Aug 2016

The Swan-Canning

Estuarine Response Model

(SCERM) v1

Model Validation and Performance Assessment

Aquatic Eco Dynamics

Department of Parks and Wildlife

SWAN CANNING RIVERPARK

THE UNIVERSITY OF WESTERN AUSTRALIA

Government of Western Australia Department of Water

Executive Summary

To support the sustainable management of the Swan-Canning Estuary (SCE) in Western Australia, an "Estuarine Response Model" platform has been developed to assist in supporting our understanding of the drivers of water quality, and to assess management initiatives. This report summarises assessment of the TUFLOW-FV – AED2 coupled hydrodynamic-biogeochemical modelling platform applied to the SCE over the period from 2008-2012. Two model domains were assessed for the system, one spanning the "Upper Swan" (upstream of the Narrows, where many of the current water quality issues are focused), and the second spanning the "Full Domain" (from Fremantle to Gt Northern Hwy).

The model was configured to operate in 3D and predicted the changes in salinity, temperature, and velocity, in addition to water quality parameters including those related to light, suspended sediment, oxygen, nutrients and phytoplankton. The model parameters were manually adjusted to fit the available monitoring data from 2008-2009, however, note that parameters were largely set based on values from the literature review presented in the accompanying report (Hipsey et al. 2016). A total of 53 monitoring sites were included in the assessment, for 14 measured water quality attributes, and where possible surface and bottom values were individually assessed. The simulation was run for a further two years as a validation, giving a total simulation period from 2008-2012, and allowed the model performance to be assessed in both wet and dry years.

The model was able to accurately predict most aspects of the system, with prediction quality in the order (best to worst): salinity, temperature, oxygen, nutrients, phytoplankton, turbidity. Compared to model applications presented for other sites in Australia and overseas, the model performed very well in capturing salinity, temperature, oxygen, and for some of the nutrient pools. Reasonable predictions were obtained for other nutrient pools and chlorophyll-a. Further work is specifically required to improve the predictions of Dissolved Organic Nitrogen (DON), Suspended Solids (SS) and ortho-phosphate (PO_4) in the next round of model development and calibration.

In addition to the validation against the monitoring data, the model demonstrated its potential to provide insights into the controls on nutrient cycles and algal biomass. The model has captured the drivers of phytoplankton bloom formation and demonstrated its ability to assist in unravelling the complex interplay of temperature, salinity, light and nutrients, flushing and competition. However, it is noted that these predictions are a first attempt at capturing these dynamics, and further work is required to explore in detail and build more confidence that it is able to accurately forecast harmful algal blooms, including both biomass and hotspot of high bloom risk. Further validation of the phytoplankton module of the model against more recent data from 2013-2016 is therefore recommended.

A final model simulation was also undertaken to predict seagrass meadow productivity in the Lower Swan (using the Full Domain), however, further work is required to assess the ability of the model to capture spatiotemporal changes in seagrass biomass, and to characterise the sensitivity of seagrass productivity to the overlying water quality properties.

Several priority areas are identified for improving model accuracy and capability, characterised separately for the Upper and Lower Swan. Despite the need for continuing calibration effort and development of the model system the present study has further advanced our ability to model the SCE system and, in its present form, the model is now suitable for assessing management scenarios associated with artificial oxygenation, nutrient load management and/or climate change, bearing in mind deficiencies in the predictions outlined within the report.

Outcomes from this model development and assessment include:

- Improved capability of the Swan model(s) for future decision support use in oxygenation management;
- A model domain extending across the estuary to the ocean, that can be used as a basis for future model development of the estuary system.
- A coupled hydrodynamic-biogeochemistry-model that can simulate phytoplankton under a range of hydrodynamic conditions and provide a detailed understanding on temperature, light and nutrient controls on bloom development;

CONTRIBUTORS

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Contents

1. Introduction & Objectives

Initial steps towards the development of an Estuarine Response Model for the Swan-Canning Estuary (SCE) have been conducted through a collaborative project between the Department of Parks and Wildlife, Department of Water and The University of Western Australia over the period from 2014-2016. The overall scope and objectives of the project were:

1. To further develop the existing model in the Upper Swan to improve its ability to support the operation and management of the oxygenation plants by:
   a) Testing the model over the period 2007-2013 and by comparing against measured water quality data;
   b) Validating spatial and seasonal variability of nutrient budget;
   c) Incorporating spatial and seasonal variability in algal dynamics; and
   d) Building the role of invertebrates into oxygen and nutrient dynamics;
2. To explore the capacity of the model in the Upper Swan to predict phytoplankton dynamics under different hydrodynamic conditions, with the focus in the first instance on broad functional groups.
3. To extend the estuary model domain to include the area between the Narrows and Fremantle.

The outcomes of this project are summarised in two reports: i) the motivation for the development of a coupled hydrodynamic-biogeochemical model of the SCE is outlined in detail in an accompanying report (Hipsey et al., 2016), which also justifies the model approach and scientific basis based on prior data collection and research that has been undertaken; and ii) this report complements that description by focusing on documenting the model application and performance of the model, with the above project objectives in mind. Specifically, this report aims to:

- Describe the approach to the application of the "TUFLOW-FV – AED2" hydrodynamic-biogeochemical model platform to the SCE and the simulations undertaken;
- Document the results of the model simulations undertaken (using the parameters presented in the accompanying volume), and to compare the results against historical data collected within the system (where available) over the period from 2008-2012;
- Comment on the performance of the model and identify areas for further improvement and ongoing calibration effort.

These aims address all three of the project objectives, however, note that the inclusion of invertebrates (1d) is being undertaken by Sam Robinson as part of his ongoing PhD work, and not further discussed in this report (readers are however referred to preliminary results assessing sensitivity of sediment fluxes to bioturbation by invertebrates presented within the accompanying science report). Note also that the period of simulation that is reported here was limited to 2008-2012 to enable more efficient running of the model.

An overview of the model domains and simulation setup details is presented in Section 2, and results of the model are presented in Section 3 (Upper Swan) & Section 4 (Full Domain). Results are presented for a range of relevant variables including salinity, temperature, turbidity, oxygen, nutrients and phytoplankton, and preliminary results from a test of a seagrass module are also summarised.

2. Model Setup & Simulated Variables

The estuary is simulated using the TUFLOW-FV hydrodynamic model which is dynamically coupled with the AED2 water quality model. For more information on the two models refer : http://www.tuflow.com/FV%20Documentation.aspx. Two domains are simulated with the model platform. The first domain extends the previous reported application of this model to the Upper Swan (Hipsey et al., 2014), spanning from the Narrows to Great Northern Highway (Figure 1a), and the second domain spans the full extent of the estuary from Fremantle to Great Northern Highway (Figure 1b). Prior to validation of the biogeochemical model variables, the version of TUFLOW-FV used in the previous report was updated to the 2015 version, and a sensitivity assessment of the model to spatial mesh resolution of the Upper Swan region was undertaken (Appendix A). This identified that increasing resolution was only marginally advantageous in terms of salt-wedge prediction but with substantial computational cost. The final mesh used was therefore considered a compromise between accuracy and model run-time. AED2 version 1.1 was used for water quality simulation.

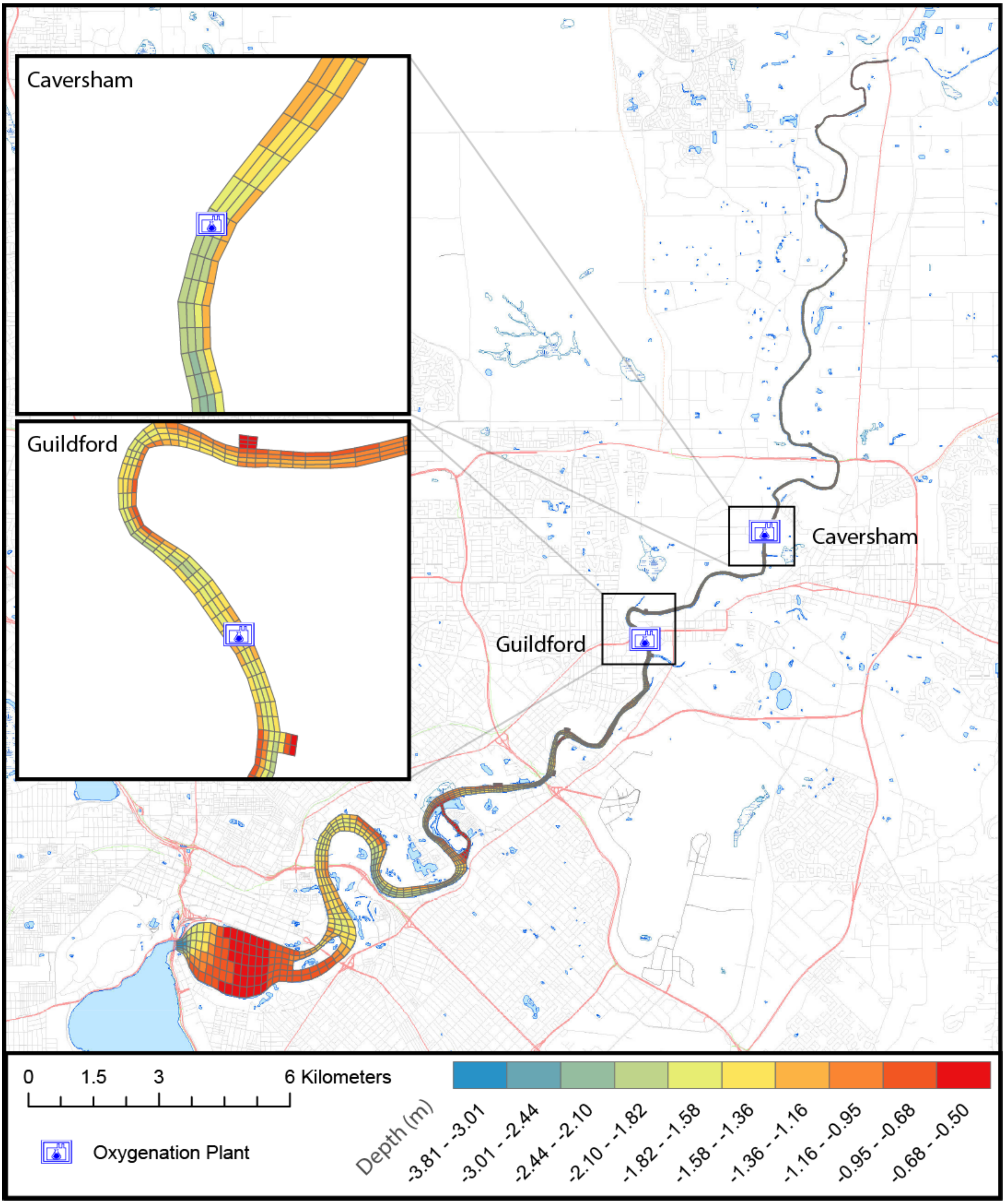

Figure 1a. Upper Swan model domain (as used in the "Upper Swan" and "Full Domain" simulations).

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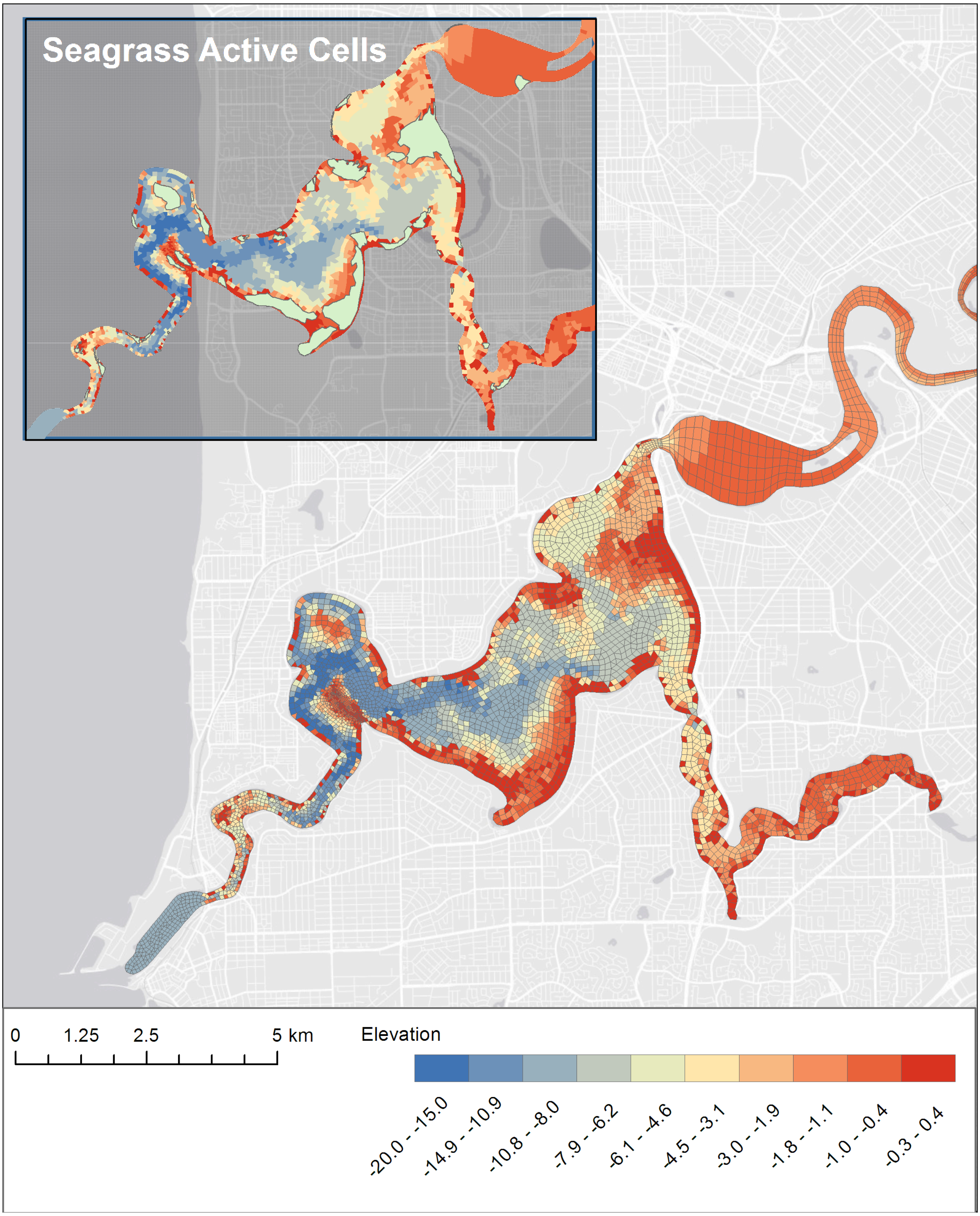


Figure 1b. Lower Swan model domain (as used in the "Full Domain" simulations). Inset shows the regions where seagrass (*Halophila*) biomass was configured to be present.

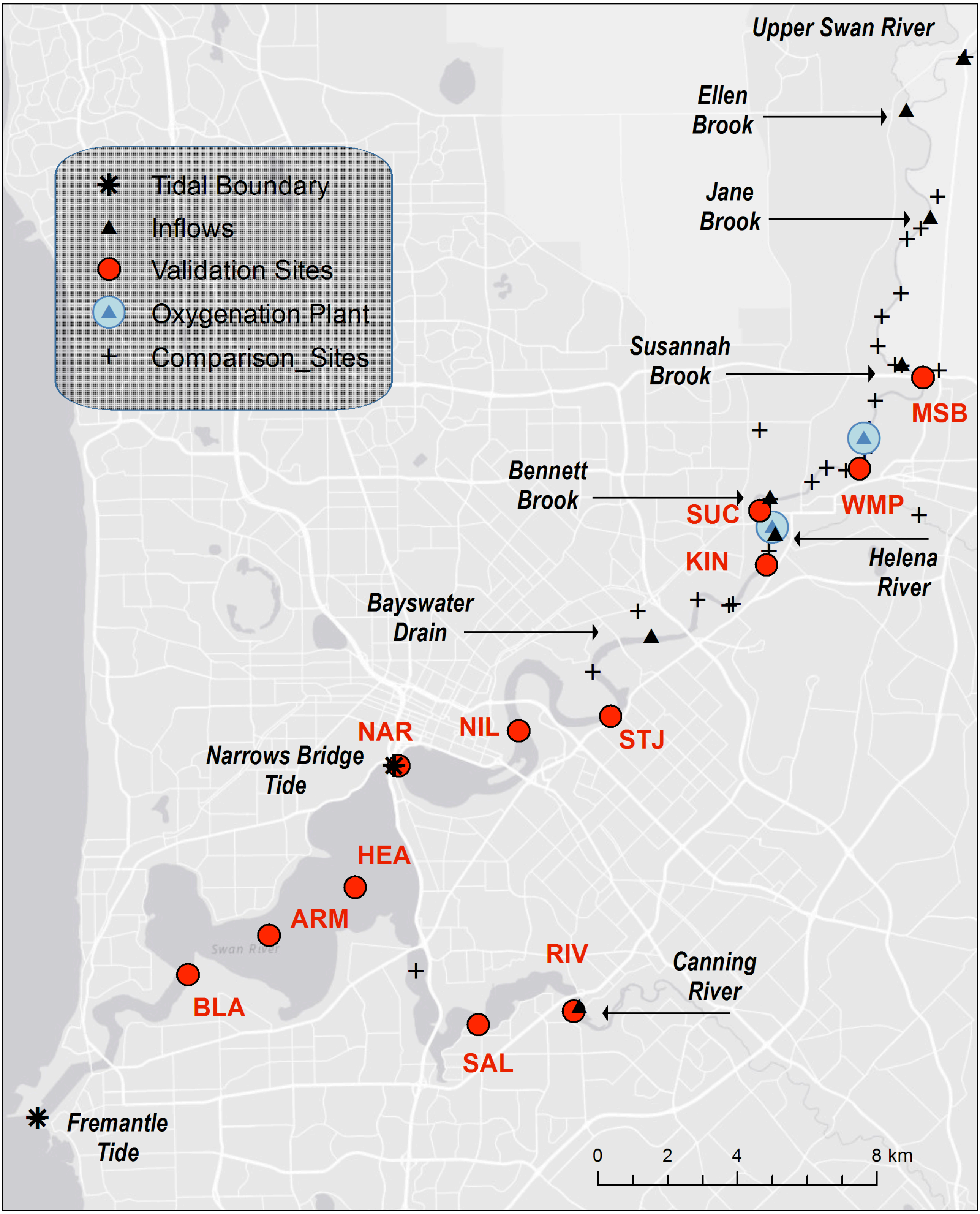


Figure 2. Location of tidal and inflow boundary locations, oxygenation plants and sites used to assess the model. The Validation sites are shown in this report but others were used during the model assessment and calibration.

The full-domain simulation includes the same mesh upstream of the Narrows and is identical in configuration except the ocean boundary condition is applied at Fremantle instead of the Narrows (Table 1). Note the full-domain simulation ends at the Kent St weir, and does not include the Kent St weir pool (see Hipsey et al., 2014, for more information on this region).

Table 1. Summary of the boundary condition data used for both of the developed model domains.

Boundary Condition	Full domain (Hydrodynamics)	Full domain (Water Quality)	Upper Swan domain (Hydrodynamics)	Upper Swan domain (Water Quality)
Tidal forcing	Data from the Fremantle tide gauge from the DOT is applied at Fremantle, also using data from the DOW Fremantle (**FREO**) sampling point	DOW 6160258	Data from the Barrack St Jetty gauge from the DOT is applied at the Narrows, also using data from the DOW Narrows (**NAR**) sampling point.	DOW 6160262
Upper Swan River	DOW 616076	DOW 616076	DOW 616076	DOW 616076
Ellen Brook	DOW 616189	DOW 616189	DOW 616189	DOW 616189
Jane Brook	DOW 616178	DOW 616088	DOW 616178	DOW 616088
Susannah Brook	DOW 616099	DOW 616099	DOW 616099	DOW 616099
Helena River	DOW 616086	DOW 616086	DOW 616086	DOW 616086
Bennet Brook	DOW 616084	DOW 616084	DOW 616084	DOW 616084
Bayswater Drain	DOW 616082	DOW 616082	DOW 616082	DOW 616082
Canning River	DOW 616082	DOW 6162994	N/A	N/A
Guildford Oxy Plant	As described in Hipsey et al. (2014)		As described in Hipsey et al. (2014)	
Caversham Oxy Plant	As described in Hipsey et al. (2014)		As described in Hipsey et al. (2014)	
Meteorological data	DAFWA South Perth Meteorological Station Data		DAFWA South Perth Meteorological Station Data	

Variables simulated within the models are summarised in Table 2. For detailed overview of these variables and how they are computed the reader is referred to the accompanying report (Hipsey et al., 2016). In total, 23 state (transportable) variables were simulated from the "aed2_tracer", "aed2_oxygen", "aed2_nitrogen", "aed2_phosphorus", "aed2_organic_matter", "aed2_phytoplankton" and "aed2_macrophyte" modules, and 42 diagnostic variables were output (of which only several are presented here). The *Halophila* biomass was only included in the "full-domain" simulation, and set to be included only in the cells within the meadow zones identified in Forbes and Kilminster (2016), as shown in Figure 1b.

Users are able to download the model input files, including model configuration details and boundary condition data, from: https://github.com/AquaticEcoDynamics/StudySites/tree/master/TFV_AED2_Swan_Models

The model parameters were manually adjusted to fit the available monitoring data from 2008-2009 by running numerous calibration simulations, however, note that parameters were largely set based on values from the literature review presented in the accompanying report (Hipsey et al. 2016). A total of 53 monitoring sites were included in the assessment (Appendix B), for 14 measured water quality attributes, and where possible surface and bottom values were individually assessed. The simulation was run for a further two years as a validation, giving a total simulation period from 2008-2012, and allowed the model performance to be assessed in both wet and dry years.

Note that model was assessed against the monitoring data at all sites, of which only 10 are used to summarise model performance here. The correlation (R^2) and mean average error (MAE) were computed for each site and the range across the sites (considering both the top and bottom of the estuary) are reported for each variable below. These are categorised as being weakly, moderately or highly accurate by assessing the model predictions and the R^2 and MAE relative to what is typically reported in the literature for water quality models, as described by the summary of Arhonditsis and Brett (2004). Note that it is possible to have a good prediction with low R^2, if the model is capturing the mean concentration but not the "noise" in the observational data. Similarly, the model may have a good R^2, but poor MAE, indicating the predictions are biased (e.g., as a consistent under- or over-prediction). These factors are considered in categorising prediction performance.

Table 2: Relevant variables being simulated in the current model validation and assessment.

Variable	Units *	Common Name	Process Description
Physical variables			
T	°C	Temperature	Temperature modelled by hydrodynamic model, subject to surface heating and cooling processes
S	psu	Salinity	Salinity simulated by the hydrodynamics model, impacting density. Subject to tributary, drain and groundwater inputs, and evapo-concentration
EC	uS cm^{-1}	Electrical conductivity	Derived from salinity variable
$\boldsymbol{I_{PAR}}$	mE m^{-2} s^{-1}	Shortwave light intensity	The PAR fraction of incident light, I_0, is attenuated as a function of depth
$\boldsymbol{I_{UV}}$	mE m^{-2} s^{-1}	UV light intensity	The UV fraction of incident light, I_0, is attenuated as a function of depth
η_{PAR}	m^{-1}	PAR extinction coefficient	Bandwidth specific extinction coefficient computed based on organic matter and suspended material
η_{UV}	m^{-1}	UV extinction coefficient	
Core biogeochemical variables			
DO	mmol O_2 m^{-3}	Dissolved oxygen	Impacted by photosynthesis, organic decomposition, nitrification, surface exchange, and sediment oxygen demand
RSi	mmol Si m^{-3}	Reactive Silica	Algal uptake and subsequent sedimentation, sediment flux
FRP	mmol P m^{-3}	Filterable reactive phosphorus	Algal uptake, organic mineralization, sediment flux; adsoprtion/desorption to/from particles
FRP-ADS	mmol P m^{-3}	Particulate inorganic phosphorus	Adsoprtion/desorption of/to free FRP
$\boldsymbol{NH_4^+}$	mmol N m^{-3}	Ammonium	Algal uptake, nitrification, organic mineralization, sediment flux
$\boldsymbol{NO_3^-}$	mmol N m^{-3}	Nitrate	Algal uptake, nitrification, denitrification, sediment flux
CPOM	mmol C m^{-3}	Coarse particulate organic matter	Breakdown to POM by macroinvertebrates
DOC-R	mmol C m^{-3}	Refractory DOC	Enzymatic hydrolysis to more labile DOM, sediment flux, photolysis
DON-R	mmol C m^{-3}	Refractory DON	
DOP-R	mmol C m^{-3}	Refractory DOP	
DOC	mmol C m^{-3}	Dissolved organic carbon	Mineralization, algal excretion
DON	mmol N m^{-3}	Dissolved organic nitrogen	
DOP	mmol P m^{-3}	Dissolved organic phosphorus	
POC	mmol C m^{-3}	Particulate organic carbon	Enzymatic hydrolysis (breakdown) to DOM, settling, algal mortality, and loss to grazing
PON	mmol N m^{-3}	Particulate organic nitrogen	
POP	mmol P m^{-3}	Particulate organic phosphorus	
TP	mmol P m^{-3}	Total Phosphorus	Sum of all P state variables
TN	mmol N m^{-3}	Total Nitrogen	Sum of all N state variables
TKN	mmol N m^{-3}	Total Kjedahl Nitrogen	Sum of relevant N state variables
CDOM	mmol C m^{-3}	Chromophoric Dissolved Organic Matter	Related from DOC-R and DOC concentrations
Plankton groups			
BGA	mmol C m^{-3}	Cyanobacteria	Growth based on photosynthesis, respiration, excretion and mortality, and loss to grazing
CRYPT	mmol C m^{-3}	Cryptophytes	
DIATOM	mmol C m^{-3}	Diatoms	
DINO	mmol C m^{-3}	Karlodinium/Dinoflagellate group	
GRN	mmol C m^{-3}	Chlorophytes	
TCHLA	ug Chla L^{-1}	Total Chlorophyll-a	Sum of the algal groups, converted to pigment concentration
Benthic groups			
HALO	mmol C m^{-2}	Halophila biomass	
Suspended sediment and related properties			
$\boldsymbol{SS_s}$	g SS m^{-3}	Suspended solids groups	Settling, resuspension
Turbidity	NTU	Turbidity	Computed based on SS, TCHLA, CPOM and POM

(*) – indicates not configured in SCERM v1

BOLD – indicates a simulated state variable subject to transport and mass conservation, other variables are derived

3. Model Assessment: Upper Swan

The following sub-sections describe the model output specific to the Upper Swan domain, and comment on the model performance and potential reasons for discrepancies, where relevant.

Water Source Apportionment

Prior to assessment of the model water quality variables against monitoring data, the model was run with individual non-reactive tracers (i.e., a "virtual dye") in each of the inputs to the Upper Swan domain to allow characterisation of the extent to which each input was contributing to the overall estuary water mass. The below image (Figure 3) shows the relative contribution of the 6 main sources of water within the domain during a day in July; see the linked animation to understand its variation over time. The results indicate that:

1. The domain is dominated by water from the Narrows or from the Upper Swan (Avon) inflows for most of the year, but pulses in winter from the other major tributaries are clearly identifiable and in some regions contribute up to 50% of the water. Their downstream influence can span 10-20km below the input point.
2. Note this assessment does not consider groundwater contribution which maybe important during the period following the major winter inflows, and further work is required to assess the significance of this water source.

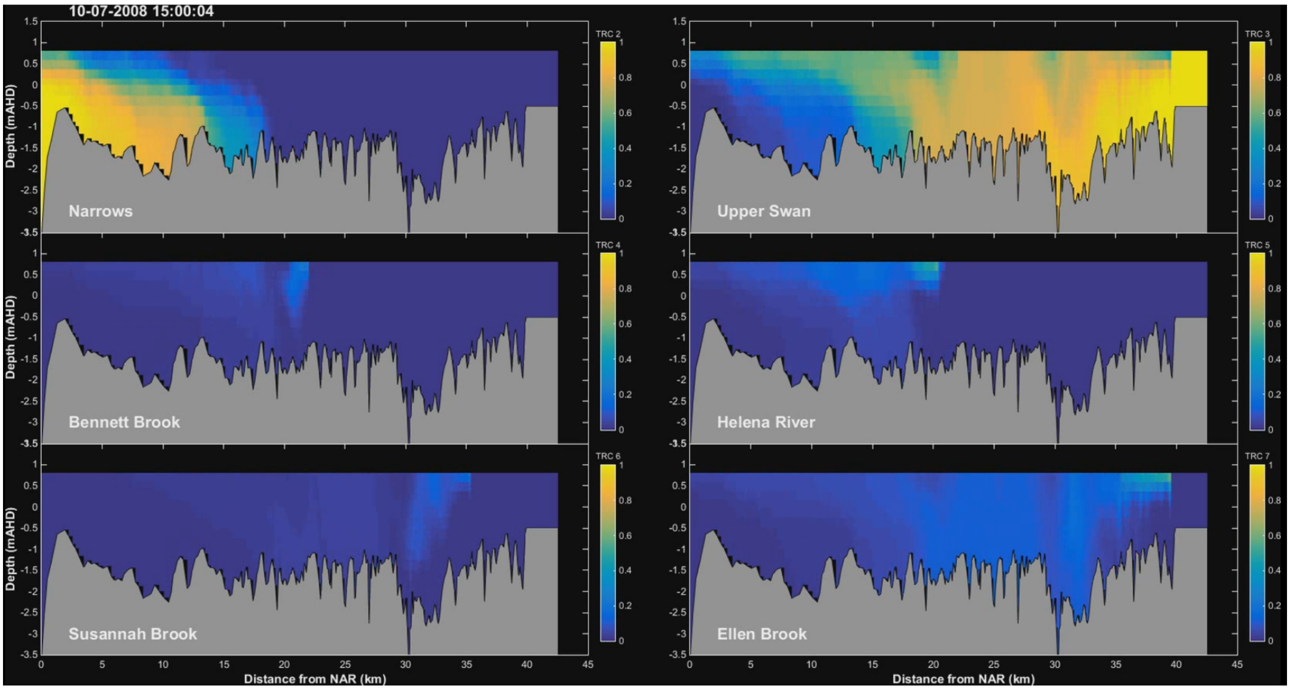


Figure 3. Tracer concentrations entering from each inflow source into the Upper Swan domain. The value indicates the relative contribution of that source to the water at any given location within the domain. View animation @ http://aed.see.uwa.edu.au/research/projects/swan/Swan_SourceTracers.avi

Retention Time

In addition to the tracer simulation we computed the age of the water within the domain, assuming any new water from the inflows or downstream boundary condition (across the Narrows in this case) had an initial age of 0. The results indicate that:

3. The variation in water retention time over the multi-year simulation period is similar upstream of STJ.
4. Depending on the flow hydrograph, the water persists in summer from 70 >150 days, in the Upper Swan.
5. There is a large variability from year to year in the age of water.

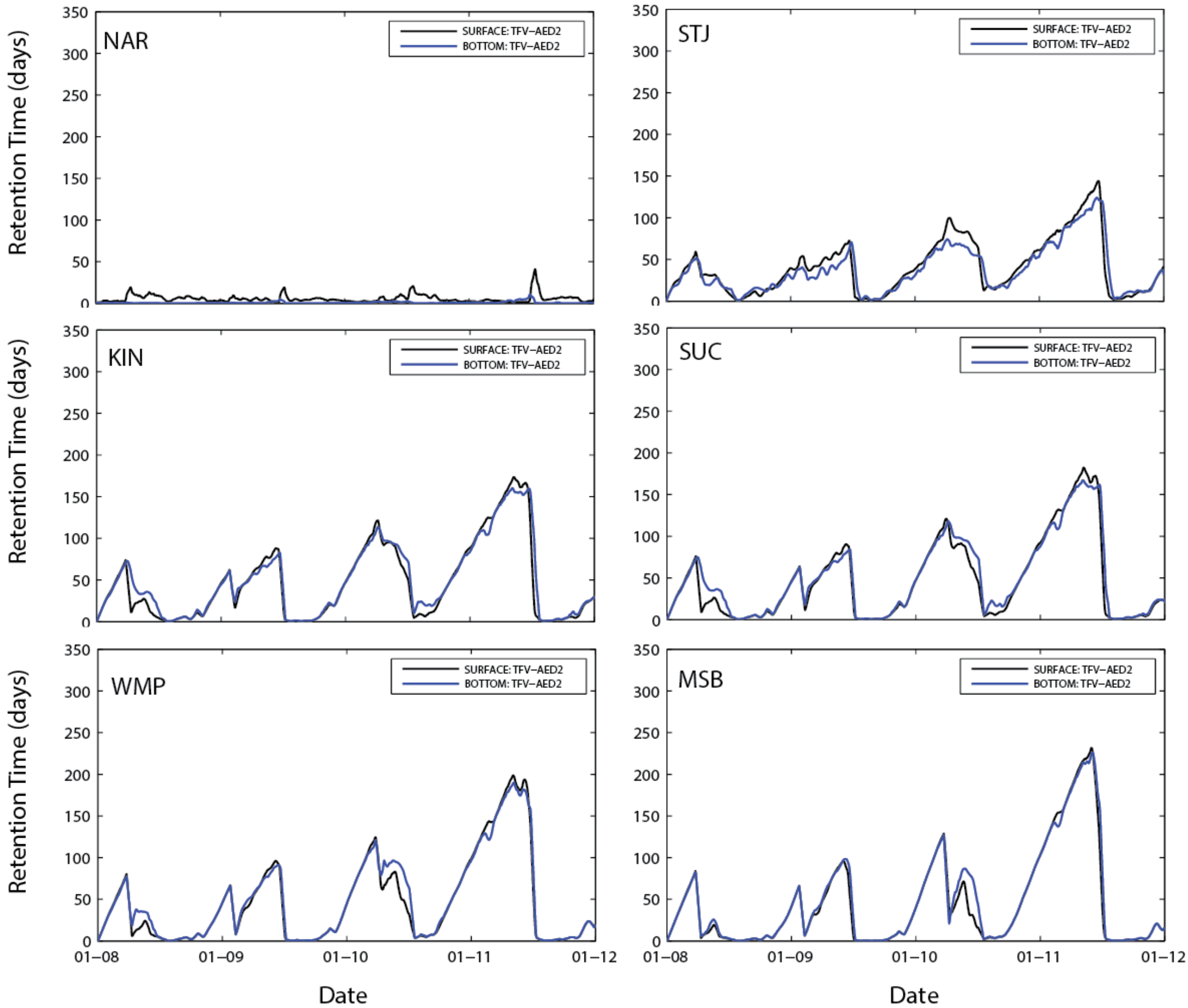


Figure 4. Retention time of water at each site. Note the Narrows site age is based on water entering the system through the Narrows bridge has having a relative age of 0.

Salinity

6. The model confidently captures the vertical and horizontal variation in salinity over the multi-year simulation period.
    - Correlation: $R^2 = 0.90 - 0.97$
    - Average Error: MAE = 1.7 psu

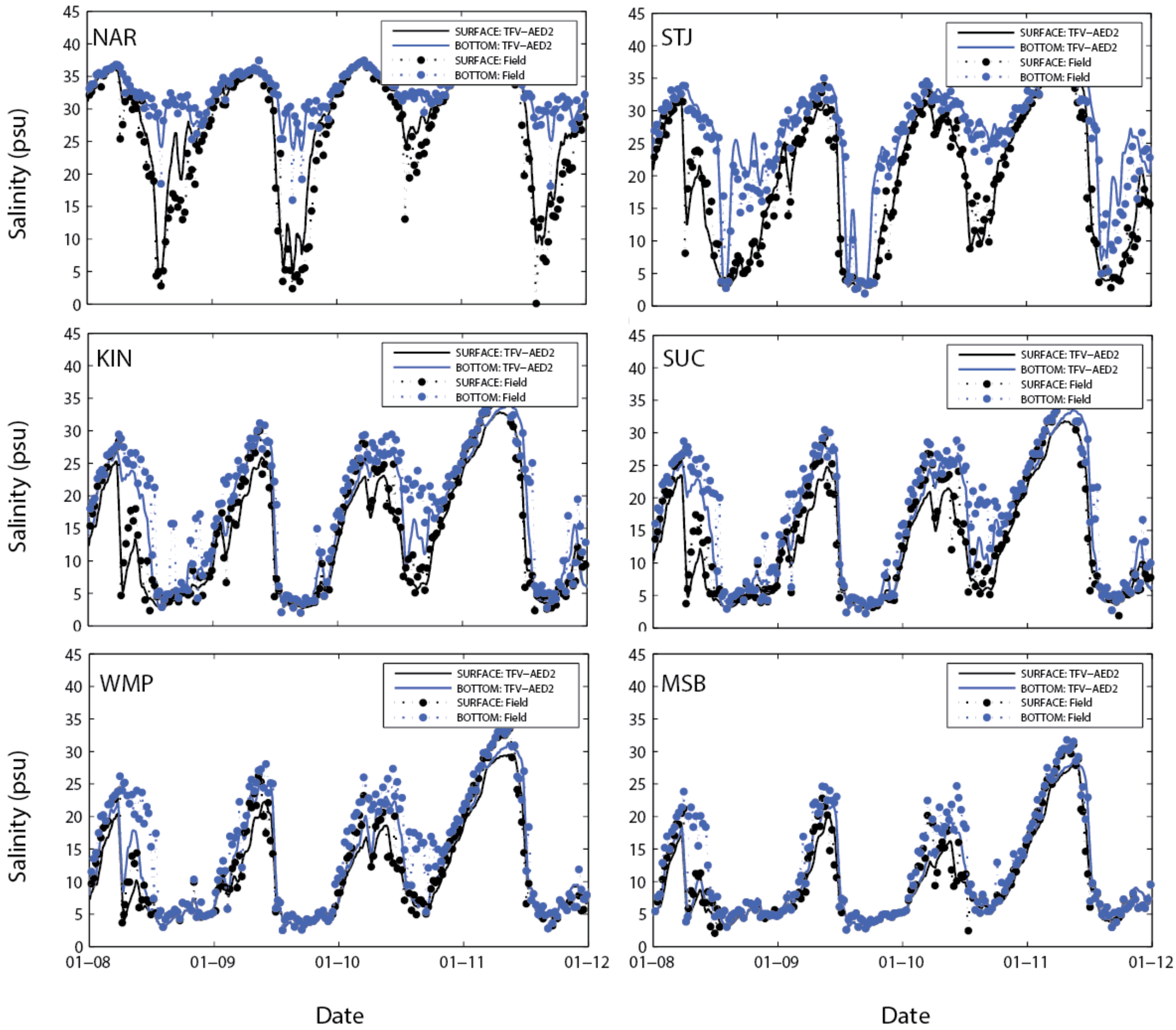


Figure 5. Salinity at six sites within the Upper Swan.

Temperature

7. The model confidently captures the seasonal variation in temperature over the multi-year simulation period:
   - Correlation: R^2 = 0.97 - 0.98
   - Average Error: MAE = 1.3 °C
8. However, the upstream stations (e.g., WMP, MSB) over-heat the water in the peak of summer, suggesting local shading may be playing a role where the river becomes narrower.
9. Diurnal temperature changes were not assessed, however, it is recommended that this be undertaken in the future to better calibrate the surface heat flux parameters.

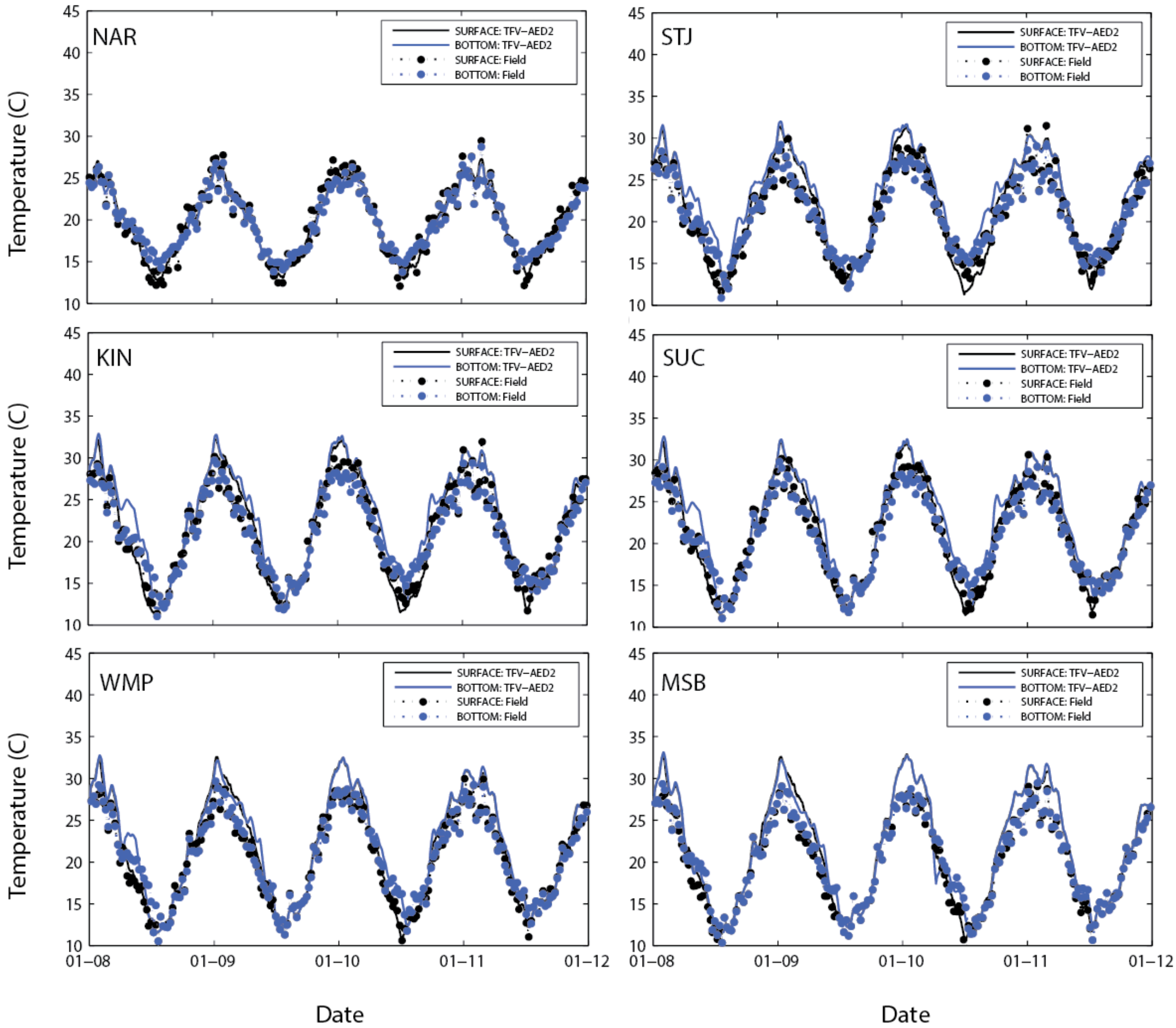


Figure 6. Temperature at six sites within the Upper Swan.

Suspended Solids (SS)

10. The model reasonably captures the seasonal variation in SS over the multi-year simulation period.
    - Correlation: R^2 = 0.22 - 0.80
    - Average Error: MAE = 4.4 mg/L
11. The SS concentration is predicted well during the storm peaks, particularly in the upstream stations, however, the background concentration during dry periods is under predicted.
12. The model has not included resuspension or a fine sediment size group, and it is recommended these are added in the next model version to maintain the dry-weather particle concentrations seen in the field data.
13. The summer under-prediction may cause and over-prediction of photosynthesis rates due to inadequate light attenuation.

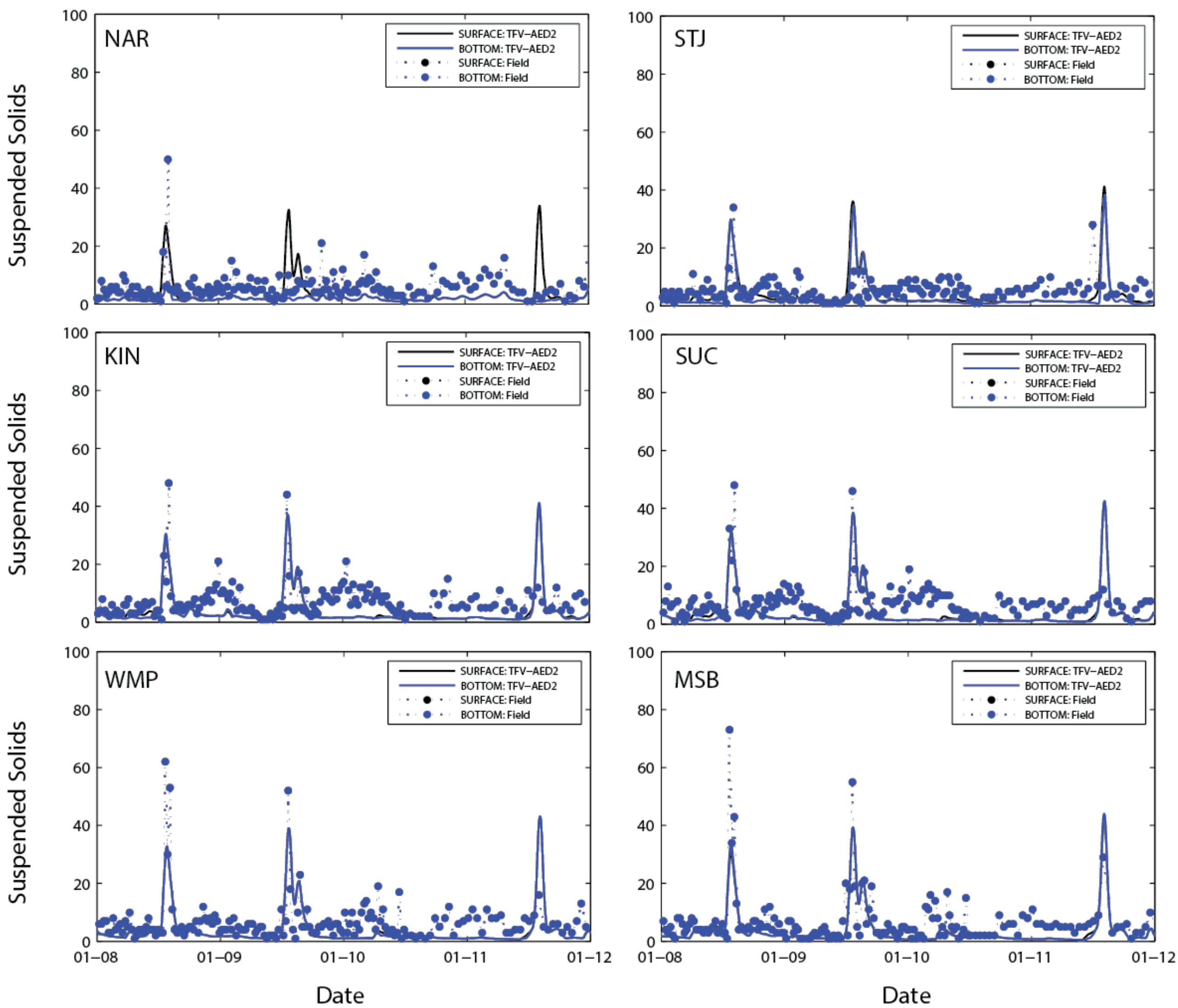


Figure 7. Suspended solids at six sites within the Upper Swan.

Turbidity

14. The model under-predicts the turbidity over the simulation period:
    - Correlation: R^2 = 0.20 - 0.42
    - Average Error: MAE = 10.5 NTU
15. The turbidity levels are significantly under-predicted, suggesting the conversion parameters for particulates to turbidity are too low, and also the overall particulate concentrations are too low (SS, Chl-a, POM).
16. Turbidity does not directly affect light in the model (since light is impacted by the individual components that constitute turbidity), so the under-prediction is not expected to have a large impact on photosynthesis predictions.

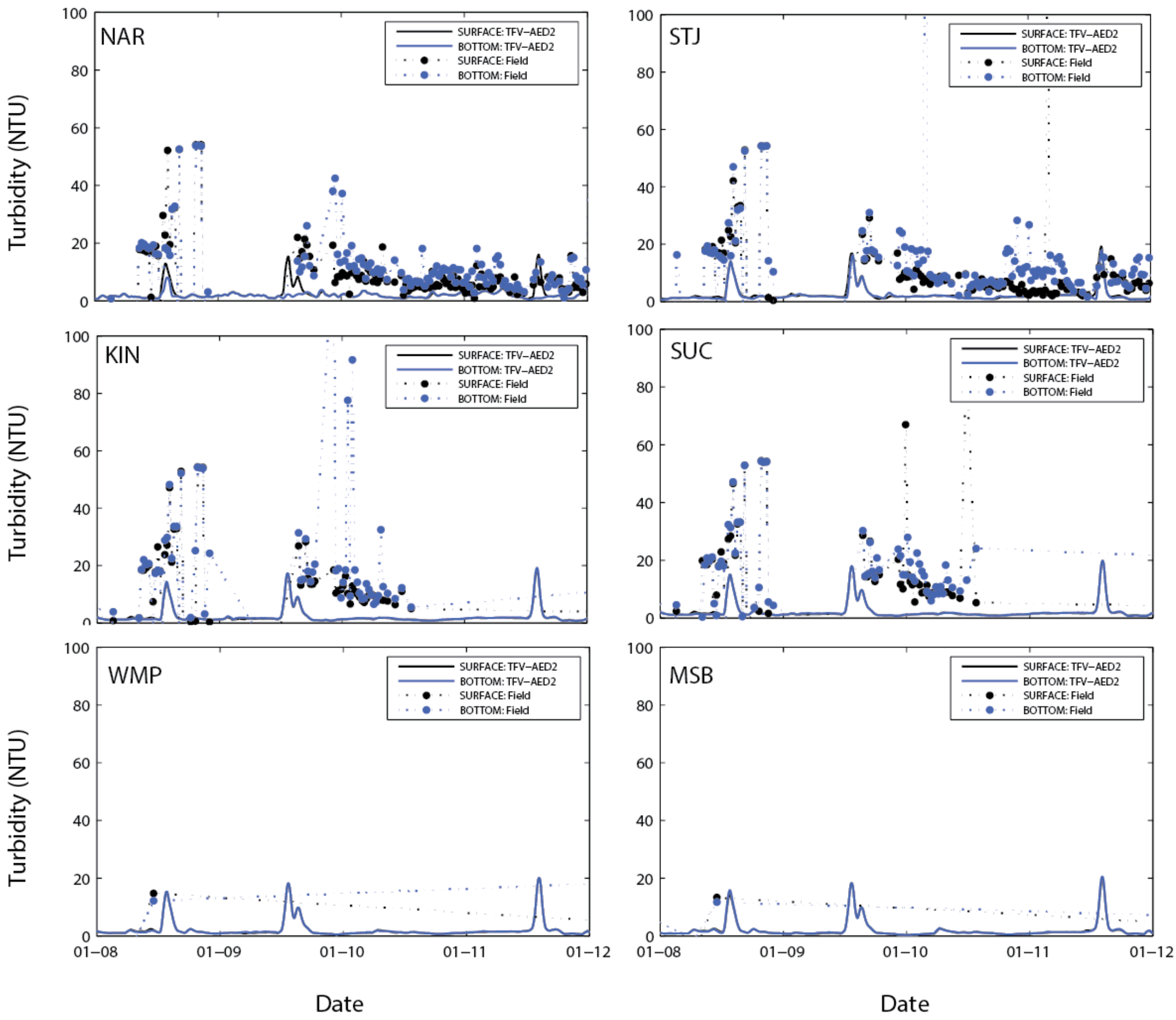


Figure 8. Turbidity at six sites within the Upper Swan.

Light Extinction Coefficient (K_d)

17. The light extinction coefficient is predicted to change throughout the domain and in response to large flow events, ranging from 0.5 to >10 /m.
18. This is the product of CDOM, SS and Chl-a, and is consistent with data in Kostoglidis et al. (2006).
19. It may be under-predicted in Summer due to the SS under-prediction, described above.

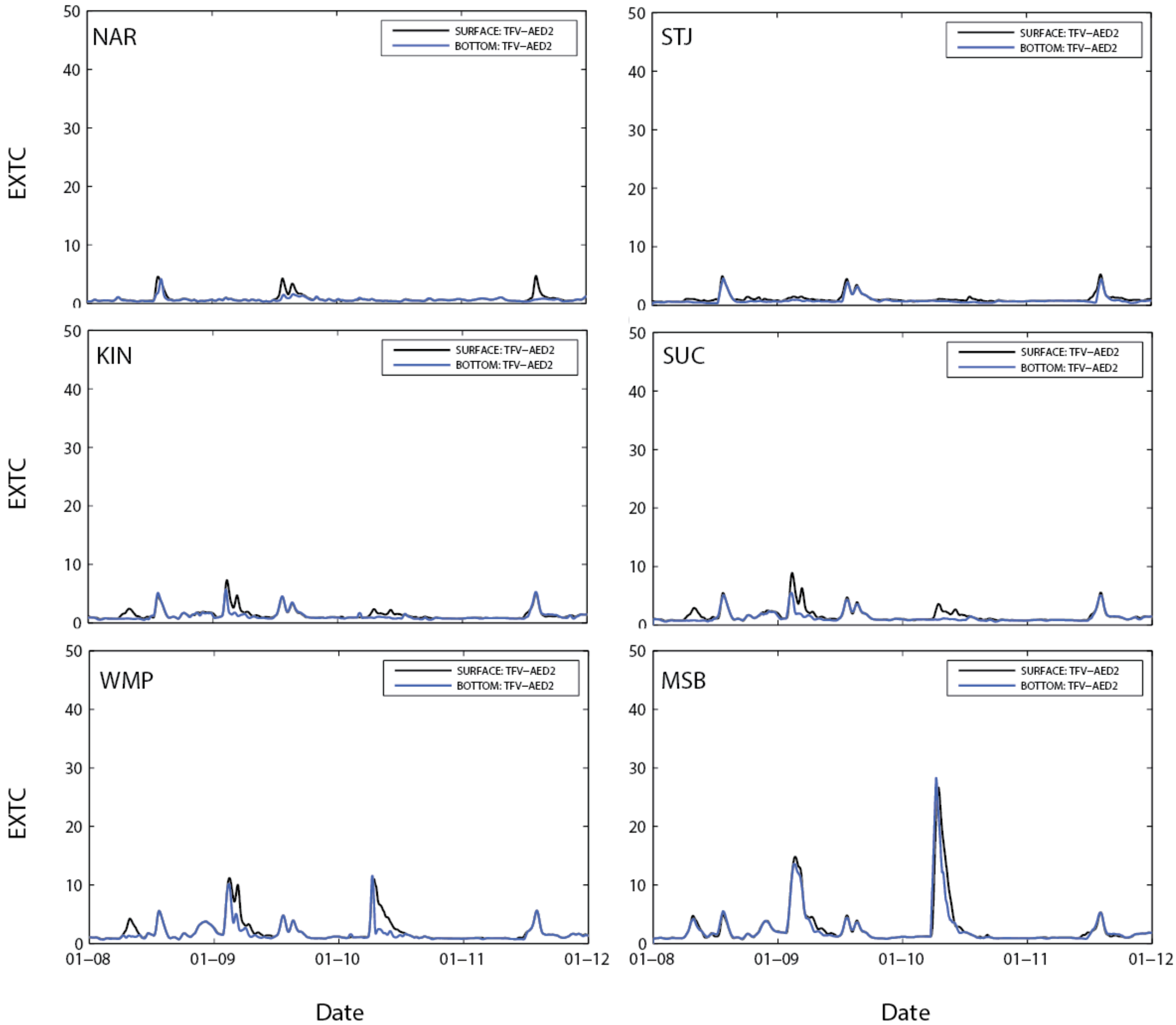


Figure 9. Light extinction (/m) at six sites within the Upper Swan.

Dissolved Oxygen (DO)

20. The model captures the oxygen concentration very well over the simulation period, including the seasonal variability, the horizontal variation and the degree of vertical stratification:
    - R^2: 0.60 – 0.74 (bottom) and 0.25 – 0.57 (surface)
    - MAE: 1.3 mg/L
21. The extent of sediment drawdown of oxygen is well predicted across the Upper Swan domain.
22. The summer period of 2009-2010 is under-predicted in the surface layer. This is likely due to inadequate oxygen production during the large algal bloom at this period (e.g., see Figure 19). Whilst the model captures the bloom timing, it under-predicts the final magnitude, and therefore the degree of oxygen super-saturation. Therefore, improvements in capturing the mechanisms of algal bloom formation in the Upper Swan will resolve this issue.

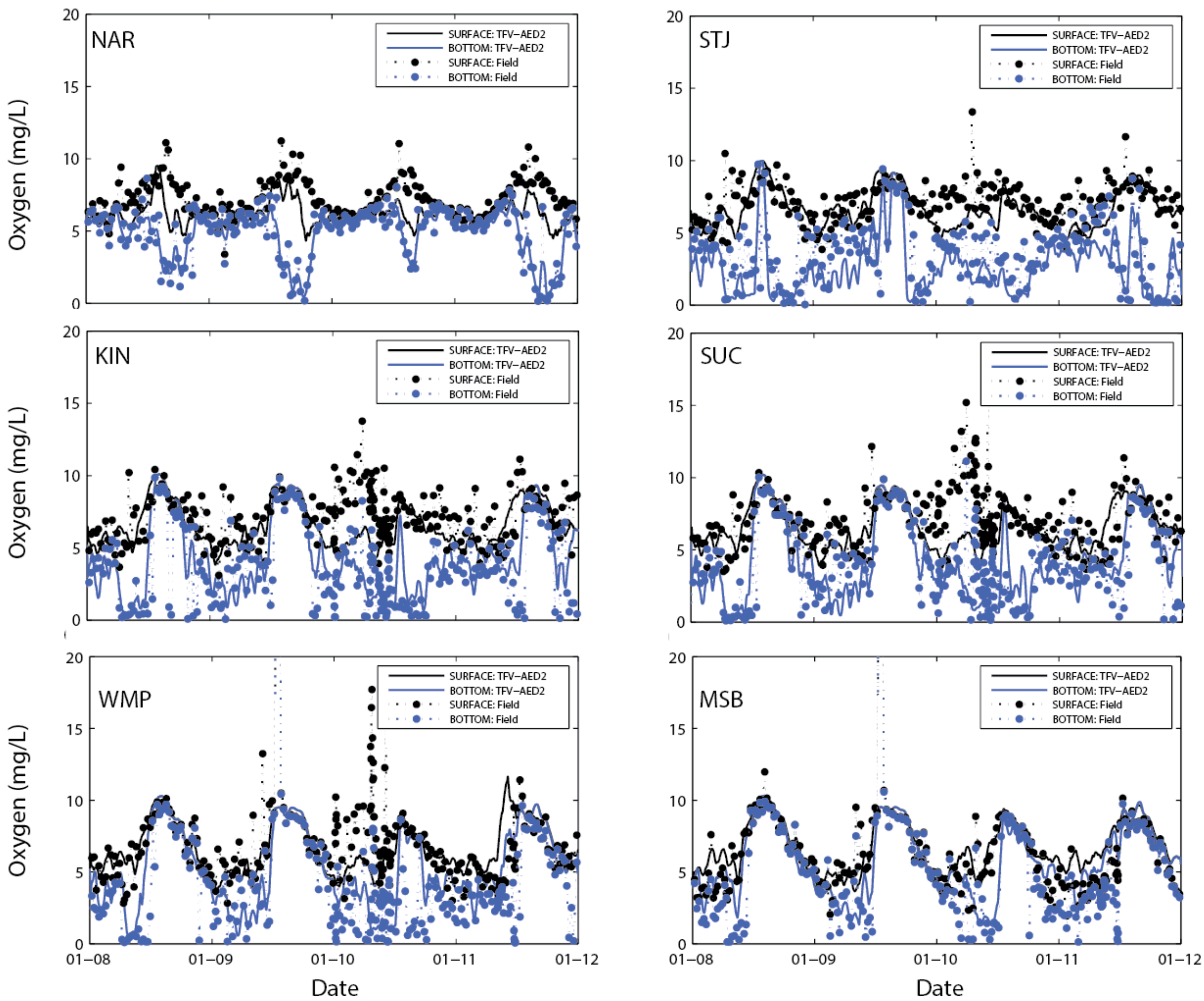


Figure 10. Dissolved oxygen concentration at six sites within the Upper Swan.

Phosphorus: Total Phosphorus (TP)

23. The model captures the total phosphorus (TP) concentration reasonably well over the simulation period, including the seasonal variability, and horizontal variation:
    - R^2: 0.44 – 0.68
    - MAE: 1.8 mmol/m^3
24. The model simulations miss some large bottom spikes in TP, and over-predict the TP peak at the end of summer, which is related to PO_4, described below.

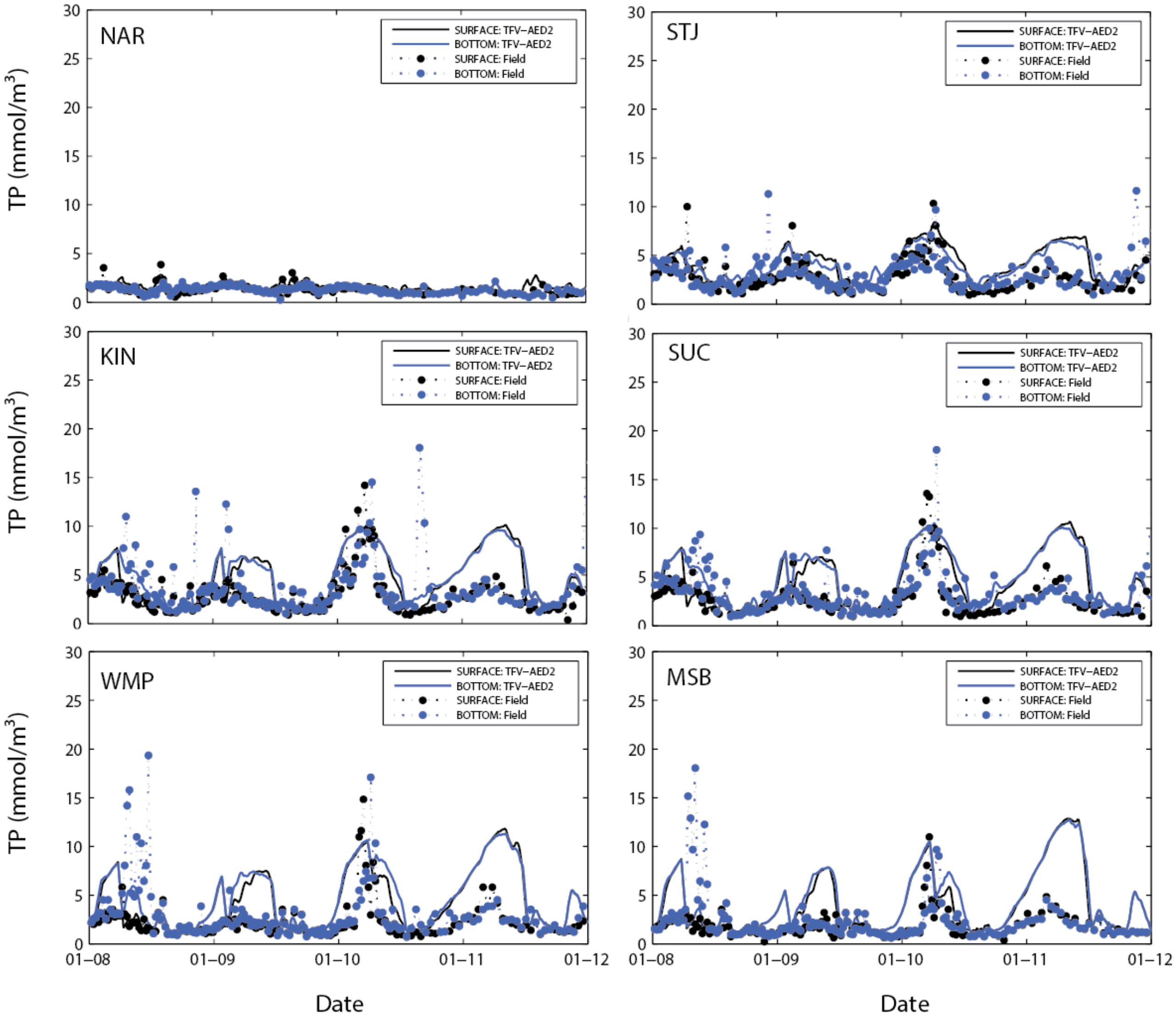


Figure 11. Total Phosphorus concentration at six sites within the Upper Swan.

Phosphorus: Phosphate (PO_4)

25. The model captures the phosphate concentration reasonably well over the simulation period, including the seasonal variability, and horizontal variation:
    - R^2: 0.33 – 0.58
    - MAE: 1.37 mmol/m^3
26. The model simulations miss some large bottom spikes in PO_4, and over-predict the magnitude and duration of the PO_4 peak at the end of summer.
27. Parameters controlling the sediment release of PO_4, and sensitivity to overlying oxygen therefore need to be re-calibrated to slow the diffusive flux under high oxygen conditions and to increase it during anoxic events. The over-prediction may also be due to inadequate P uptake by phytoplankton which should be further explored.

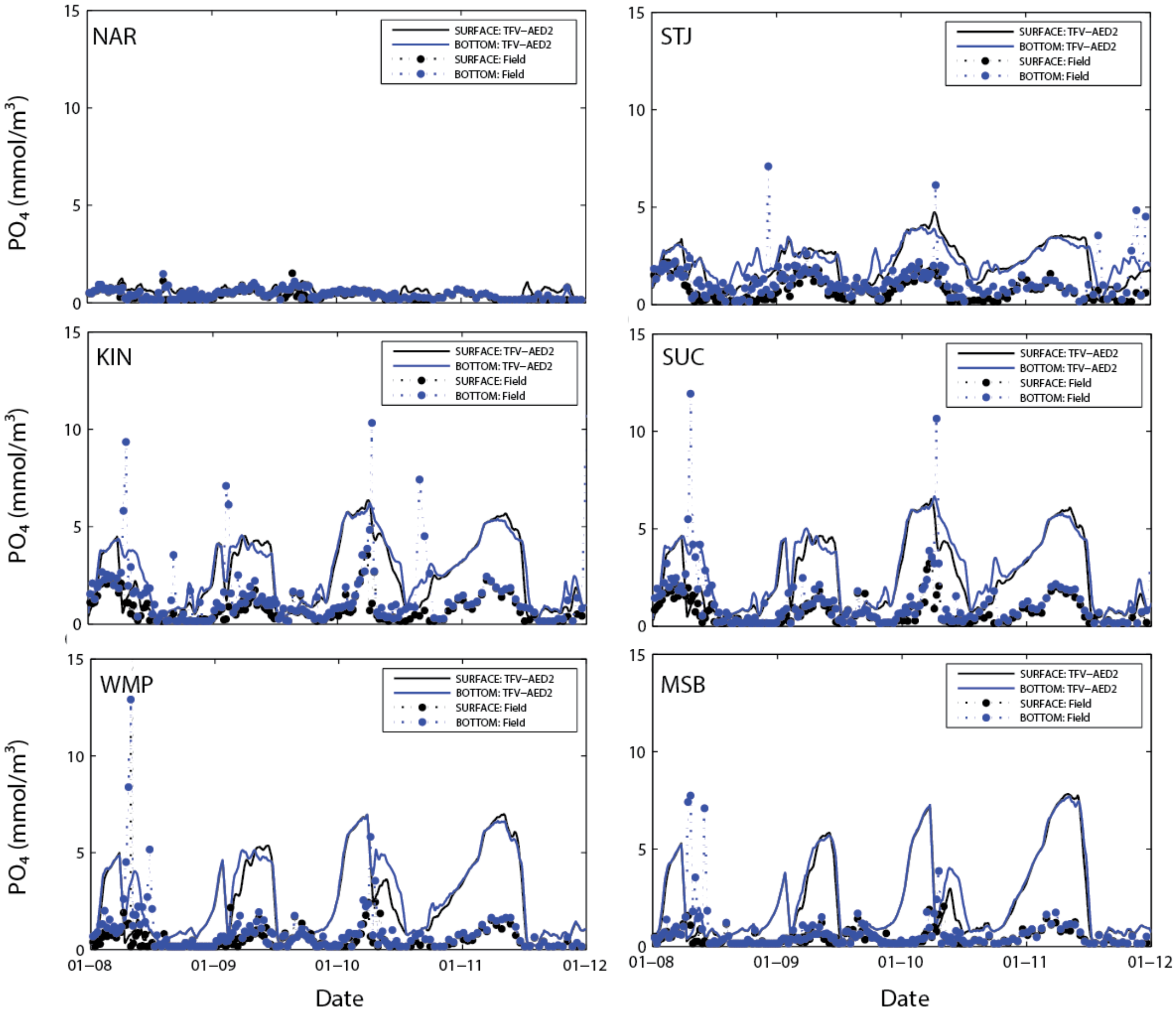


Figure 12. Phosphate concentration at six sites within the Upper Swan.

Silica: Reactive Silica (RSi)

28. The model captures the silicate concentration very well over the simulation period, including the seasonal variability, and variation

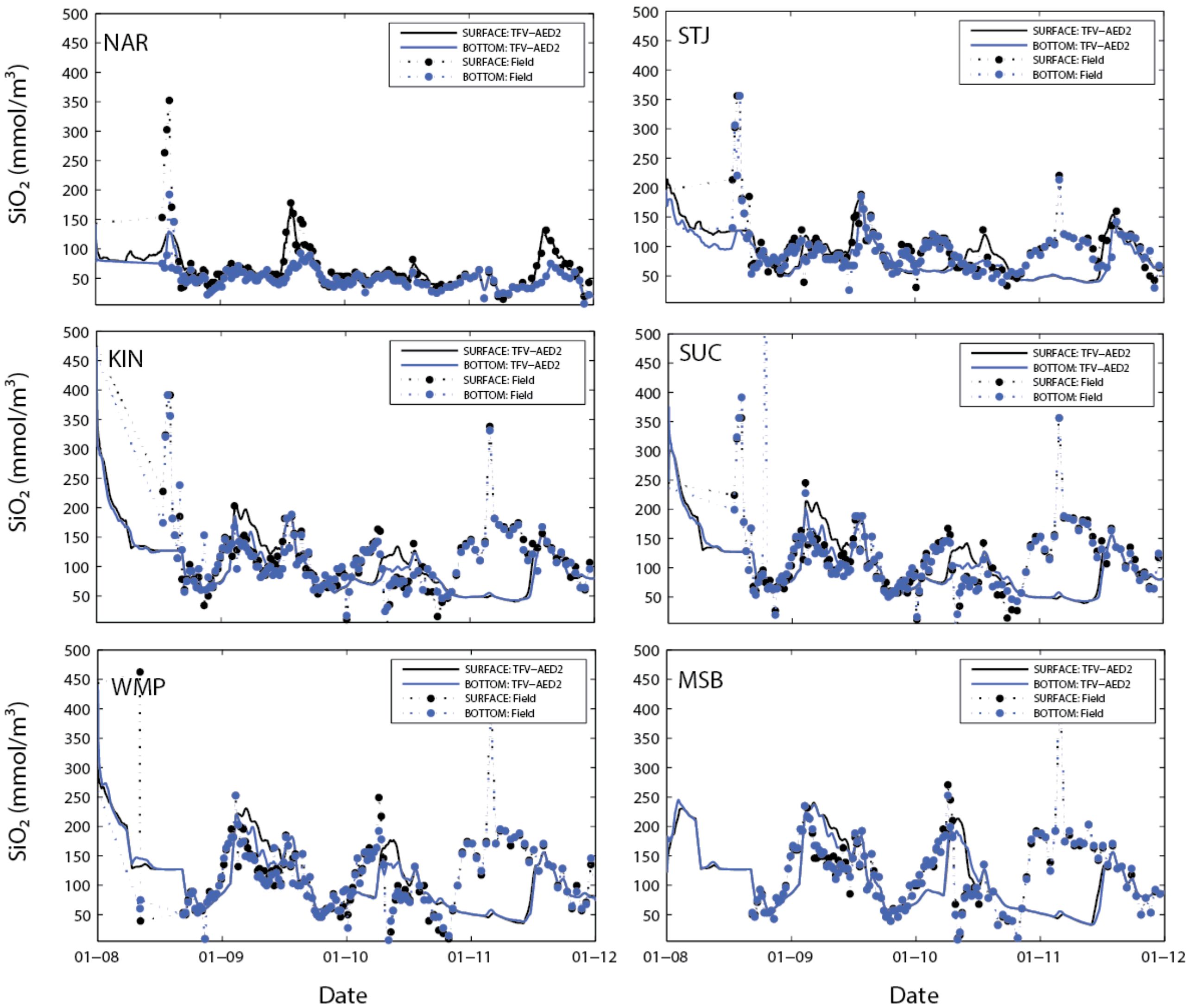


Figure 13. Silica concentration at six sites within the Upper Swan.

Nitrogen: Total Nitrogen (TN)

29. The model captures the total nitrogen (TN) concentration very well over the simulation period, including the seasonal variability, and variation along the estuary:
    - R^2: 0.40 – 0.81
    - MAE: 34 mmol/m^3
30. The model slightly over-predicts the summer dry period TN in the upstream sites.

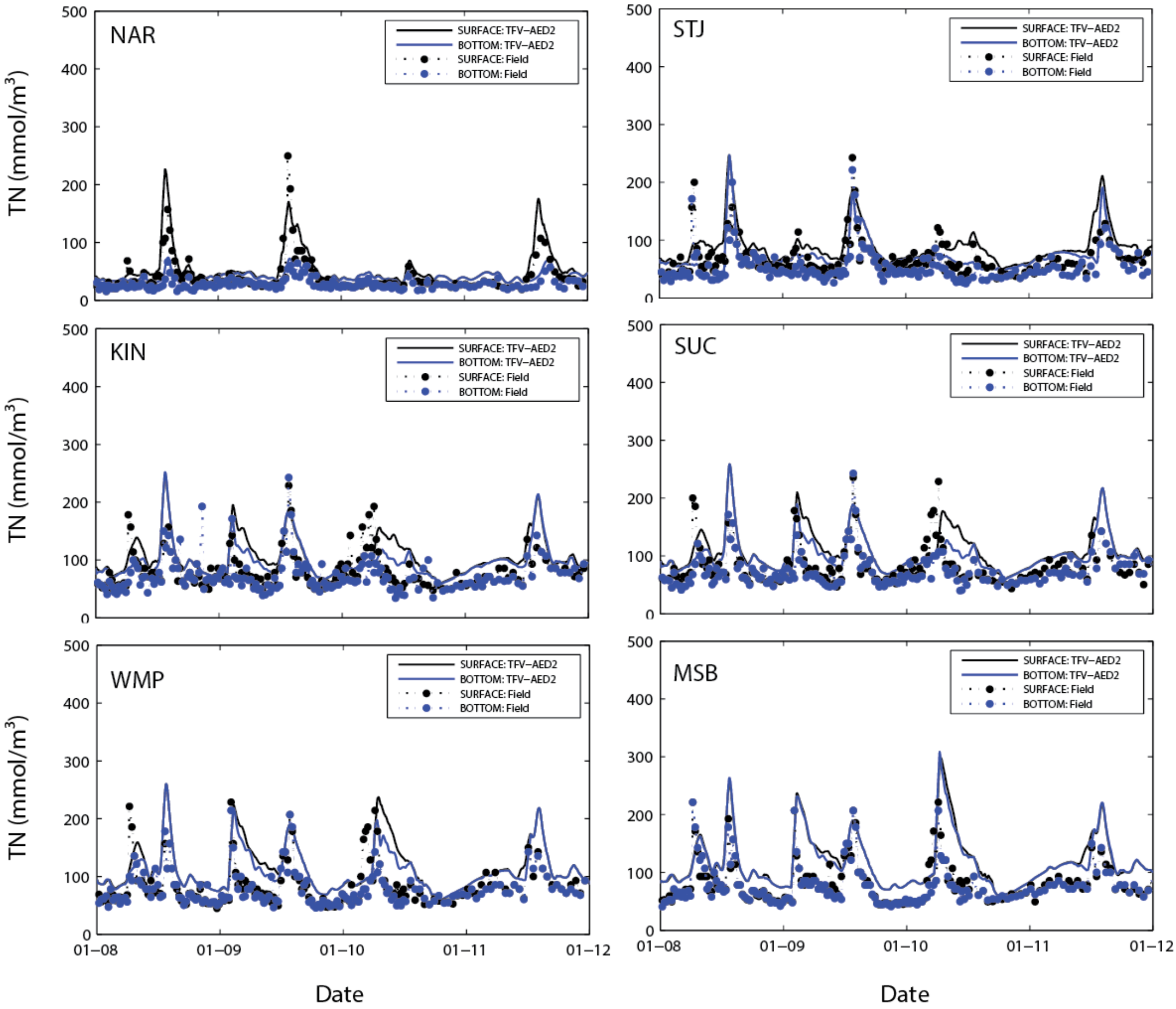


Figure 14. Total Nitrogen concentration at six sites within the Upper Swan.

Nitrogen: Ammonium (NH_4)

31. The model captures the ammonium concentration very well over the simulation period, including the high variability, and variation along the estuary:
    - R^2: 0.30 – 0.51
    - MAE: 3.49 mmol/m^3
32. Some of the very high NH4 peaks in the bottom waters away from the SUC oxygenation plant are under-predicted.

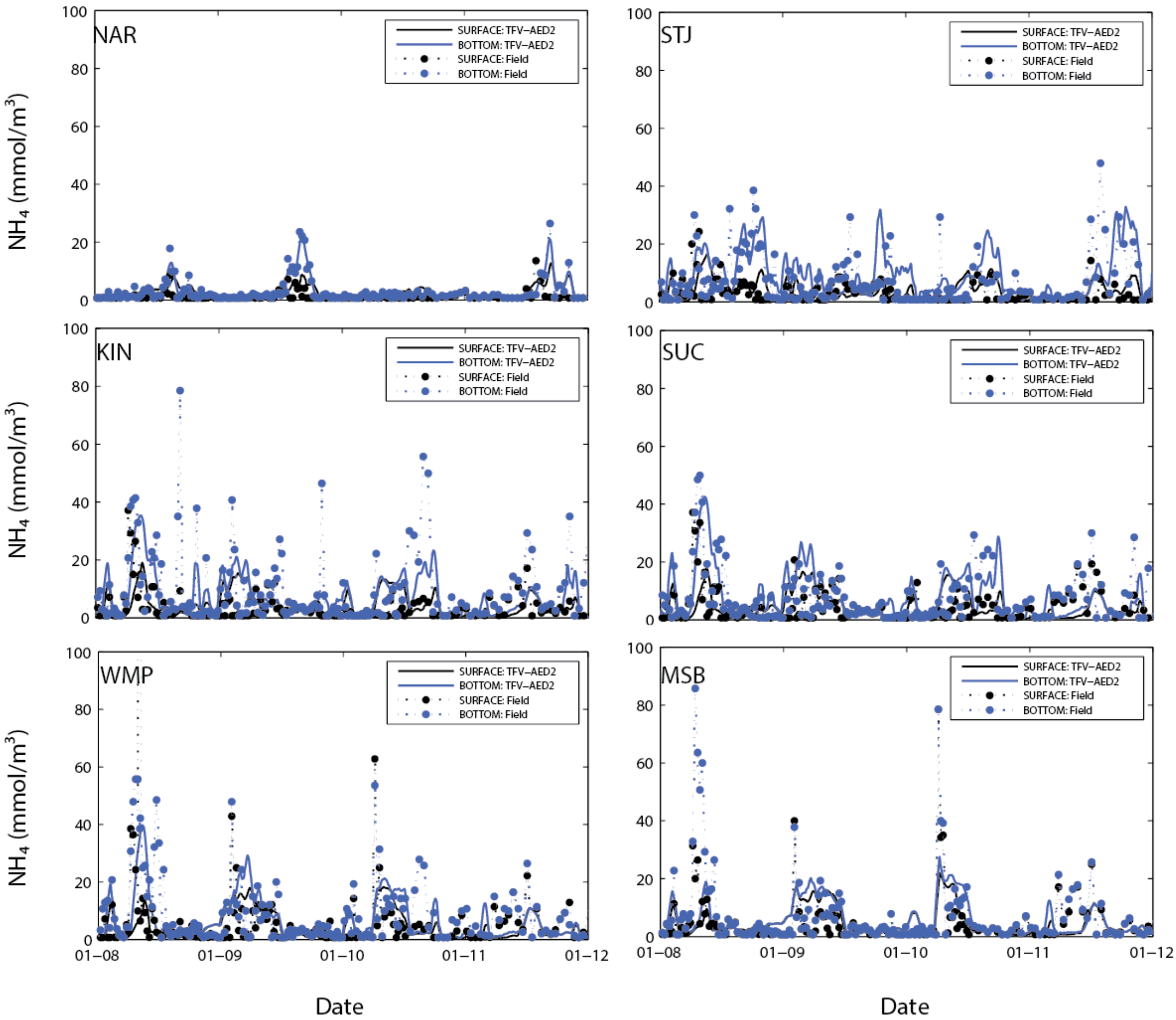


Figure 15. Ammonium concentration at six sites within the Upper Swan.

Nitrogen: Nitrate (NO_x)

33. The model captures the nitrate concentration very well over the simulation period, including the high seasonality, and attenuation of the inflow load along the estuary:
    - R^2: 0.44 – 0.92
    - MAE: 4.50 mmol/m^3
34. The spikes are linked to inflow events, but it is unclear the extent to which the error is related to sparse boundary forcing data vs internal process rates, and this should be further explored.

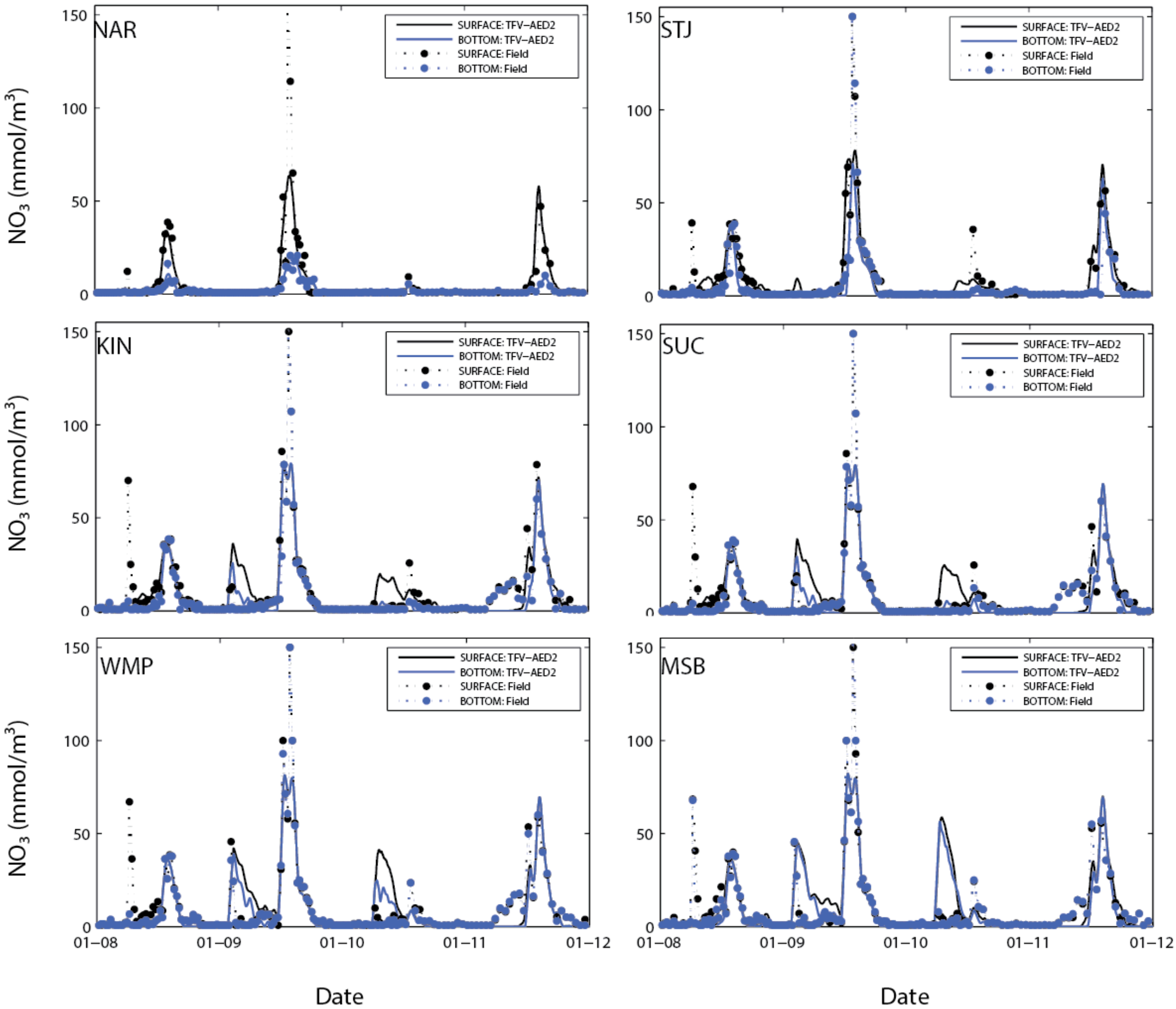


Figure 16. Nitrate concentration at six sites within the Upper Swan.

Nitrogen: Dissolved Organic Nitrogen (DON)

35. The model reasonably captures the DON concentration over the simulation period, but over-predicts the concentration over the summer-autumn period.
    - o R^2: 0.10 – 0.41
    - o MAE: 15.2 mmol/m^3
36. The seasonality of the DON concentration is over-exaggerated in the simulation, suggesting an over-supply of sediment DON during summer or inadequate rates of photolysis or mineralisation of phytoplankton exudate.
37. The dominant fraction of total DON is DON-R (generally >80%).

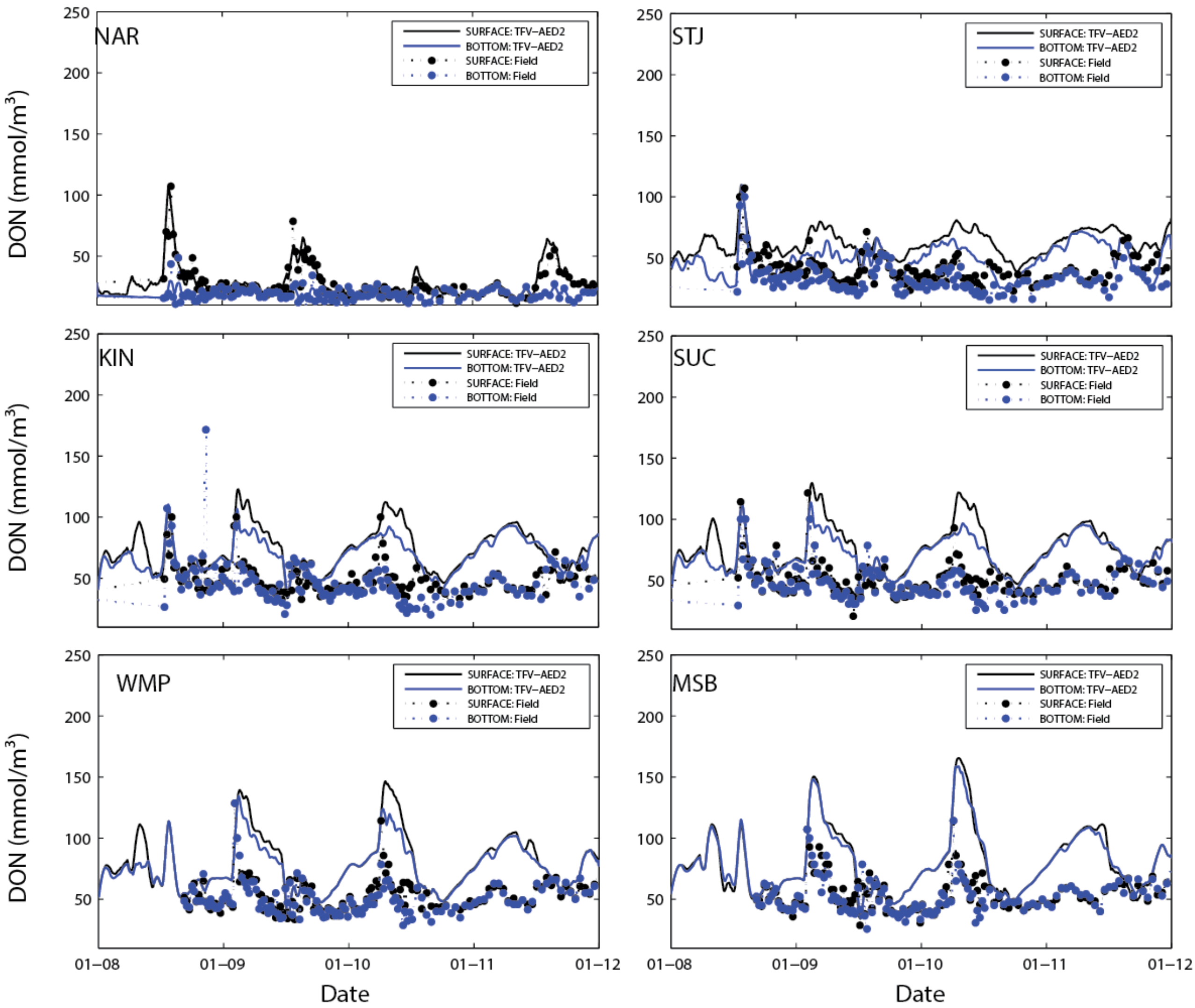


Figure 17. Dissolved Organic Nitrogen concentration at six sites within the Upper Swan.

Carbon: Dissolved Organic Carbon (DOC)

38. The model captures the DOC concentration to a high degree of accuracy over the simulation period, with a slight over-prediction:
    - R^2: 0.30 – 0.51
    - MAE: 580 mmol/m^3
39. The DOC concentration is over-predicted slightly in the upper stations, suggesting an over-supply of sediment DON during summer or inadequate rates of photolysis or mineralisation of phytoplankton exudate.
40. The dominant fraction of total DOC is DOC-R (generally >90%).

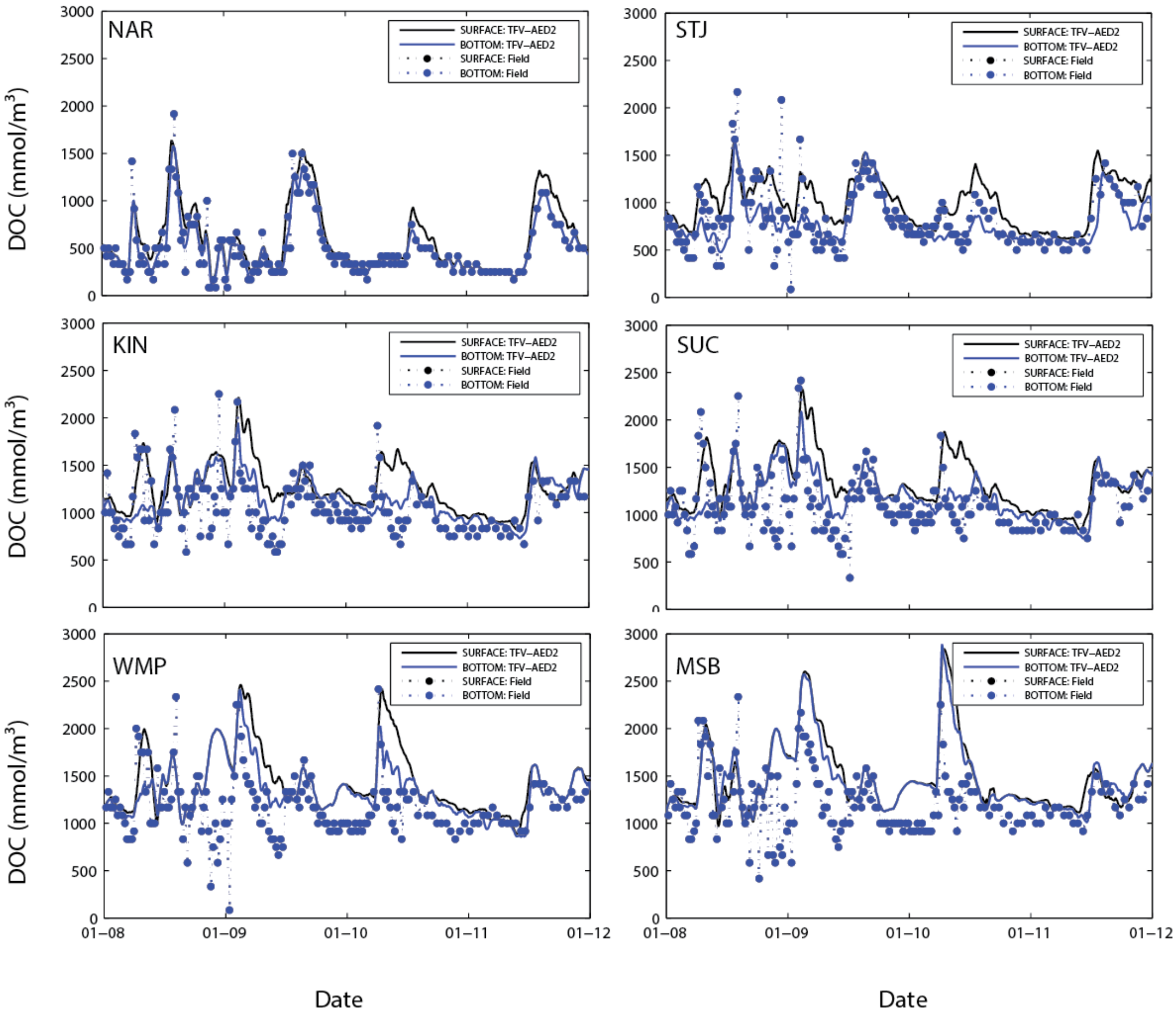


Figure 18. Dissolved Organic Carbon concentration at six sites within the Upper Swan.

Phytoplankton: Chlorophyll-a (TCHLA)

41. The model captures the chlorophyll-a concentration (from the optical sonde) to a moderate degree of accuracy over the simulation period, with a slight over-prediction:
    - o R^2: 0.20 – 0.42
42. The model has a tendency to over-predict the bottom Chl-a and under-predict the surface concentration. This is most likely due to the lack of vertical migration configured in the dinoflagellate group, which is known to form high accumulations near the surface under low mixing conditions.

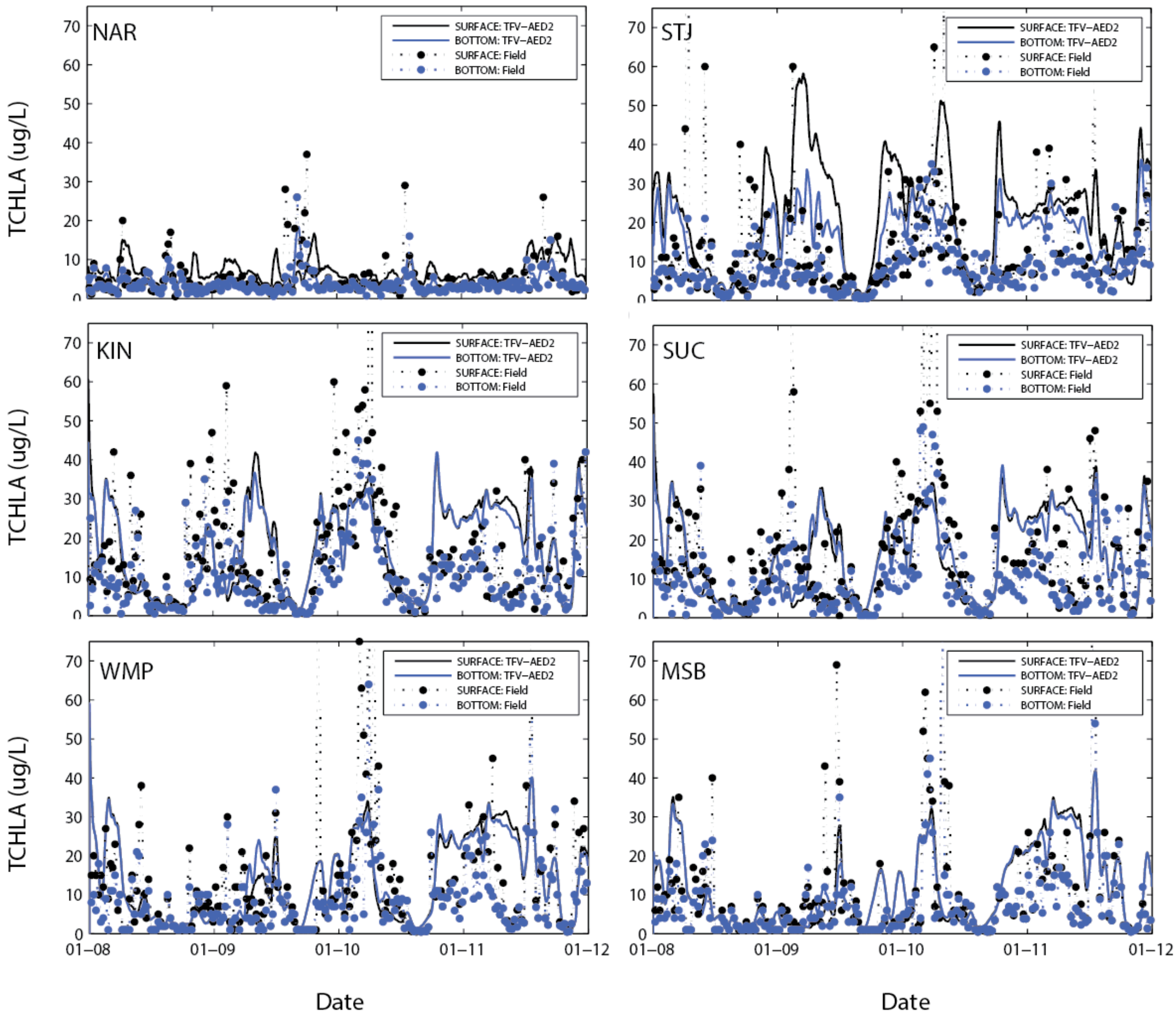


Figure 19. Total Chlorophyll-a concentration at six sites within the Upper Swan.

Phytoplankton: Chlorophytes (GRN)

43. GRN was found to have relatively low concentration and occasional presence over the Upper Swan domain.

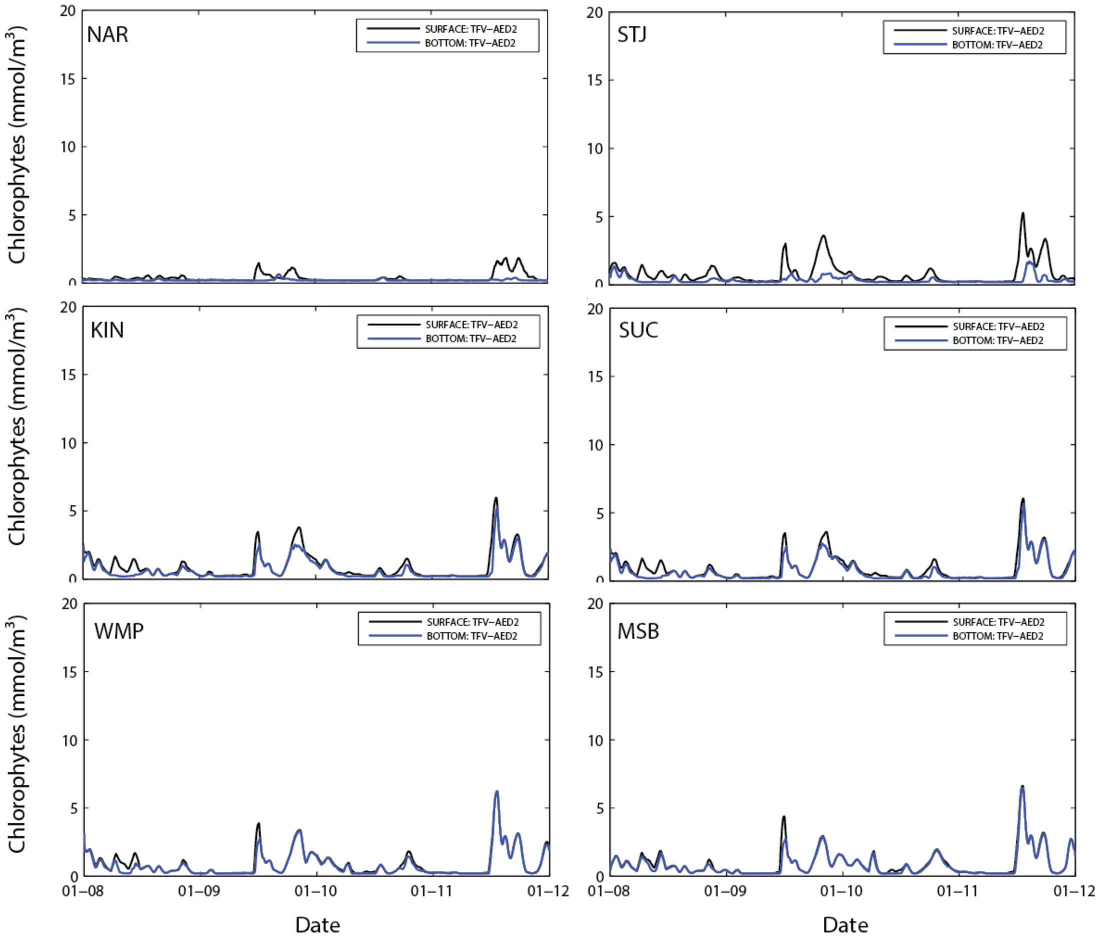


Figure 20a. Chlorophytes (GRN) carbon concentration at six sites within the Upper Swan.

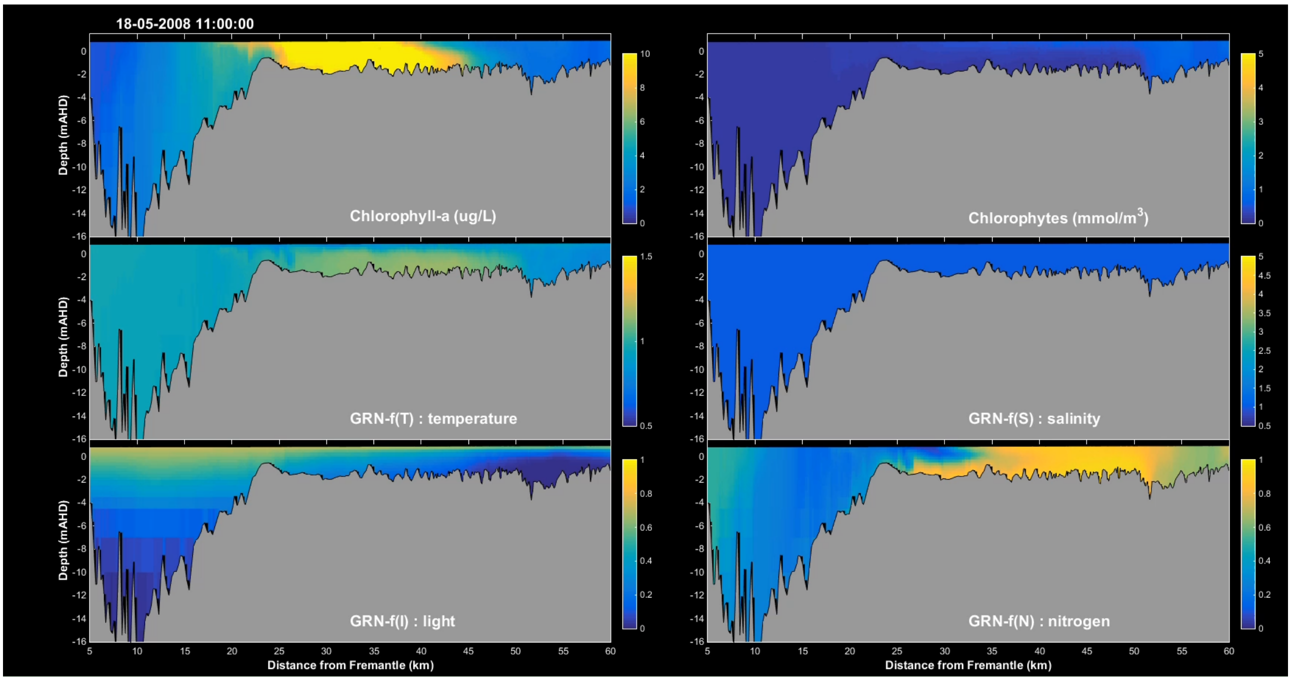


Figure 20b. Chlorophytes (GRN) biomass and growth limitations taken during a snapshot.
View animation @ http://aed.see.uwa.edu.au/research/projects/swan/GRN.avi

Phytoplankton: Cyanobacteria (BGA)

44. The BGA group was found to have relatively low concentration over the Upper Swan domain, with occasional minor peaks during freshwater conditions.

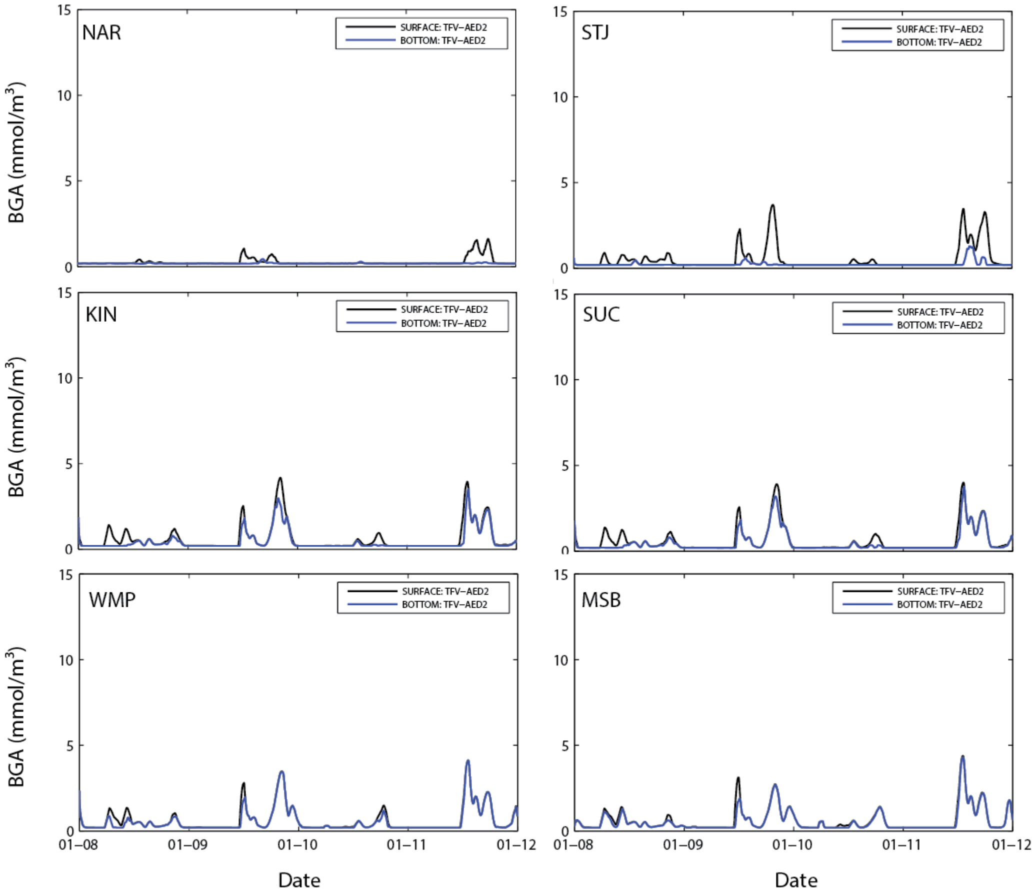


Figure 21a. Cyanobacteria (BGA) carbon concentration at six sites within the Upper Swan.

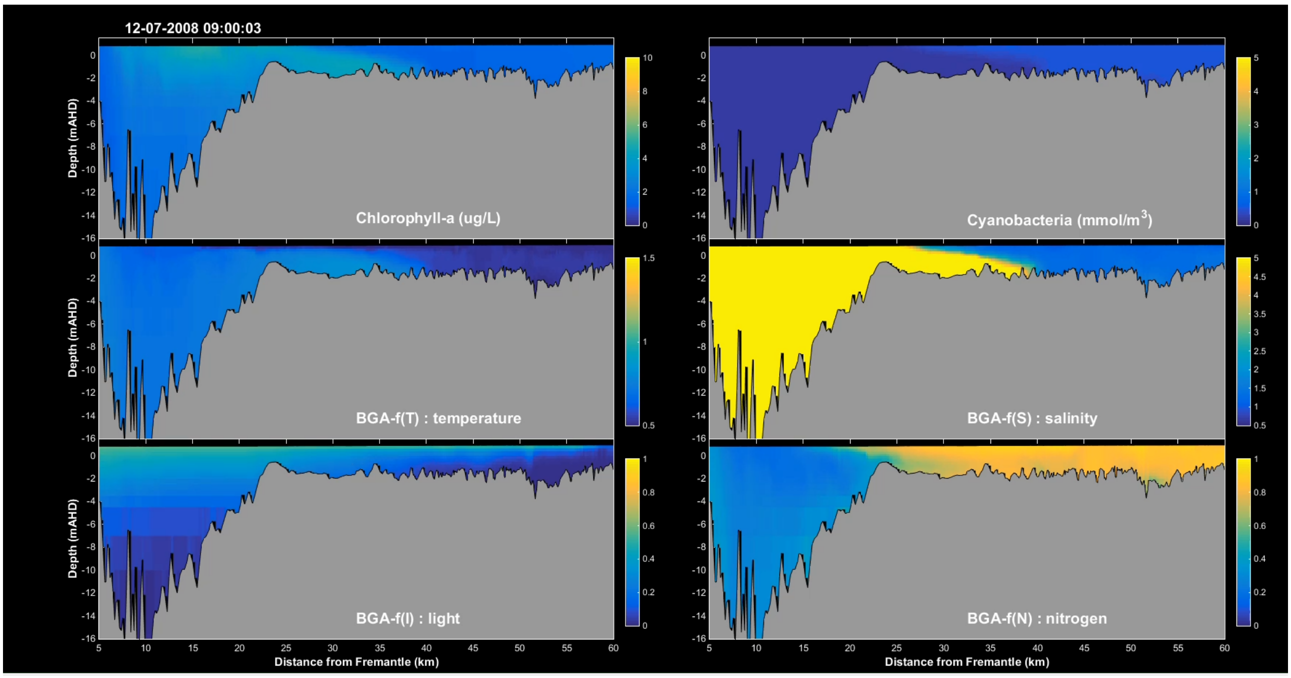


Figure 21b. Cyanobacteria (BGA) biomass and growth limitations shown during a snapshot in 2008.
View animation @ http://aed.see.uwa.edu.au/research/projects/swan/BGA.avi

Phytoplankton: Cryptophytes (CRYPT)

45. CRYPT was predicted to have relatively high concentrations over the Upper Swan domain, mainly during summer, and less during periods of high flow.

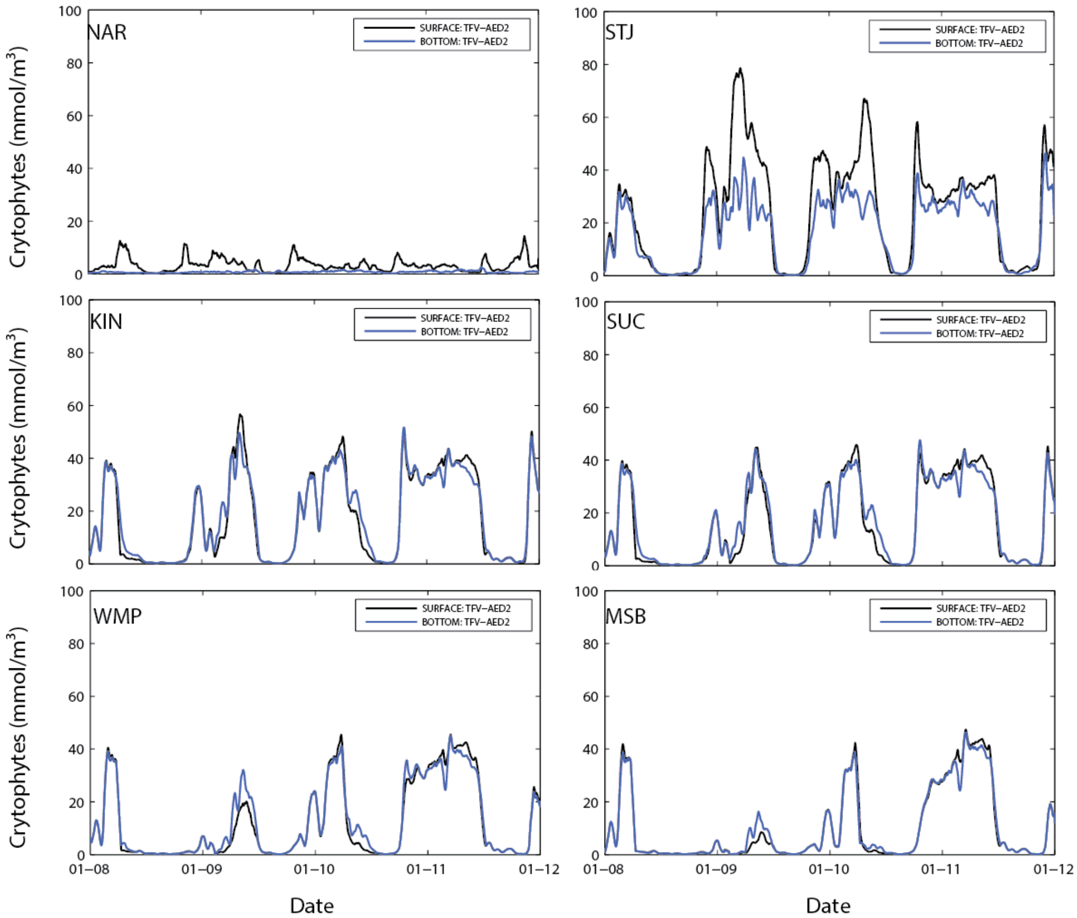


Figure 22a. Cryptophytes (CRYPT) carbon concentration at six sites within the Upper Swan.

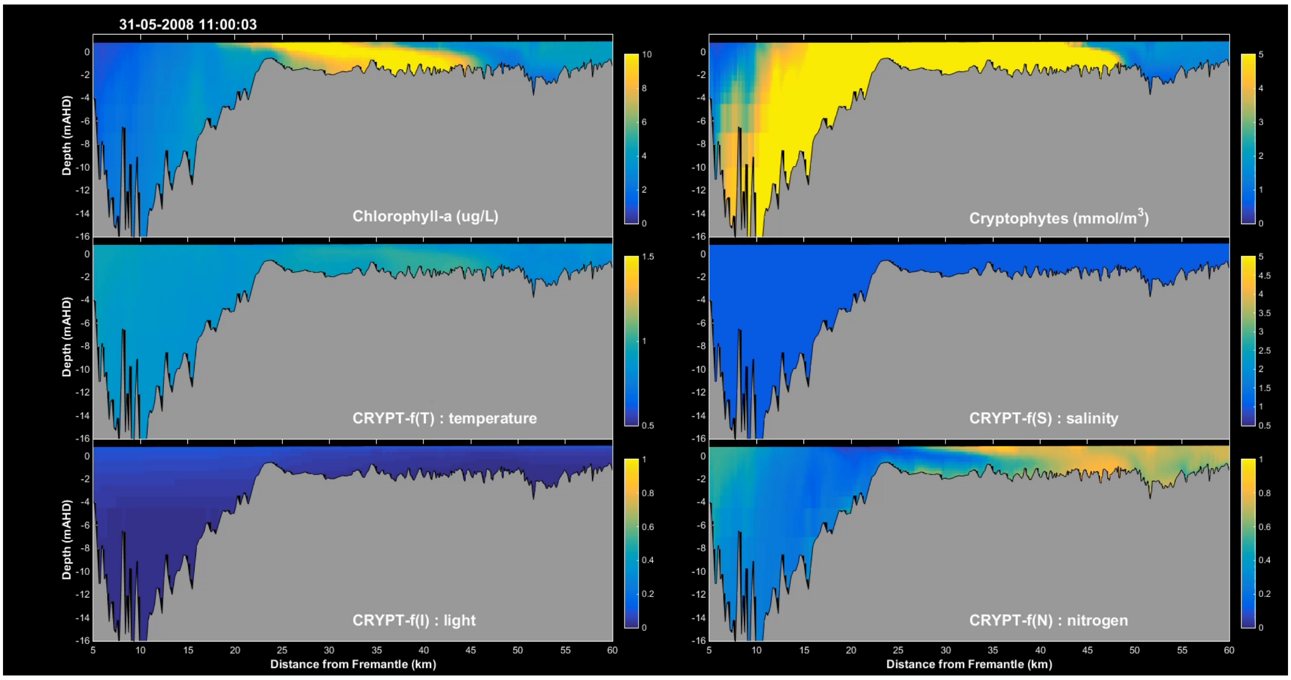


Figure 22b. Cryptophyte (CRYPT) biomass and growth limitations shown during a snapshot in 2008. View animation @ http://aed.see.uwa.edu.au/research/projects/swan/CRYPT.avi

Phytoplankton: Diatoms (DIAT)

46. DIAT was predicted to have relatively low concentration over the Upper Swan domain, with occasional minor peaks during freshwater conditions.

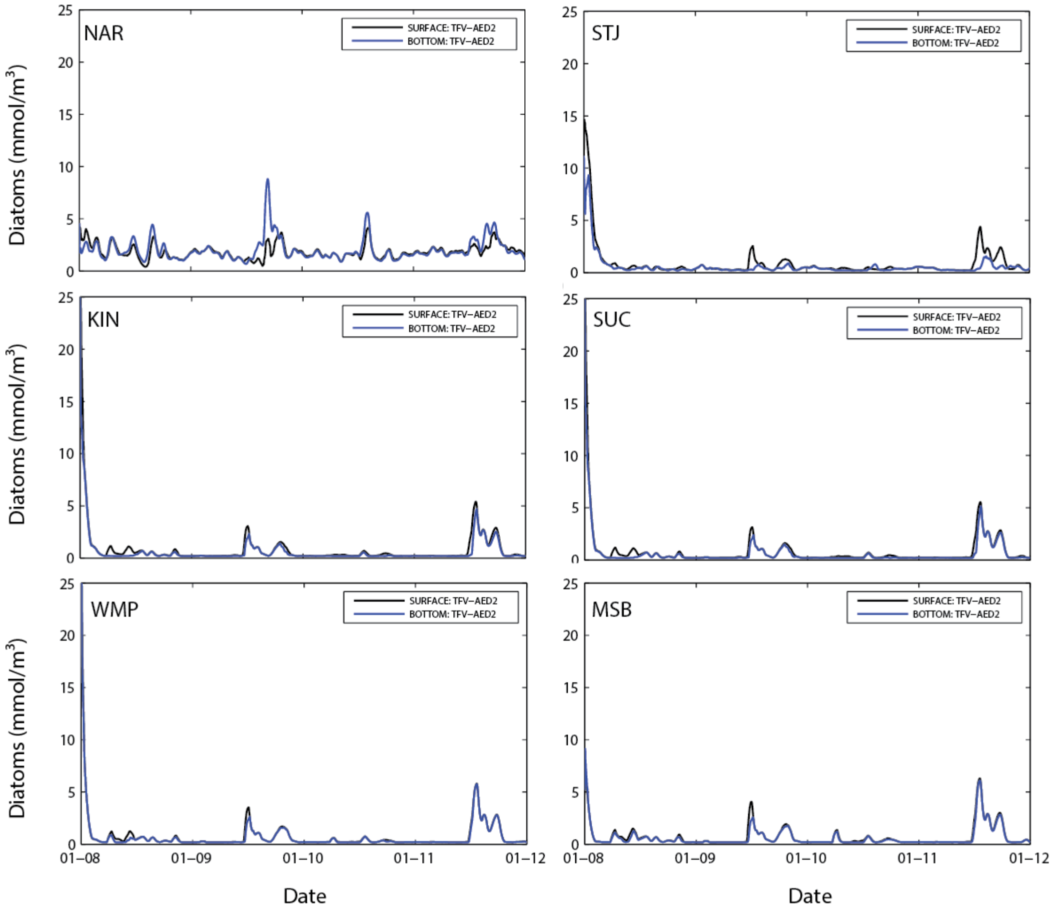


Figure 23a. Diatoms (DIAT) carbon concentration at six sites within the Upper Swan.

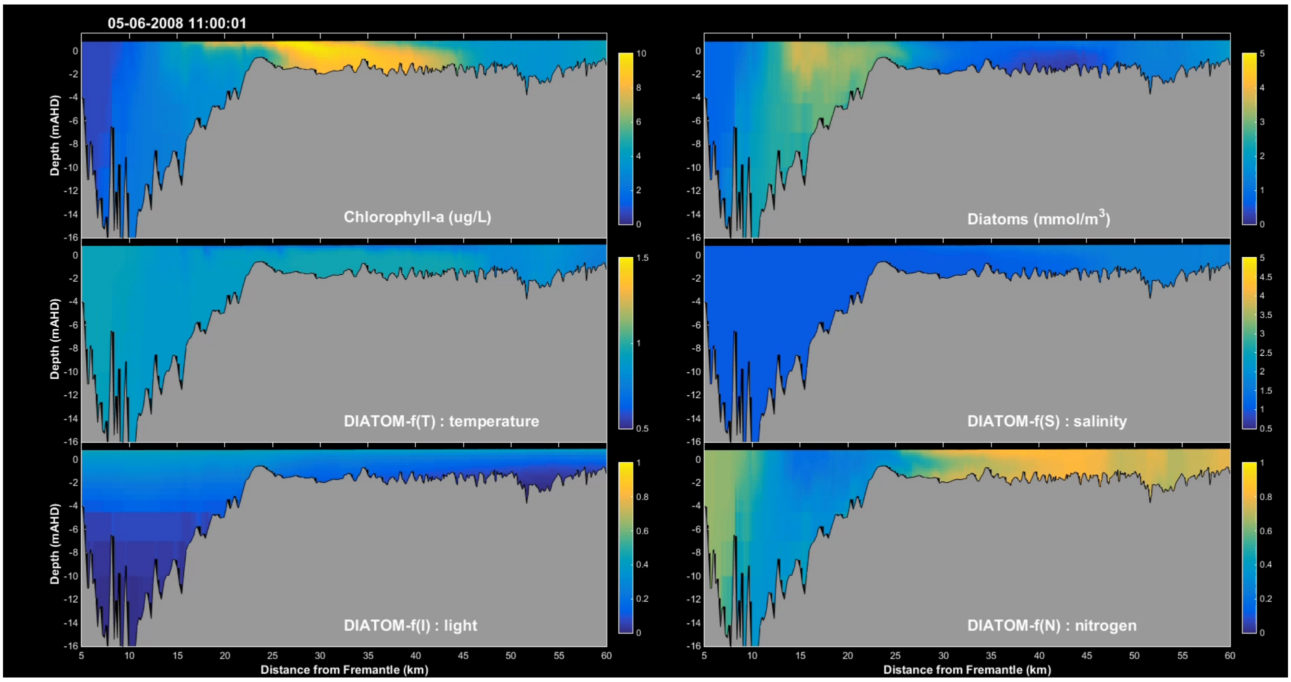


Figure 23b. Diatom (DIAT) biomass and growth limitations shown during a snapshot in 2008.
View animation @ http://aed.see.uwa.edu.au/research/projects/swan/DIATOM.avi

Phytoplankton: Dinoflagellates (DINO)

47. The DINO group was predicted to have moderate concentration over the Upper Swan domain, peaks occurring throughout the year.

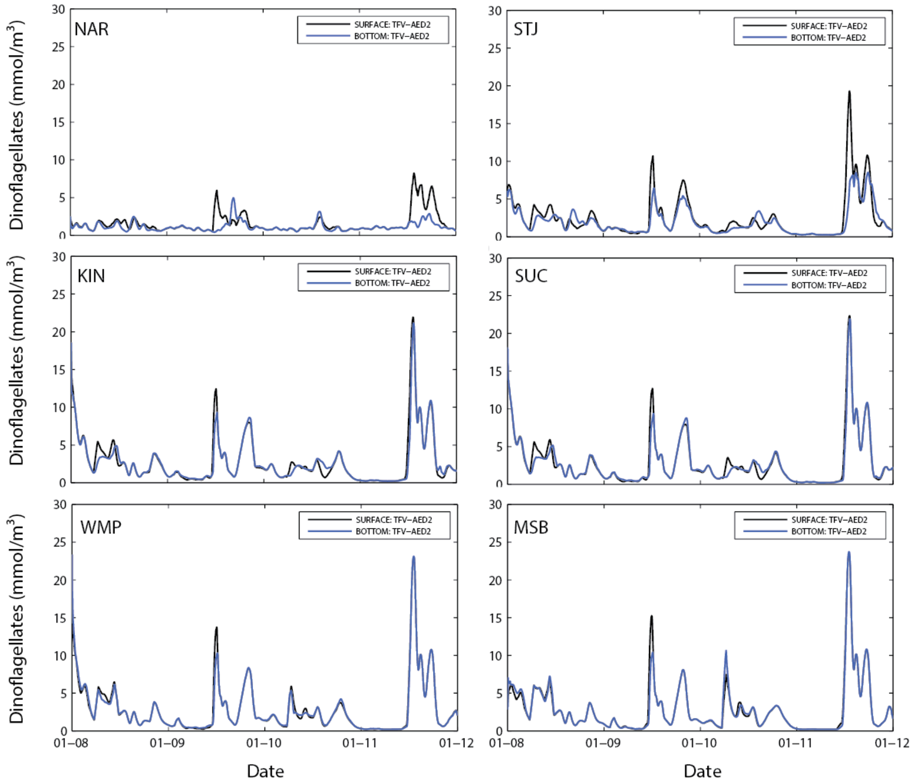


Figure 24a. Dinoflagellate (DINO) carbon concentration at six sites within the Upper Swan.

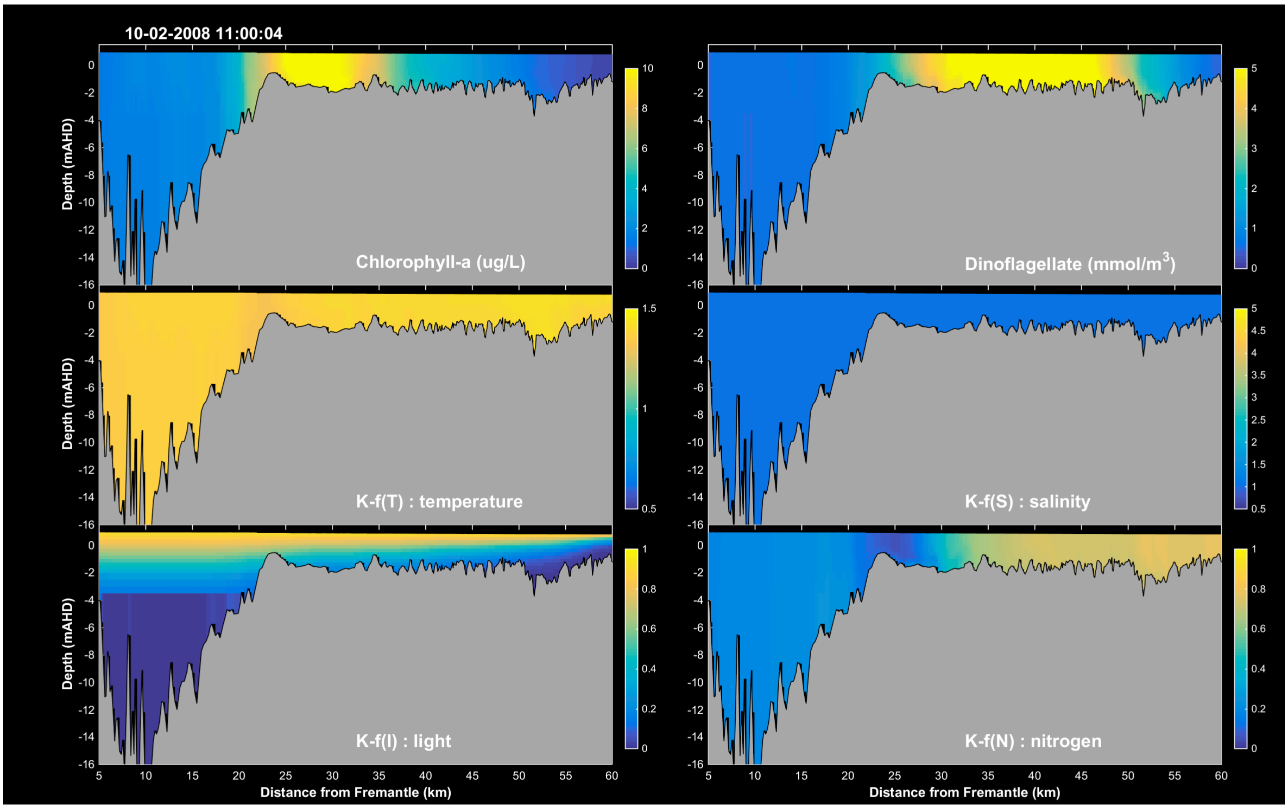


Figure 24b. Diatom (DIAT) biomass and growth limitations shown during a snapshot in 2008.
View animation @ http://aed.see.uwa.edu.au/research/projects/swan/DINO.avi

Summary

48. Summary views of the model predictions are available as animations to help visualise the dynamic processes occurring within the estuary. Snapshots of the system are presented below (Figure 25) for the summer and winter of 2008.

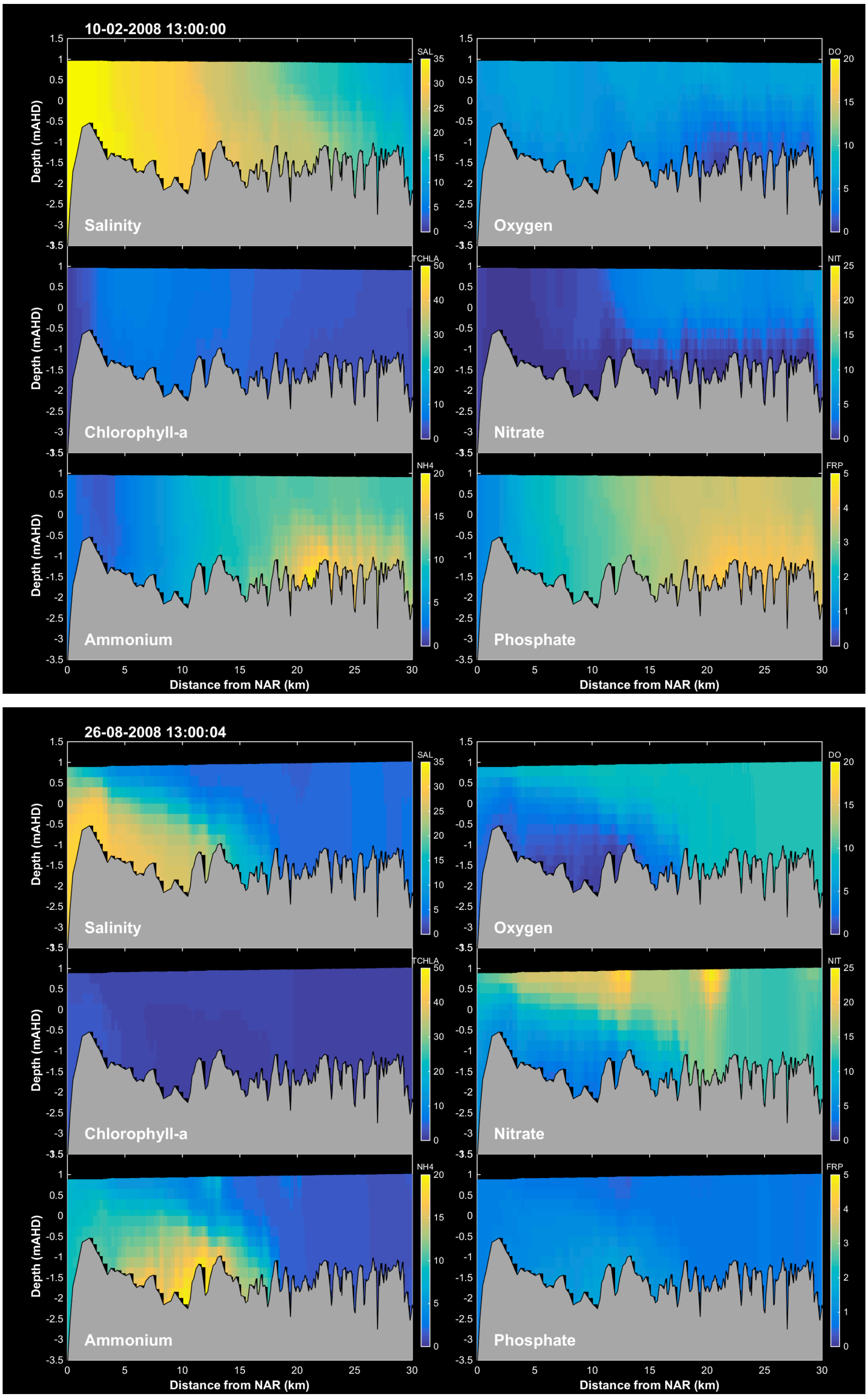


Figure 25. Summary animation of water quality attributes in the Upper Swan.
View animation @ http://aed.see.uwa.edu.au/research/projects/swan/Upper_Domain.avi

49. The risk of algal bloom formation was approximated by looking at the combined factors influence growth and mortality of each group – denoted as "bloom potential" (Figure 26).

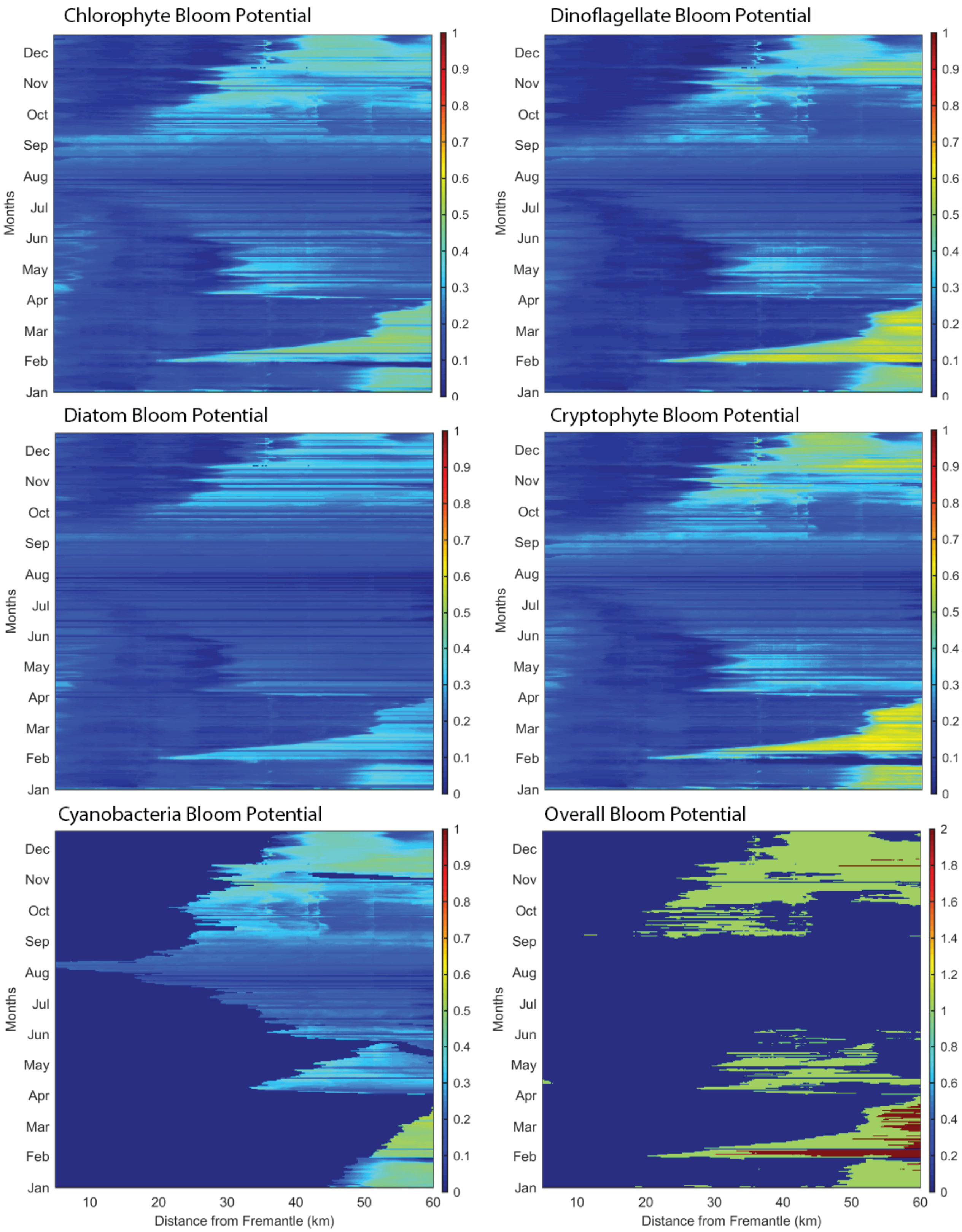


Figure 26. Simulated "bloom potential" during 2008 for each simulated group (relative growth scale varying from 0-1), and categorisation of bloom potential of the overall phytoplankton community (bottom right; 0 indicates limited potential, 1 indicates moderate potential, 2 indicates high potential for rapid growth). Note that the results are indicative only and need further testing against known occurrence from field data.

4. Model Assessment: Lower Swan

The following sub-sections describe the model output specific to the Full Domain simulation, and comment on the model performance and potential reasons for discrepancies, where relevant.

Salinity & Temperature

50. Salinity is accurately captured in the main Lower Swan basin (as indicated at ARM and HEA) and in the Upper Swan (STJ and KIN), but is less well-captured in the upper reaches of the Canning estuary.
51. Results indicate an under-prediction in flow over the Kent St weir or from other inputs and further work is required to improve the water and salt balance within this region.

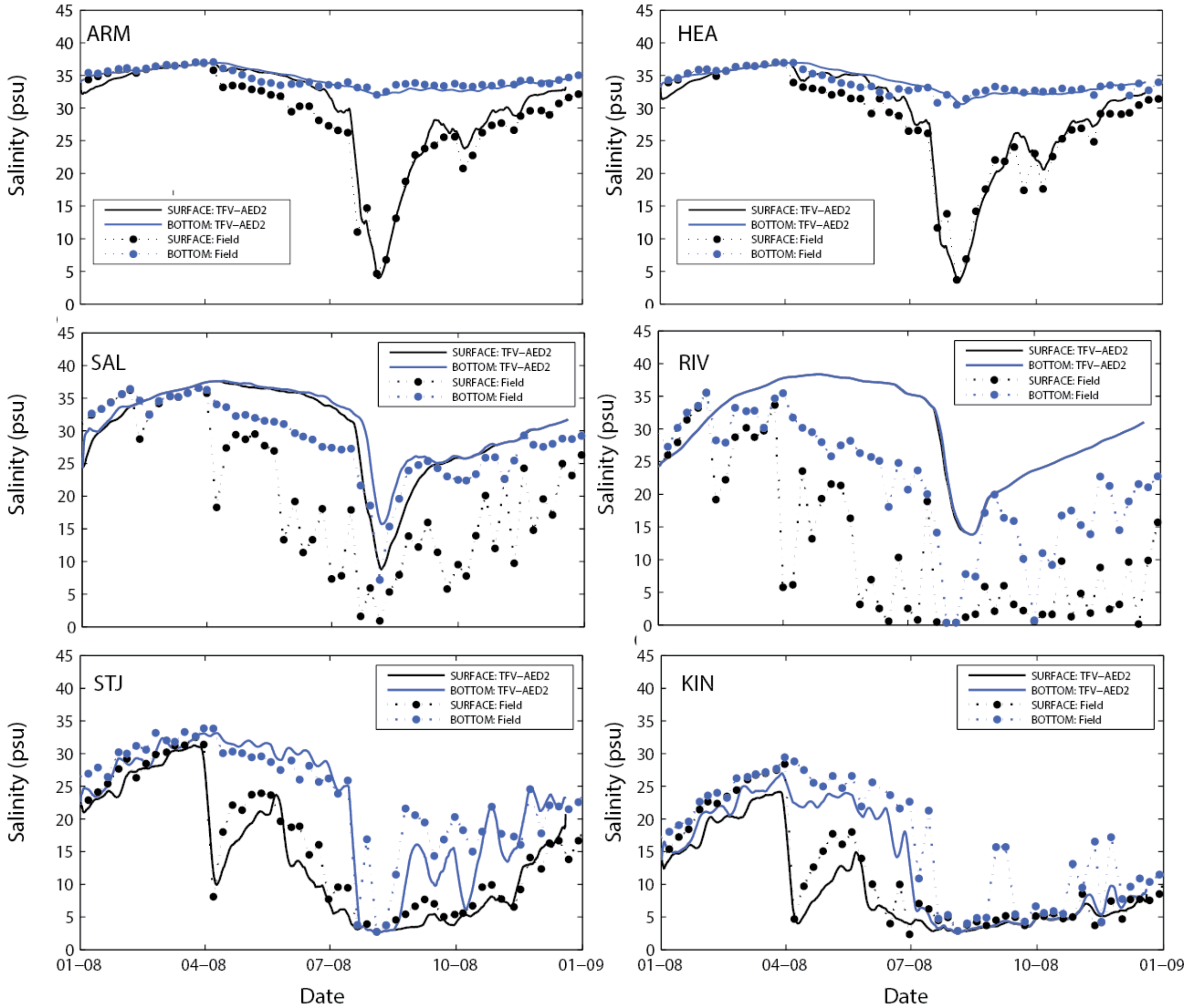


Figure 27. Salinity at six sites across the Lower and Upper Swan.

52. Temperature seasonality is well captured in the main Lower Swan basin (as indicated at ARM and HEA) however in this simulation there is a tendency for a under prediction in winter within the upper reaches of the Canning, and a tendency for over-prediction in the Upper Swan.

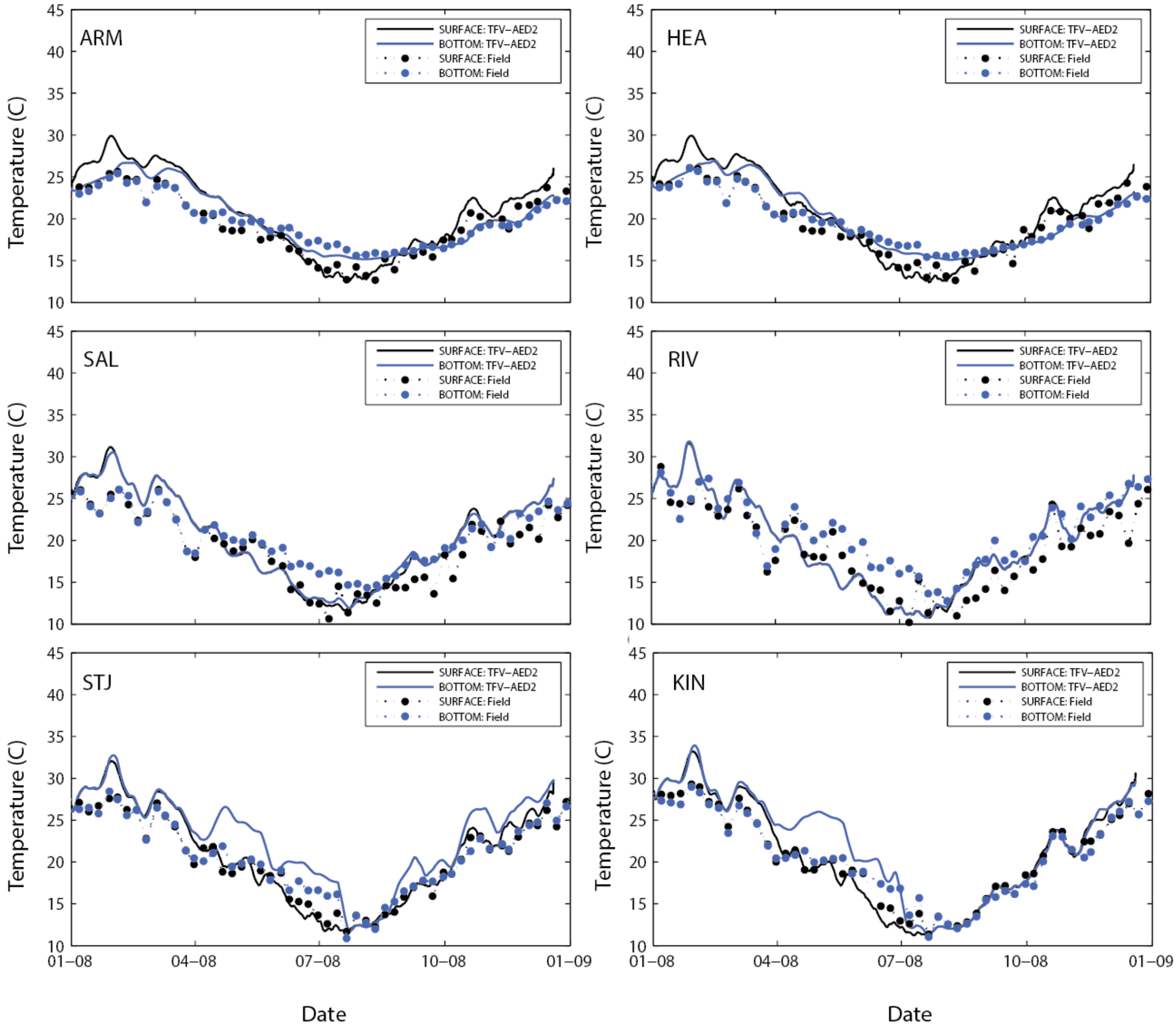


Figure 28. Temperature at six sites across the Lower and Upper Swan.

Light & Turbidity

53. SS is reasonably captured, but as indicated in the prior section, has a tendency for under-prediction during low flow periods.

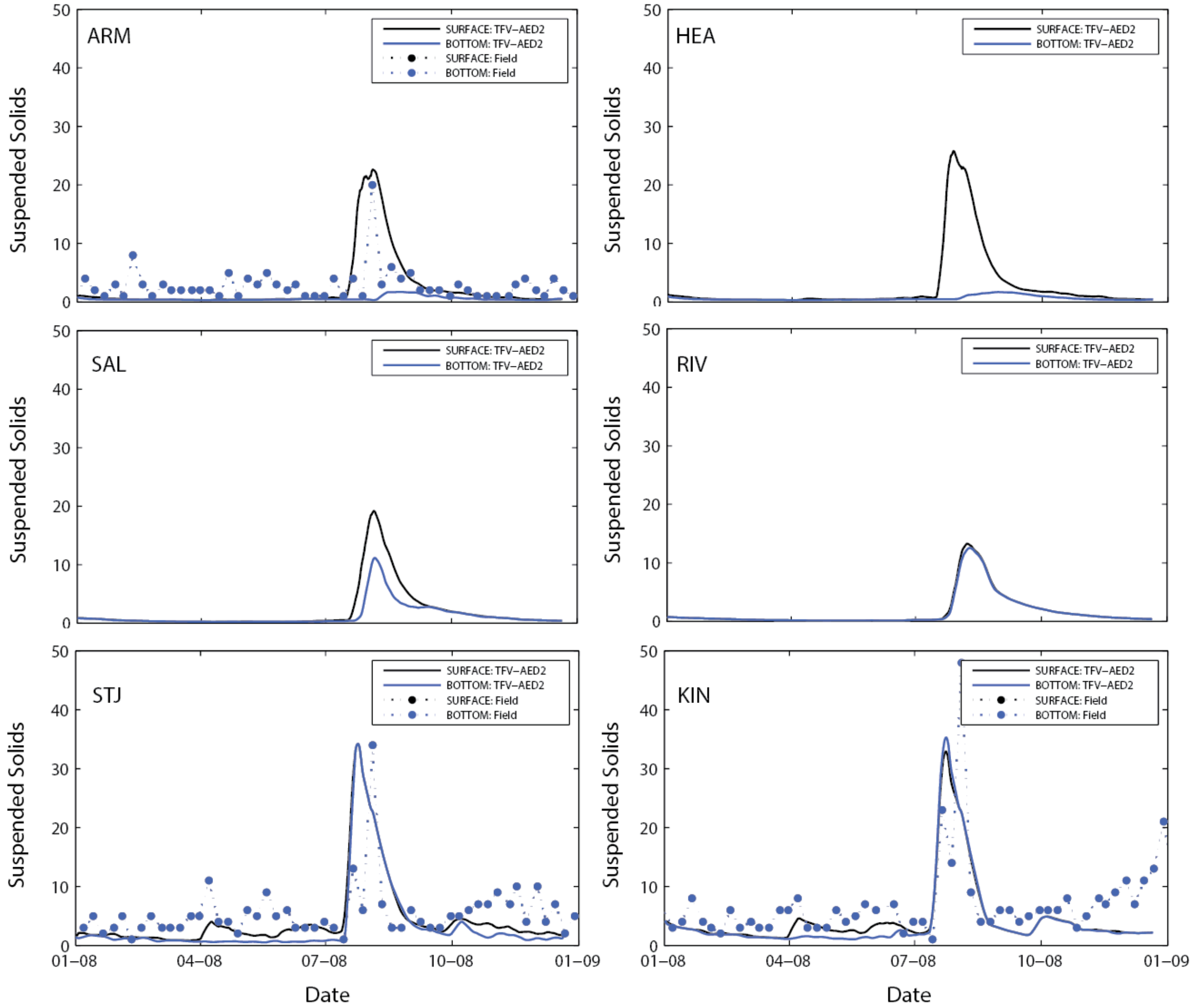


Figure 29. Suspended solids at six sites across the Lower and Upper Swan.

Dissolved Oxygen

54. Oxygen is reasonably captured in the Upper and Lower Swan, however appears to have a slight under-prediction in the surface oxygen in the ARM site. This is potentially due to the assumption of uniform windspeed across the domain.
55. Bottom oxygen in the upper Canning estuary site (RIV) is also not low enough, however this is likely due to the freshwater flow and salinity error at this location described above.

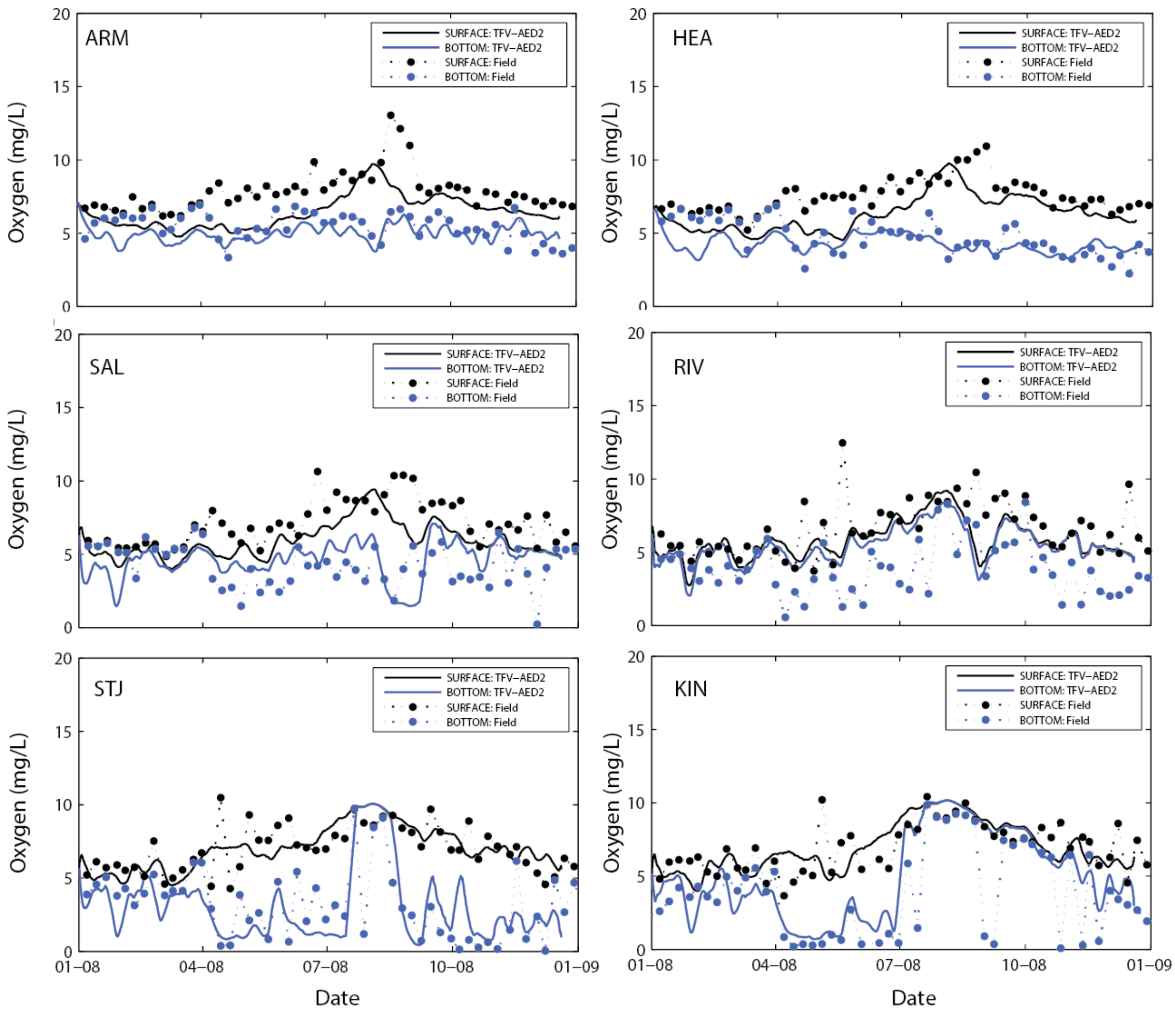


Figure 30. Dissolved oxygen at six sites across the Lower and Upper Swan.

Seagrass meadows (HALO)

56. The new AED2 seagrass module developed within this project was able to predict gross and net productivity of *Halophila* beds, as indicated by the snapshot presented in the below figure.

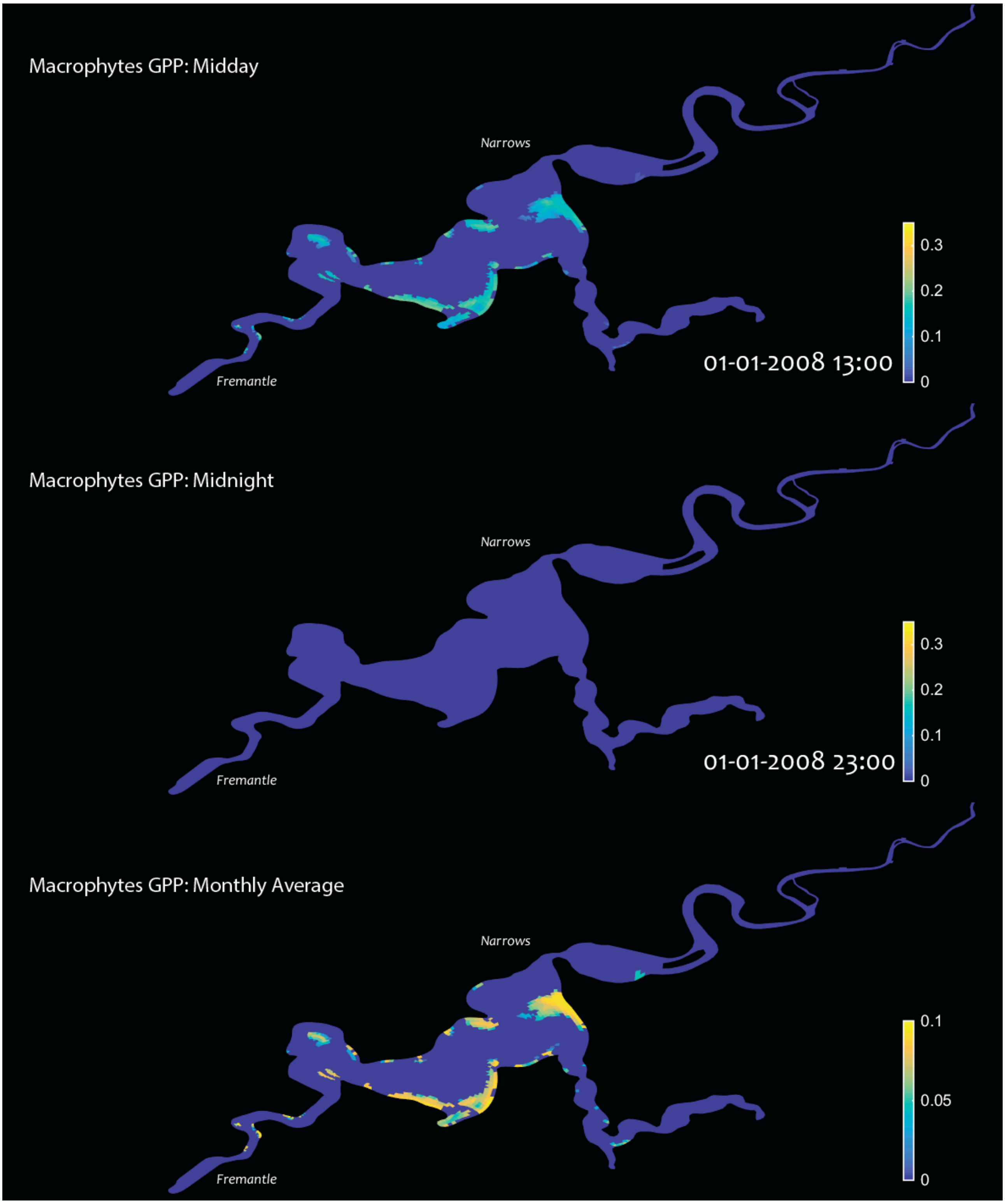


Figure 26. Predicted productivity (GPP) for two snapshots (top) and as a monthly average for Jan (bottom). Colour scale indicates relative growth rate per day (/d).

5. Key Points and Further Work

Model Performance

Overall, the model development and application presented in this report further advances the prior model application presented for oxygen assessment in Hipsey et al. (2015) by: a) extending the model to fully account for light, nutrients, organic matter and phytoplankton, and b) extending the scale of the domain to include the Lower Swan. A thorough assessment of the model was undertaken by comparing predictions against monitoring data from 52 sites for 14 variables both in the surface and bottom waters. This has been presented for the period from 2008-2012, spanning years of moderate and low flow conditions. Table 3 indicates a summary of the model performance.

Compared to model applications presented for other sites in Australia and overseas, the model performed very well in capturing salinity, temperature, oxygen, and for some of the nutrient pools. Reasonable predictions were obtained for other nutrient pools and chlorophyll-a. Further work is specifically required on to improve the predictions of DON, SS and PO_4 in the next round of model calibration.

In its present form the model is now suitable for assessing the management scenarios associated with artificial oxygenation, nutrient load management and/or climate change, bearing in mind deficiencies in the predictions outlined in the previous sections. The model has captured the drivers of phytoplankton formation across functional groups and demonstrated its ability to assist in unravelling the complex interplay of temperature, salinity, light and nutrients, flushing and competition. However, it is noted that these predictions are a first attempt at capturing these dynamics, and extensive further work is required to further build confidence the model is able to accurately forecast phytoplankton risk hotspots. Further validation of the phytoplankton module of the model against more recent data from 2013-2016 is therefore recommended.

Table 3. Summary of the models performance against the observed data. Key: +++ = high accuracy; ++ indicates moderate accuracy; + indicates low accuracy; na = indicates not assessed during this project.

	Upper	Lower	Canning
Water level	na	na	na
Salinity	+++	+++	+
Temperature	++	++	++
Suspended Solids	+	+	+
Turbidity	+	+	+
Oxygen	++	++	+
Nitrate	++	na	na
Ammonium	+	na	na
Organic Nitrogen	+++	na	na
Total Nitrogen	+++	na	na
Phosphate	+	na	na
Organic Phosphorus	na	na	na
Total Phosphorus	+++	na	na
Silica	++	na	na
Chlorophyll-a	++	na	na

Current model usability

The development of an integrated estuarine model for the Swan-Canning has been significantly advanced during this latest development period. The model is performing well, and is suitable to run scenarios to inform many aspects of management. We envisage that the current model could be used to explore scenarios to answer the following questions (for example):

- With declines in river flows forecast to continue into the future, what is the effect on the location, duration and hypoxic extent of the salt-wedge? (e.g. scenarios for 2030, 2050, 2100)
- How does artificial oxygenation influence the nutrient budget in the Upper Swan estuary (compare scenarios with and without the oxygenation plant)?
- How will the environmental drivers of algal growth (e.g. temperature, light, nutrients) vary under alternate flow and nutrient management options?
- Can we explain the current pattern of Halophila presence based on light alone, or are other factors important?

Focus Areas for Model Improvement

Priority areas for work on model improvement for the Upper Swan (not in order):

- Upstream solar radiation shading and wind-speed reduction due to fringing vegetation
- Fringing wetland ecohydrology, salt incursion and tree decline.
- Dinoflagellate and cyanobacteria vertical migration
- Turbidity relationship to SS, Chl-a and POM
- Suspended solid particle size distribution
- Sediment nutrient flux predictions
- DOM reactivity and photolysis
- Ungauged stormwater inputs
- Groundwater nutrient inputs
- Sediment resuspension
- Fish-kill risk index

Priority areas for work on model improvement for the Lower Swan (not in order):

- Two-dimensional meteorological forcing
- Macroalgal dynamics, and hotspot locations for wrack formation; links to wind fields and meadow location.
- Seagrass biomass variation and sensitivity to water column turbidity, and validation with data from seagrass indicator sampling.

References

Arhonditsis, G. B., & Brett, M. T. (2004). Evaluation of the current state of mechanistic aquatic biogeochemical modeling. Marine Ecology Progress Series, 271, 13–26.

Forbes, V.R. and Kilminster, K. (2016) Monitoring seagrass extent and distribution in the Swan-Canning estuary. *Water Science Technical Series, Report no. 70*, Western Australia Department of Water, Perth Australia.

Hipsey, M.R., Kilminster, K., Busch, B.D., Bruce, L.C. and Larsen, S. (2014) Modelling oxygen dynamics in the Upper Swan estuary and Canning Weir Pool. *AED Report #R25*, The University of Western Australia, Perth, Australia. 99pp.

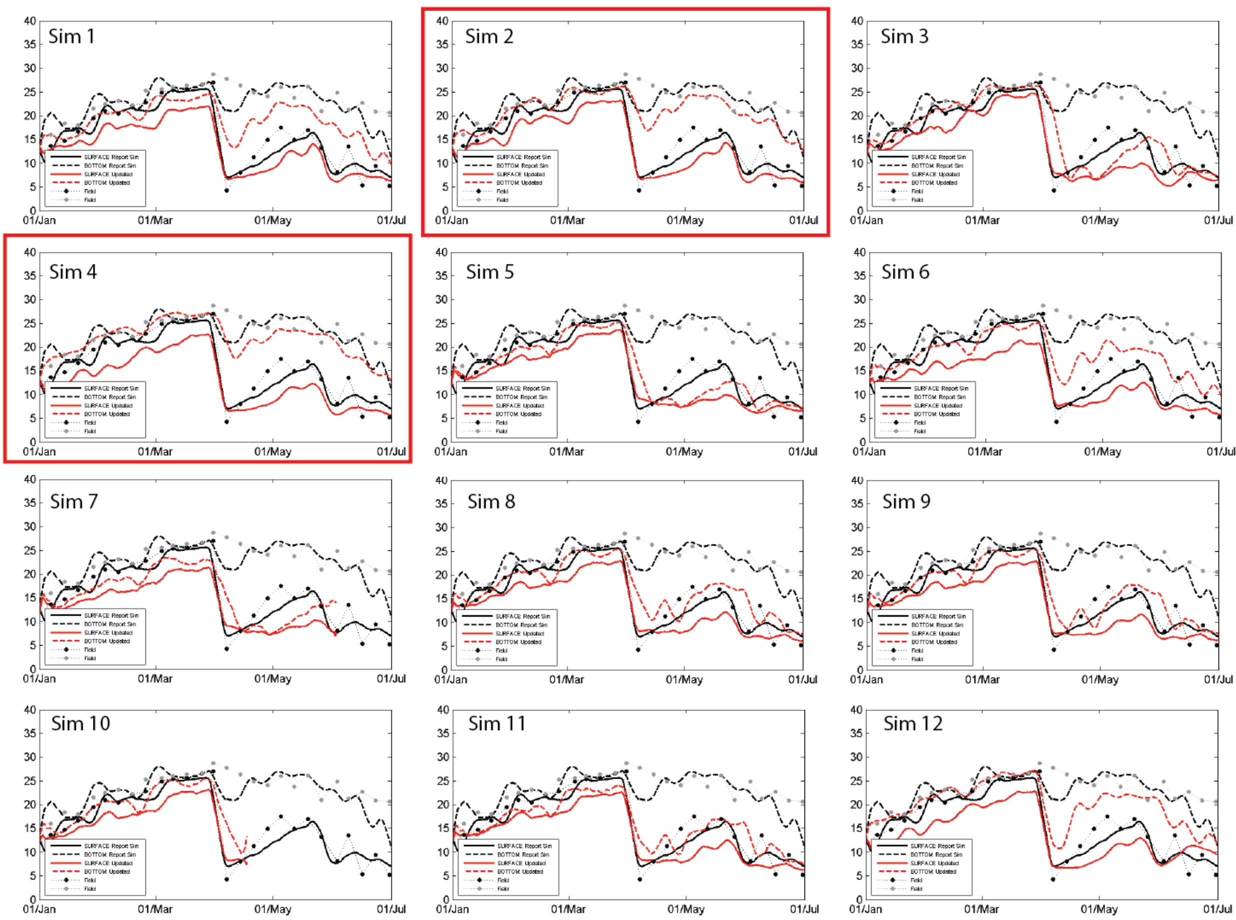
Hipsey, M.R., Kilminster, K., Robinson, S., Gedaria. A, Trayler, K., 2016. The Swan-Canning Estuary Response Model (SCERM) v1: Model Science Basis and Parameterisation. *AED Report #R28*, The University of Western Australia, Perth, Australia. 50pp.

Kostoglidis, A., Pattiaratchi, C.B. and Hamilton, D.P. (2005) CDOM and its contribution to the underwater light climate of a shallow, microtidal estuary in south-western Australia. *Estuarine Coastal Shelf Science* **63**, 469–477.

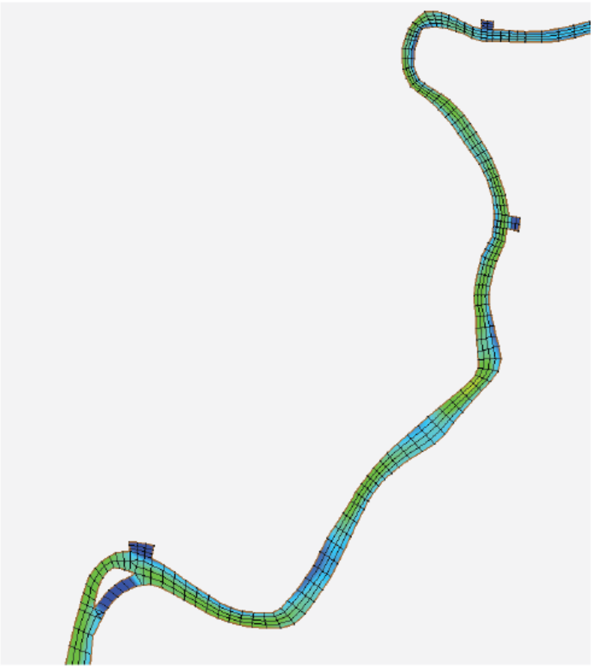
Appendix A – Hydrodynamic model pre-assessment

A mesh assessment and version comparison was undertaken at the start of the project to assess sensitivity of model predictions of the salt-wedge structure to changes in the model version and grid resolution. The table summarise the scope and range of changes assessed. The accompanying image below indicates the range of results obtained and selected approach prior to simulation of water quality attributes. The image over page indicates the changes to up-stream mesh to develop the high-resolution domain.

ID	Simulation Name	Grid Description	Inflow Scaling	Tidal Scaling	Met Description	GOTM Description	Z Layers	FVC File Changes
Sim 1	swan_2008_channel	Hi Res Channel, No Tributaries	1	1	Original 2013 Met File, scaling same as report	Original 2013 GOTM File	Original	Original
Sim 2	swan_2008_channel_GOTM2_Z2	Hi Res Channel, No Tributaries	0.8 (Upper Only)	1	Original 2013 Met File, scaling same as report	LEN Scale == 10,	Refined (Z2)	global horizontal eddy viscosity == 0.2
Sim 3	swan_2008_channel_GOTM2_Z3_Met	Hi Res Channel, No Tributaries	0.8 (Upper Only)	1	Updated Aditya Met File	LEN Scale == 10,	Further Refined (Z3)	global horizontal eddy viscosity == 0.2
Sim 4	swan_2008_channel_GOTM2_Z3_nMet	Hi Res Channel, No Tributaries	0.8 (Upper Only)	1	All Met Off	LEN Scale == 10,	Z3	global horizontal eddy viscosity == 0.2, iHeat == 0
Sim 5	swan_2008_tribs_GOTM2_Z3_Met	Hi Res Channel, Tributaries On	0.8 (Upper Only)	1	Updated Aditya Met File	LEN Scale == 10,	Z3	global horizontal eddy viscosity == 0.2, iHeat == 1
Sim 6	swan_2008_tribs_GOTM2_Z3_Rain	Hi Res Channel, Tributaries On	0.8 (Upper Only)	1	Rainfall Only	LEN Scale == 10,	Z3	global horizontal eddy viscosity == 0.2, iHeat == 0
Sim 7	swan_2008_tribs_GOTM2_Z3_Wind	Hi Res Channel, Tributaries On	0.8 (Upper Only)	1	Wind Only	LEN Scale == 10,	Z3	global horizontal eddy viscosity == 0.2, iHeat == 0
Sim 8	swan_2008_tribs_GOTM2_Z3_scaleWind	Hi Res Channel, Tributaries On	0.8 (Upper Only)	1	All Met (new), Wind Scale == 0.6	LEN Scale == 10,	Z3	global horizontal eddy viscosity == 0.2, iHeat == 1
Sim 9	swan_2008_tribs_GOTM2_Z3_scaleWind_2	Hi Res Channel, Tributaries On	1	1	All Met (new), Wind Scale == 0.6	LEN Scale == 10,	Z3	global horizontal eddy viscosity == 0.2, iHeat == 1
Sim 10	swan_2008_tribs_GOTM2_Z3_GridTest	Hi Res Channel, Tributaries On, No Islands	0.8 (Upper Only)	1	All Met (new), Wind Scale == 0.6	LEN Scale == 10,	Z3	global horizontal eddy viscosity == 0.2, iHeat == 1
Sim 11	swan_2008_tribs_GOTM2_Z3_scaleWind_SO22	Hi Res Channel, Tributaries On	0.8 (Upper Only)	1	All Met (new), Wind Scale == 0.6	LEN Scale == 10,	Z3	global horizontal eddy viscosity == 0.2, iHeat == 1, Spatial Order == 2,2
Sim 12	Initial_v19_FABMv2_2008_smth_QC	Original 2013 report grid Based on Hipsey et al 2014	1	1	No Met	Original 2013 GOTM File	Original	Original, iHeat == 0

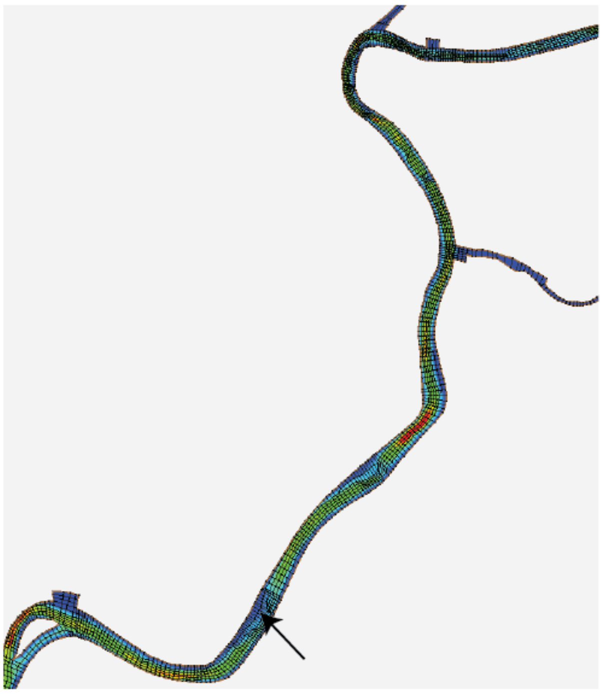


2013 Report Grid (with Cell Outlines)



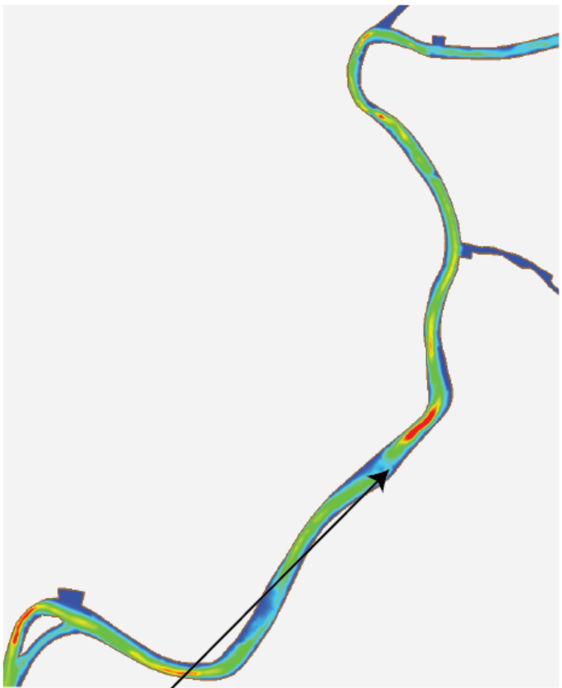
2013 Report Grid (w.out Cell Outlines)

2014 Grid Update (with Cell Outlines)



Uneven distribution of
cells to capture details

2014 Grid Update (w.out Cell Outlines)



Better representation of “holes”

Appendix B – Monitoring stations used for model assessment

ID	Short Name	Full Name
616011	SWN4*	WALYUNGA
616027	SEA*	SEAFORTH
616040	GILM	GILMOURS FARM
616076	SWN5*	GT NORTHERN HIGHWAY
616082	SWS10*	SLADE STREET
616084	SWN12*	BENARA RD (200M D-S OF SWN1)
616086	SWN10*	WHITEMAN ROAD
616088	SWN7*	GT NTHN HWY ROAD BRIDGE
616092	ANA*	ANACONDA DRIVE
616099	SWN11*	RIVER ROAD
616178	SWS8*	NATIONAL PARK
616189	SWN3*	RAILWAY PARADE
6160118	CAV	CAVERSHAM AVENUE JETTY
6160119	REG	REG BOND PARK
6160121	LLH	LILAC HILL
6160258	BLA	BLACKWALL REACH
6160259	ARM	ARMSTRONG SPIT
6160262	NAR	NARROWS BRIDGE
6160263	NIL	NILE ST
6160764	MAY	MAYLANDS SWIMMING POOL
6160930	MULB_FARM	MULBERRY FARM
6161086	MSB	MIDDLE SWAN BRIDGE
6161821	KIN	KINGSLEY ROAD
6161837	RIV	RIVERTON BRIDGE
6161838	SAL	SALTER POINT
6161869	HEA	HEATHCOTE
6161870	STJ	ST JOHN OF GOD HOSPITAL
6161878	RON	RON COURTNEY ISLAND
6161879	SUC	SUCCESS HILL
6162045	KMO	KING'S MEADOW OVAL
6162300	VIT	VITOX PLANT
6162994	KEN*	KENT STREET WEIR U/S
6163143	SWN1*	BENARA ROAD
6163179	SCB	SOUTH CANNING BRIDGE
6163346	CAS	CASTLEDARE
6163499	UJB*	UPSTREAM OF JANE BROOK
6163500	POL	UPPER SWAN POWER LINES
6163833	JBC	JANE BROOK CONFLUENCE
6163932	WBRP	WOODBRIDGE RIVERPARK
6163933	ANS	SWAN OXY PROFILING ANSTEY RD
6163948	VIT_US_S	VITOX UPSTREAM_S
6163949	VIT_US	VITOX UPSTREAM_B
6163950	VIT_DS_S	VITOX DOWNSTREAM_S
6163951	VIT_DS	VITOX DOWNSTREAM_B

6163956	RBH	UPPER SWAN RED BRICK HOUSE
6163957	GAZ	UPPER SWAN GAZEBO
6163958	JET	UPPER SWAN PRIVATE JETTY
6163959	FBR	UPPER SWAN FOOTBRIDGE CROSSING
6163960	WFL	FALLEN TREE BY WHITE FENCE LINE
6164394	CAV_DS	CAVERSHAM OXY DOWNSTREAM
6164395	CAV_US1	CAVERSHAM OXY UPSTREAM
6164648	CAV_US2	CAVERSHAM OXY UPSTREAM 2

- Indicates station data used for tributary WQ specification (boundary condition), not validation