. In addition an ArcView extension module ‘MODESTIS’ was developed to link the GIS system with the DIVAST hydrodynamic and primary production modelling system. This development allows a user to customise the transfer of data and operational parameters into the DIVAST system and view model results. GIS was employed to provide the following functions during the project.

Preparation of Bathymetric Data - Airborne remote sensing and field surveyed bathymetry data using GPS were used to update the Admiralty charts particularly in areas of shifting sandbanks in Wexford Harbour and to provide an estimate of depths in the River Slaney up to Edermine Bridge. From these data a bathymetric model was developed via interpolation of the data to the 30 m resolution as required by the primary production model.

Location of Field Survey Data - Locations of field survey data were imported into the GIS and the positional information converted from the WGS positional system into the Irish National Grid.

Runoff Modelling - The input of freshwater to the harbour was estimated on a monthly basis. Runoff for much of the catchment area was available from the Irish Office of Public Works records. Runoff for additional sub-catchments was derived from an area-weighted estimate based on those adjacent catchments where runoff was known using GIS.

Link to DIVAST - A GIS interface was developed to provide an operator controlled linkage to the DIVAST system. This supports the modification and transfer of datasets and model system parameters to DIVAST and presentation of datasets from DIVAST. Nutrient modelling simulations can be performed under conditions specified by the user. Model results stored within the GIS can be visualised in relation to other datasets held within the GIS. MODESTIS provides a user-friendly modelling system with the potential for adoption in other studies.

An overview of the methodology discussed above showing the links between the various aspects of the research: data collection, modelling, and GIS user interface, is presented in Figure (3).

Results

The chlorophyll_a production model requires initial water quality parameters to be specified for each grid cell to begin its computations. However, water quality data were only available for selected sampling stations corresponding to only a few grid points of the model. As many variables are strongly correlated with salinity, the relationship between nutrient concentrations and salinity was used to extrapolate from field measurements to the entire estuary in order to start the model. Significant relationships were found for all variables with salinity, except chlorophyll_a; in the case of chlorophyll_a the average of the recorded values was used as an initial value in the model. Initial salinity values for each grid point in the estuary were predicted using the solute transport model which takes into account marine salinity, freshwater discharges and mixing processes. These spatially distributed salinity values and the derived relationships were then used to specify initial water quality parameters to the model.

Having established the baseline conditions of water quality through a field measurement program, it was necessary to collate the available information on freshwater, industrial and domestic discharges into the Harbour. Typical nutrient loadings for wastewater treatment works and major companies in Wexford Harbour are shown in Table (2).

Model Validation

Before the model was used to simulate the nutrient dynamics and phytoplankton production within Wexford Harbour, various components of the model were validated against oceanographic data. The hydrodyanamic component of the model described above was first validated against measurements of water elevations and currents. Water elevations were recorded at Edermine Bridge and the Wexford Boat Club, and current speeds and directions recorded in the main harbour as shown in Figure (1). Figure (4) presents a comparison between predicted and measured water elevations while Figure (5) presents a comparison between predicted and measured currents speeds and directions. These figures show that there is good correlation between the data and the model predictions for both the water elevations and the current velocities respectively.

The solute transport component of the water quality model was validated against measurements of salinity throughout the harbour. For the validation simulation, the initial concentration of salinity within the study area was specified as zero, saline water was allowed into the model domain across the seaward boundary at a concentration of 35 ppt and mean freshwater inflows were included with a salinity concentration of 0ppt. The model was run for the month of July with a run-time of two spring-neap tidal cycles (28 days) in order to ensure steady-state conditions were reached. The model results were compared to EPA measured data recorded in July 1998 (Neill, 1999). These measurements were taken on two separate dates and at two stages of the tide, high and low water, thereby representing a maximum and minimum concentration respectively at each of the sampling stations. Figure (1) shows the locations (A-E) at which measurements of salinity existed while Figure (6) presents a comparison of model predicted and measured salinities at these locations. By inspection it is seen that again good correlation is observed between the data and predictions.

The validation of the model using salinity as a tracer is very important in this research as it demonstrates that the transport and diffusion mechanisms of the model are functioning correctly. In this situation the validation exercise is particularly useful as the data points had a reasonably good spatial distribution throughout the harbour and the measured salinity varied from sea water concentration to brackish water concentration; the model accurately predicted the spatially varied salinity concentrations giving good confidence in the predictive capabilities of the solute transport model.

Salinity modelling is important not only with regards to validating the solute transport model but also directly in assessing the trophic status of a waterbody. In a recent EPA report (2001), trophic assessment criteria are explicitly related to salinity levels. For example, it is stated that in intermediate salinity waters (17 psu median) the average chlorophyll_a concentration should not be greater than 15 mg/m^3, while in fully saline waters (35 psu median) the average chlorophyll_a concentration should not be greater than 10 mg/m^3. Therefore, it is extremely important that models developed can accurately predict salinity.

For each of the Wexford Harbour model simulations results were output as a function of time at 10 predefined locations. The model also produced images of the study area at certain instances of time showing the spatial variation of a specific parameter within the study area at that particular time (henceforth referred to as snapshots). A description of model simulations using the validated model are outlined below and selected results presented.

Hydrodynamics Results

The hydrodynamic model was run for a fourteen day spring-neap cycle. Mean freshwater flows and zero wind conditions were assumed. The velocities at each grid point of the model were output at two stages of the final tidal cycle of the simulation corresponding to the times at which mid-ebb tide and low water occurred. The results are presented in Figures (7a) and (7b) respectively. As current velocities always reach their maximum values close to the times of mid-flood and mid-ebb tides, it can be seen from Figure (7a) that the greatest current speeds are reached within the mouth of the Slaney estuary as it nears Wexford Town and within the main channel near Raven Point. The maximum current velocities within this area, near Raven Point, are in the region of 1.3 m/s, which is quite fast compared to the average current velocity in the harbour of approximately 0.1 m/s.

Figure (8) shows the current velocities calculated by the model for Point C (see Figure (1)) halfway between spring and neap tides. When these velocities were examined an important feature of the tidal conditions within Wexford Harbour was noted. It was observed that the ebb tide duration exceeds that of the flood tide by approximately 45-60 minutes, as shown in the diagram. This compares with the An Foras Forbatha report (An Foras Forbatha WR/C51, 1980) where it is stated that the ebb tide duration in the harbour exceeded that of the flood tide by more than 30 minutes each tide. This longer ebb tide possibly allows a greater amount of nutrients to be carried out of the harbour towards open sea, thereby increasing the waste assimilation capacity within the harbour.

Chlorophyll_a Results

During the development of the phytoplankton production model, numerous simulations were executed to tune the model so that it would more accurately predict phytoplankton production within the study area. A key factor in the growth of phytoplankton is light availability. Attenuation of light occurs due to absorption and scatter by water and particles suspended in the water column. Indeed, phytoplankton itself also contributes to light attenuation within the water column. Due to high levels of suspended solids, estuaries typically have relatively low light availability compared to open seas; therefore, particular attention was given to the simulation of light attenuation within the model and its effects on chlorophyll_a production. Ensuing sensitivity tests led to the discovery that light limitation had a highly significant effect on phytoplankton production within the harbour. This agrees with literature, Brennan et al. (1998) states that generally during eutrophication, light rather than nutrients tends to become limiting, while McMahon et al. (1992) found that light was the limiting factor for phytoplankton productivity in the Shannon Estuary.

The relationship between chlorophyll_a production and light is given by:

$$\frac{\partial C_P}{\partial t} = \hat{G}.G_{RTS}.G_N.G_L.C_P \tag{1}$$

where, C_P = concentration of chlorophyll_a

$\hat{G}$ = maximum growth rate for phytoplankton under optimal conditions

G_{RTS} = temperature correction factor

G_N = nutrient limitation factor

G_L = light limitation factor

The light limitation factor, G_L, is given by:

$$G_L = \left[\log\left(\frac{I_H + I_O}{I_H + I_O^{-K_A H}}\right)\right]\frac{f}{K_A H} \tag{2}$$

where, I_H = light level at which phytoplankton growth is half the maximum rate

I_O = surface light intensity

f = photoperiod (sunlight fraction of day)

K_A = light attenuation coefficient

H = depth of water

The original DIVAST model employed a value for light attenuation obtained from literature (Brown and Barnwell, 1987):

$$K_A = 0.09 + 0.0088(C_P) + 0.054(C_P)^{2/3} \tag{3}$$

Using the expression for K_A from (3), initial model simulations were over-predicting chlorophyll_a levels within Wexford Harbour by a considerable amount. Light attenuation within a water column may vary quite significantly from estuary to estuary based on turbidity and chlorophyll_a levels. Therefore, in order to improve the simulation of light attenuation within the water column a new light attenuation relationship was developed for Wexford Harbour. Following detailed analysis of recorded chlorophyll_a concentrations and secchi disk readings the following relationship between light attenuation and chlorophyll_a was derived and included in the model:

$$K_A = 1.9976 + 0.0143(C_P) \tag{4}$$

This modified version of DIVAST is referred to as the revised DIVAST model below.

Model simulations were carried out using the original and revised models to compare predictive capabilities. The models were run for the month of July and results were compared to EPA measured data recorded in July 1998 (Neill, 1999). The measurements were taken on two separate dates and at two stages of the tide, high and low water, thereby representing a maximum and minimum concentration respectively at each of the sampling stations. Chlorophyll_a predictions using the original and revised models are compared against each other and the EPA data, at Point F in the harbour, see Figure (9). It can be seen from this comparison that the revised model is substantially more accurate than the original model and was, therefore, used for subsequent simulations. The revised model was then run for a full spring-neap tidal cycle to simulate phytoplankton growth during the month of July. The results obtained from the water quality simulation are presented below.

Figures (10a) and (10b) show contour plots of the chlorophyll_a concentrations within the study area as calculated by the model at high water and low water, respectively, on a spring tide. Upon investigation of Figures (10a) and (10b), it can be seen that the highest levels of chlorophyll_a calculated by the model, up to 100 mg/m^3, are located in the southeast of the harbour. These results agree with the findings of the surveys carried out by the EPA in 1998 which found that samples with maximum concentrations in the region of 100 – 120 mg/m^3 were recorded in the region of the South Slob (Neill, 1999). A chlorophyll_a value of 30 mg/m^3 is taken to indicate significantly enhanced phytoplankton growth while concentrations in excess of 100 mg/m^3 are very high (Neill, 1999).

Summary and Conclusions

A methodology has been developed to perform accurate and efficient assessment of the primary production of brackish waters and has been applied to Wexford Harbour, an important Irish estuary located on the southeast coast of Ireland. The approach involves using high-resolution computer based models to compute water circulations patterns and chlorophyll_a concentrations in conjunction with data collection and GIS. Data for the development of the model were obtained from extensive literature reviews and field measurements. These data included bathymetry, freshwater inflows, waste discharges, baseline water quality data and light attenuation coefficients. The Wexford Harbour hydrodynamic model was validated against measured water elevations and current speeds and directions ensuring a high degree of confidence in the model predictions. The solute transport component of the model was validated by predicting salinity fluxes throughout the harbour and comparing the results to measured data; good agreement was observed.

The effects of light attenuation on chlorophyll_a production were considered. Using model default values obtained from literature it was observed that the model over-predicted chlorophyll_a production. From the field data, a relationship between light attenuation, turbidity, and chlorophyll_a concentrations was developed. When this relationship was incorporated into the model it was observed that model predictions greatly improved. A simulation of chlorophyll_a production throughout the harbour was then carried out and presented. The results obtained agreed well with known behaviour of the harbour based on EPA surveys, showing that highest production occurs in the southeast area of the harbour.

The model has been incorporated into a GIS entitled MODESTIS which allows non-expert users to carry out chlorophyll_a production simulations of the harbour. The user can choose the locations of discharge points, discharge characteristics, baseline water quality parameters, model kinetic constants, simulation time periods and specifications of results. The system includes an archived database of hydrodynamic results which ensures the model runs more efficiently than if it had to recompute these during each simulation. This system will shortly be installed on an EPA in-house PC and used by staff for water quality management.

Acknowledgements

The authors wish to thank the Irish Environmental Protection Agency for permission to publish this paper and supporting the research and development project entitled "Investigation of nutrient inputs, fluxes and productivity in selected brackish waters" on which this paper is based.

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Figure Captions

Figure (1): Plan view of Wexford Harbour study area.

Figure (2): Locations of sampling stations.

Figure (3): Flow chart showing main elements of research and the links between them.

Figure (4a): Comparison of predicted and measured water elevations at Edermine Bridge.

Figure (4b): Comparison of predicted and measured water elevations at Wexford Boat Club.

Figure (5a): Comparison of predicted and measured current velocities in Wexford Harbour.

Figure (5b): Comparison of predicted and measured current directions in Wexford Harbour

Figure (6): Comparison of predicted and measured maximum and minimum salinity concentrations at selected points in Wexford Harbour.

Figure (7a): Vector plot of current velocities in Wexford Harbour at mid-ebb, spring.

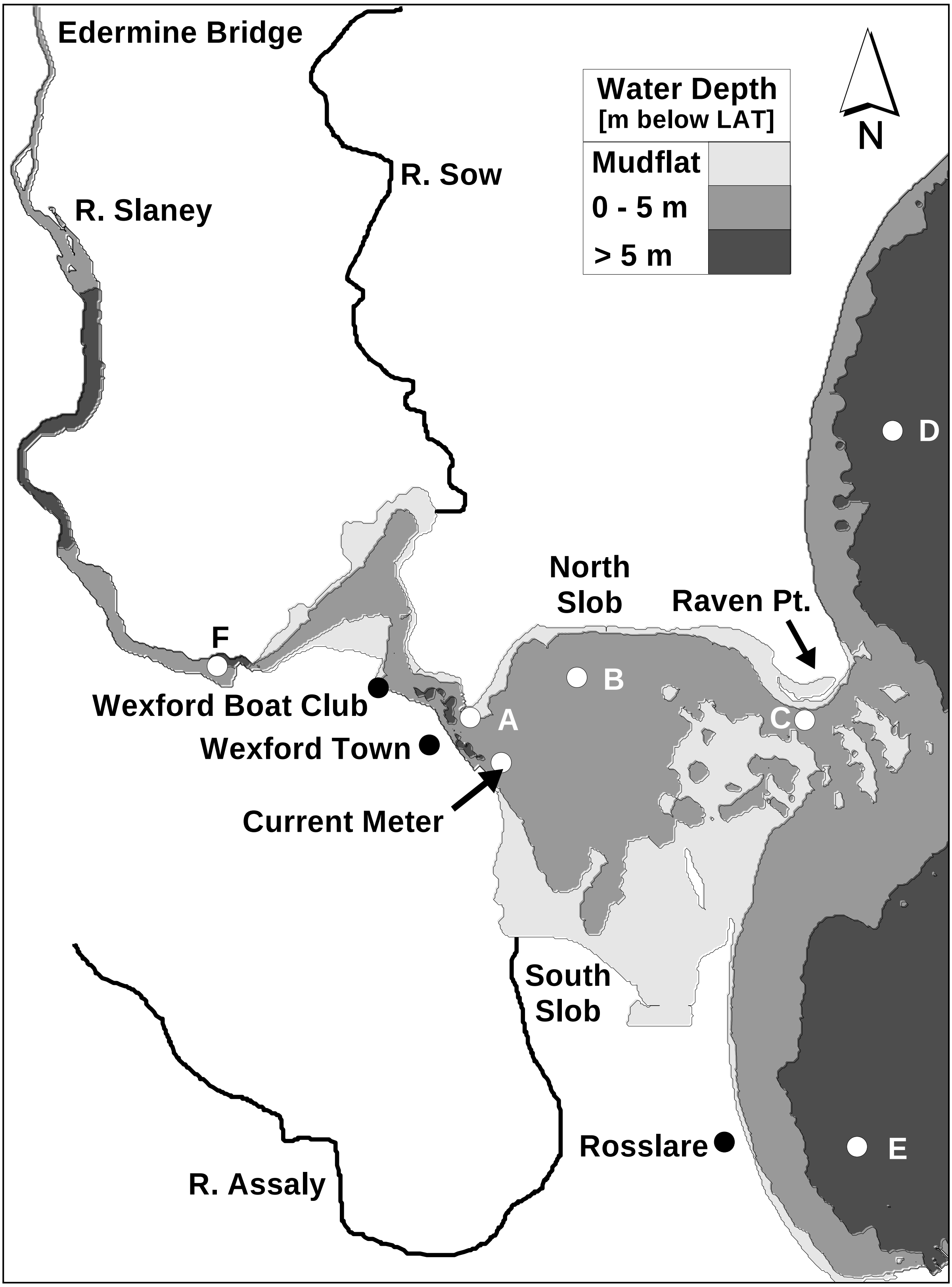
Figure (7b): Vector plot of current velocities in Wexford Harbour at low water, spring.

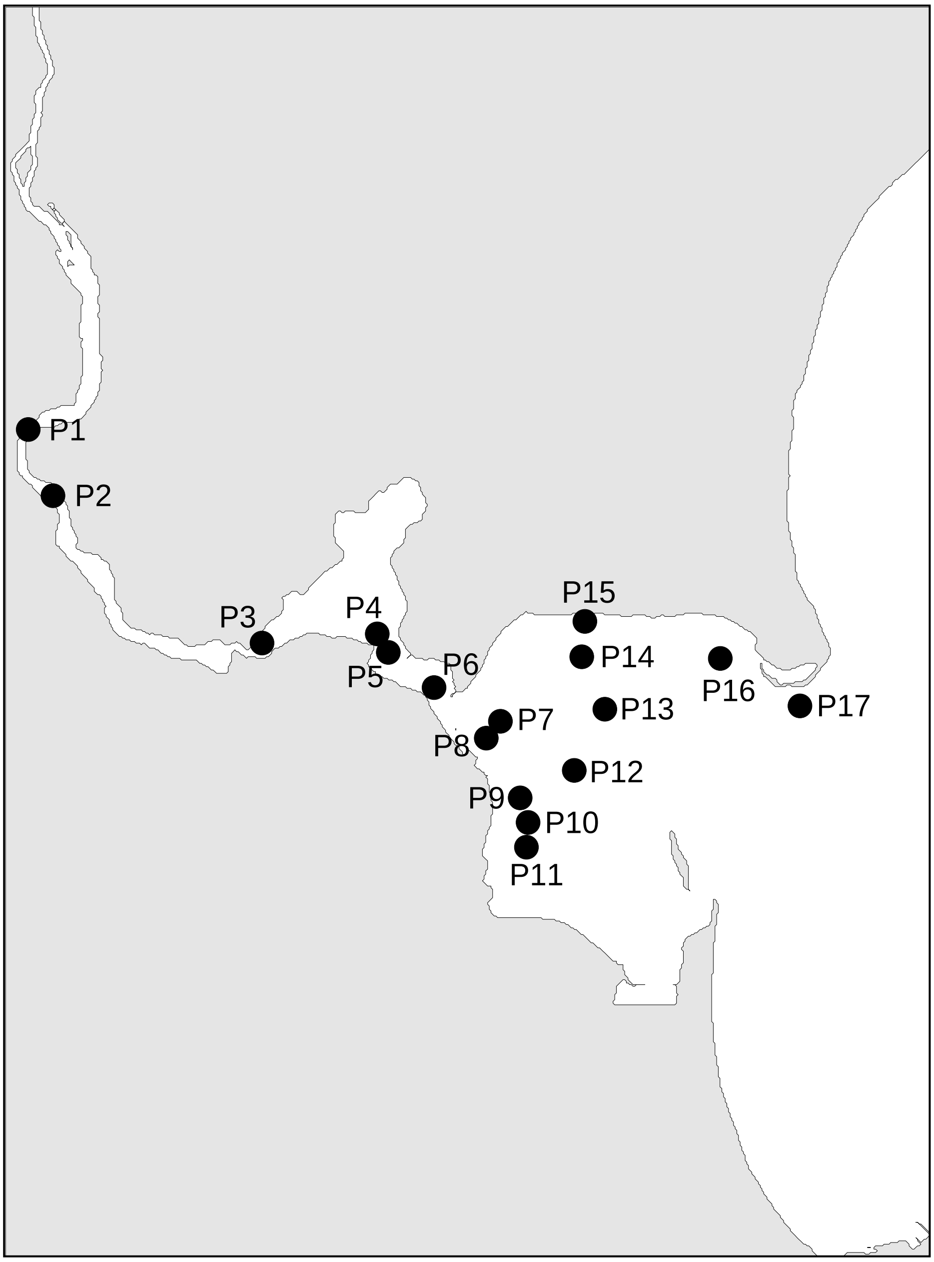
Figure (8): Model current velocities predicted at Point C over a single tidal cycle.

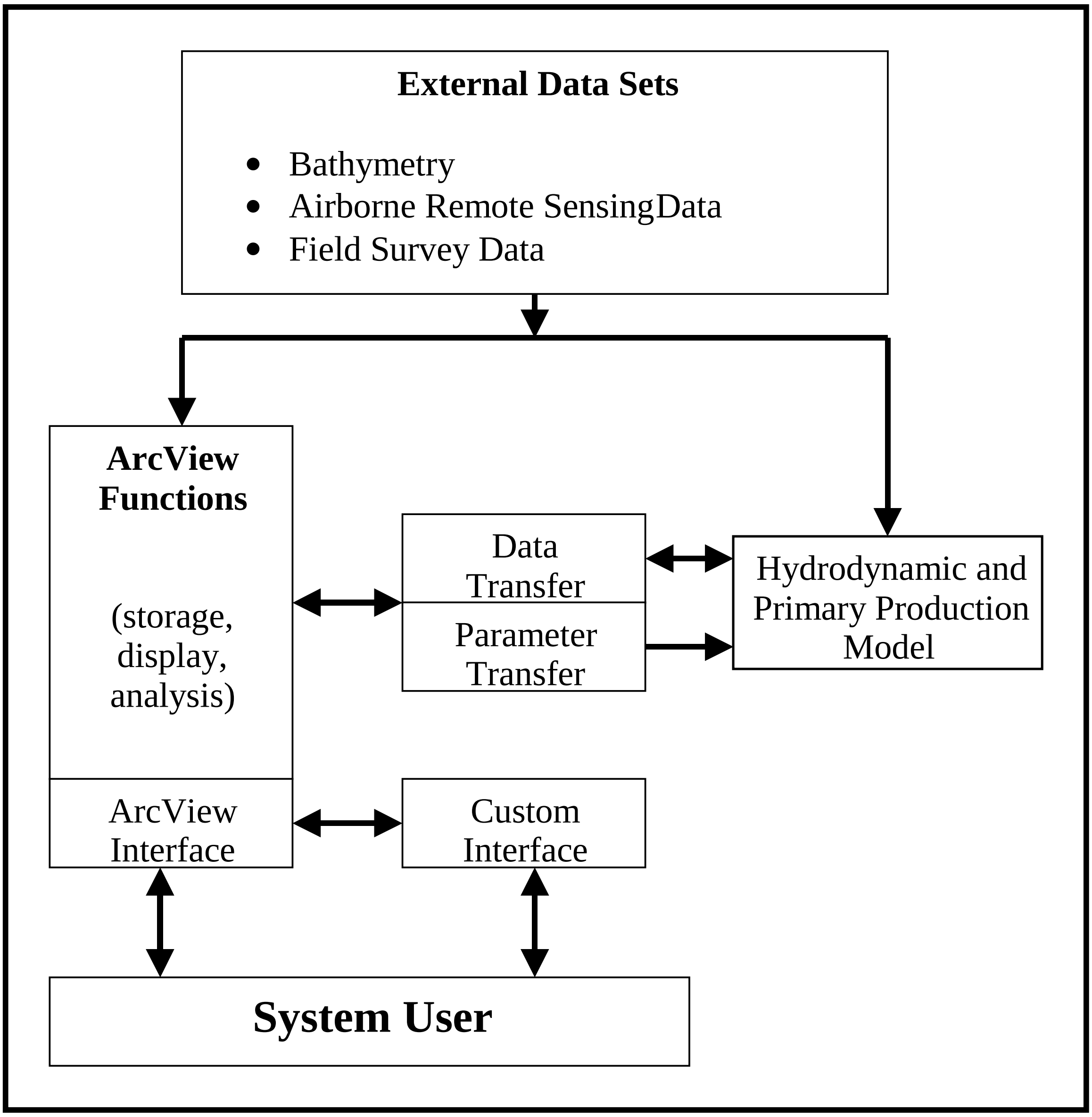
Figure (9):Comparison of original and revised model results at Point F.

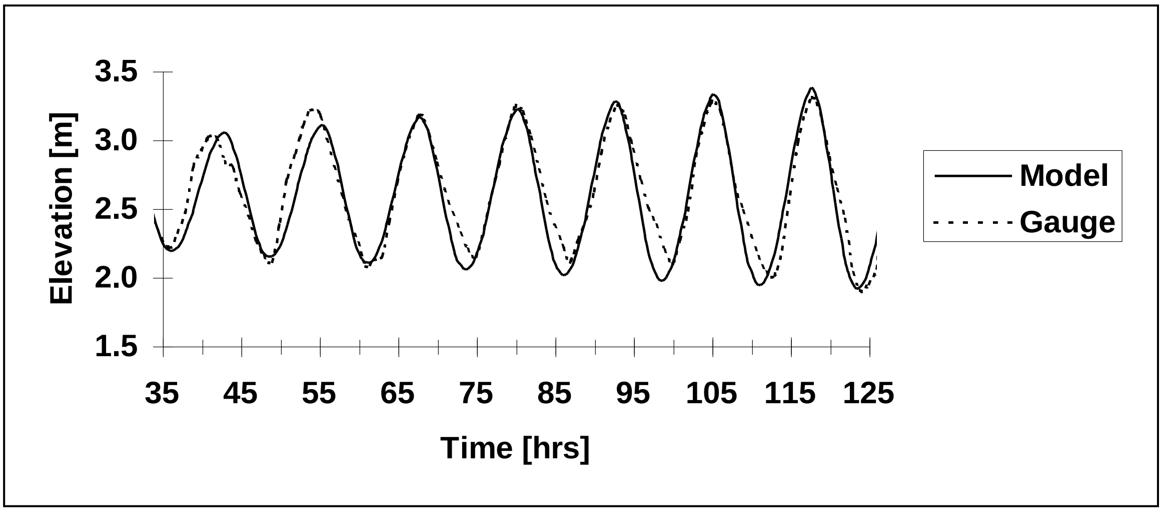
Figure (10a): Chlorophyll_a concentrations calculated by model at high water.

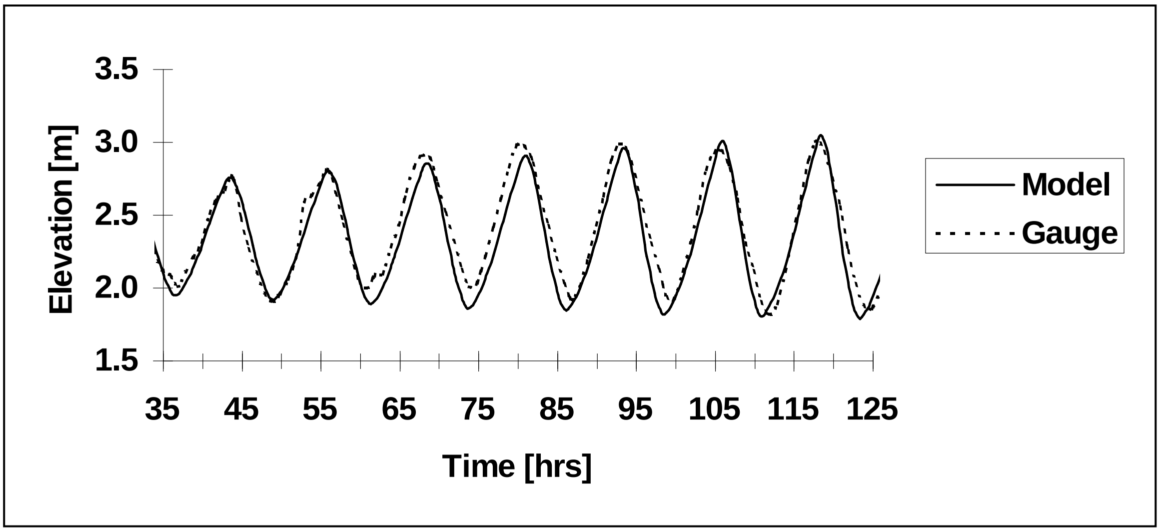
Figure (10b): Chlorophyll_a concentrations calculated by model at low water.

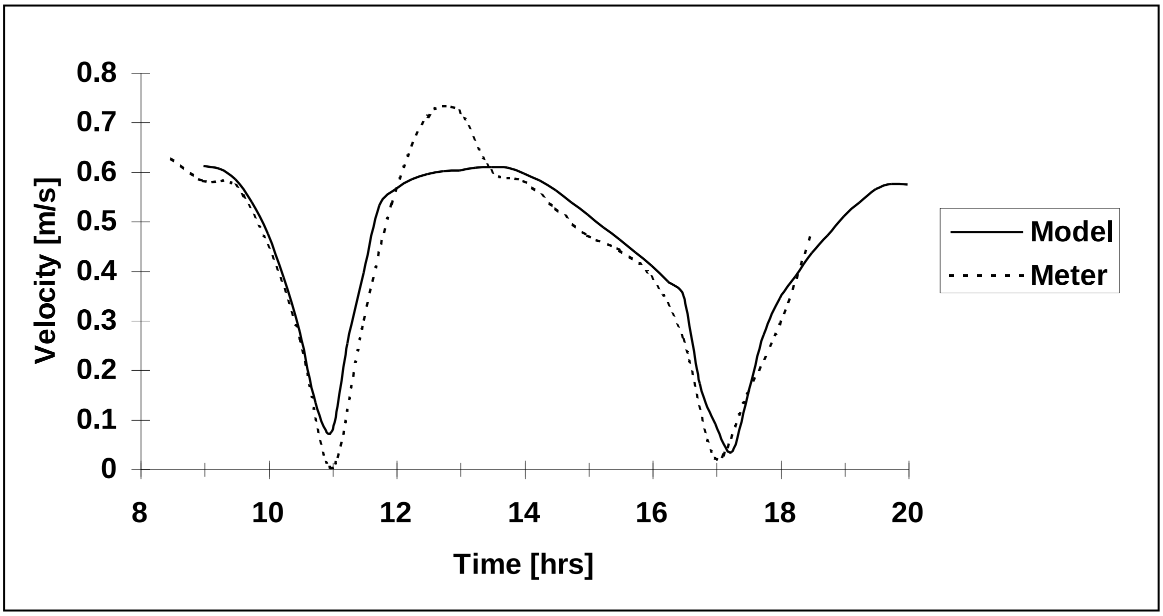

Edermine Bridge
R. Sow
R. Slaney
Water Depth
[m below LAT]
Mudflat
0 - 5 m
> 5 m
N
D
North
Slob
Raven Pt.
F
B
Wexford Boat Club
A
C
Wexford Town
Current Meter
South
Slob
Rosslare
E
R. Assaly

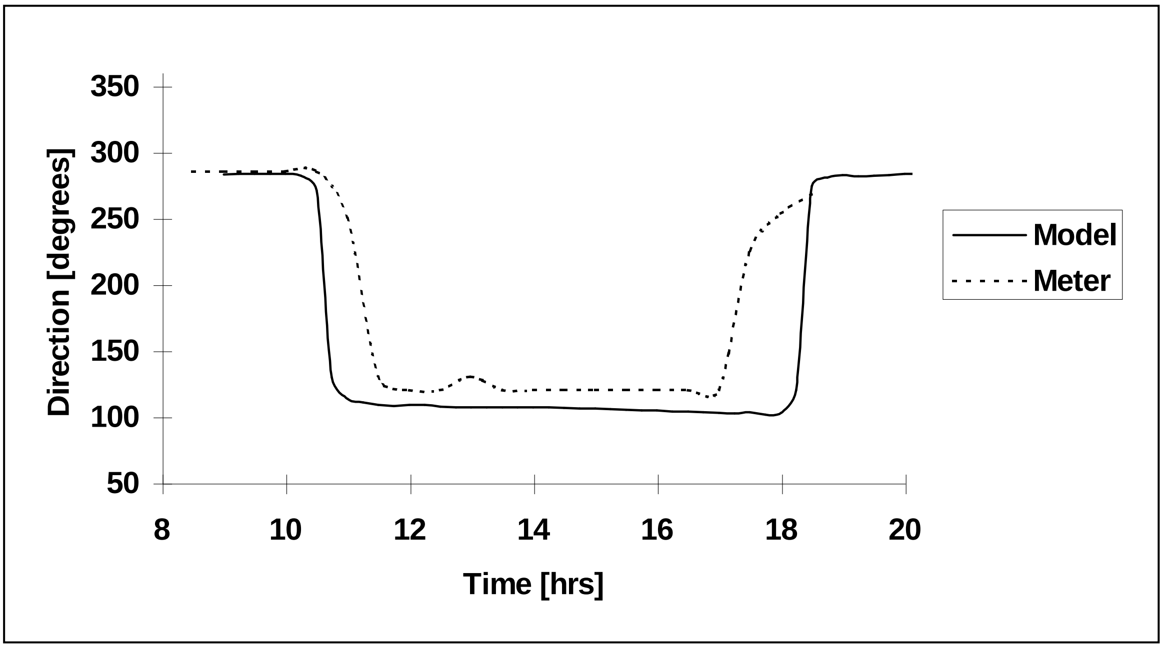

P1
P2
P3
P4
P5
P6
P7
P8
P9
P10
P11
P12
P13
P14
P15
P16
P17

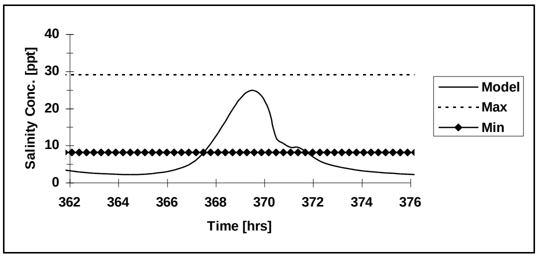

External Data Sets
Bathymetry
Airborne Remote SensingData
Field Survey Data
ArcView Functions
(storage, display, analysis)
Data Transfer
Parameter Transfer
Hydrodynamic and Primary Production Model
ArcView Interface
Custom Interface
System User


3.5
3.0
2.5
2.0
1.5
Elevation [m]
35
45
55
65
75
85
95
105
115
125
Time [hrs]
Model
Gauge

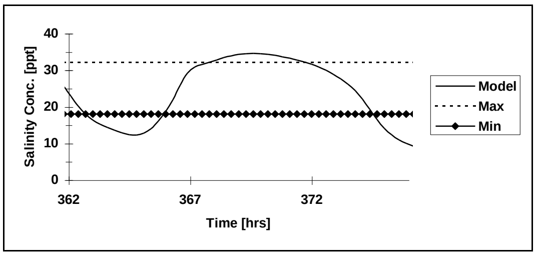

3.5
3.0
2.5
2.0
1.5
Elevation [m]
35
45
55
65
75
85
95
105
115
125
Time [hrs]
Model
Gauge


0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Velocity [m/s]
8
10
12
14
16
18
20
Time [hrs]
Model
Meter

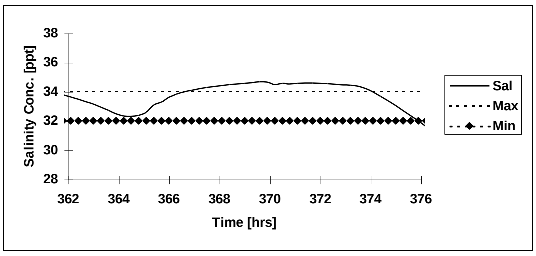

350
300
250
200
150
100
50
Direction [degrees]
8
10
12
14
16
18
20
Time [hrs]
Model
Meter



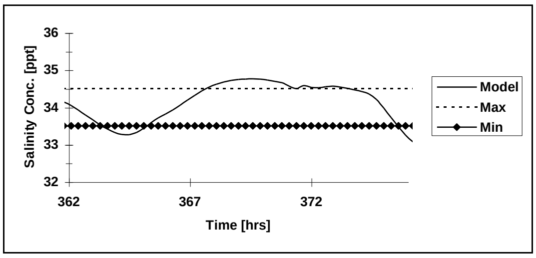
Point A



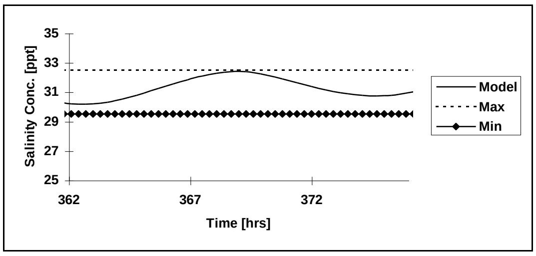
Point B



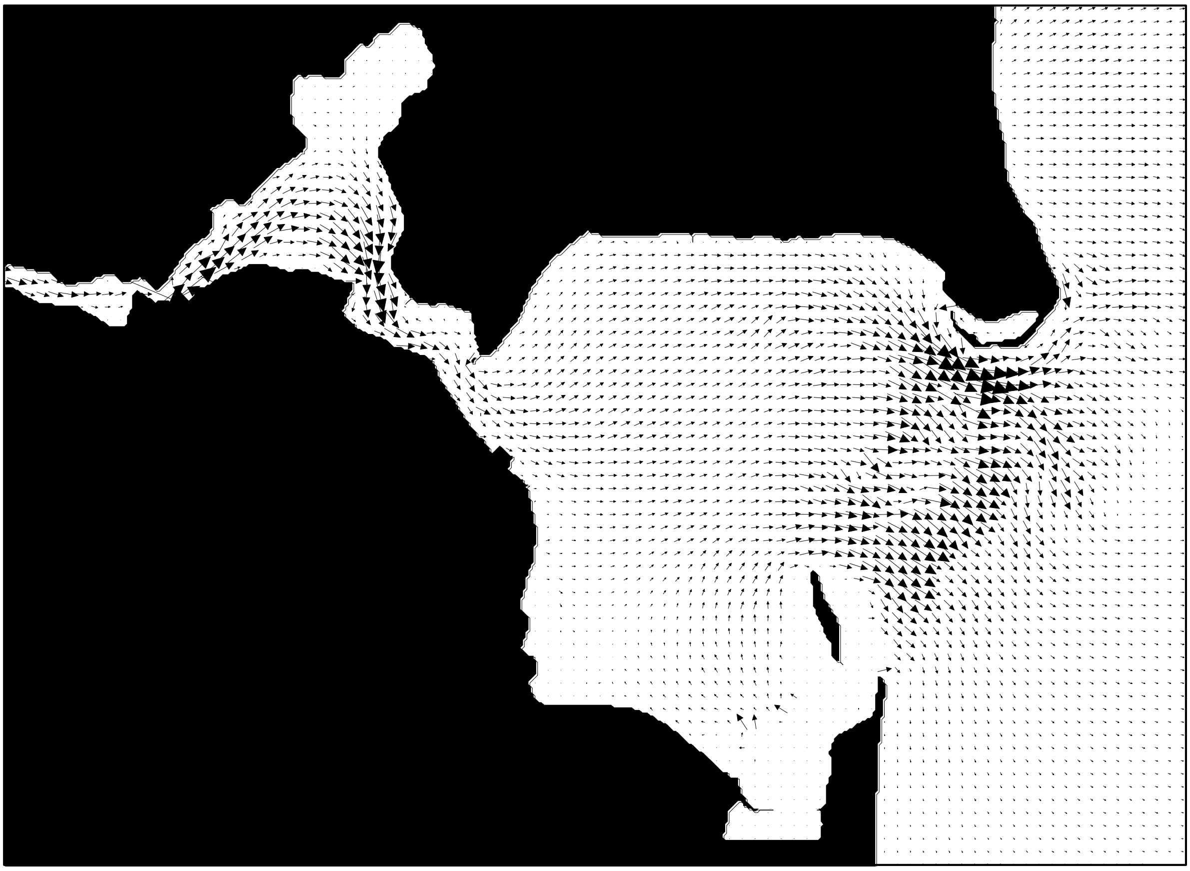
Point C

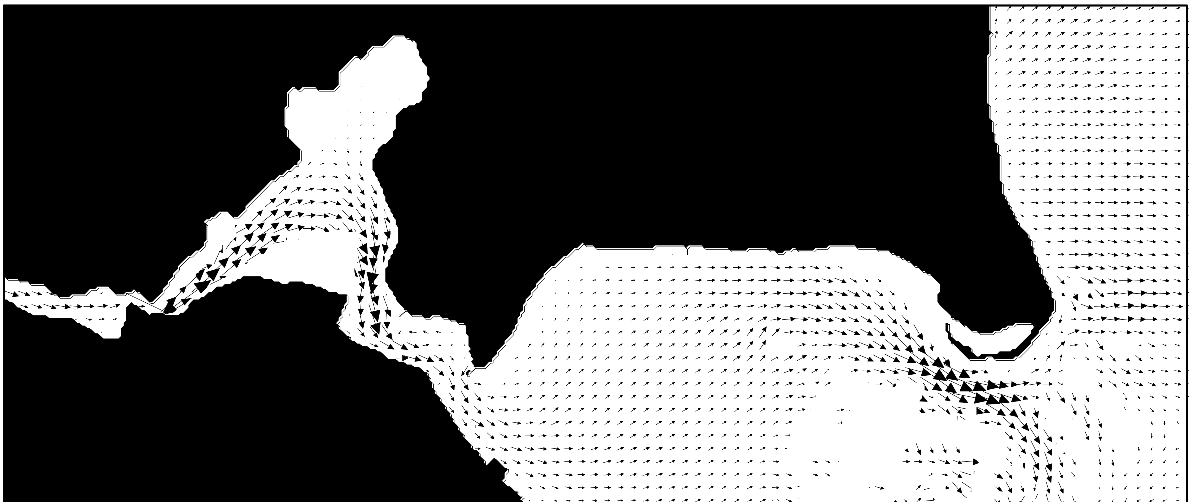


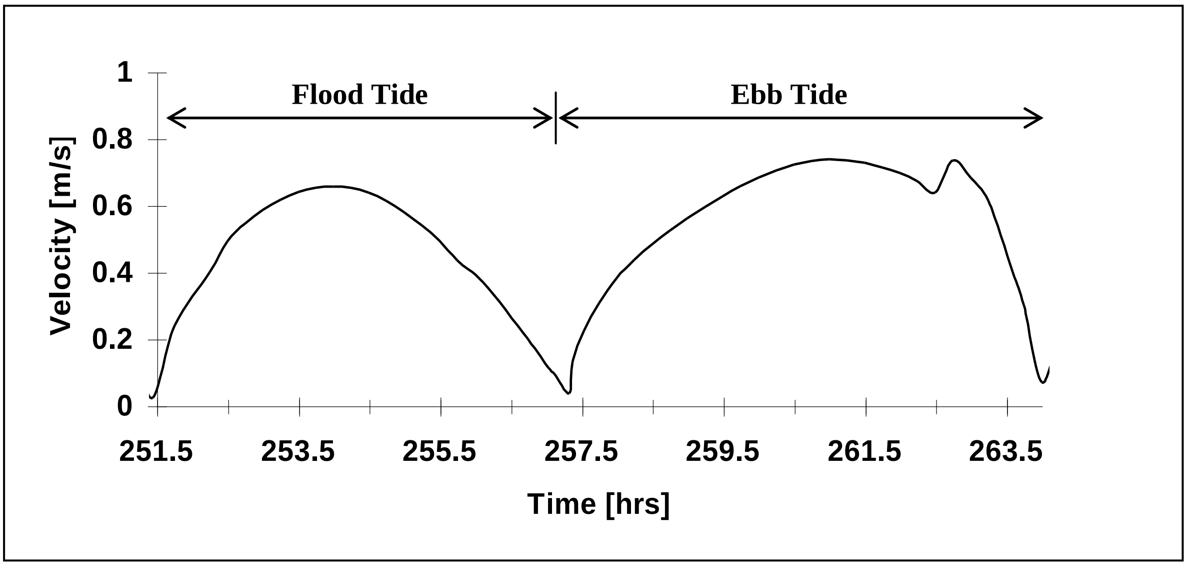
Point D

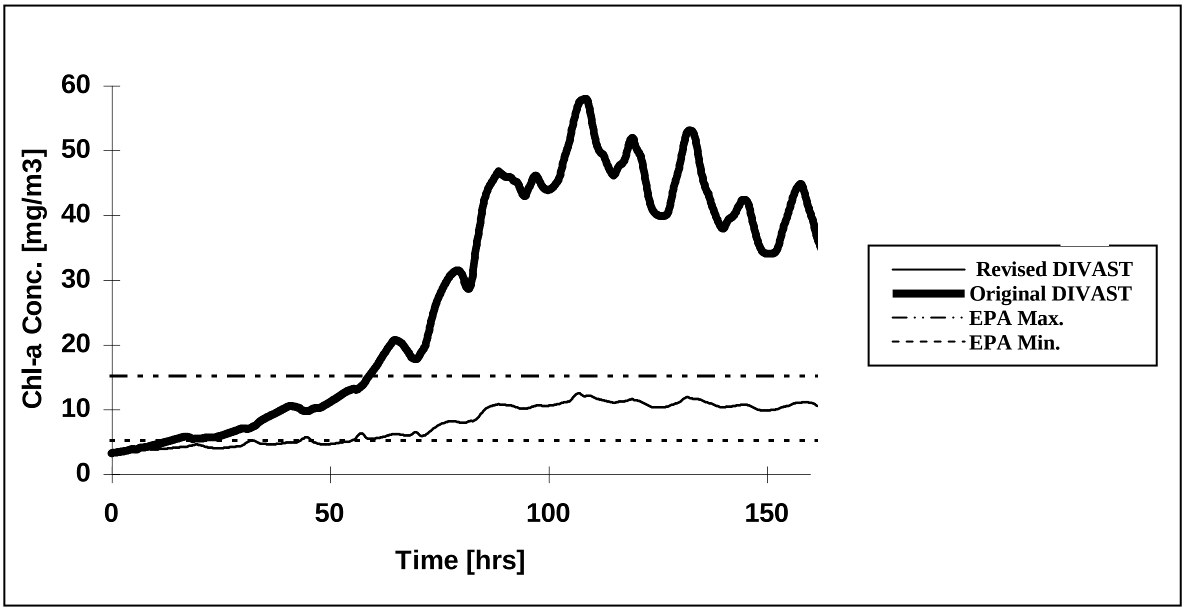


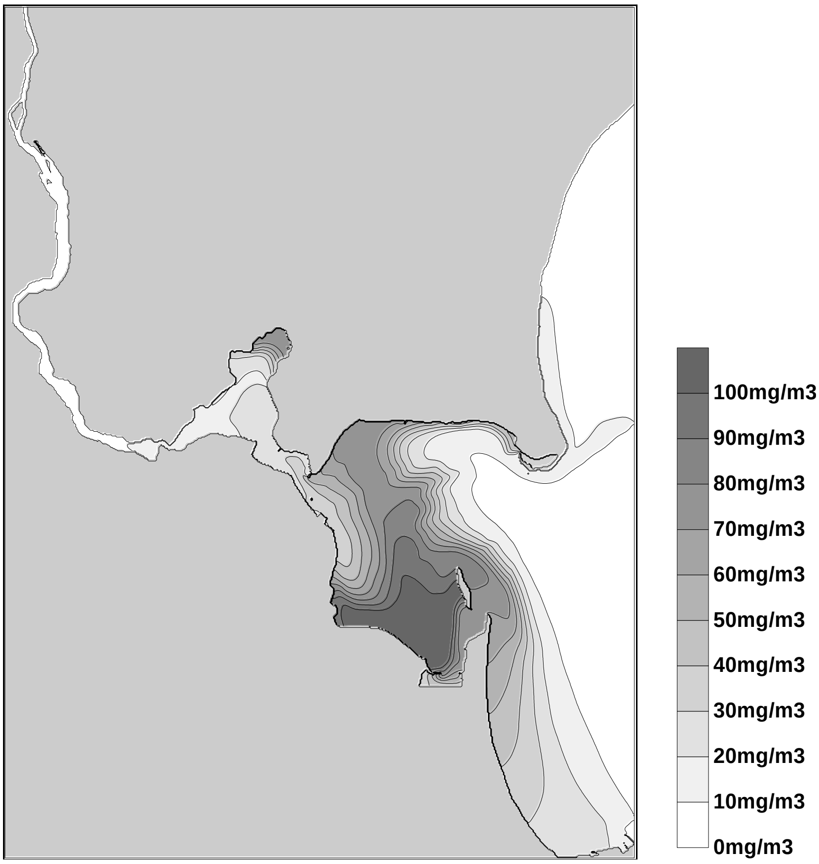
Point E

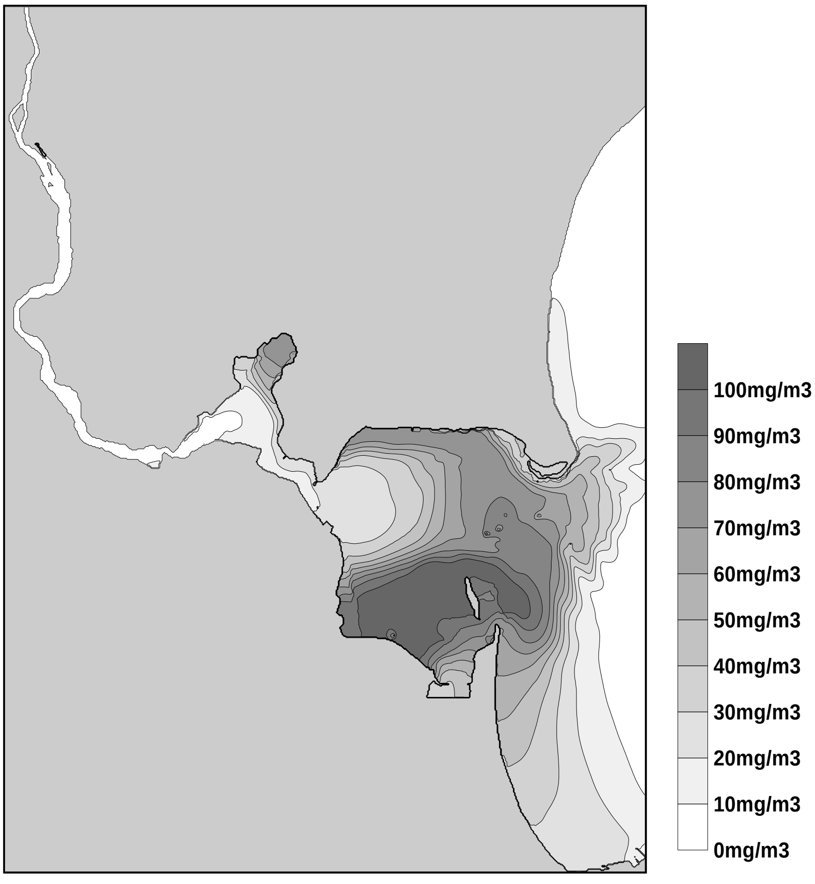





Flood Tide
Ebb Tide
Velocity [m/s]
1
0.8
0.6
0.4
0.2
0
251.5
253.5
255.5
257.5
259.5
261.5
263.5
Time [hrs]


Chl-a Conc. [mg/m3]
60
50
40
30
20
10
0
0
50
100
150
Time [hrs]
Revised DIVAST
Original DIVAST
EPA Max.
EPA Min.


100mg/m3
90mg/m3
80mg/m3
70mg/m3
60mg/m3
50mg/m3
40mg/m3
30mg/m3
20mg/m3
10mg/m3
0mg/m3


100mg/m3
90mg/m3
80mg/m3
70mg/m3
60mg/m3
50mg/m3
40mg/m3
30mg/m3
20mg/m3
10mg/m3
0mg/m3

Date	No. of Samples
18th June 1998	33
25th June 1998	26
1st September 1998	24
3rd September 1998	33
8th September 1998	28
10th September 1998	29
12th September 1998	19
4th February 1999	16
10th February 1999	32

Table (1): Sampling dates.

Outfall	**Flow [m^3/day]**	**BOD [kg/day]**	**Amn. N [kg/day]**	**Nitrate [kg/day]**	**Ortho-P [kg/day]**	**TN [kg/day]**	**TP [kg/day]**
Town Sewer	2770.7	969.8	-	-	-	138.5	41.56
Castlebridge	247.0	2.13	0.12	4.16	2.08	-	-
Wexford Creamery	955.2	850.13	2.18	17.19	7.55	-	-
Cow & Gate	564.0	0.00	0.33	4.03	2.34	-	-
Schoepp Velours	8256.0	1502.59	56.97	0.83	0.58	-	-
SOLA ADC	21.6	0.00	0.00	0.06	0.01	-	-

Table (2): Nutrient loadings at wastewater treatment works and major companies in Wexford Harbour.