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Modelling the impact of river flow, macronutrients and solar radiation on the eutrophication status of small estuaries

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Abstract:	Small, semi-enclosed basins have often been the location of human settlements; however, this has subjected them to extensive anthropogenic use, negatively impacting the water quality and increasing their susceptibility to eutrophication. A coupled depth-averaged hydrodynamic-biogeochemical model has been configured of the shallow, microtidal Christchurch Harbour estuary, Dorset UK, to investigate processes driving declines in ecosystem health with particular emphasis on understanding the impact of changing river flows, river nutrient inputs and solar radiation. Instances of summer oxygen undersaturation and increased levels of chlorophyll were found to coincide with regions within the estuary yielding long residence times, even under low nutrient conditions. Inverse relationships between time undersaturated and both river flow and river nutrient concentration were observed but with no significant correlation between time undersaturated and solar irradiance which we attribute to the estuary's shallow nature. Our results showed that although river flow controls estuarine renewal, river nutrient concentration plays the greatest role in driving eutrophication development in small, shallow semi-enclosed basins.
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To whom it may concern,

Please find submitted a new manuscript entitled "Modelling the impact of river flow, macronutrients and solar radiation on the eutrophication status of small shallow estuaries " by R. Huggett et al., which we are submitting as an original research article to Journal of Marine Systems.

Surface water quality across the world has been deteriorating in the last two decades[1] with recent research suggesting only 53% of surface water bodies in the European Union to be of the 'good' quality dictated by the Water Framework Directive[2]. Studies of small shallow estuaries for water quality, specifically eutrophication susceptibility, are limited due to a lack of long-term time-series; however, as they make up a large portion of the UK coastline, it is important to understand the interaction between river flow, river nutrient inputs and solar irradiance in these systems and identify the main causes of declines in ecosystem health.

In this paper, we assess the influence of river flows, riverine nutrient concentrations and solar irradiance on eutrophication development in small shallow estuaries, using the microtidal Christchurch Harbour estuary as a case study. To our knowledge, modelling at such small scales in this way has not been carried out before but our work indicates it is possible with the model yielding a good agreement with validation data. We demonstrate the importance of nutrient concentrations and river flows on ecosystem health within this small, shallow system and highlight how light is not a limiting factor in algal growth for such systems. We compare the work to our previous study[3] on the same case study site to compare our findings regarding the location of eutrophication development with residence times across the estuary. Our work can be used in other estuaries to identify the point at which a system may begin to see declines in water quality.

We feel this novel work on eutrophication development in small, shallow estuarine systems, which is considerably less well understood than in their larger counterparts, fits well into the scope of the Journal.

We confirm that this manuscript has not been published elsewhere and is not under consideration by another journal. All authors have approved the manuscript and agree with its submission to Journal of Marine Systems. We have no conflicts of interest to disclose.

Author contributions as follows:

Rebecca Huggett (PhD student) developed the water quality model used in the study, analysed the data produced and wrote the manuscript.

Prof. Duncan Purdie (primary supervisor) carried out data collection, provided validation data for the model, and assisted in data analysis and the writing of the manuscript.

Dr Ivan Haigh (secondary supervisor) helped with model configuration, and assisted in data analysis and the writing of the manuscript.

As part of the Your Paper Your Way service, we have submitted the paper as a Word document with all figures, the graphical abstract and highlights as separate individual files.

Regarding the figures, we would require for all to be published in colour. All figures will be 2-column fitting images.

Thank you for your consideration of this manuscript. Please contact Rebecca Huggett at r.huggett@soton.ac.uk with any correspondence relating to this manuscript.

Yours faithfully,

Rebecca Huggett

[1] N. N. Rabalais, R. J. Diaz, L. Levin, R. E. Turner, D. Gilbert, and J. Zhang, "Dynamics and distribution of natural and human-caused coastal hypoxia," *Biogeosciences Discuss.*, vol. 6, pp. 9359–9453, 2009.

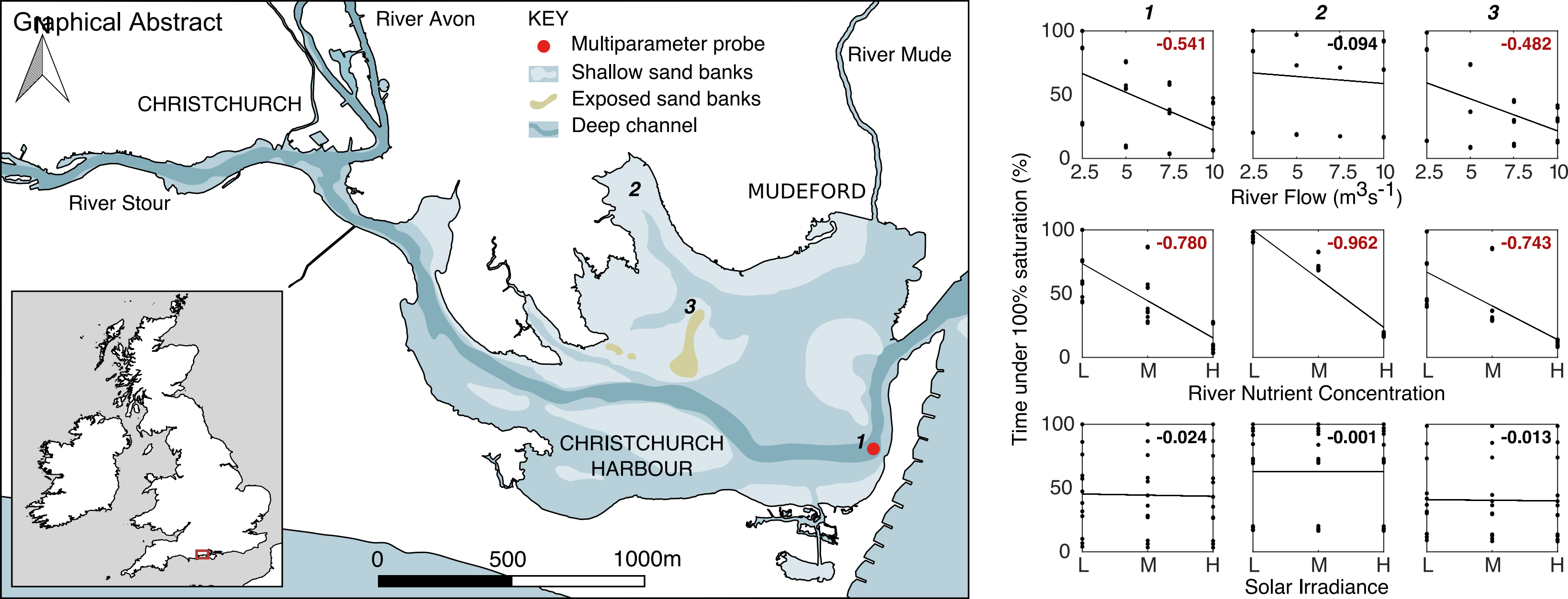
[2] European Commission, "Report from the Commission to the European Parliament and the Council on the Implementation of the Water Framework Directive (2000/60/EC) River Basin Management Plans," *Off. J. Eur. Communities*, p. 14 pp, 2012.

[3] R. D. Huggett, D. A. Purdie, and I. D. Haigh, "Modelling the Influence of Riverine Inputs on the Circulation and Flushing Times of Small Shallow Estuaries," *Estuaries and Coasts*, 2020.

Highlights

- A coupled hydrodynamic-biogeochemical model of Christchurch Harbour was established
- The model can predict conditions leading to eutrophication
- Eutrophic susceptible areas coincide with long residence times
- Ephemeral hypoxic waters were identified under high river nutrient inputs
- Algal growth in small shallow estuaries is likely not light limited

Graphical Abstract



Modelling the impact of river flow, macronutrients and solar radiation on the eutrophication status of small shallow estuaries

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Abstract

Small, semi-enclosed basins have often been the location of human settlements; however, this has subjected them to extensive anthropogenic use, negatively impacting the water quality and increasing their susceptibility to eutrophication. A coupled depth-averaged hydrodynamic-biogeochemical model has been configured of the shallow, microtidal Christchurch Harbour estuary, Dorset UK, to investigate processes driving declines in ecosystem health with particular emphasis on understanding the impact of changing river flows, river nutrient inputs and solar radiation. Instances of summer oxygen undersaturation and increased levels of chlorophyll were found to coincide with regions within the estuary yielding long residence times, even under low nutrient conditions. Inverse relationships between time undersaturated and both river flow and river nutrient concentration were observed but with no significant correlation between time undersaturated and solar irradiance which we attribute to the estuary's shallow nature. Our results showed that although river flow controls estuarine renewal, river nutrient concentration plays the greatest role in driving eutrophication development in small, shallow semi-enclosed basins.

Keywords

Eutrophication; Macronutrients; Microtidal; Modeling; Shallow; UK, Dorset, Christchurch Harbour

1 Introduction

Nutrient enrichment in rivers is a burgeoning problem globally, leading to increased occurrences of eutrophication further downstream in estuarine and coastal regions. Estuaries are considered some of the most productive regions in the world's oceans (McLusky & Elliott, 2004) due to high nutrient fluxes from rivers; however, over-enrichment of nutrients into estuaries as a result of increased anthropogenic activity is becoming a growing issue and is now recognised as a major pollution threat (Fletcher, 1996). In particular, semi-enclosed coastal waters typically accumulate more anthropogenic waste due to reduced flushing abilities compared to systems with open boundaries to the sea (Owen & Sandhu, 2000; Shirodkar et al., 2012).

Water quality in European estuaries and coastal waters has seen increased scientific scrutiny over the last four decades, in part due to directives set out by governing bodies as a means of tackling the declines observed with increased anthropogenic activities that may impact surface waters. These directives highlighted the necessity of comprehensive guidelines upon which a systems' health can be accurately described. One of the main conditions assessed is the eutrophic conditions of the surface waters in question. The increased demand for food, and thus use of fertilisers on farms (Rabalais et al., 2009; Seitzinger et al., 2010), is just one of many growing factors prompting changes to the eutrophic conditions in many water bodies across the European Union (van Wijnen et al., 2015).

Eutrophication is the process by which water enriched with nutrients promotes increased rates of primary production leading to extensive growth of algae (Meyer-Reil & Köster, 2000). This phenomenon typically occurs in the summer months in temperate coastal waters (Dokulil &

Teubner, 2011) when a combination of increased water temperatures, surface incident light, and nutrient concentration provide ideal growing conditions for algae. The resulting enhanced biomass can lead to numerous damaging effects on the ecosystem. An example of one of these is the decline in dissolved oxygen (DO) concentration at depth as a result of organic matter degradation within the water column (Evans & Scavia, 2013). A small algal bloom should not leave long lasting damaging effects on an ecosystem; however, persistent algal blooms are harder to recover from and may lead to prolonged periods of low oxygen. An estuarine system with a long flushing time will be more prone to the development of algal blooms (Patgaonkar et al., 2012; Warwick et al., 2018) and will be unable to remove the oxygen poor waters.

As a global phenomenon, eutrophication has been recognized as an increasing environmental problem over the last three decades with some estuarine and coastal systems subject to detailed analysis (e.g. China; Wang et al. (2016), North America; Kemp et al. (2005), South America; Struijk & Kroeze (2010), Australia; Haynes (2011), and India; Bhavya et al. (2016)) . Although previous research (Corredor et al., 1999) has suggested tropical ecosystems are more sensitive to nutrient inputs than temperate waters, research into eutrophication and hypoxia have seen greater advances in temperate regions due to the larger anthropogenic influence on estuarine and coastal ecosystems at higher latitudes (Howarth et al., 2011). Despite this emphasis on temperate systems, there remain extensive knowledge gaps as the focus of previous research has been primarily on larger estuaries and coastal regions, such as the Baltic Sea (Meier et al., 2011) with small, shallow estuaries being less well studied and as a result, eutrophication in these types of systems is not well documented. It is postulated that small semi-enclosed systems are of particular risk as their reduced assimilative capacity will promote a greater change in water quality (Shirodkar et al., 2012).

To elucidate the processes that underpin eutrophication development in small systems, the influencing factors must first be understood. In this paper we utilise a hydrodynamic model, coupled to a biogeochemical model, to predict the proclivity of small, shallow estuaries to eutrophic events under varying environmental conditions.

The aim of this paper is thus to assess how river flow, nutrient inputs and solar radiation influence eutrophic conditions in Christchurch Harbour, a small shallow enclosed microtidal estuary on the south coast of England. The aim will be achieved by addressing the following three objectives focused on Christchurch Harbour:

1. To investigate the impact of changing river flow on eutrophic events;
2. To assess the influence of nutrient inputs on eutrophic events; and
3. To investigate the impact of solar radiation on eutrophic events.

Christchurch Harbour is a microtidal estuary characterized by its shallow bathymetry and lagoon-type shape (Fig. 1). The estuary is tidally driven but high flows in the two main rivers supplying freshwater into the system, the Hampshire Avon and the Stour, have been shown to alter the dominant physical control on circulation (Huggett et al., 2020). The estuarine system flows into the English Channel through a narrow 47 m wide channel, henceforth referred to as the Run. The basin is typically well-mixed (Gao & Collins, 1994; ABP, 2009) due to its shallow nature and relatively long flushing times in the summer months when river flows are minimal (Huggett et al., 2020). Oxygen under-saturation has been observed under these conditions (Murray, 1966); however, eutrophication events have not been previously investigated. The Christchurch Harbour estuary is an important system to study due to the chalk beds through which the River Avon and its tributaries flow, producing chalk streams. With approximately 250 chalk streams worldwide 85% of which are located within England (O'Neill & Hughes, 2014; Salter & Singleton-White, 2019), these systems are fairly unique and form a distinct habitat for numerous species due to the clear water produced as a result of filtering through the porous chalk rocks. This has prompted much of the river/estuarine system to be designated a Special Area of Conservation (SAC) with many parts of the catchment classed as Sites of Special Scientific Interest (SSSI; Whitehead et al., 2014). Due to its protected status, it is necessary to ensure ecosystem health is maintained; however, nutrient pollution in the Avon has been a growing issue, resulting in the development of algae growth and consequently eutrophication (Whitehead et al., 2014; Pirani et al., 2016). From 2012 to 2017 the Christchurch Harbour Macronutrients Project was established to provide extensive monitoring of the system and thus improve understanding of macronutrient behaviour in the Hampshire Avon, River Stour and Christchurch Harbour over a range of spatial and temporal scales (Panton et al., 2020). Throughout this monitoring program, low oxygen saturations and high chlorophyll concentrations were detected in the upper estuary during summer months. This observational data, obtained from both automated continuous monitoring (Beaton et al., 2017) and discrete sampling (Panton et al., 2018; Panton et al., 2020), will be most beneficial for use in the current model calibration, validation and parameterisation.

This paper is structured as follows. Section 2 describes the biogeochemical model configuration and validation. The simulations undertaken are described in Section 3. Results are presented in Section 4 and discussed in Section 5. Finally, conclusions are given in Section 6.

2 Model configuration and validation

A pre-existing hydrodynamic model of the estuary from Huggett et al. (2020) was used for this study and this was subsequently coupled to a biogeochemical model described here. The configuration and validation of these models are described in the next section.

2.1 Model configuration

The MIKE software is a modelling tool developed to simulate physical, biological, and chemical processes in estuaries, lakes, coastal waters and seas (DHI, 2017; Abbaspour & Zohdi, 2018). Developed by the Danish Hydraulic Institute (DHI), MIKE utilizes a flexible grid, making it an ideal modelling framework for shallow environments due to the ability to apply graded mesh resolution (Robins et al., 2011). The depth-averaged hydrodynamic model used in this study was configured in the 2-dimensional tool MIKE 21, and is described in detail in Huggett et al. (2020). The model domain, encompassing the Christchurch Harbour estuary up to the tidal limits of the River Avon and River Stour as well as a large coastal area outside of the estuary, with an unstructured grid used to allow for high spatial resolution within the estuary (less than 5m), as shown in Fig. 2 a & b. A 2-dimensional approach was chosen for this case study of Christchurch Harbour due to it being a small, shallow, microtidal system that is predominately well-mixed. This method is similar to those applied by Umgiesser et al. (2004) and Cucco & Umgiesser (2006) to the Venice Lagoon system. The hydrodynamic model was coupled to a biochemical model here, using the ECOLAB module of MIKE 21.

The MIKE 21 ECOLAB module is a state-of-the-art numerical tool designed for ecological modelling (DHI, 2013) that is coupled to the MIKE 21 hydrodynamic model. The ECOLAB module is based on processes including advective transport, biological, physical, and chemical transformations, and sediment settling and resuspension. Multiple approaches can be used within the ECOLAB module as there are numerous predefined models (referred to as templates) aimed at specific ecological processes (Liungman & Moreno-Arancibia, 2010). The Eutrophication 2 template was used for the work described here. This template describes nutrient cycling, phytoplankton and zooplankton growth, growth and distribution of rooted vegetation and macro algae in addition to simulating oxygen conditions. The simulation results then describe the concentrations of phytoplankton, chlorophyll-*a*, zooplankton, organic matter (detritus), organic and inorganic nutrients, oxygen and area-based biomass of benthic vegetation over time (DHI, 2013).

The open boundary, driven using water levels for the hydrodynamic model as described in Huggett et al. (2020), was forced by constant nitrate, nitrite, phosphate, chlorophyll-a, Phytoplankton (C, N, and P), Zooplankton C, Detritus (C, N, and P), ammonia, dissolved oxygen, temperature and salinity for the water quality model. The oxygen, chlorophyll, nitrate, phosphate, and ammonia concentrations were obtained from the quasi-monthly WIMS dataset (www.environment.data.gov.uk/water-quality) at the Needles Baseline Survey location (see Fig. 2a).

Two riverine water sources were added to the model at the tidal limits of the River Avon and River Stour. These point sources were forced with both real 15 minute data from the National River Flow Archive (downloaded from https://nrfa.ceh.ac.uk/data and data presented in Fig. 3a) for validation purposes, and constant values for the main simulations. In addition to the freshwater, the river point sources were also driven by constant nitrate, nitrite, phosphate, chlorophyll-a, Phytoplankton (C, N, and P), Zooplankton C, Detritus (C, N, and P), ammonia, dissolved oxygen, and temperature values. The oxygen, chlorophyll, nitrate, phosphate, and ammonia concentrations were taken from the WIMS archive with a quasi-monthly temporal resolution.

These simulations were carried out on an individual PC with a 3.6GHz processor and 16GB of

RAM. Runs took 72 hours to complete 30 days of simulation. To compromise between resolution and computational expense, results were saved every 120 minutes of simulation time.

2.2 Validation

The biogeochemical model was validated against oxygen and chlorophyll concentrations, all of which have been previously collected and analysed through the Christchurch Harbour Macronutrients Project. Validation simulations were run for 124 days from 25th July 2014 12:00:00 to the 26th November 2014 12:00:00. This period in 2014 was the chosen modelling interval as it coincided with available high frequency water quality validation data for Christchurch Harbour. The first 16 days of the simulation results, during the model warm up period, were removed and excluded from the validation. Statistical tests were used to assess model performance in accurately reproducing water quality parameters at the Ferry pontoon in the estuary (Fig. 1). To evaluate the model skill, the root mean square error (RMSE), mean absolute error (MAE) and standard deviation of the absolute errors (STD AE) were calculated. The correlation coefficient was also derived.

Comparisons of the predicted and observed dissolved oxygen and chlorophyll concentrations within the estuary are shown in Fig. 4a & b, respectively. The results show good agreement within the estuary with a RMSE for DO of 1.73 mg/L and 0.0052 mg/L for chlorophyll. The model clearly predicts the daily trends and accurately captures variation in patterns in both parameters to a high level of accuracy. The MAE for DO and chlorophyll are low (1.54 mg/L and 0.0012 mg/L, respectively) as are the STD AE (0.79 mg/L and 0.0051 mg/L, respectively). Overall, the model does a good job of reproducing dissolved oxygen and chlorophyll concentrations across the domain and we can therefore confidently use the model to analyse the controls on eutrophication development within the estuary.

3 Methodology

3.1 River Flow

The first objective is to assess the influence of river flow on eutrophic events in Christchurch Harbour. Using the configured hydrodynamic model and coupled biogeochemical model, sensitivity tests were undertaken with constant river flows applied to represent observed ranges in the River Avon and River Stour. The river discharge values chosen represent very low summer flows (2.5 m^3s^{-1}), low summer flows (5 m^3s^{-1}), average summer flows (7.5 m^3s^{-1}), and high summer flows (10 m^3s^{-1}). In addition to these values, simulations of no flow (0 m^3s^{-1}) were carried out as a control. In each case, the same constant river flows were applied to both rivers (i.e. 10 m^3s^{-1} in each river, amounting to a total input into the estuary of 20 m^3s^{-1}).

3.2 Nutrient Inputs

The second objective is to identify the impact of nutrient concentration on eutrophic events in Christchurch Harbour. As with the river flow sensitivity tests, constant riverine nutrient concentrations were applied to the model, representing observed ranges in the two rivers (see Fig. 3 c & d). The riverine nutrient concentration values chosen represent low concentrations (3.8 mg N l^{-1} and 0.056 mg P l^{-1}), average concentrations (4.6 mg N l^{-1} and 0.095 mg P l^{-1}), and high concentrations (9.5 mg N l^{-1} and 0.73 mg P l^{-1}).

3.3 Solar Radiation

The third objective is to investigate the influence of solar radiation on eutrophic events in Christchurch Harbour. Similarly to the river flow and nutrient simulations, sensitivity tests were undertaken with a range of solar irradiances applied over the entire domain (based on daily solar irradiance values at Hurn for 1957-1968 and 1981-2017 from the British Atmospheric Data Centre archive; www.data.ceda.ac.uk). The solar radiation curves were chosen to represent low summer solar irradiance patterns, average summer solar irradiance patterns, and high summer solar irradiance patterns (see Fig. 3b). These solar irradiance curves were applied to simulations with numerous combinations of river flow and river nutrient concentrations.

All non-validation simulations were run for 52 days from 10th June 2017 00:00:00 to the 1st August 2017 00:00:00. As the model takes time to warm up and settle, only results within July 2017 were considered. July 2017 was the chosen modelling period as this coincided with the hydrodynamic validation data and the simulations carried out in the hydrodynamic analysis (Huggett et al., 2020). Estuarine surveys conducted by the Environment Agency in the early 2000s and the Macronutrients Project in 2014 (Panton et al., 2020) provided evidence of high chlorophyll concentrations (over 0.05 mg/L) in July over numerous years, thus making this an ideal time period in which to model the system for eutrophication.

4 Results

4.1 River Flow

To understand the role of freshwater inputs to the estuary on the development of eutrophication, numerous model run sensitivity tests with different river flows were undertaken. As the results are taken from a 2D model, values discussed here are depth averaged. These simulations indicate that fluvial input has a large influence on the oxygen and chlorophyll concentrations across the harbour. The spatial results for oxygen saturation (Figs. 5a-d) show the northernmost section of the system (Region 8 - for locations see map; Fig. 1b) exhibits undersaturation to some degree under all river flows studied. Correlations analysed between the amount of time spent undersaturated and river flow rate indicate primarily negative relationships. The main exception to this being the West (Region 7) of the estuary which exhibits a strong positive correlation of 0.944 (Fig. 6a).

The number of instances in which dissolved oxygen concentrations fell below 4 mg/L and 2 mg/L for over 4 hours are presented in Fig. 7. Examination of these results highlights that the simulations with no river input exhibit the greatest number of occurrences at all locations for concentrations below 4 mg/L, with the exception of the Shallows (Region 9) where the greatest number of occurrences are observed under higher flows. It should be noted that only the Shallows and the North indicated values below 4 mg/L at instances when the river flow was greater than 0 m^3s^{-1} and these were the only locations in which concentrations below 2 mg/L were observed. No locations presented values below 2 mg/L for over 4 hours during the no flow scenarios.

The spatial chlorophyll concentration results presented in Figs. 8a-d typically show a decline in concentration across the estuary as river flow increases. The number of instances in which chlorophyll concentration daily averages exceeded 0.015 mg/L (Fig. 9) indicates strong variability with river flow. In the no flow scenario there were no recorded instances (Fig. 9). Maximum occurrences are observed for flows of 2.5 m^3s^{-1} but as river flow increases further, the number of times daily averages exceed 0.015 mg/L fall. An exception to this is the North which recorded daily averages over 0.015 mg/L for most simulation days.

4.2 Nutrient Inputs

To build upon the river flow results and elucidate the influence of fluvial nutrient inputs on the development of eutrophication, different riverine nutrient concentration sensitivity tests were undertaken. Under all river flow scenarios, the simulations with the low and mean nutrient concentrations showed large regions of the estuary (typically Regions 8 and 9) with oxygen undersaturation to levels as low as 50% (Figs. 5a-d i-vi). As river flow increases (from 2.5 to 10 m^3s^{-1}), the area and degree of the undersaturation decreases with pockets of high oxygen saturation water developing under the mean nutrient concentration conditions at flows greater than 5 m^3s^{-1}.

The general trend under the highest nutrient input is different (Figs. 5a-d vii-ix). The oxygen saturation during river flows of 2.5 m^3s^{-1} are more consistent across the estuary and values are typically much greater than those during the lower nutrient simulations with most of the harbour exhibiting saturations over 100%. Despite this, Region 8 sees lowest saturations with a very small part of this area being undersaturated. As river flow increases, the oxygen saturation gradually decreases with large regions becoming undersaturated when river flows reach 10 m^3s^{-1}. During flows of 7.5 m^3s^{-1} and 10 m^3s^{-1}, the northernmost sections see large increases in oxygen saturation with values exceeding 250% over much of this region. The correlation between nutrient inputs and time spend undersaturated suggests an inverse relationship across all timeseries locations with an average correlation of -0.701 (Fig. 6b).

The results in Fig. 7 suggest the number of occasions in which oxygen concentrations fell below 4 mg/L and 2 mg/L are influenced by the nutrient supply to the system. Under all river flow conditions, the Shallows (Region 9) of the harbour has the greatest number of occurrences compared to all other locations. Typically, the number of incidents of significant undersaturations at all locations is greatest when the river flow is 0 m^3s^{-1}. During the low nutrient conditions, the number of occurrences below 4 mg/L at the Shallows are high (over 40) except when river flows are 2.5 m^3s^{-1} when no instances were observed. When nutrient concentrations are increased to mean values, instances of DO below 4 mg/L are numerous under all river flow conditions with instances below 2 mg/L greater under this nutrient regime than the low concentration simulations. A decline in occurrences is then observed under the highest nutrient conditions with values falling below 20 instances.

As with the oxygen saturation results, chlorophyll concentrations for the low and mean nutrient concentration simulations indicated different trends to the higher nutrient concentration scenarios. Under the low and mean nutrient inputs (Figs. 8a-d i-vi), chlorophyll concentrations across the harbour were low, at less than 0.01mg/L, with Region 8 found to have slightly lower concentrations than the rest of the system. As river flow increases, the average chlorophyll concentration within the estuary decreases further. The high nutrient simulations (Fig, 7a-d vii-ix) produced much greater average chlorophyll concentrations. Maximum concentrations were found at Region 8, in contrast to the lower nutrient simulations, with values exceeding 0.6 mg/L. Similar to the saturation results, as river flow increases, average chlorophyll concentrations across the harbour decreases with the South (Region 4) and central (Region 5) parts of the estuary seeing chlorophyll concentrations falling below 0.01 mg/L. Despite this decline, chlorophyll concentrations in Region 8 remain over 0.6 mg/L but the extent of these high chlorophyll waters reduces as river flow increases.

Daily averages of chlorophyll exceed 0.015 mg/L only when the nutrient concentration is set to the highest values (Fig. 9). At all other nutrient concentrations, the chlorophyll values did not exceed the 0.015 mg/L level.

4.3 Solar Radiation

To evaluate the influence of incident solar radiation on the development of eutrophication, various solar irradiation sensitivity tests were carried out alongside the nutrient and river flow simulations. The results appear consistent with minimal difference found to occur under the different solar conditions for all nutrient and river flow simulations (Figs. 5a-d). The timeseries results (Fig. 7) concur with the spatial results, indicating negligible change between the different solar simulations. Analysis of the relationship between solar irradiance and the time spent undersaturated show no correlation at any of the timeseries locations (Fig. 6c).

Despite this lack of influence on the oxygen concentration, solar radiation appeared to influence the number of occurrences in which daily chlorophyll averages exceeded 0.015 mg/L (Fig. 9). As the solar irradiance was increased, the number of times chlorophyll averages were found to exceed 0.015 mg/L increased by varying degrees across all locations, particularly during river flows of 2.5 m^3s^{-1}.

5 Discussion

The aim of this study was to assess how river flow, nutrient inputs and solar radiation influence eutrophic conditions in the shallow semi-enclosed microtidal basin of Christchurch Harbour during a mid-summer period. Our previous study on the physical processes in the system (Huggett et al., 2020) indicated long flushing times under low riverine input conditions being the most likely to produce eutrophic waters as localized regions of the estuary receive minimal circulation due to the shallow bathymetry under such circumstances. To confirm if these areas are indeed most susceptible to eutrophic conditions, we analysed modelled combinations of nutrient concentration, solar irradiance and riverine inputs to the estuary. Following an algal bloom, oxygen concentrations at depth would be expected to fall due to the decomposition of organic matter that takes place. Thus, to best analyse the influence of river flow, nutrient inputs and solar irradiance on the eutrophication status, oxygen saturations and concentrations, and chlorophyll concentrations were the primary parameters considered both temporally and spatially in this discussion.

5.1 River Flow

The first objective was to assess the influence of river flow on the development of eutrophic conditions in the Christchurch Harbour estuary. We propose a system with oxygen undersaturation is one in which eutrophic or hypoxic conditions are likely to occur and thus use a saturation level of less than 100% to identify at risk regions. In Huggett et al. (2020), flushing times were used as proxies for areas susceptible to declines in water quality in the Christchurch Harbour estuary. The results here will be compared to those in Huggett et al. to confirm if the use of particle tracking models as a means of determining regions at risk of developing eutrophic conditions is suitable. The results presented here found the northernmost sections of the estuary (Regions 8 and 9) to exhibit the most symptoms of eutrophication, in agreement with the results in Huggett et al. (2020), with these areas of the estuary appearing prone to development of high chlorophyll concentrations. Riverine inputs appear to have a large control on the build-up of high chlorophyll waters; however, even at river flows of 10 m^3s^{-1}, concentrations within the northern parts of the harbour remain high. At river flows of 2.5 m^3s^{-1}, the rest of the estuary sees much higher chlorophyll concentrations than under higher fluvial conditions, a strong indication that at these low river flows the system is very susceptible to declines in water quality.

5.2 Nutrient Concentrations

The second objective was to assess the influence of nutrient inputs on eutrophic events in the Christchurch Harbour estuary. In addition to identifying the areas most at risk to declines in water quality, determining the conditions under which eutrophic and hypoxic conditions occur in small, shallow systems was an important aim of this work. To identify periods of both eutrophication and hypoxia, DO and chlorophyll concentrations were analysed. Eutrophic conditions were defined as periods when either the DO rolling 4-hour average was less than or equal to 4 mg/L or the chlorophyll daily average was greater than or equal to 0.015 mg/L (chlorophyll reference value from Tett et al., 2007). Hypoxic events were defined as periods when the DO 4-hourly average was less than or equal to 2 mg/L. These methods are similar to those applied by Nezlin et al. (2009).

The results of this analysis clearly demonstrate the at risk regions of the Christchurch Harbour system. Much of the central estuary and main channel presented no occasions of oxygen concentrations below 4 mg/L; however, the north of the harbour and the shallow regions were identified as having numerous occasions when oxygen concentrations fell below the 4 mg/L level. The same regions also indicated hypoxic tendencies with concentrations falling below the 2 mg/L level on some occasions.

In all river flow scenarios, under the lower nutrient concentrations the same northern section of the estuary exhibit long residence times and shows reduced oxygen saturation with values falling to 50%. Under the higher nutrient concentrations, although values appear lowest within this northern section, saturations remain above 100%. We interpret the high oxygen saturations documented in the northern sections of the harbour under the high nutrient inputs to indicate increased photosynthetic oxygen production as a result of high algal biomass. We propose the expected oxygen consumption due organic matter degradation has not yet outpaced the increased oxygen production at the surface and thus undersaturation will not occur until later. For these simulation results, the expected inverse relationship between oxygen concentration and water residence time is thus not observed and a negative correlation between river flow and time spent undersaturated is detected. An alternative explanation is that the very low saturations observed from the lower nutrient simulations may not be caused by algal blooms, but rather are a byproduct of the long residence times and lack of ventilation in that part of the estuary. This could be confirmed with the deployment of a water quality probe in these shallow sections of the harbour to gather measured data from this part of the system.

5.3 Solar Radiation Influence

The third objective was to investigate the impact of solar radiation on modelled eutrophic events in the Christchurch Harbour estuary. When observing the impact of solar radiation on the development of eutrophication, it is interesting to note only minimal differences in chlorophyll across the system. Greater solar irradiance does appear to hold some influence on chlorophyll concentrations with very slight increases in the number of occurrences of high values observed; however, differences in spatial variation in chlorophyll concentrations between low and high irradiance appear negligible. Light is one of the main factors limiting primary production but this lack of variation between the light levels analysed indicates, in this system, typically light levels in July are not the parameter dictating algal growth. It is probable the very shallow nature of Christchurch Harbour allows high enough light levels throughout the water column, even under lower surface incident light levels, to permit algal growth.

The control simulations, when river flows are set to $0 m^3 s^{-1}$, suggest frequent instances of low DO; however, there were no occasions under this flow regime in which the daily average of chlorophyll exceeded the 0.015 mg/L level. This suggests the low oxygen concentrations present when there is no flow are a result of a lack of ventilation across the estuary rather than the incoming coastal waters bringing in high enough nutrient concentrations to promote algal growth.

An important factor underpinning this work is the assumption that small and large estuarine systems behave differently. As large systems are subjected to more extensive monitoring, modelling and thus yield more publications, analysis of smaller systems by comparison falls short. Until more scientific documentation of their behaviour is released, we must thus assume that small estuarine basins interact differently to changes in river flow, nutrient inputs and solar irradiance levels than their larger counterparts. It is known that flushing times for such small systems are much shorter than for larger estuaries and a well-mixed system with a short residence time is assumed resistant to declines in water quality; however, we previously (Huggett et al., 2020) showed this does not imply an entire system is risk free and Verity et al. (2006) has shown even small estuaries characterized by short residence times can show gradual declines in oxygen concentrations, with some instances leading to hypoxia when placed under continuous anthropogenic stress. We have established through this modelling study that the main controls of eutrophication development in Christchurch Harbour are nutrient inputs and riverine flow being more dominant factors than solar irradiance. This is consistent with work by Nezlin et al. (2009) who found that despite solar radiation being significantly correlated with DO concentrations in bottom waters towards the head of their study site (the Upper Newport Bay estuary, California), there was no correlation between the two parameters in the surface waters at the seaward end. As Christchurch Harbour is very shallow, the system is not limited by solar input in summer and therefore fluctuations in solar irradiance produce insignificant changes to the eutrophic conditions when compared to nutrient and riverine inputs, perhaps in contrast to many larger and deeper estuaries which rely on increased solar radiation to promote growth throughout the water column.

The methodologies and results presented here could be used to better understand the conditions controlling the development of algal blooms and provide estimates of tipping points for other estuaries with similar characteristics i.e. microtidal, shallow bathymetry, high riverine input, and small size. There are numerous small, shallow, semi-enclosed microtidal systems with which results for Christchurch Harbour could be applied to better comprehend potential changes in ecosystem health. Using our results, we can predict how water quality in small microtidal systems such as Christchurch Harbour will respond to changes in freshwater flows, nutrient inputs, and solar conditions. With climate change predictions indicating significant declines in summer river flows in temperate systems (Christierson et al., 2012; Robins et al., 2016) and an expected rise in nutrient runoff and changes in macronutrient composition (Statham, 2012), we can gain a better understanding of how the small estuaries that make up most of our coastlines will respond by projecting the results from Christchurch Harbour to similar systems. This will allow us to be better prepared should a system's influencing factors appear to be in line with those conducive to eutrophication development.

We acknowledge a 3D modelling approach is preferred; however, we justify the use of a 2D model for Christchurch Harbour due to it being a mostly well-mixed and a very shallow system. Future work could consider application of a 3D model to Christchurch Harbour to see if better understanding of eutrophication development could be gained. A further simplification of this study is the omission of wind. Further examination of Christchurch Harbour would include a more in depth analysis of the influence of wind on the location and transience of algal blooms.

6 Conclusions

The overall aim of this paper was to assess how river flow, nutrient inputs and solar radiation influence eutrophic summer conditions in a small, shallow estuary. Applying the 2D hydrodynamic model of Christchurch Harbour we previously developed in MIKE 21 (Huggett et al., 2020), a coupled water quality model was applied to the case study site. The model accurately replicates the biogeochemistry of Christchurch Harbour proving it is possible to model the water quality of small, shallow, well mixed estuarine systems, even one with a complicated tidal cycle. This paper has focused on three objectives: the first was to assess the influence of river flow on eutrophic events in the Christchurch Harbour estuary; the second to investigate the impact of nutrient concentrations on eutrophic events in Christchurch Harbour; and the third objective was to investigate the impact of solar radiation on eutrophic events in the Christchurch Harbour estuary. The model results indicated that although a greater solar radiation will yield a slight increase in primary production, the solar influence on the development of algal blooms is much less than that of changes to nutrient concentrations from riverine inputs. Comparison of the results from the water quality modelling and the particle tracking work we previously carried out (Huggett et al., 2020) confirms the particle tracking residence time results can be accurately used as a proxy for regions susceptible to declines in ecosystem health. The localized areas in the estuary identified by the particle tracking model to exhibit long flushing times are also the regions found to have high chlorophyll concentrations and reduced oxygen saturation. However, to gain a better understanding of the influencing factors behind the high chlorophyll and low oxygen levels, the biogeochemical model is required. Indeed, we suggest our findings can be used to predict the conditions likely to promote development of eutrophication for similar semi-enclosed small, shallow basins. We have shown that although occurrences were low, the results here indicate hypoxia does occur and highlight that even small systems with relatively short flushing times are susceptible to declines in system health.

List of figures

Fig. 1 Christchurch Harbour and the surrounding areas. Located in the centre of the UK's south coast, Christchurch Harbour exits into Christchurch Bay in the English Channel as shown in (a). The sample location at the ferry pontoon where an EXO 2 Sonde multiprobe was deployed (50˚43'11.69"N 001˚44'37.16"W) is highlighted in (b). Also included are the names and positions of nine timeseries locations chosen to represent different regions of the estuary and used in the results and discussion

Fig. 2 Model grid and bathymetry. The model area and entire grid are shown in (a). The thick line represents the open tidal boundary and the black circle is the location of the WIMS dataset The Needles Baseline Survey timeseries (50˚38'17.06"N 001˚39'7.45"W) from which some data was used to force the model boundary. (b) is the model grid within the estuary. The bathymetry of the entire domain and bathymetry of the estuary are shown in (c) and (d), respectively. This bathymetry was interpolated on to the grid. For more details see Huggett et al. (2020)

Fig. 3 Riverine and nutrient inputs in the Hampshire Avon and River Stour, and solar irradiance for the Dorset region. Cumulative frequency of river flows into Christchurch Harbour from the Hampshire Avon at Knapp Mill (since 1975) and the River Stour at Throop (since 1973) in (a). Average solar radiation, taken form the weather station at Hurn, are shown in (b) alongside high values representing maximum values measured from 1957-1968 and 1981-2017 and low values which represent low summer irradiance patterns. The cumulative frequency nutrient inputs at Knapp Mill and Throop for nitrate and phosphate from 2000 to 2017 are presented in (c) and (d), respectively

Fig. 4 Model validation. Model output and measured data for dissolved oxygen concentration (a) and chlorophyll concentration (b) at the ferry pontoon for July 2014. Included is the root mean square error (RMSE), mean absolute error (MAE), standard deviation of the absolute error (STD AE), and the correlation coefficient (CC)

Fig. 5 Spatial percent oxygen saturation results under varying sensitivity tests. The results for changing river flows are as shown in (a) 2.5 m^3s^{-1}, (b) 5 m^3s^{-1}, (c) 7.5 m^3s^{-1}, and (d) 10 m^3s^{-1}. In each of a-d, the first row represents the lowest riverine nutrient concentration inputs, the second mean riverine nutrient concentration inputs, and the bottom the greatest riverine nutrient concentration inputs. Then, in each of a-d, the first column represents the lowest solar irradiance inputs, the second the mean solar irradiance inputs, the third column is the highest solar irradiance inputs. For details on values used, go to Section 3

Fig. 6 Correlations between the amount of time oxygen concentration spent undersaturated and (a) river flow, (b) riverine nutrient concentration, and (c) solar irradiance. In each case the nine timeseries locations are included with their respective correlations. Statistically significant correlations are in red

Fig. 7 The number of instances in which dissolved oxygen concentrations fall below 4 mg/L (eutrophic) and 2 mg/L (hypoxic) under varying sensitivity tests. Results for values below 4 mg/L are represented by filled circles and the results for below 2 mg/L by filled squares (only the North and Shallow timeseries results shown for the below 2 mg/L results). The first row represents the lowest riverine nutrient concentration inputs, the second mean riverine nutrient concentration inputs, and the bottom the greatest riverine nutrient concentration inputs. The first column represents the lowest solar irradiance inputs, the second the mean solar irradiance inputs, the third column is the highest solar irradiance inputs. For details on values used, go to Section 3

Fig. 8 Spatial chlorophyll concentration results under varying sensitivity tests. The results for changing river flows are as shown in (a) 2.5 m^3s^{-1}, (b) 5 m^3s^{-1}, (c) 7.5 m^3s^{-1}, and (d) 10 m^3s^{-1}. In each of a-d, the first row represents the lowest riverine nutrient concentration inputs, the second mean riverine nutrient concentration inputs, and the bottom the greatest riverine nutrient concentration inputs. Then, in each of a-d, the first column represents the lowest solar irradiance inputs, the second the mean solar irradiance inputs, the third column is the highest solar irradiance inputs. For details on values used, go to Section 3

Fig. 9 The number of days in which average chlorophyll concentrations exceed 0.015 mg/L under varying sensitivity tests. Only results under the highest riverine nutrient concentration are presented. Results under the lowest solar irradiance inputs are shown in a, mean solar irradiance inputs results in b, and highest solar irradiance inputs in c. For details on the nutrient and solar values used, go to Section 3

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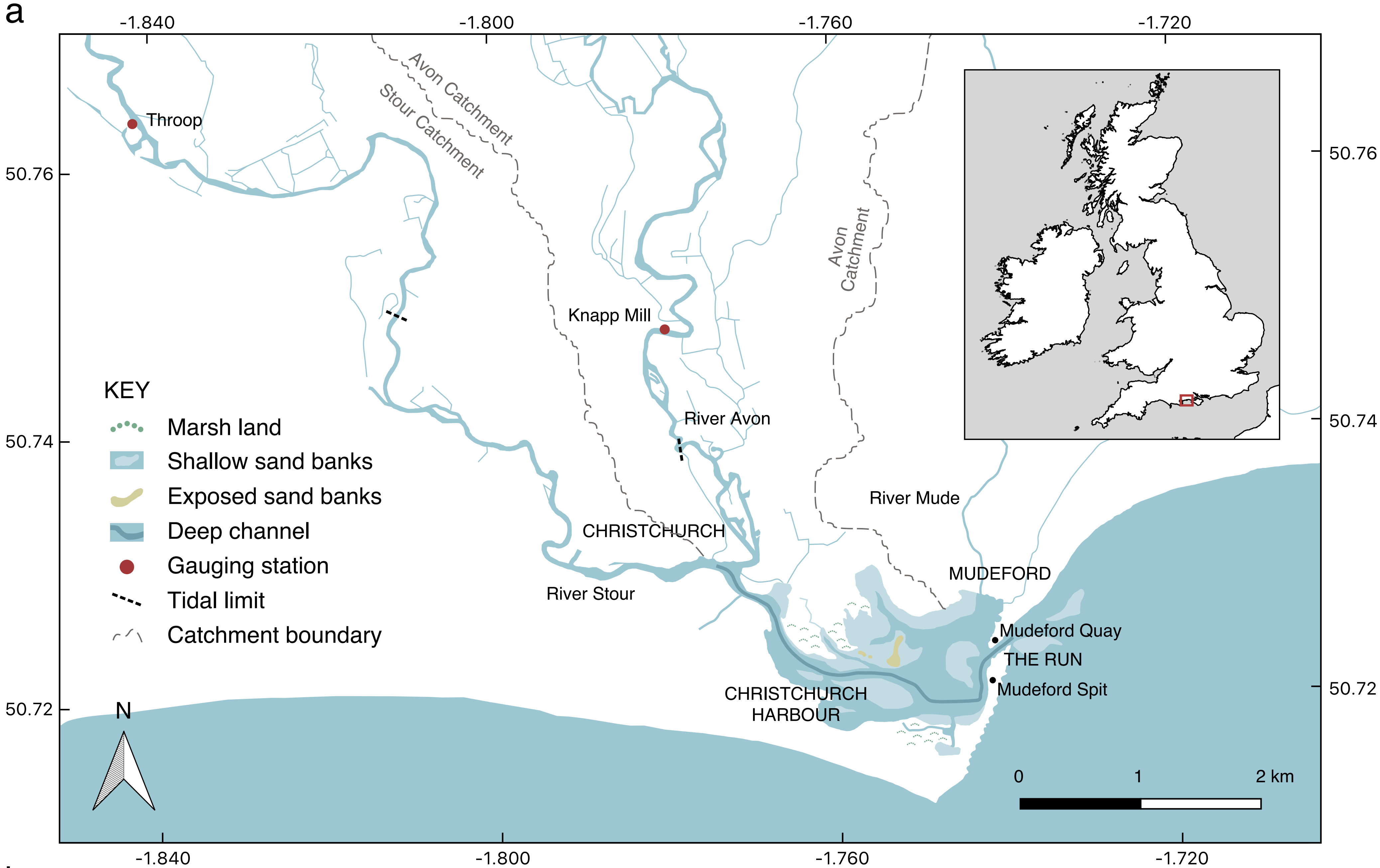

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CHRISTCHURCH
River Stour
MUDEFORD
Mudeford Quay
THE RUN
Mudeford Spit
CHRISTCHURCH HARBOUR
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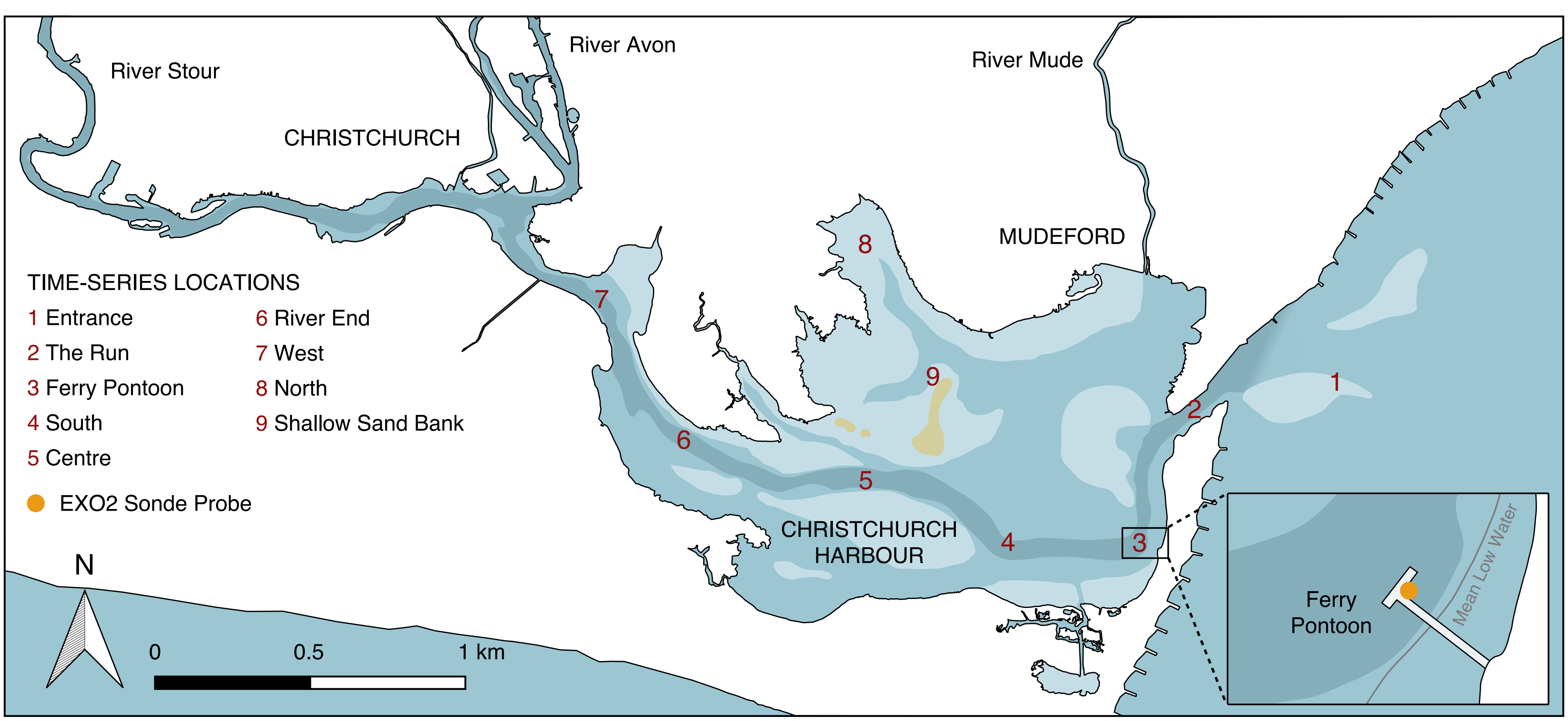

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4 South
5 Centre
6 River End
7 West
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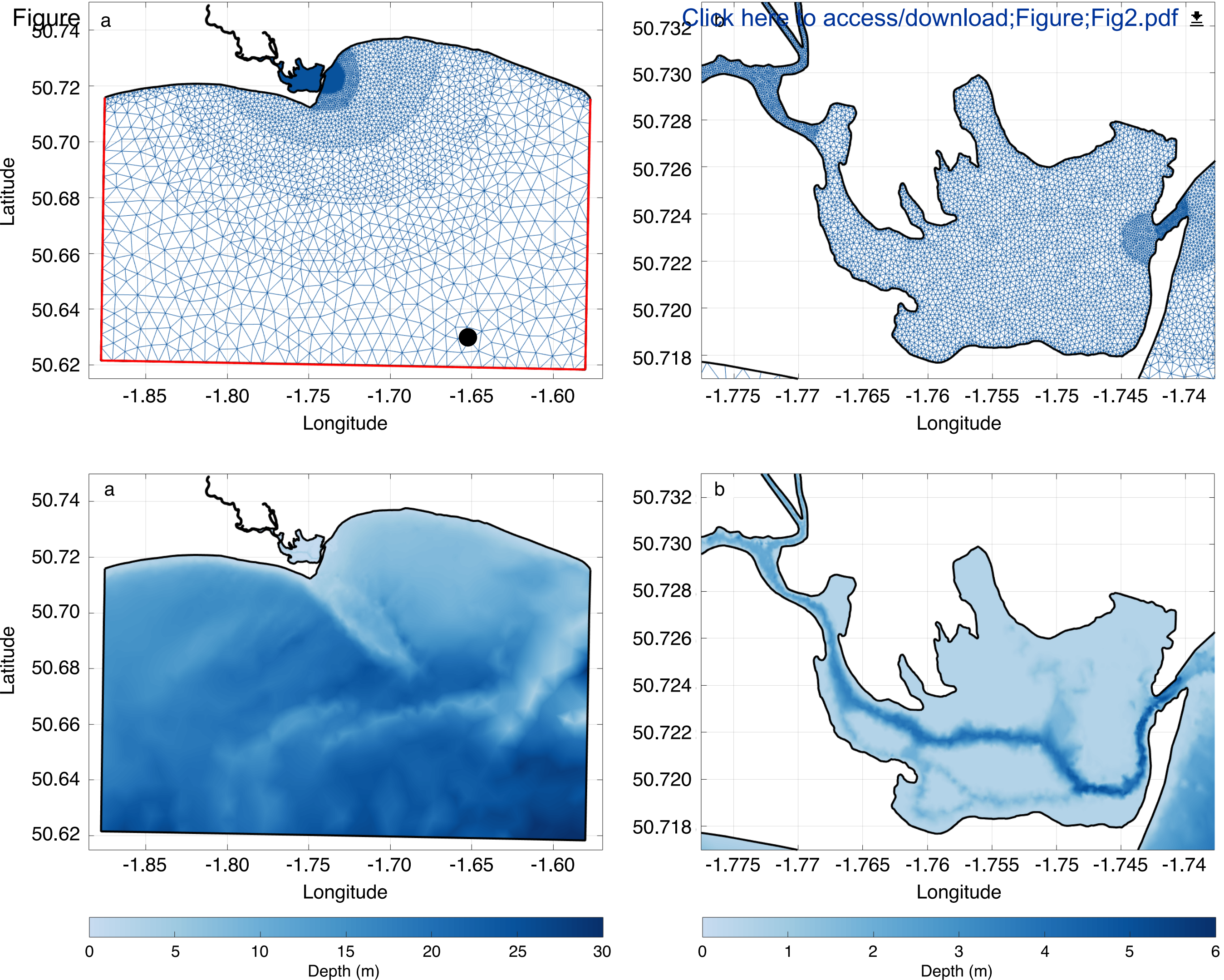
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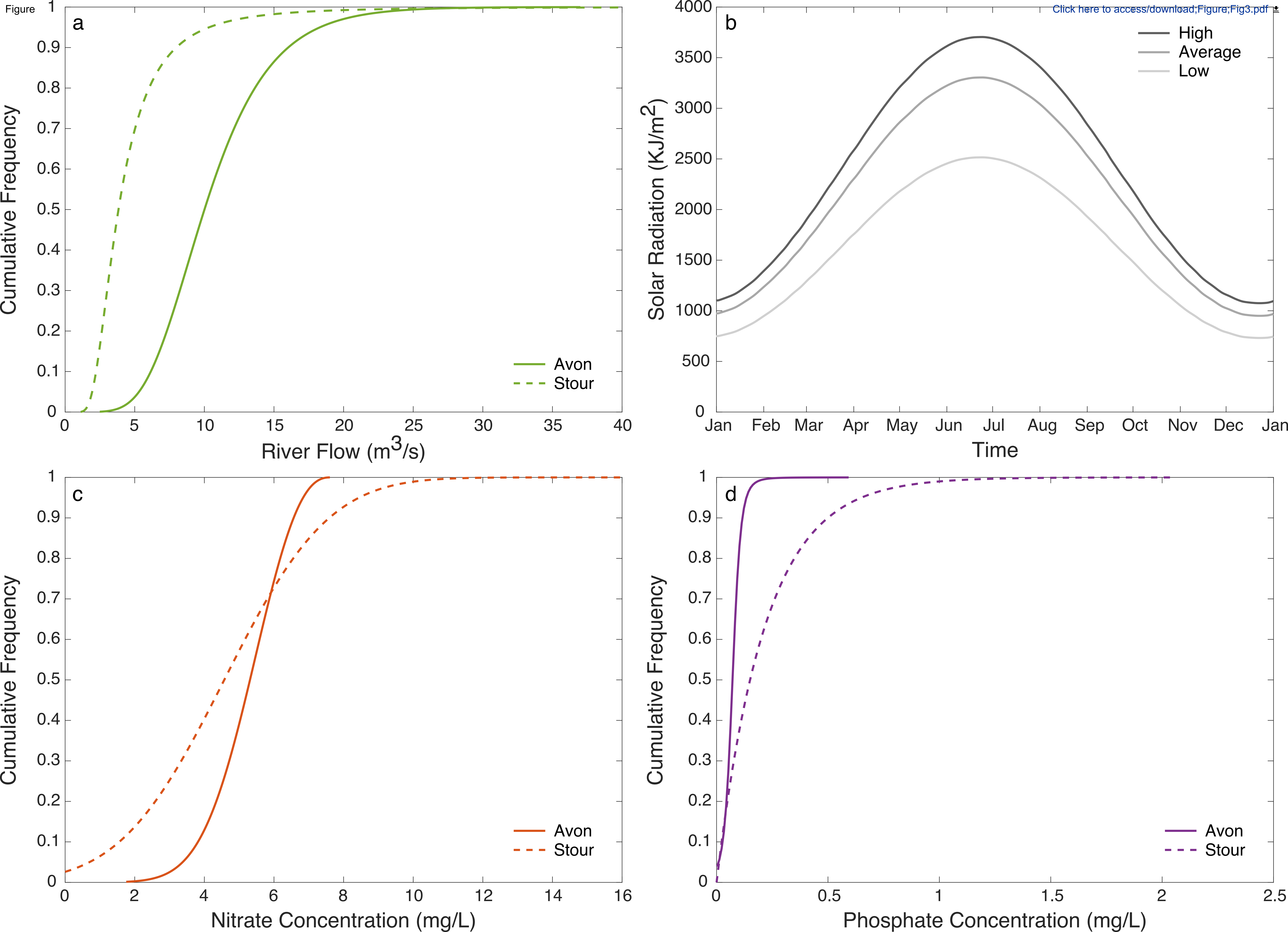
Figure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River Flow (m3/s)
Avon
Stour
b
Solar Radiation (KJ/m2)
Time
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Average
Low
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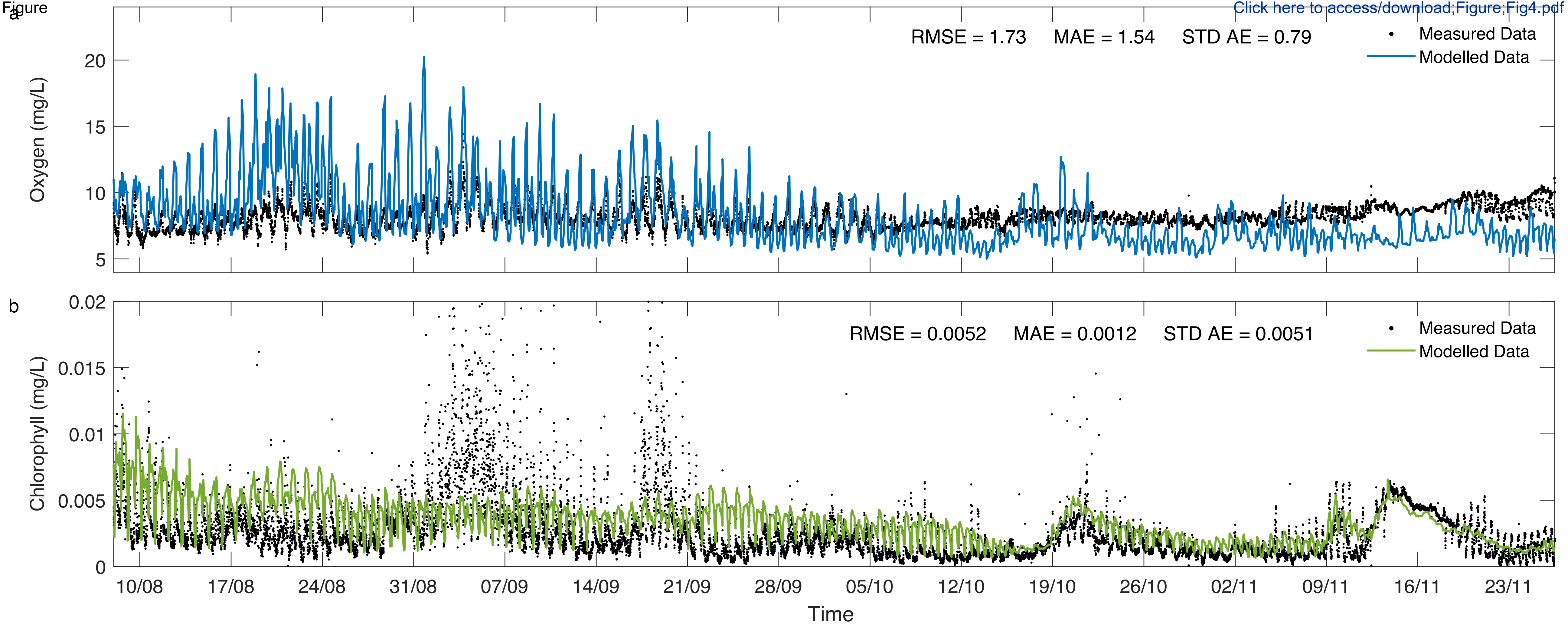
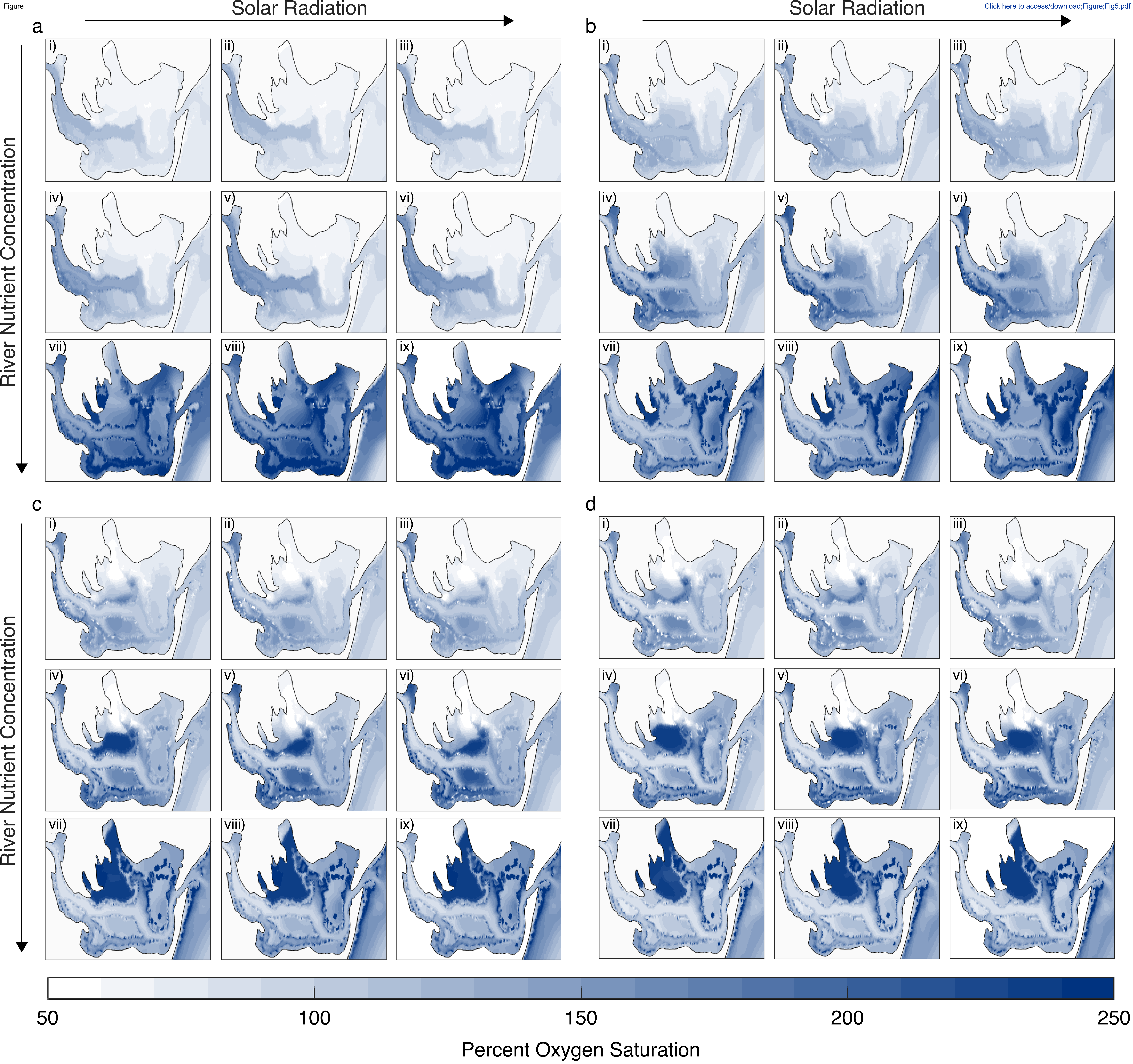
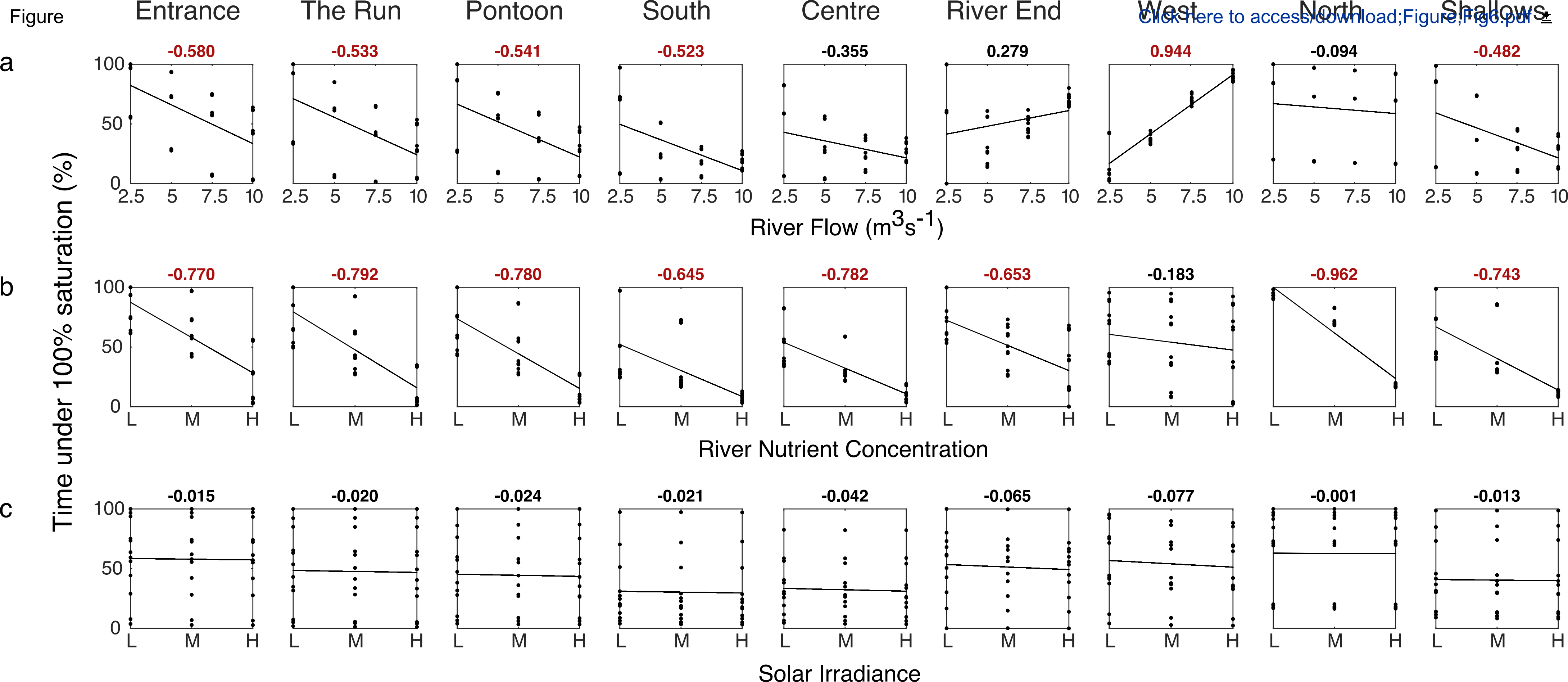
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
c
Cumulative Frequency
Nitrate Concentration (mg/L)
Avon
Stour
d
Cumulative Frequency
Phosphate Concentration (mg/L)
Avon
Stour

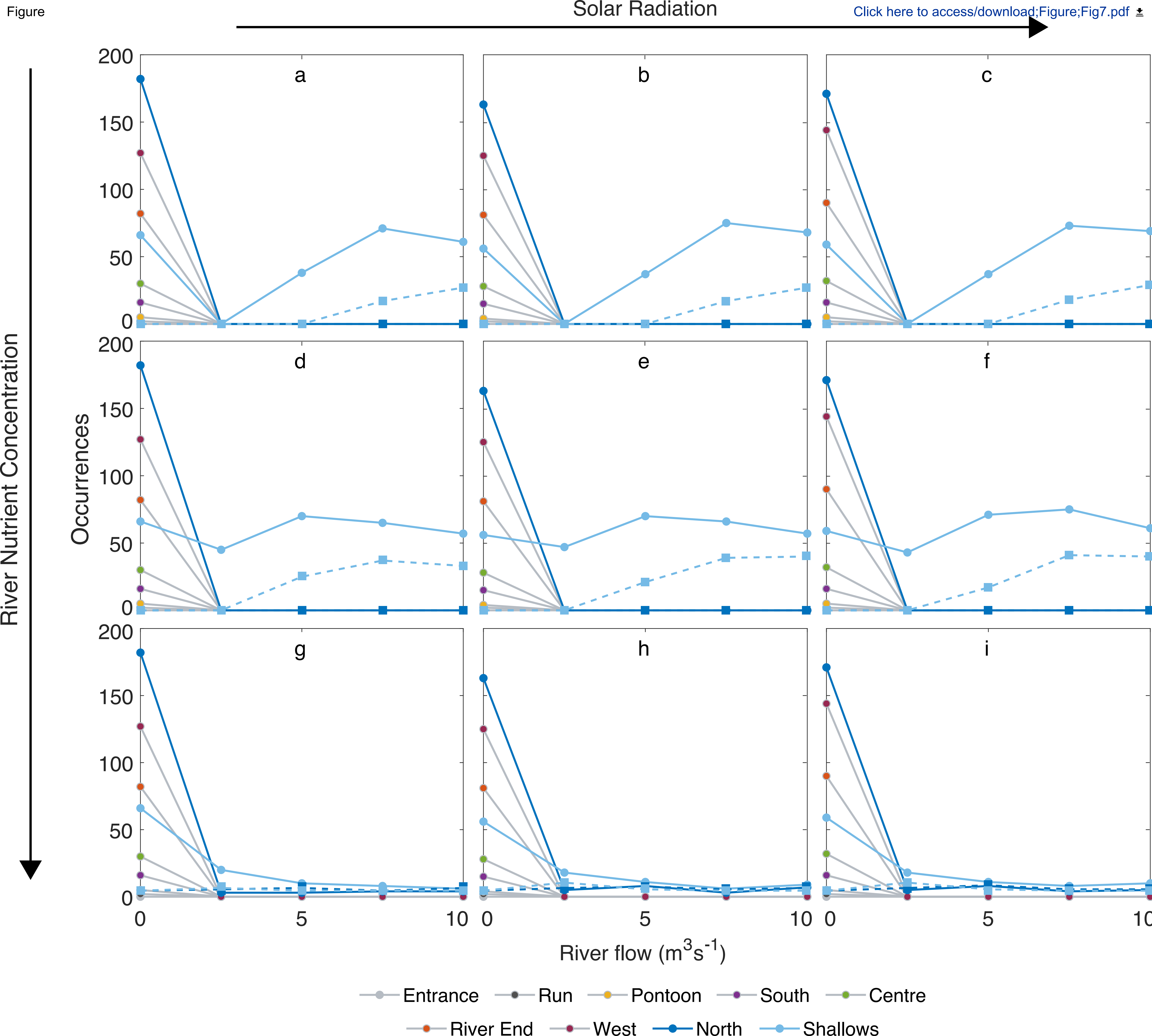
Figure

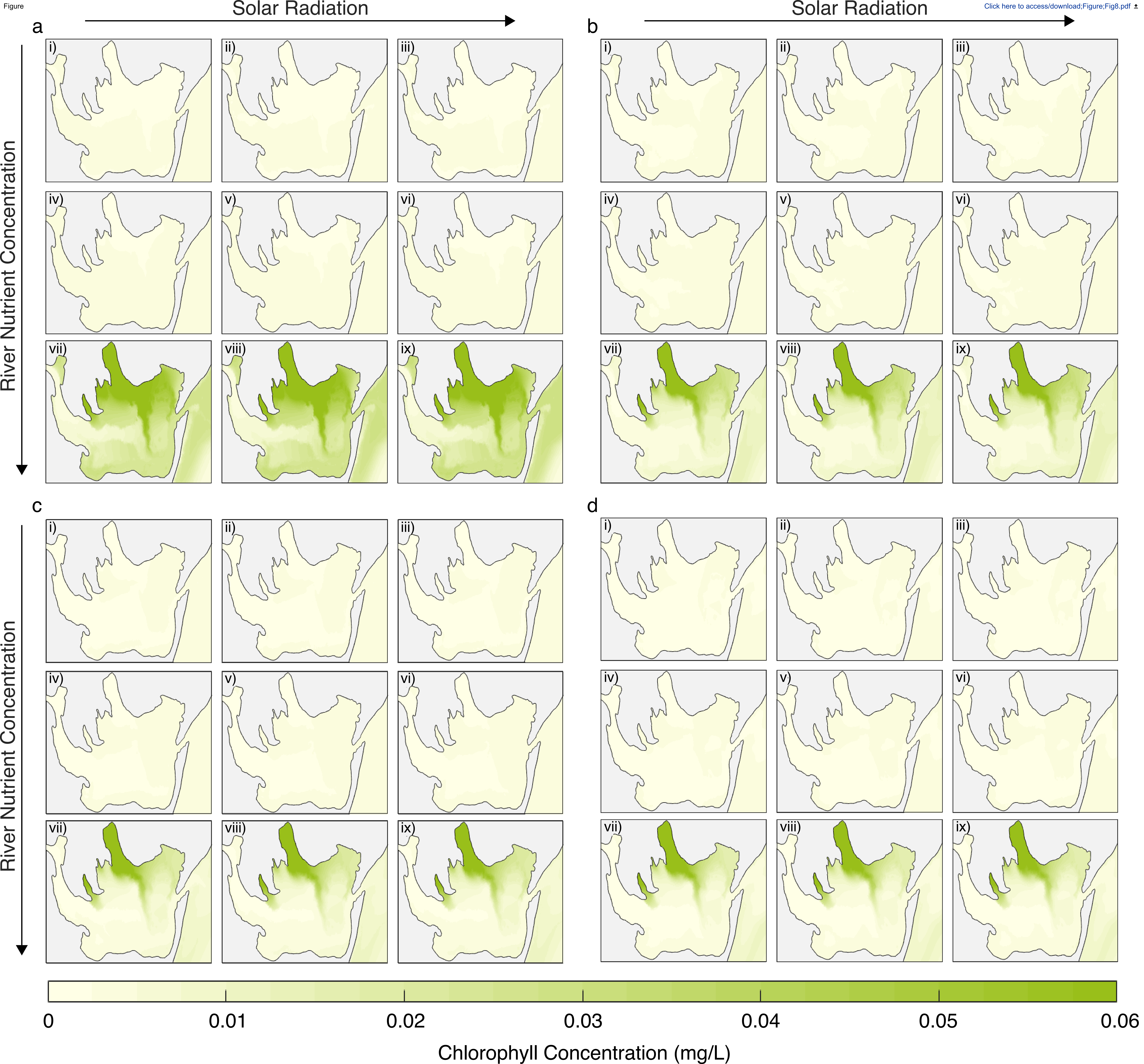

a
RMSE = 1.73
MAE = 1.54
STD AE = 0.79
Measured Data
Modelled Data
Oxygen (mg/L)
20
15
10
5
b
RMSE = 0.0052
MAE = 0.0012
STD AE = 0.0051
Measured Data
Modelled Data
Chlorophyll (mg/L)
0.02
0.015
0.01
0.005
0
10/08
17/08
24/08
31/08
07/09
14/09
21/09
28/09
05/10
12/10
19/10
26/10
02/11
09/11
16/11
23/11
Time

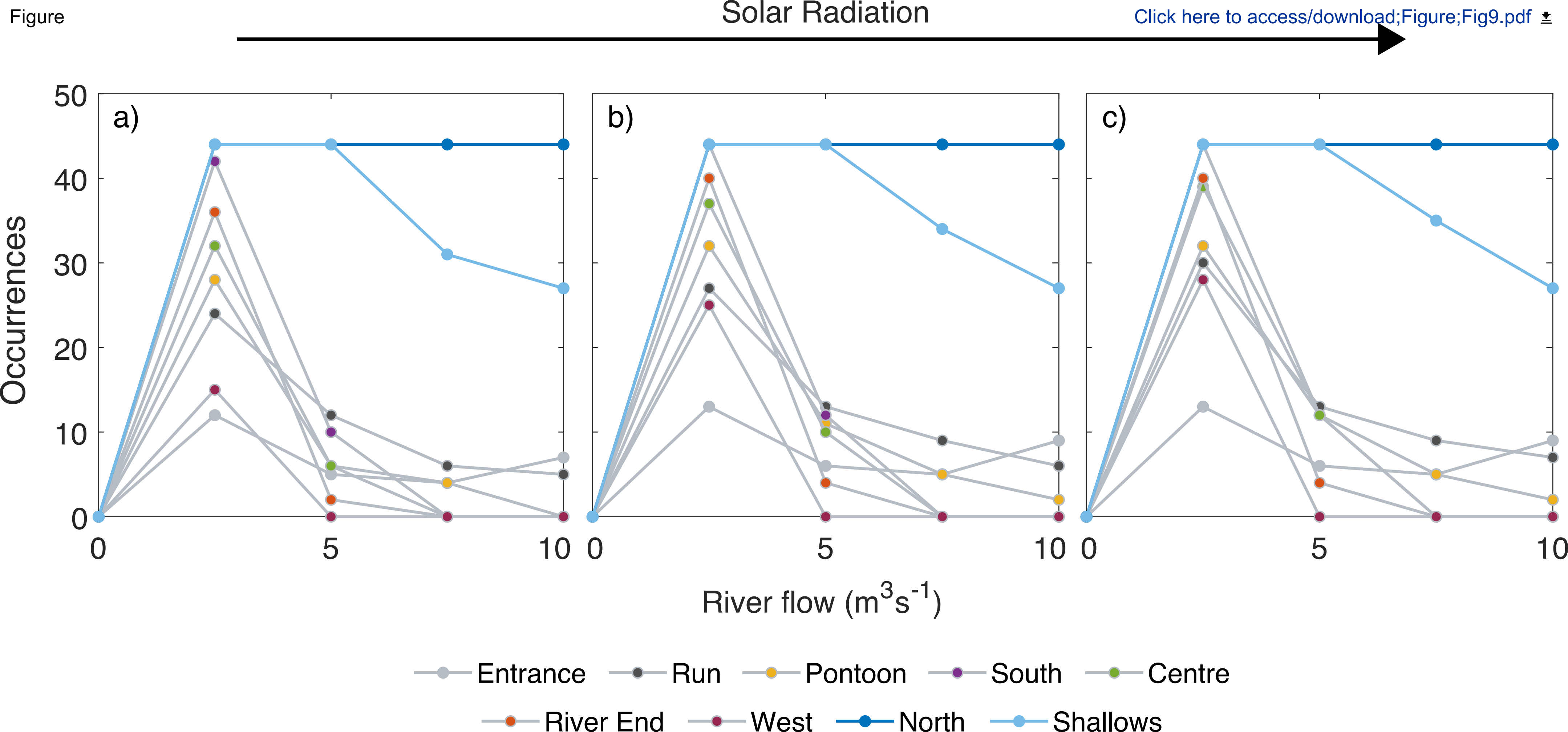

Solar Radiation
Solar Radiation
River Nutrient Concentration
River Nutrient Concentration
a
b
c
d
i)
ii)
iii)
iv)
v)
vi)
vii)
viii)
ix)
50
100
150
200
250
Percent Oxygen Saturation

Figure


Entrance
The Run
Pontoon
South
Centre
River End
West
North
Shallows
a
-0.580
-0.533
-0.541
-0.523
-0.355
0.279
0.944
-0.094
-0.482
River Flow (m3s-1)
b
-0.770
-0.792
-0.780
-0.645
-0.782
-0.653
-0.183
-0.962
-0.743
River Nutrient Concentration
c
-0.015
-0.020
-0.024
-0.021
-0.042
-0.065
-0.077
-0.001
-0.013
Solar Irradiance
Time under 100% saturation (%)


Solar Radiation
River Nutrient Concentration
Occurrences
a
b
c
d
e
f
g
h
i
200
150
100
50
0
0
5
10
River flow (m^{3}s^{-1})
Entrance
Run
Pontoon
South
Centre
River End
West
North
Shallows


Solar Radiation
Solar Radiation
River Nutrient Concentration
River Nutrient Concentration
a
b
c
d
i)
ii)
iii)
iv)
v)
vi)
vii)
viii)
ix)
0
0.01
0.02
0.03
0.04
0.05
0.06
Chlorophyll Concentration (mg/L)


Solar Radiation
Occurrences
a)
b)
c)
River flow (m3s-1)
Entrance
Run
Pontoon
South
Centre
River End
West
North
Shallows