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# Assessment of nutrients and macroalgae growth in Poole Harbour, UK

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*Abstract*— **A high-resolution depth-averaged hydrodynamic model was developed for Poole Harbour, UK, with the aim to test water quality scenarios for reducing nutrient levels. These scenarios were developed from a separate Combined Macroalgae and Phytoplankton (CPM) model, a simple linked box model that can be used to calculate nutrient concentrations and the biomass of phytoplankton and macroalgal communities. For the CPM model to function, exchange rates between the different parts of the water body are required. The flushing rates of Poole Harbour are calculated from the hydrodynamic model. Furthermore, as there is uncertainty in what leads to the spatial distribution of macroalgae growth, the hydrodynamic model was used to investigate any links between environmental conditions, nutrient concentrations and macroalgae growth.**

## I. INTRODUCTION

Poole Harbour is a water body, located on the south coast of the UK, whereby high nutrient concentrations have led to large growth of macroalgae along the shorelines and mud flats. Large macroalgae mats can have negative environmental impacts by reducing the total area of mudflats available to wading birds [1], in addition to reducing dissolved oxygen leading to anoxia in benthic communities within the sediments and lead to nitrogen loading within Poole Harbour waters [2]. Investigations into the feasibility of the removal of macroalgae as a mitigation measure to reduce nutrients and improve water quality is ongoing [3]. Nutrients are fed into the harbour via farm run offs into a number of rivers, notably the River Frome and River Piddle, in addition to a number of outfalls from sewage treatment works at Wareham, Lytchett and Holes Bay. Historically, very high levels of nutrients were found within the harbour. Within the last few decades water quality controls were implemented reducing nutrient inputs from point sources. However, the trend of the amount of nutrients from ground water diffuse sources is increasing as historic run off and land use is still slowly working through the surrounding water table. As such, the aim of the study was test a range of water quality scenarios to investigate how nutrient levels could be further reduced. Furthermore, there is a degree of uncertainty as to what leads to the spatial distribution of macroalgae growth within Poole Harbour. Therefore, the secondary aim was to identify possible links between environmental conditions, nutrient concentrations and macroalgae growth.

## II. HYDRODYNAMIC MODEL

### A. Model Domain

A high-resolution depth-averaged model of the Poole Harbour, UK, was built with an unstructured triangular mesh, using the hydrodynamic software Telemac-2D (v7p1). The model domain extends between 1.646°W – 2.239°W and 50.362°N – 50.737°N. The unstructured mesh was discretised with 76,448 nodes and 145,947 elements. Along the open boundary, the mesh has a resolution ranging between 200m to 5km, reducing to 100m along the coastline. Within Poole Harbour the resolution is further refined to 30m. Bathymetry of the outer domain was sourced from the Department for Environment, Food & Rural Affair's UKSeaMap 2010 [4]. The resolution of the bathymetry points from this dataset are 1 arc-second (~30m). Within Poole Harbour, bathymetry was provided by Environment Agency with a resolution of 20m. The hydrodynamics are forced along the open boundaries using 11 tidal constituents (M2, S2, N2, K2, K1, O1, P1, Q1, M4, MS4 and MN4) from the OSU TPXO European Shelf 1/30° regional model. After a spin up period of 5 days, the model was run for 30 days to cover a full spring-neap cycle. Four fresh water inputs are included within the model domain, representing the Rivers Piddle, Frome, Sherford and Corfe. The model uses a k-ε turbulence model with velocity diffusivity set to $1\times10^{-6}$ m$^2$/s, representing the kinematic viscosity of water. In the absence of accurate wide spread sediment data, the Nikuradse law for bottom friction was used, with a constant value of roughness length, $k_s$ =0.04, applied to the whole model domain.

### B. Validation

Validation data have been obtained from the British Oceanographic Data Centre (BODC) for surface elevation at the Bournemouth tide gauge, whose location is shown in Fig. 1. After a spin-up period, the model was run for 30 days from 19/05/2012 00:00 to 19/06/2012 00:00. Comparisons of the modelled free surface elevation and observed tidal elevations, at Bournemouth, is shown in Fig. 2.

To validate the free surface elevations, three statistical tests have been applied: the coefficient of determination, the root mean squared error (RMSE) and the scatter index. The scatter index is the RMSE normalised by the mean of the observations. It is widely used in the validation of wave models [5-7], meaning there is a wide source of literature for
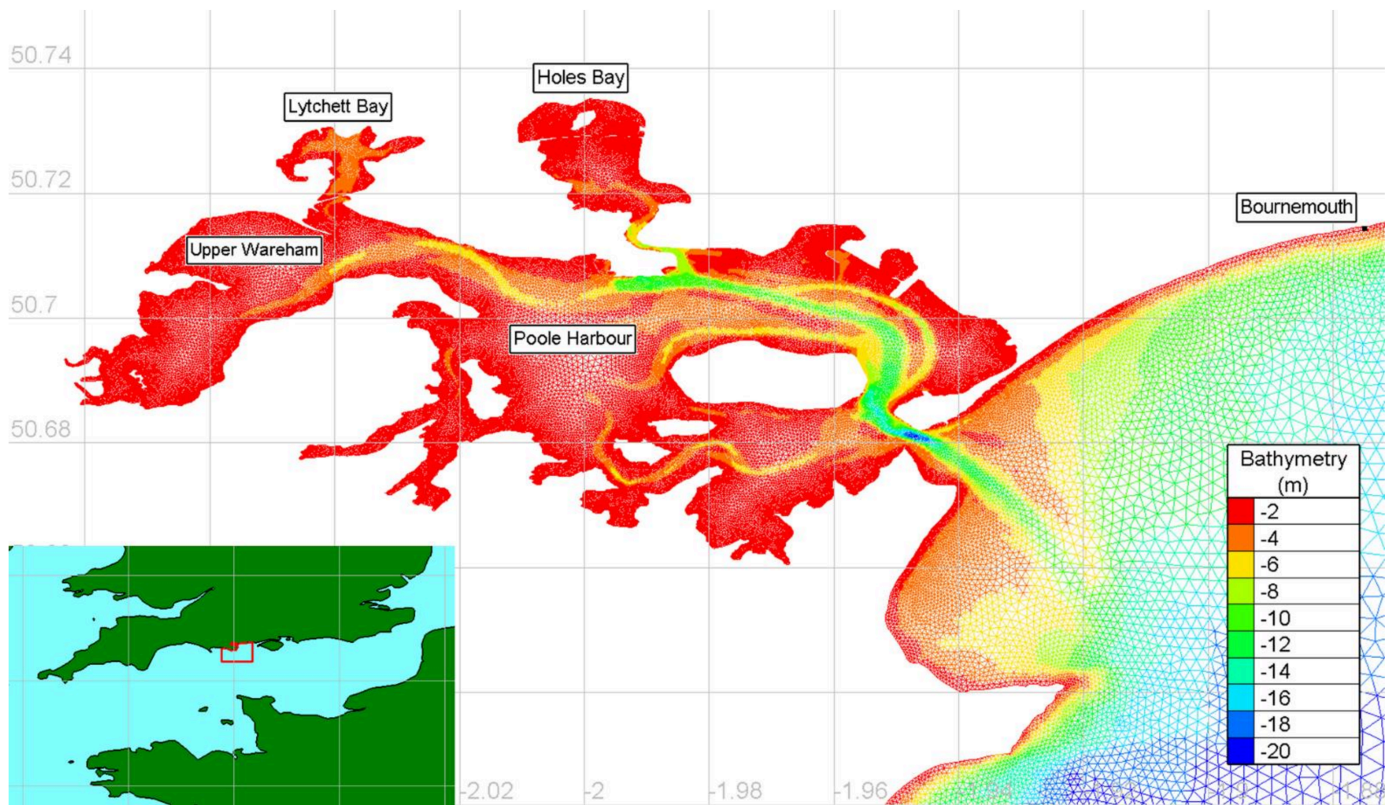
Figure 1. *Model computational domain with the location of tide gauge, used for validation.*
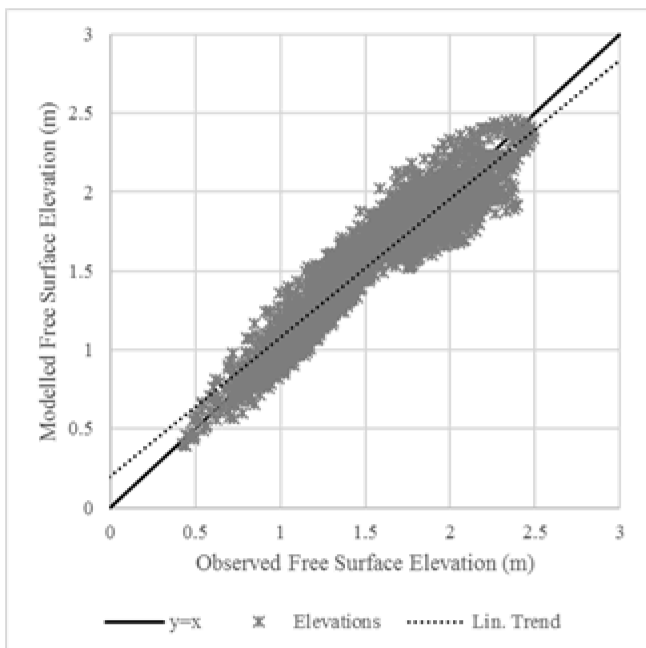


Figure 2. *Comparison of modelled free surface elevation and observations from BODC tide gauge. The black line represents a y=x relationship.*

comparable values. However, there is no comparison for validating tidal elevations. For this study, a scatter index of less than 10% will be considered a good validation. Tab. 1 summarises the validation statistics of the Bournemouth tide gauge. The presented validation represents the preliminary assessment of the model's performance whilst other sources of data are obtained to validate the model beyond a single tide gauge.

TABLE 1. VALIDATION STATISTICS OF THE BOURNEMOUTH TIDE GAUGE.

| Tide Gauge | R$^2$ | RMSE (m) | Scatter Index (%) |
|---|---|---|---|
| Bournemouth | 0.83 | 0.15 | 9.08 |

### C. Modelling nutrients

To investigate the spatial distribution of nutrients, specifically the total dissolved inorganic nitrogen (DIN), the nutrients have been introduced as a single passive tracer. There are two types of sources: riverine inputs and sewage treatment works (STW). The riverine inputs include the River Frome (6.54 m$^3$/s), Piddle (2.47 m$^3$/s), Sherford (0.57 m$^3$/s) and Corfe (0.51 m$^3$/s). There are three STWs: Wareham, Lytchett and Poole East. The location of the source inputs is shown in Fig. 3. As the Wareham STW flows into the River Piddle, the concentrations of both the river and the STW are combined as a single source. The coefficient for diffusion of tracers was set to 0.1.

Before the tracer initial conditions were applied to the model, the hydrodynamics were spun-up for a period of 5 days, after which the model was run with the tracer for 30 days to ensure a steady state was reached. This 30-day period
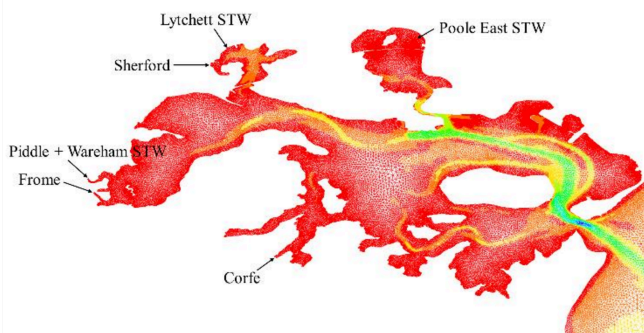
Figure 3. *Nutrient riverine sources and sewage treatment works.*

provided the starting point for a 30-day base case reference. Based on observations provided by the Environment Agency, the initial background concentration of DIN in Poole Harbour and the English Channel was 0.75 mg/l, with 0.94 mg/l applied to Holes Bay.

### III.    COMBINED PHYTOPLANKTON & MACROALGAE MODEL

#### A. Model Description

The Combined Phytoplankton and Macroalgae (CPM) model v2.0 is a simple linked box model that can be used to calculate nutrient concentrations and the biomass of phytoplankton and macroalgal communities as a function of nutrient inputs, light climate and physical characteristics of a given water body. The model is best viewed as a tool to aid interpretation of the data and as a means of exploring the factors affecting growth in a given water body – rather than as providing a single predictive 'answer'. In principle, the CPM model uses mechanistic, theory-based, descriptions of the physical and biological processes involved in the growth of seaweeds and planktonic micro-algae. For this paper, the CPM model has been used to assess and provide water quality scenarios for boundary conditions of further Telemac models. The CPM model is a separate model and does not couple with Telemac.

The model algorithms are programmed in the Matlab language but the package is not required for the model to be run by an end user. The CPM model is installed on a Windows PC as an executable file along with a free runtime library that allows the model to be run independently of Matlab. The original CPM model combined two earlier models developed for the Environment Agency (EA): one for phytoplankton, based on the CSTT model [8-11] and one for macro-algae [12,13]. A schematic summary of the main features of the model is shown in Fig. 4.

Several kinds of primary producers are found in estuaries. Micro-algae are found in the water column, as the phytoplankton, and in or on the sea-bed, as the microphytobenthos. Attached larger producers include seaweeds (macro-algae) and aquatic macrophytes (such as seagrasses and salt-marsh plants). The current CPM model simulates phytoplankton and macro-algae. In a given water body, the total biomass of these producers is assumed to be controlled by the least available, or limiting, resource. This
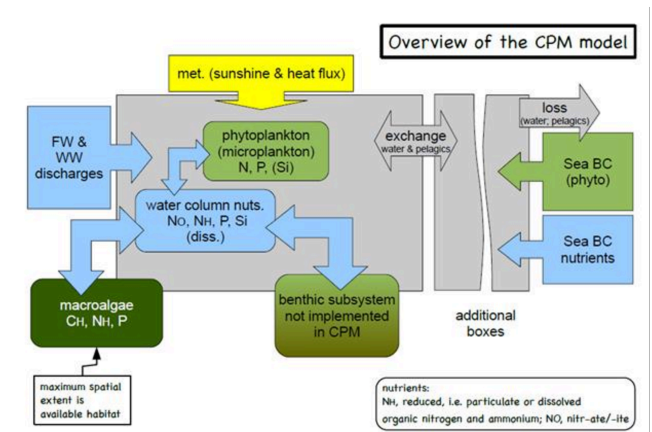


Figure 4. *Overview of the Combined Phytoplankton & Macroalgae (CPM) model.*

can be a nutrient (nitrogen or phosphorous), light or, for macroalgae, available space. If nutrients are controlling biomass then the total biomass of primary producers stops increasing when the rate of nutrient input equals the rate of consumption. The biomass achieved when this occurs is the 'equilibrium' biomass value and is the maximum attainable for a given loading of the limiting nutrient.

Ignoring all complicating factors, this maximum biomass (B) is simply given by:

$$B = q \, S/L \qquad (1)$$

where q is the yield of biomass from unit assimilated nutrient, S (mg/day) is the input rate of the limiting nutrient coming from both direct inputs and coastal waters and L (/day) is the loss rate. For estuarine phytoplankton, L is a combination of the estuary flushing rate and grazing losses; for macroalgae, it is less clear exactly what L relates to but is a general loss term that includes predation and storm-driven removal of fronds.

For the static equilibrium model, predictions are ultimately based on this simple relationship. For the case of light limitation an analogous equilibrium relationship can be derived. The dynamic model solves the underlying equations for the rate of change of phytoplankton and macroalgae biomass without requiring assumptions of equilibrium. As Eq. 1 suggests, the equilibrium prediction can be made with a minimum of information about the water body, whereas the dynamic model requires additional input data reflecting the requirement to simulate a seasonal cycle.

The model allows a water body to be split into an arbitrary number of linked compartments. The division is constrained to be a 'tree' structure, so that each box is linked to a single upstream downstream box (although a given box can have many upstream boxes linking to it). For a multi-box setup, the transports between boxes need to be specified in the form of an average exchange rate in a similar manner to the exchange rate with outside waters.
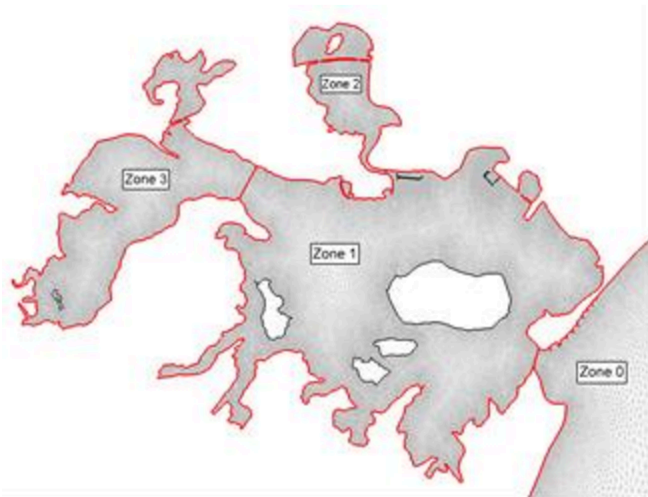
Figure 5. *Delineation of Telemac model domain into CPM box zones.*

### B. Calculating flushing rates

To calculate nutrient concentrations and the biomass of phytoplankton and macroalgal communities, the Poole Harbour water body has been split into four distinct zones, as shown in Fig. 5. Zone 1 is Poole Harbour, Zone 2 is Holes Bay, Zone 3 is Upper Wareham and Zone 0 is the English Channel or the 'open sea'.

The methodology as described by [14] been used to calculate the flushing rates between the four zones. Each zone is filled in turn with a uniform value of a non-decaying tracer. A decay curve can then be fitted to the total mass of the tracer in the start zone over the course of the simulation run as it leaves and exchanges with the rest of the model domain. Zone 2 and 3 are filled in isolation to calculate the exchange between Zone 2 to Zone 1 and Zone 3 to Zone 1.
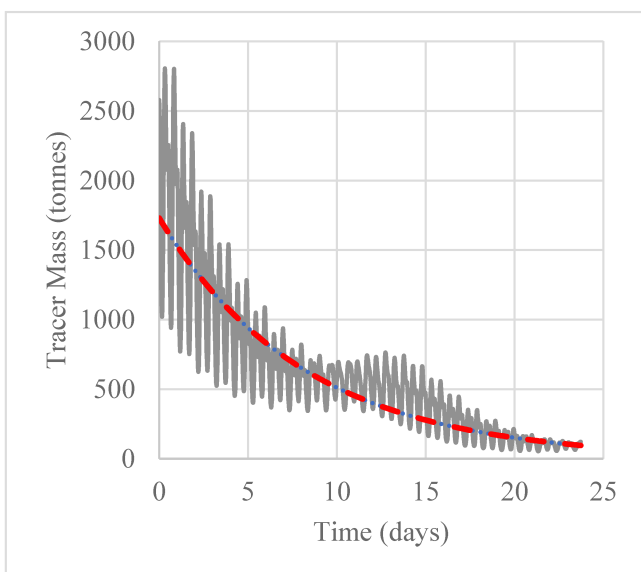


Figure 6. *Decay curve fitted to the total tracer mass in Zone 3, Upper Wareham.*

Whereas, Zone 1, 2 and 3 are filled together to calculate the exchange between Zone 1 and Zone 0.

Fig. 6 shows the decay curve fitted to the total tracer mass calculated in Zone 3, Upper Wareham. Based on the fitted decay curves, the daily net volumetric exchanges between the four zones was:

- Zone 3 to Zone 1 (Upper Wareham to Poole Harbour): 11.47%

- Zone 2 to Zone 1 (Holes Bay to Poole Harbour): 0.55%

- Zone 1 to Zone 0 (Poole Harbour to open sea): 3.48%

### C. Water quality scenarios

Based on the calculated exchanges rates five scenarios were developed, using the CPM model, to test the impact of different water quality control measures.

- Case 1 – 1730 tonnes/annum Nitrogen

- Case 2 – No Poole East STW to Holes Bay

- Case 3 – Reduction in average rural STWs

- Case 4 – CMP algal density < 1 kg/m$^2$

- Case 5 – CPM algal density < 0.5 kg/m$^2$

Case 1 represents a 20% reduction in the total annual nitrogen, through a reduction from riverine inputs. The inputs from the STWs remain the same as the base case. Historically, Holes Bay is an area of high occurrence of algal growth along with high nutrient loads. As such, Case 2 investigates the impact of removing the STW input into Holes bay. Case 3 investigates the impact of reducing the nutrient inputs from the Wareham and Lytchett STWs. Case 4 and 5 represent the reduction in nutrient inputs from both riverine and STW sources, as calibrated by the CPM model, to achieve the respective algal densities.

The modelling of the water quality scenarios is a two-stage process. The CPM model is used to provide the boundary conditions for nutrient levels which are then modelled using the separate Telemac model. The CPM model assesses the nutrient loads over an annual period to encompass the life cycle of the macroalgae and phytoplankton. Whereas, the Telemac model represents the nutrient distribution over a spring-neap cycle, as detailed in Section II. Fig. 7 shows the mean concentration of DIN over 30-day model period, for the reference base case and the five scenarios.

The concentrations in Poole Harbour are dominated by the combination of the River Piddle and the Wareham STW sources. This is clearly seen in Case 3 which has a lower input concentration, meaning the concentration within Poole Harbour is significantly lower compared to the base case. This is in part due to the large flow rate, as the tracer mass in the model domain is the multiplication of input volume and concentration.
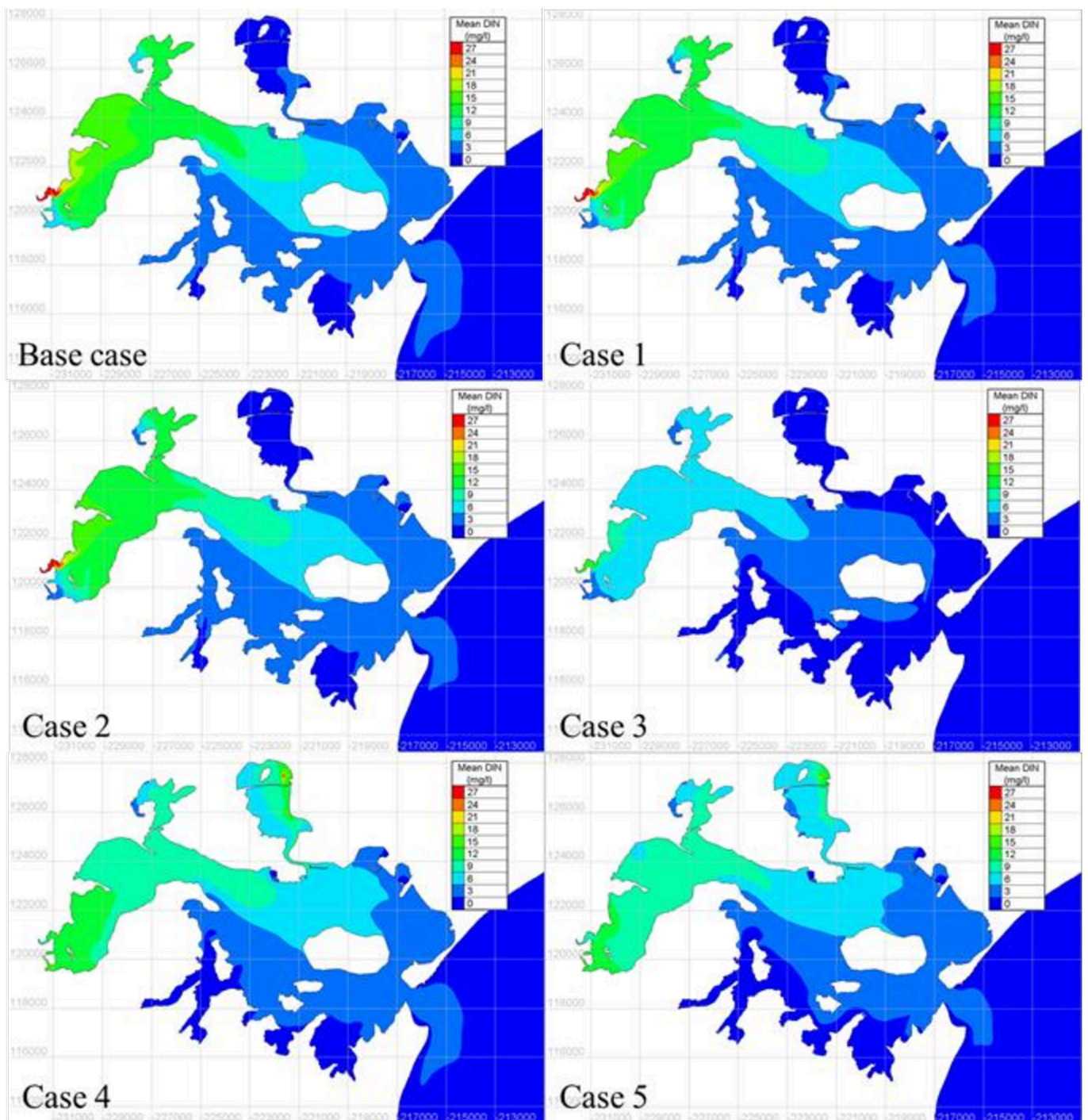
Figure 7. *Mean concentration of DIN (mg/l) over 30-day model period, for the reference base case and the five scenarios.*

Whilst concentrations from the STW are larger, their corresponding input flow rates are much smaller meaning their influence is much smaller. Despite this, one surprising result was the low concentration of DIN in Holes Bay. Field measurements suggest the bay has a high background concentration due to the presence of the STW outfall meaning algae mats are frequently observed. However, the model suggests the influence is much smaller. Due to the very low flushing rate and source input, the high concentrations may be due to historical nutrients stored within the sediment from a previous outfall from a power station, which was decommissioned in 1993. Only in Case 4 and 5 are higher concentrations seen in Holes Bay, due to a higher than current source input.
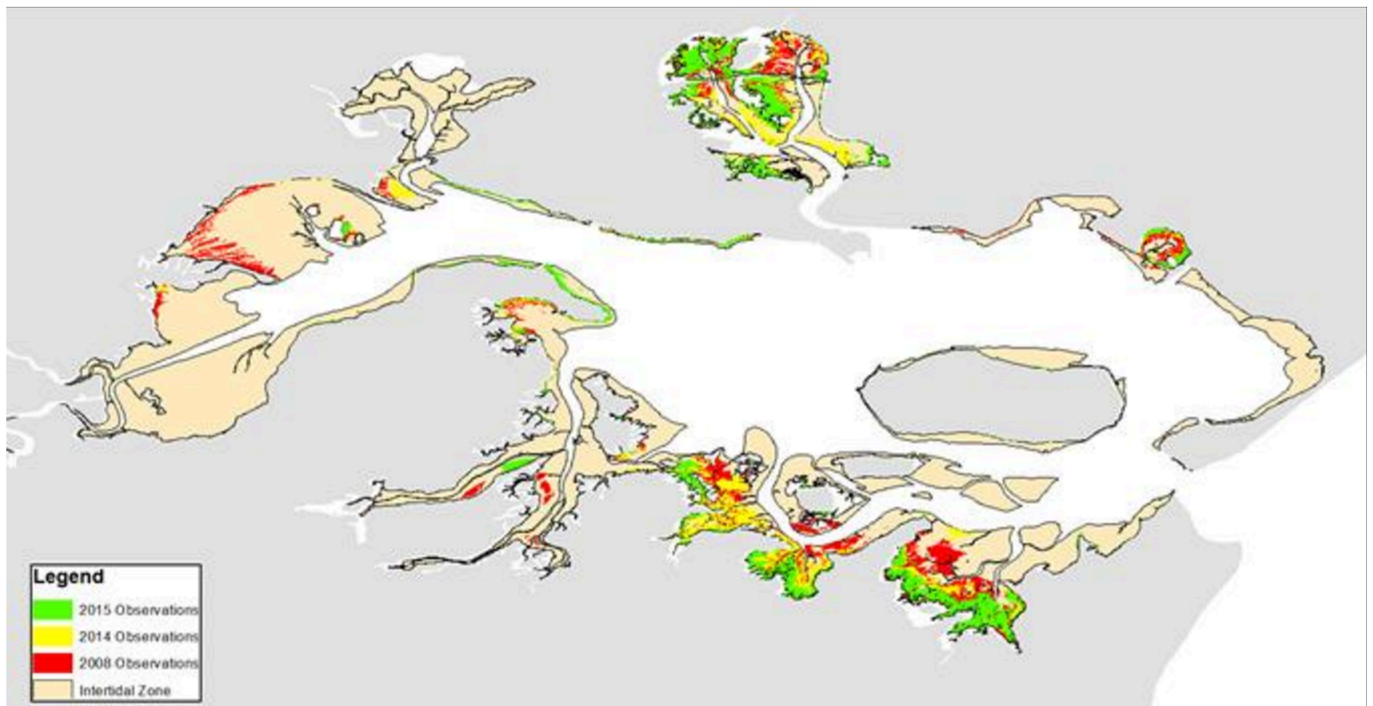
Figure 8. *Spatial distribution of observed macroalgae growth, in 2008, 2014 and 2015.*
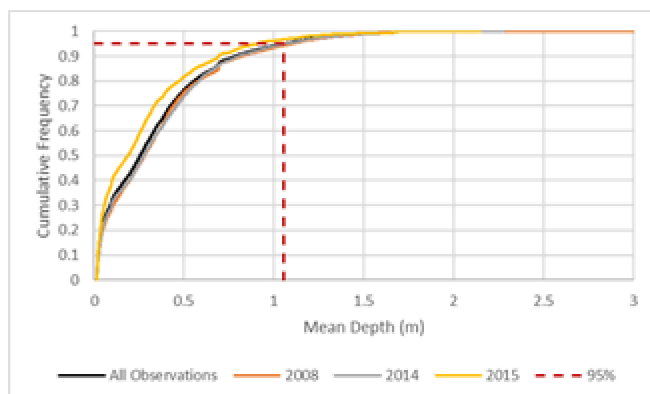


Figure 9. *Cumulative frequency distribution of mean depth at the location of observed macroalgae growth.*
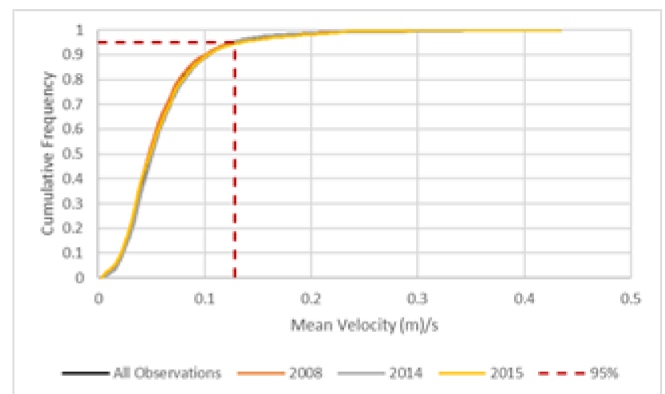


Figure 10. *Cumulative frequency distribution of mean velocity at the location of observed macroalgae growth.*

## IV.    SPATIAL DISTRIBUTION OF MACROALGAE

### A. *Initial assessment*

Three of the model variables were considered as potential indicators for macroalgae growth: mean water depth, mean velocity and mean winter DIN concentrations. To assess the variables, the model values were extracted from the model base case at the locations of known macroalgae growth. A cumulative distribution of the extracted variables was then plotted. As the nutrient concentrations are highest in the winter, the nutrient levels modelled in the five scenarios and base case represent a winter concentration, as distributed of a spring-neap cycle. Field assessments, mapping the spatial distribution of macroalgae growth within the Poole Harbour water body,

were conducted during 2008, 2014 and 2015 and are shown in Fig. 8. The modelled base case represents the winter levels of DIN with the present water management controls before any new control measures have been implemented, meaning the single model should be representative of the spatial distribution of DIN for 2008, 2014 and 2015. However, to assess any potential temporal variation, cumulative distributions were plotted for all the observed locations combined, as well as the individual field campaigns. Results shown in Fig. 9 and 10 shows that mean water depth and velocity are good indicators with 95% of the observations found below 1.05m depth and 0.13m/s velocity. This can visually be seen in the spatial distribution, in Fig. 8, where the macroalgae growth is restricted to the intertidal zone. The use of mean winter DIN concentrations was less clear as an indicator. Whilst 85% of the observations were between

1 and 4.5 mg/l, macroalgae was located in areas with concentrations over four standard deviations from the mean. Similar conclusions were found for a study of macroalgae growth in the Medway Estuary, UK, where bed shear stress was a controlling factor and nutrient supply a limited role [15].

Further work is required to assess potential indicators of macroalgae growth as it is clear there are other controlling factors. Whilst depth and mean velocity were good indicators, it does not explain why then it is not more prevalent in the Upper Wareham region and Lytchett Bay, which has extensive intertidal regions. Factors such as sediment composition, light penetration and grazing should be considered. Furthermore, there may be climatic variables, such as temperature and rain fall, that are indicators. These might explain why there is a 50% reduction in the total area of macroalgae growth from the 2008 and 2015 field observations.

## V.     SUMMARY & CONCLUSION

A depth-average hydrodynamic model was developed for Poole Harbour, UK, to test water quality scenarios for reducing nutrient levels. The scenarios were developed from a Combined Macroalgae and Phytoplankton model, tuned by flushing rates calculated from the Telemac model. The hydrodynamic model was a useful tool in providing insight into the dominant sources of nutrients into the water body and most effective solutions for reduction nutrient loads.

Furthermore, the hydrodynamic model was used to identify model outputs could be used as indicators for spatial distribution of macroalgae growth. Mean water depth and velocity were shown to be good indicators. However, mean winter concentrations of nutrients were less important. Further work is required to identify other controlling factors as field observations suggest water depth and velocity are not the only indicators.

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