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The Swan-Canning Estuarine Response Model (SCERM) v2

Model validation, monitoring data assessment, and real-time operation

Aquatic Eco Dynamics

Government of Western Australia Department of Water

Department of Parks and Wildlife

SWAN CANNING RIVERPARK

Executive Summary

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 validation of the TUFLOW-FV – AED2 coupled hydrodynamic-biogeochemical modelling platform over the simulation period from 01/2015 to 06/2016 using various statistics methods to evaluate the model performance, and provide insights into the temporal and spatial variations of the estuary aquatic ecosystem. This report also compares the results from the "Tracer Model" against that from the estuarine model to identify biogeochemical hotspots where intensive biogeochemical activities occurred. Discussions regarding field physical and biogeochemical monitoring programs based on the water quality model performance and "Tracer Model" are given to provide suggestions to monitoring programs from a water quality modelling point-of-view. At last this report also present a brief introduction of our Swan-Canning real-time system, including a work diagram and example outputs.

The water quality 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 used the same parameters as in previous simulation for 2008 – 2012, with model domain spans from Fremantle to Upper Swan. Selected water quality attributes at 6 representative monitoring sites were included in the assessment, and where possible surface and bottom values were individually assessed.

Consistent to previous simulation for 2008 – 2012, the model was able to accurately reproduce the physics (salinity and temperature) of the estuary system, and well captured the variations of dissolved oxygen and some of the nutrient pools such as TP, PO_4, and RSi. Reasonable predictions were obtained for other nutrient pools and chlorophyll-a. The statistics and thalwegs plots across the estuary suggest the model was able to predict the spatial heterogeneity from Lower Swan to Upper Swan. 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. A new version of water quality model is under development with improvements on sediment suspension and seagrass biology that are expected to improve further modelling work.

Regarding the modelling regions, the Lower Swan had the best modelling performance, while Middle Swan and Upper Swan showed relatively large bias in TN, Nitrate and TCHLA, indicating the need of improving modelling and monitoring capacities in Middle Swan and Upper Swan. The results from the water quality model performance analysis and the "Tracer Model" also suggest that the Middle Swan and upper branch of Canning River have high biogeochemical intensity during dry seasons, while during wet season the deep water area of Lower Swan and south Middle Swan have high biogeochemical intensity. More sampling locations along transect in Lower Swan are recommended to capture and spatial variety along transect, and higher sampling frequency of DO and phytoplankton is required to capture their daily variation to provide more information to study and simulate their behaviours.

Several priority areas are identified for improving model accuracy and capability, including sediment resuspention, Dinoflagellate and cyanobacteria vertical migration, and seagrass activities. 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 in the previous sections.

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Contents

EXECUTIVE SUMMARY 3

CONTENTS 7

1. INTRODUCTION & OBJECTIVES 9

2. METHODS 9

2.1 Estuary water quality model 9
Model Set Up 9
Model Performance Analysis Methods 12
2.2 Tracer Modelling Method 12
Model Set Up 12
Analysis Method 12

3. MODEL PERFORMANCE ASSESSMENT 13

3.1 Time series of model output against measurements at representative stations 13
Salinity 14
Temperature 15
Dissolved Oxygen (DO) 16
Phosphorus: Total Phosphorus (TP) 17
Phosphorus: Phosphate (PO_4) 18
Nitrogen: Total Nitrogen (TN) 19
Nitrogen: Ammonium (NH_4) 20
Nitrogen: Nitrate (NO_x) 21
Nitrogen: Dissolved Organic Nitrogen (DON) 22
Silica: Reactive Silica (RSi) 23
Phytoplankton: Chlorophyll-a (TCHLA) 24
3.2 Transect thalweg (whole river view) of selected variables 25
Transect thalweg plots of surface waters 25
Transect thalweg plots of bottom waters 26
3.3 Error assessment by region 27
Lower Swan – include sites of ARM, HEA, BLA, RIV 27
Middle Swan – include sites of MAY, NAR, NIL, STJ 28
Upper Swan – include sites of KIN, MSB, RON, SUC 29
Summary 30

4. HOTSPOT ANALYSIS: TRACER MODEL ASSESSMENT 31

4.1 Hotspot in dry season (February 2015) 31
4.2 Hotspot in wet season (August 2015) 32

5. ASSESSING MONITORING DATA WORTH 33

5.1 Is the current monitoring program capturing areas in the domain that are more biogeochemically active? 33
5.2 Are there strong cross-stream gradients that are not picked up? – Needs for transect monitoring 33
5.3 Does the regular monitoring adequately capture events and daily variations? - Needs for dynamic monitoring and high-frequency monitoring 34

5.4 DO WE ADEQUATELY MONITOR WHAT IS COMING INTO THE ESTUARY? - NEED TO IMPROVE BOUNDARY MONITORING 35
5.5 WOULD REDUCING SAMPLING FREQUENCY AFFECT THE MODEL VALIDATION? 36

6. REAL-TIME MODEL OPERATION 37

SCEVO MODEL AUTOMATION FRAMEWORK 37
EXAMPLE OUTPUTS, AND LINK TO WEBSITE 38

7. KEY POINTS AND RECOMMENDATIONS 38

MODEL PERFORMANCE 38
RECOMMENDATIONS TO WATER QUALITY MONITORING FROM A MODELLING POINT-OF-VIEW 38

REFERENCES 39

1. Introduction & Objectives

The motivation for the development of an Estuarine Response Model for the Swan-Canning Estuary (SCE), as well as the model approach and scientific basis, has been outlined in detail in a few relative reports (Hipsey et al., 2014; Hipsey et al., 2016a; Hipsey et al., 2016b). The aims of this report are to:

- Undertake an analysis of model performance against historical data collected at selected sites within the estuary over the period from 01/2015 to 07/2016, and give recommendations for rationalizing water quality monitoring data in light of available datasets
    - Undertake an assessment of the models performance both spatially and temporally against the historical dataset and quantify error;
    - Use "Tracer Model" Method to identify internal vs. external controls of biogeochemical variables, thus to identify areas with intensive biogeochemical activities ("biogeochemical hotspots") and make suggestions to the physical and biogeochemical monitoring programs;
    - Consider value of regular monitoring data used for the different aspects of model setup and validation, and identify shortfalls, redundancies and relative value of monitoring datasets.
- Introduce the automation framework of a real-time estuary water quality model for Swan-Canning River, with automated operation of the model driven by near real-time data, and display portal for model outputs, showing regular visualisations of the SCERM model.

An overview of model simulation details and analysis methods is presented in Section 2; model performance assessments at selected sites for a range of relevant variables including salinity, temperature, oxygen, nutrients and phytoplankton are presented in Section 3; biogeochemical 'hotspots' analysis using the results from the tracer model is presented in Section 4; discussions and recommendations on assessing monitoring data worth from the validation results and tracer modelling results are presented in Section 5; brief introduction of real-time model framework and operation is presented in Section 6; while key points and recommendations of current report is given in Section 7.

2. Methods

2.1 Estuary water quality model

Model Set Up

The estuary is simulated using the TUFLOW-FV hydrodynamic model that is dynamically coupled with the AED2 water quality model. A brief description of the model settings is given below. For more information of the models refer to the recent report of Hipsey et al. (2016a).

The modelling domain spans the full extent of the estuary from Fremantle to Great Northern Highway (Figure 1). The final mesh used was determined from previous grid sensitivity assessment to satisfy model accuracy but also compromise for model run-time ration. AED2 version 1.1 was used for water quality simulation. Boundary condition data used to force the model are summarized in Table 1.

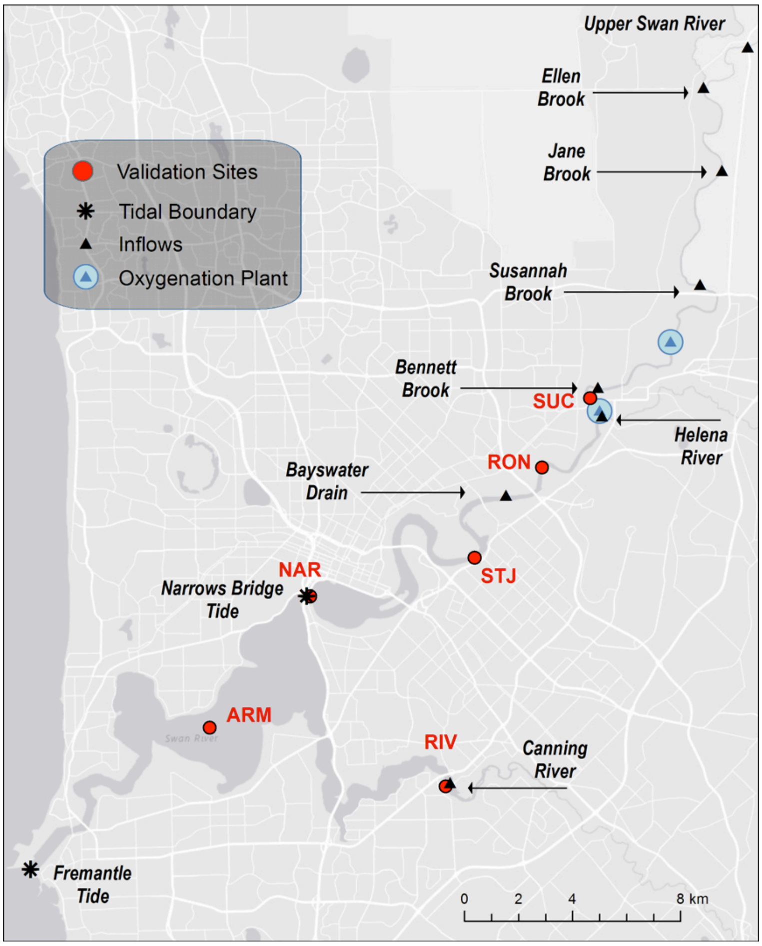


Figure 1. Model domain, inflow locations, and selected validation sites.

Variables simulated within the models are summarised in Table 2. 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 key outputs are presented here). For detailed overview of these variables and how they are computed the reader is referred to the recent report of Hipsey et al. (2016a).

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

Boundary Condition	Full domain	Upper Swan domain
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	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.
Upper Swan River	DOW 616076	DOW 616076
Ellen Brook	DOW 616189	DOW 616189
Jane Brook	DOW 616178	DOW 616178
Susannah Brook	DOW 616099	DOW 616099
Helena River	DOW 616086	DOW 616086
Bennet Brook	DOW 616084	DOW 616084
Bayswater Drain	DOW 616082	DOW 616082
Canning River	DOW 616082	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

Table 2: Variables simulated within the models. Bold indicate variables being presented 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
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
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
NH_4^+	mmol N m^{-3}	Ammonium	Algal uptake, nitrification, organic mineralization, sediment flux
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			
SS_s	g SS m^{-3}	Suspended solids groups	Settling, resuspension
Turbidity	NTU	Turbidity	Computed based on SS, TCHLA, CPOM and POM

Model Performance Analysis Methods

Various methods are used to validate and evaluate the model performance, include:

- **Time series of model output against measurements at representative stations, annotated with statistics and error metrics of**
    - r: regression coefficient, Varies between -1 and 1, with a score of 1 indicating the model varies perfectly with the observations and a negative score indicating the model varies inversely with the observations. A consistent bias may be present even when high score of r is obtained.
    - RMSE: root mean squared error, Measures the mean magnitude, but not direction, of the difference between model data and observations, and hence can be used to measure bias. Values near zero are desirable. This method is not affected by cancellation of negative and positive errors, but squaring the data may cause bias towards large events.
    - MAE: mean absolute error: Similar to RMSE except absolute value is used. This reduces the bias towards large events. Values near zero indicate good model skill.
    - MEF: modelling efficiency, measures the mean magnitude of the difference between model data and observations. This method compares the performance of the model to that only uses the mean of the observed data. A value of 1 would indicate a perfect model, while a value of zero indicates performance similar to simply using the mean of observed data.

- **Transect (whole river) thalweg medians of selected variables**
    - Transect view of measured data range against model performance from estuary mouth to upper Swan (spatial assessment)
- **Error assessment by region**
    - Scatter plots showing r, RMSE, MAE, and MEF of three regions
        - Lower Swan
        - Middle Swan
        - Upper Swan
    - Summary Table (colour coded by performance of variables an regions)

2.2 Tracer Modelling Method

A 'Tracer Model' was set up aiming at identifying the biogeochemical 'hotspots' within the estuary domain. This model is identical to the above water quality estuary model, except all the biogeochemical activities were "turned off". E.g., all the state variables, including nutrients and phytoplankton, were treated as idle tracers. They were not involved in any biogeochemical reactions but only being physically transported and mixed. After the models were run for a certain period, spatial distributions of key state variable were compared between the water quality model and the tracer model. The degrees of differences between the water quality model and the tracer model indicate how intensive the biogeochemical activities occurred.

Model Set Up

The settings of the tracer model were identical to the water quality estuary model, except all the biogeochemical reactions within the AED2 model were turned off. That means the change of spatial distribution of state variables only caused by physical transportations and mixing.

Analysis Method

The degree of difference between the water quality model and tracer model I were represented as:

$$I = \frac{\sum C_w/n - \sum C_t/n}{D_{max}}$$

where C_w and C_t are variable concentrations in the water quality model and tracer model, respectively; n is the number of model outputs in the comparison period, and D_{max} is the maximum value of difference of the domain.

Three key state variables – ammonium, nitrate, and filterable reactive phosphorus, were selected for comparisons, as they are the most active and important biogeochemical variables of the estuary ecosystem. Mean values of these variables from model outputs within two periods are compared: one is in February 2015 representing a "dry month", and another is in August 2015 representing a "wet" month (Figure 2).

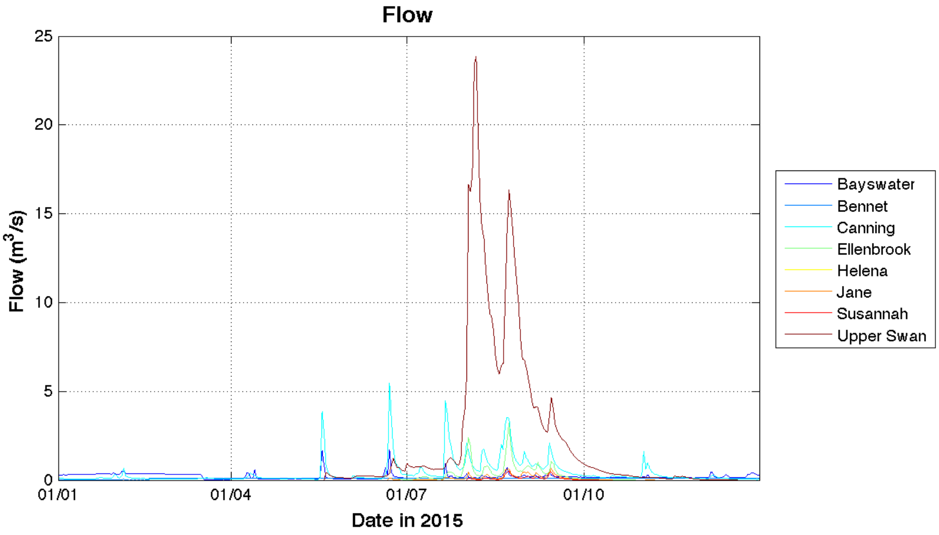


Figure 2. Flow rates at 8 inflow rivers into Swan-Canning Estuary.

3. Model Performance Assessment

3.1 Time series of model output against measurements at representative stations

The model is assessed against the monitoring data at multiple sites within the estuary, of which 6 (ARM, RIV, NAR, RON, STJ, SUC, see figure 1) are used to summarise model performance here. These sites were carefully selected as they are evenly distributed along the estuary (except RIV which represents Canning River) and rich data were available at these sites for model validations. Data from the model and monitoring is summarised over the surface and bottom due to the high degree of stratification that commonly occurs.

The following sub-sections describe the model performance on each variable and comment on the model performance and reasons for discrepancies.

Salinity

- The model confidently captures the vertical and horizontal variation in salinity over the simulation period.
    - Correlation R: 0.75 - 0.90
    - RMSE: 1.54 – 6.15 psu
    - MAE: 1.22 – 5.18 psu
    - MEF: 0.12 – 0.73

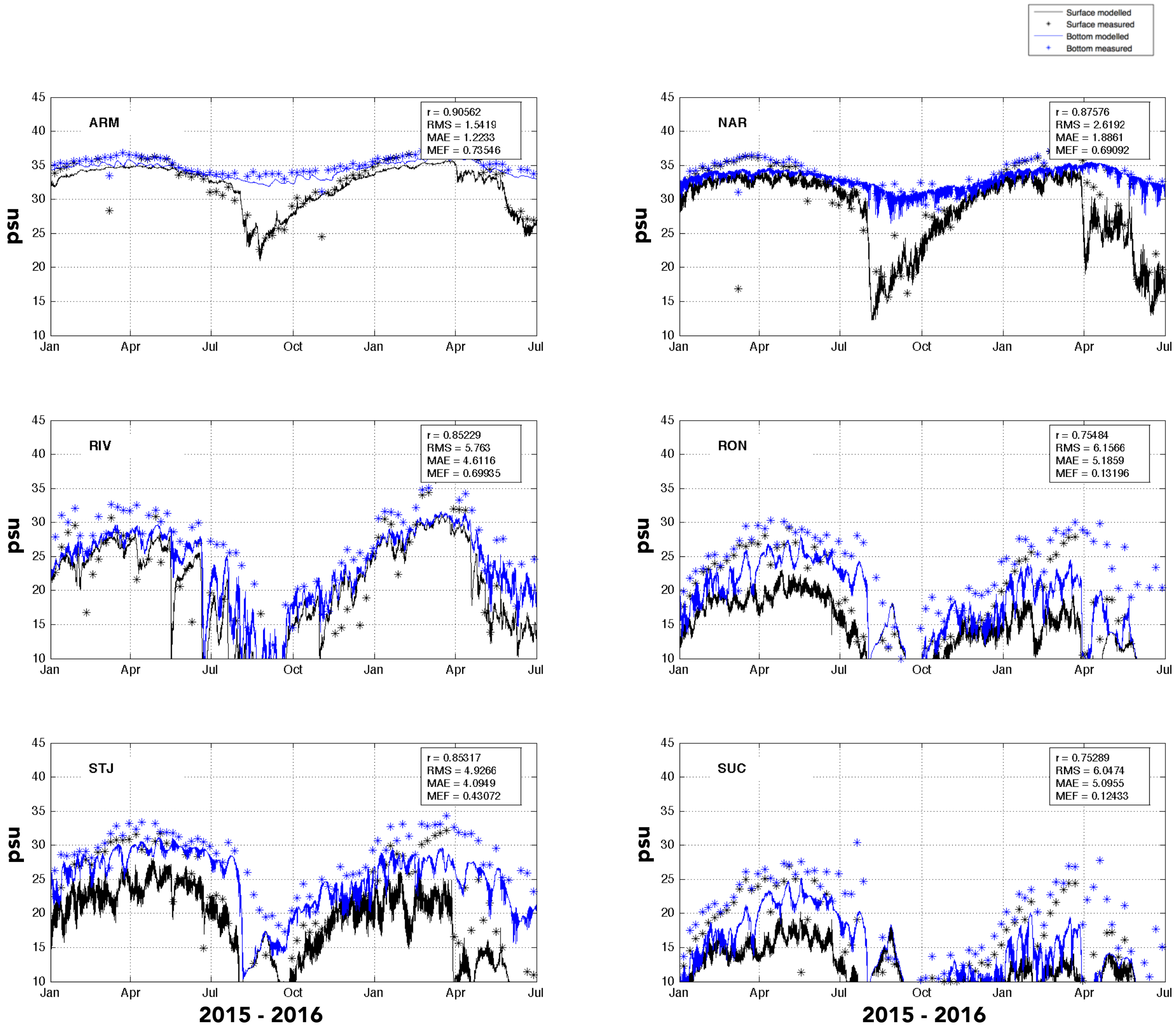


Figure 3. Salinity at six representative sites.

Temperature

- The model confidently captures the diurnal and seasonal variation in temperature over the simulation period.
    - Correlation R: 0.90 - 0.95
    - RMSE: 2.00 – 2.95 degrees
    - MAE: 1.45 – 2.36 degrees
    - MEF: 0.51 – 0.80

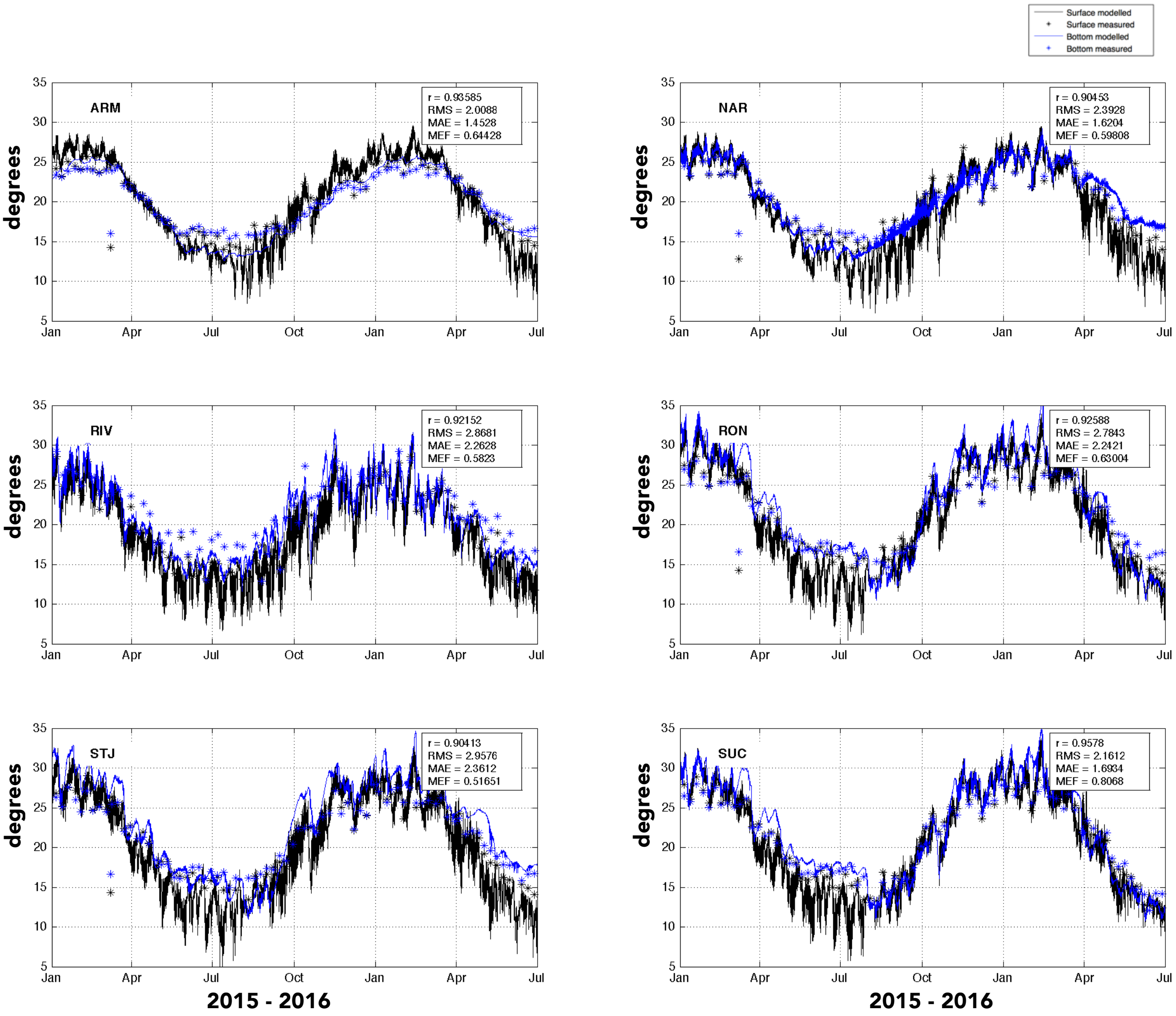


Figure 4. Temperature at six representative sites.

Dissolved Oxygen (DO)

- The model captures the seasonal variability of DO and the degree of vertical stratification over the simulation period;
- There are trends of underestimation of DO in surface and bottom water of ARM, NAR and RON. This is likely due to inadequate oxygen production from phytoplankton photosynthesis. Improvements in capturing the mechanisms of phytoplankton biology such as vertical migration will help to improve the DO prediction.
    - Correlation R: 0.51 - 0.68
    - RMSE: 1.64 – 2.57 mg/L
    - MAE: 1.28 – 2.08 mg/L
    - MEF: -1.70 – 0.16

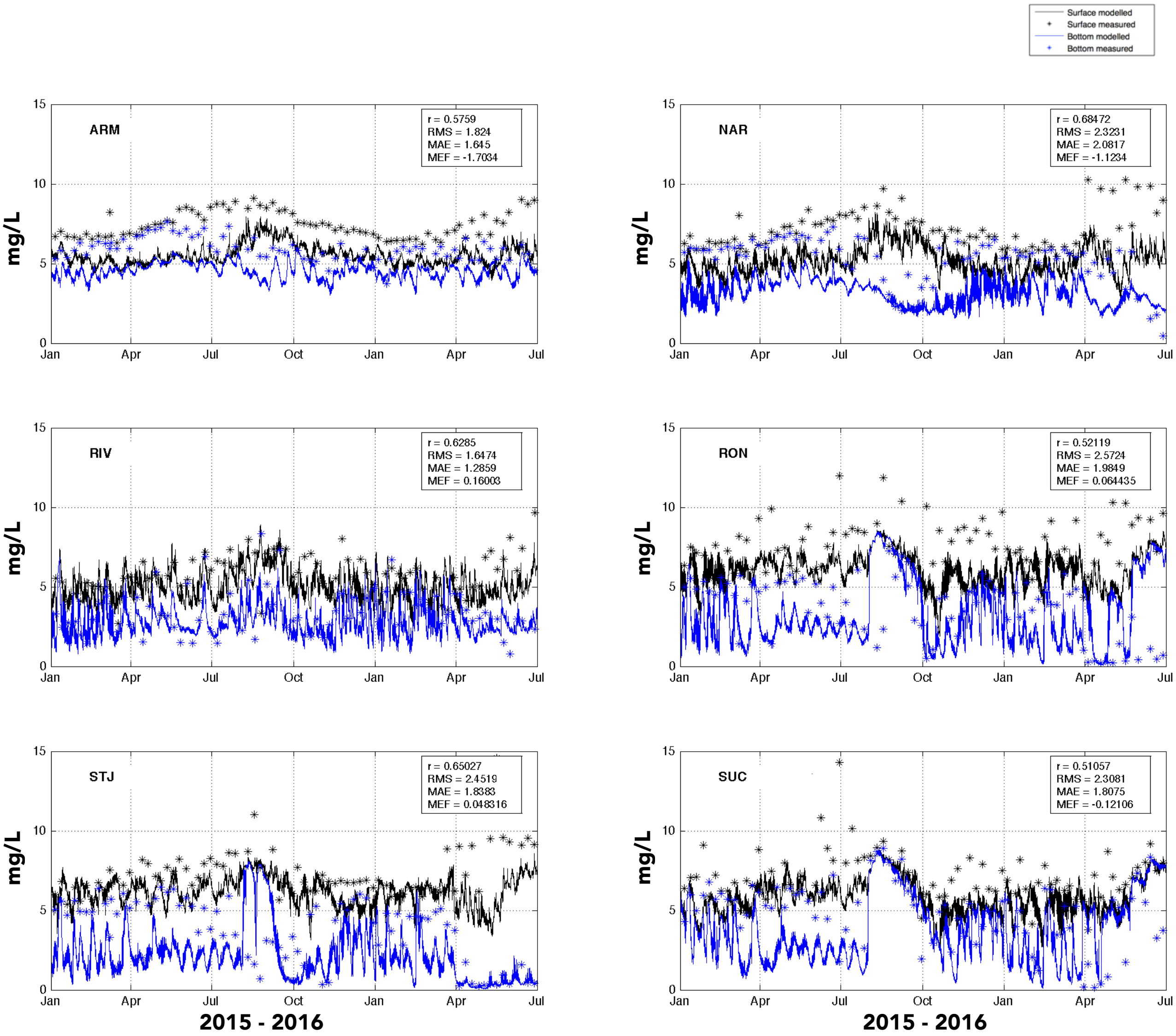


Figure 5. DO concentration at six representative sites.

Phosphorus: Total Phosphorus (TP)

- The model reasonably reproduces the seasonal TP variation over the simulation period, although there are overestimation of TP from Jan 2015 to Aug 2015 at all sites, maybe due to insufficient boundary inputs during that period.
    - Correlation R: 0.29 - 0.53
    - RMSE: 0.86 – 3.12 mmol/m^3
    - MAE: 0.72 – 2.08 mmol/m^3
    - MEF: -6.49 – 0.02

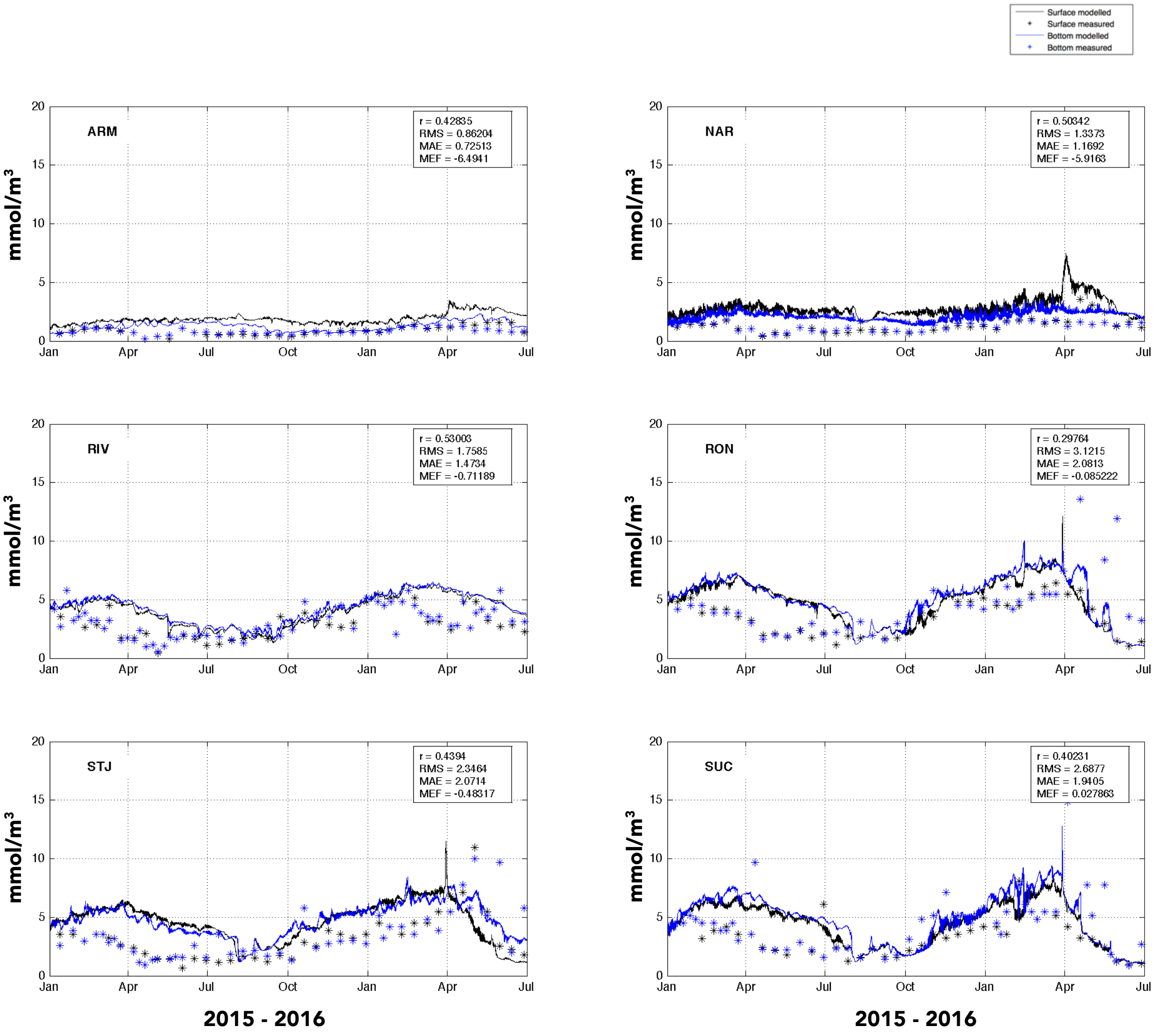


Figure 6. Total Phosphorus concentration at six representative sites.

Phosphorus: Phosphate (PO_4)

- Similar to the performance of TP, the model captures the seasonal variation of PO4 over the simulation period, while overestimations are found during Jan – Aug 2015.
  - Correlation R: 0.05 - 0.57
  - RMSE: 0.45 – 2.87 mmol/m^3
  - MAE: 0.37 – 1.28 mmol/m^3
  - MEF: -9.77 – 0.07

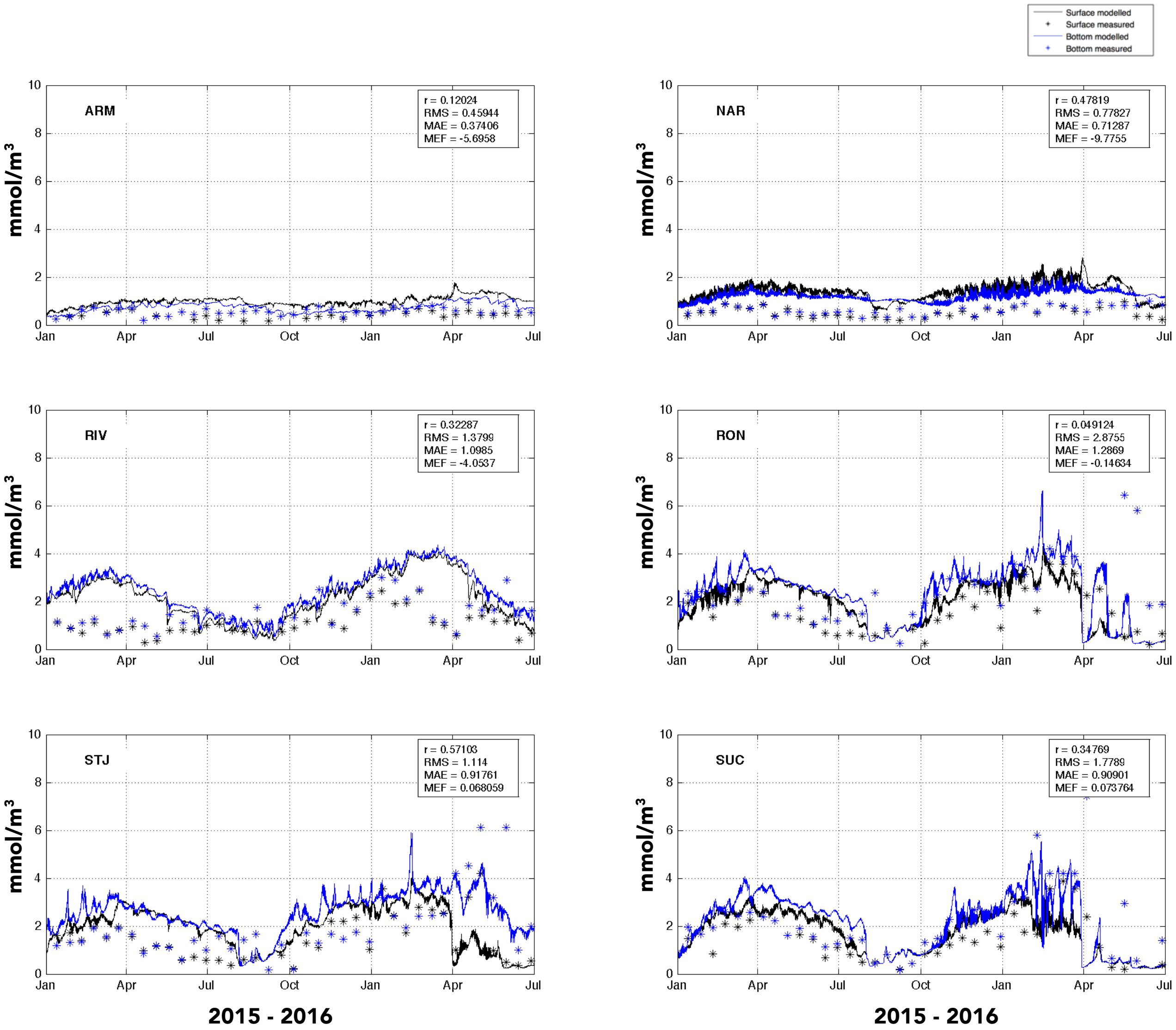


Figure 7. Phosphate concentration at six representative sites.

Nitrogen: Total Nitrogen (TN)

- The model captures the seasonal variation of TN over the simulation period. However the TN concentration in Upper Swan (RON, STJ, SUC) are consistent over-predicted. This is reflected in the statistics that the 'R' values are good in all sites while the deviations (RMSE and MAE) are high in Middle and Upper Swan sites. Given the TN prediction is good in previous runs (Hipsey et al., 2016b), this is likely due to insufficient boundary monitoring data of nitrogen to force the water quality model. Further discussions are given in Chapter 4 and Chapter 5.
    - Correlation R: 0.33 - 0.93
    - RMSE: 15.88 – 77.67 mmol/m^3
    - MAE: 11.95 – 64.50 mmol/m^3
    - MEF: -7.29 – -0.69

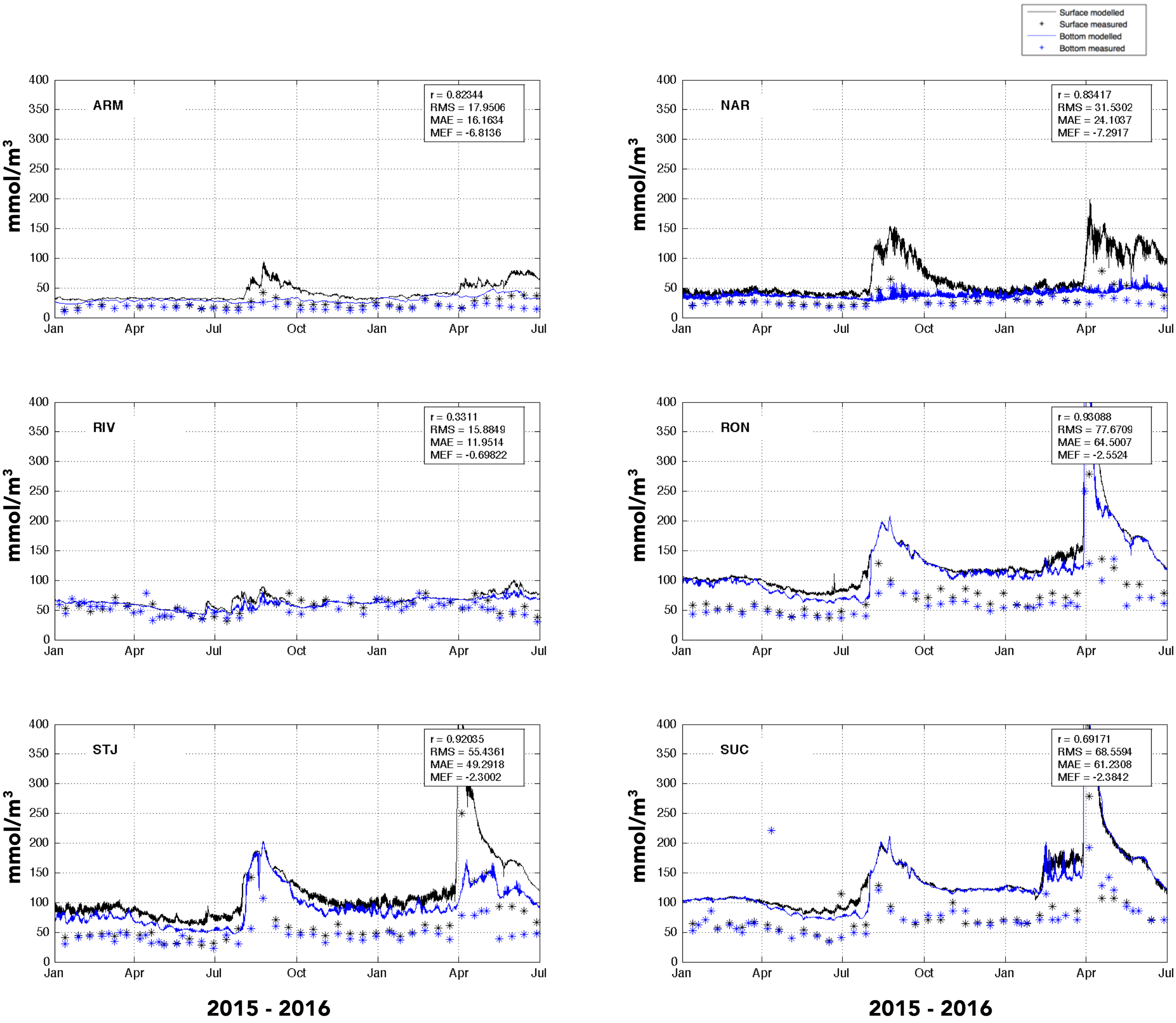


Figure 8. Total Nitrogen concentration at six representative sites.

Nitrogen: Ammonium (NH_4)

- The model captures the spatial variation of NH4 across the estuary and the vertical stratification over the simulation period; however, the NH4 behaviours at RIV and Upper Swan are intensive. Both the model and measurements show strong variations that make it difficult to get good statistics values. Again, higher frequency of monitoring at boundaries and within Upper Swan is recommended to improve the model performance.
    - Correlation R: 0.04 - 0.61
    - RMSE: 1.44 – 11.63 mmol/m^3
    - MAE: 1.05 – 6.67 mmol/m^3
    - MEF: -1.88 – 0.16

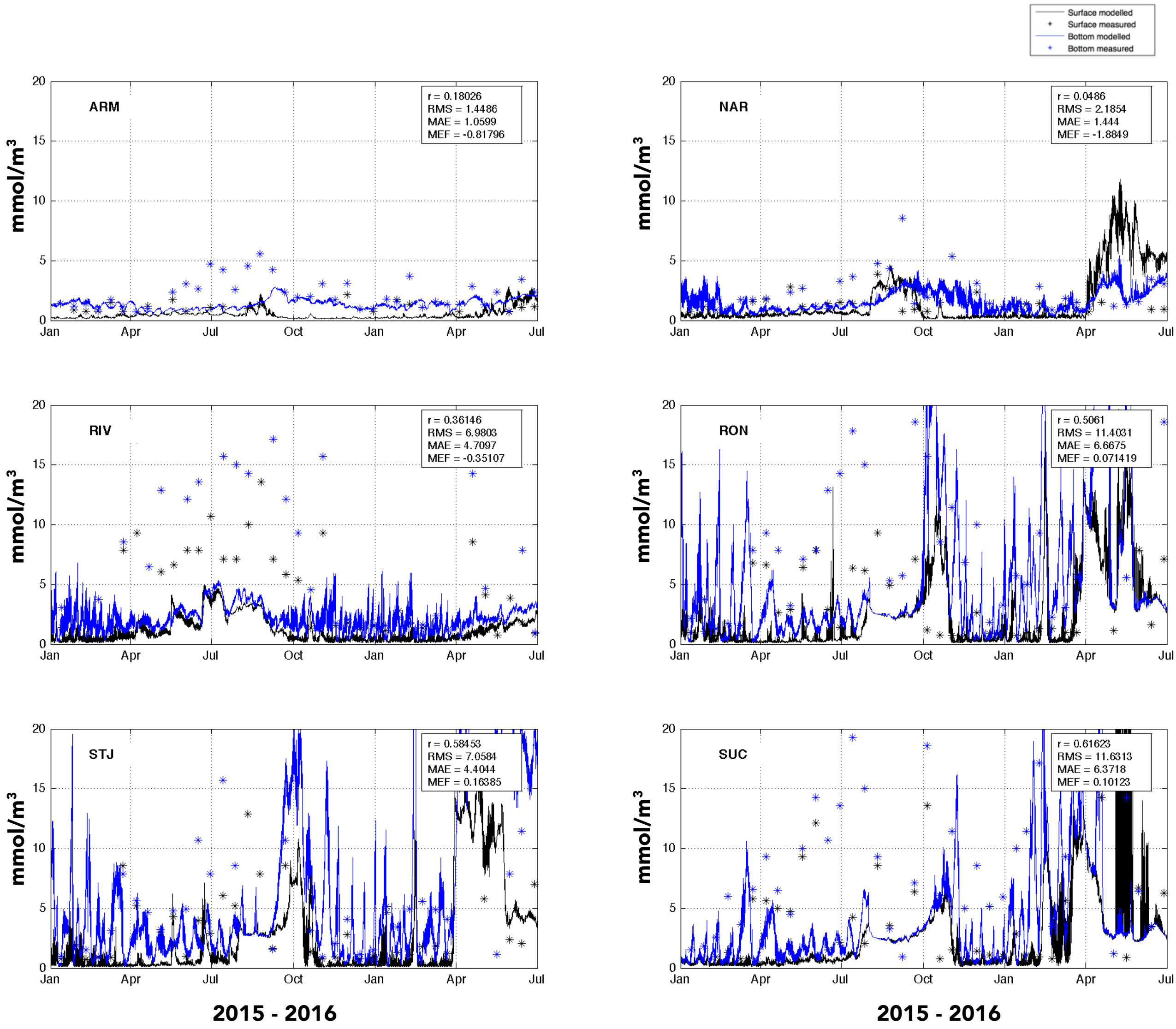


Figure 9. Ammonium concentration at six representative sites.

Nitrogen: Nitrate (NO_x)

- The model captures the spikes of nitrate over the simulation period, and the spatial variation along the estuary; however, the model generally underestimates the nitrate.
    - Correlation R: 0.23 - 0.88
    - RMSE: 1.54 – 16.03 mmol/m^3
    - MAE: 1.37 – 5.96 mmol/m^3
    - MEF: -3.86 – 0.52

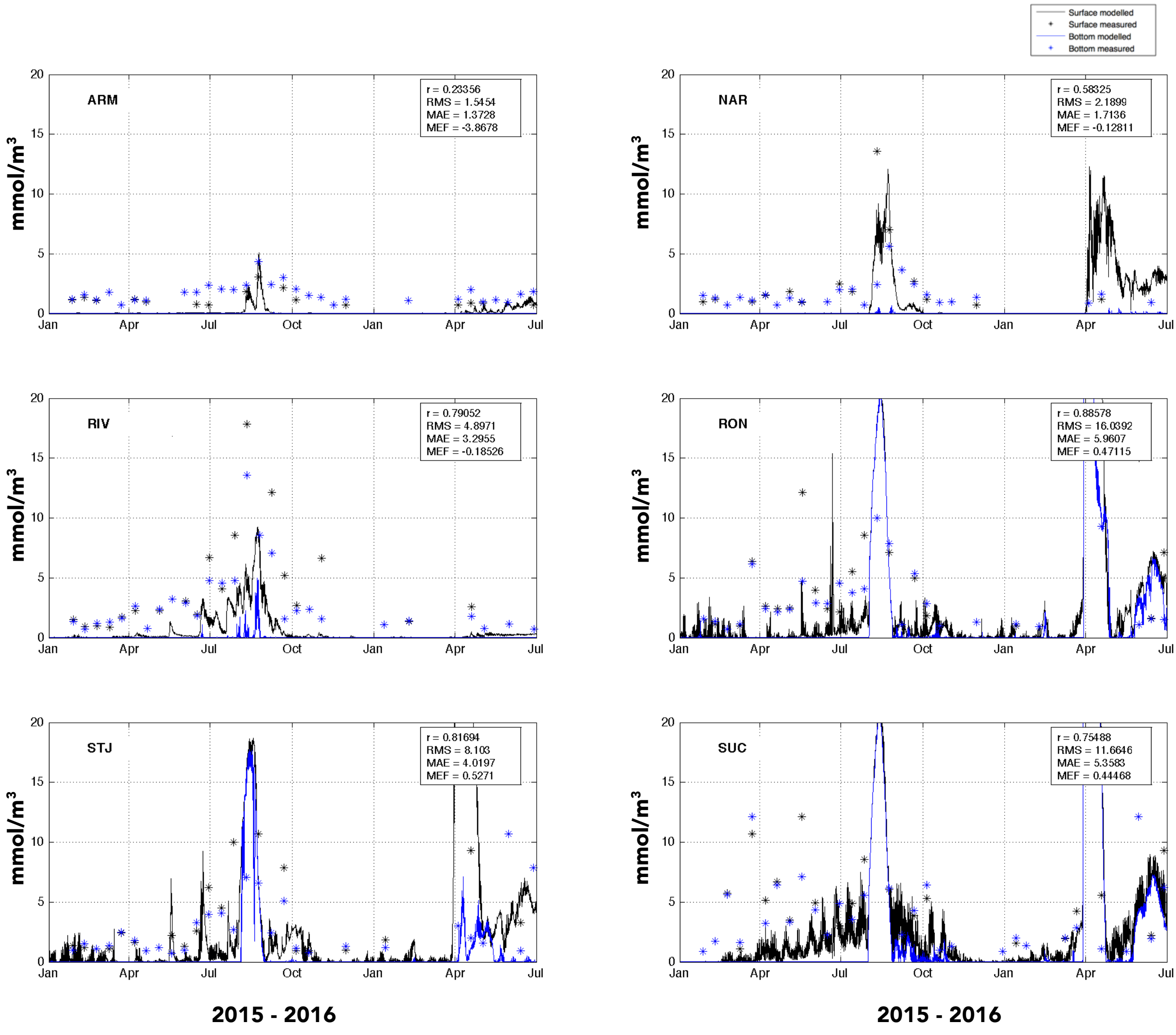


Figure 10. Nitrate concentration at six representative sites.

Nitrogen: Dissolved Organic Nitrogen (DON)

- The model captures the seasonal variation of DON over the simulation period, and the spatial variation along the estuary; however, the model tends to overestimate the DON at Upper Swan stations from Jan – Jul 2015, suggesting an over-supply of DON from boundaries or sediment during this time period or inadequate rates of mineralisation of phytoplankton exudate.
    - Correlation R: -0.08 - 0.61
    - RMSE: 5.34 – 27.24 mmol/m^3
    - MAE: 4.03 – 24.04 mmol/m^3
    - MEF: -1.71 – -0.03

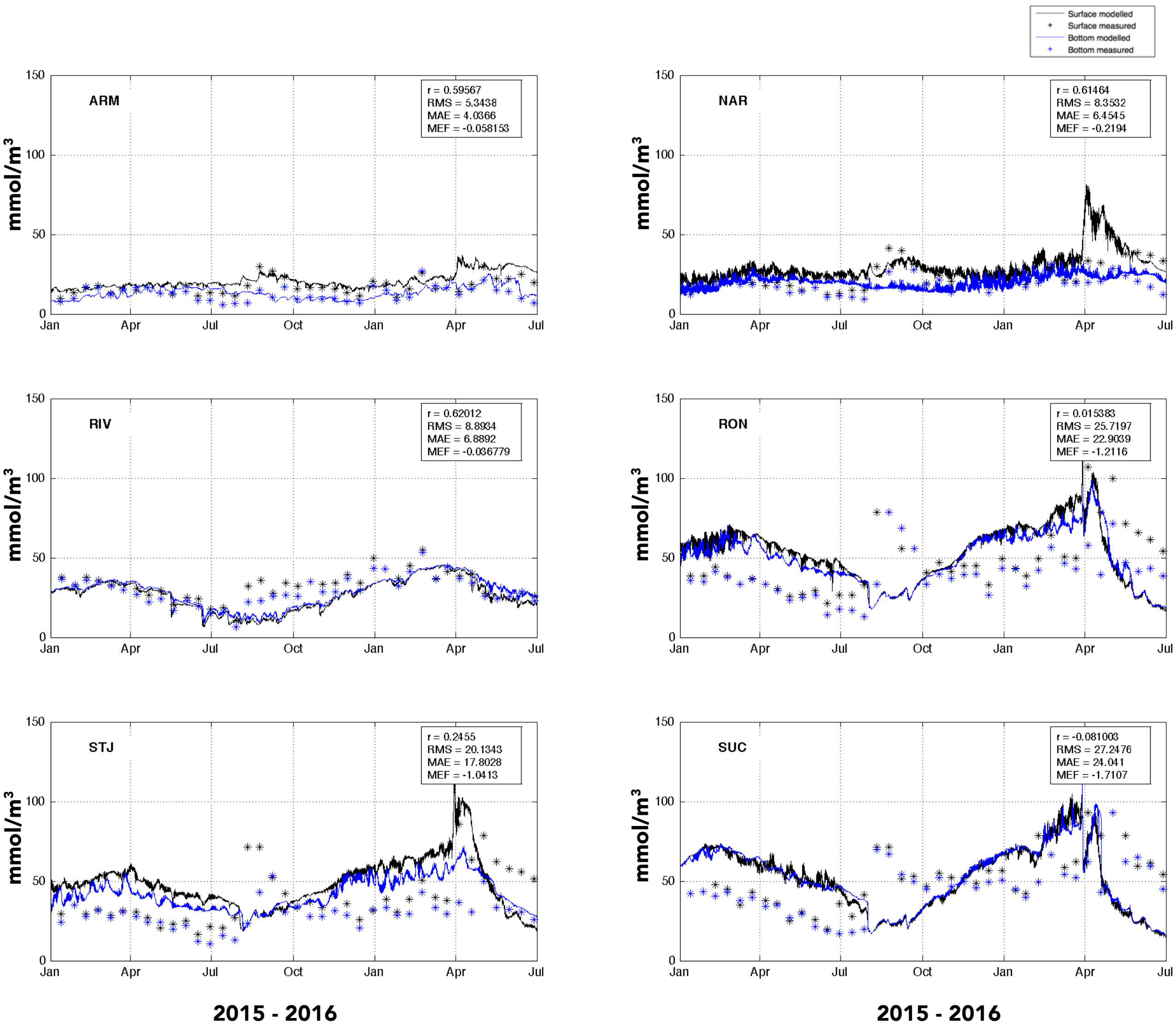


Figure 11. DON concentration at six representative sites.

Silica: Reactive Silica (RSi)

- The model captures the spikes of reactive silica over the simulation period, and the spatial variation along the estuary. The model generally underestimates the reactive silica in RIV, indicating under-supply from boundary input or over-consumption by diatom at RIV.
    - Correlation R: 0.15 - 0.66
    - RMSE: 24.55 – 41.15 mmol/m^3
    - MAE: 18.33 – 37.56 mmol/m^3
    - MEF: -4.11 – 0.08

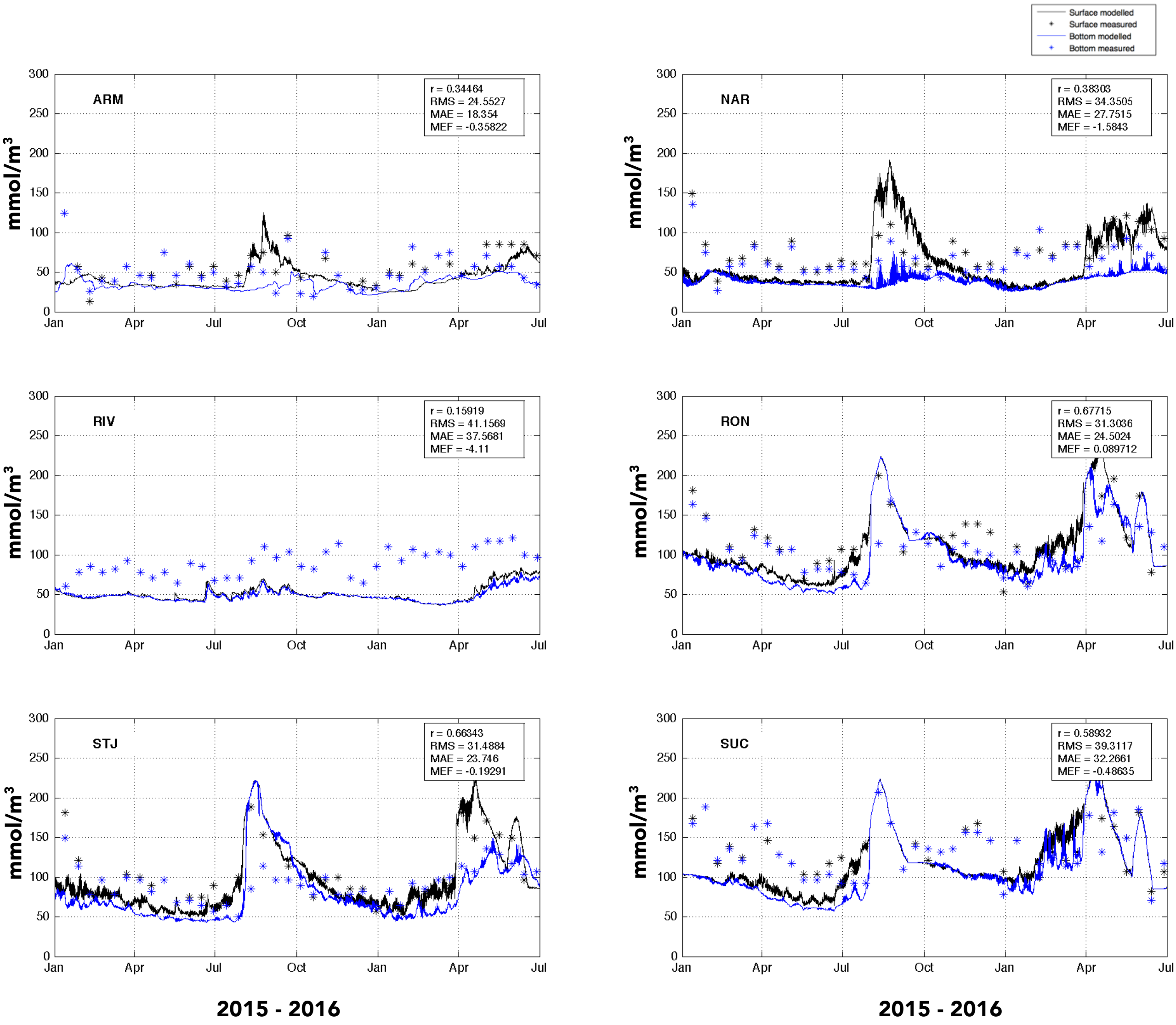


Figure 12. RSi concentration at six representative sites.

Phytoplankton: Chlorophyll-a (TCHLA)

- The model is able to capture the spatial difference between the Lower Swan, Middle Swan and Upper Swan; however, the model has a tendency to over-predict the bottom TCHLA. This is likely due to the lack of vertical migration configured in the dinoflagellate group, which allow dinoflagellate to accumulate when the river is not under turbulence. The measured TCHLA is also highly scattered, indicates the high variability of phytoplankton biology that need to improve in the water quality model.
  - Correlation R: -0.31 - 0.36
  - RMSE: 2.47 – 15.67 μg/L
  - MAE: 1. 70 – 8.55 μg/L
  - MEF: -0.60 – 0.11

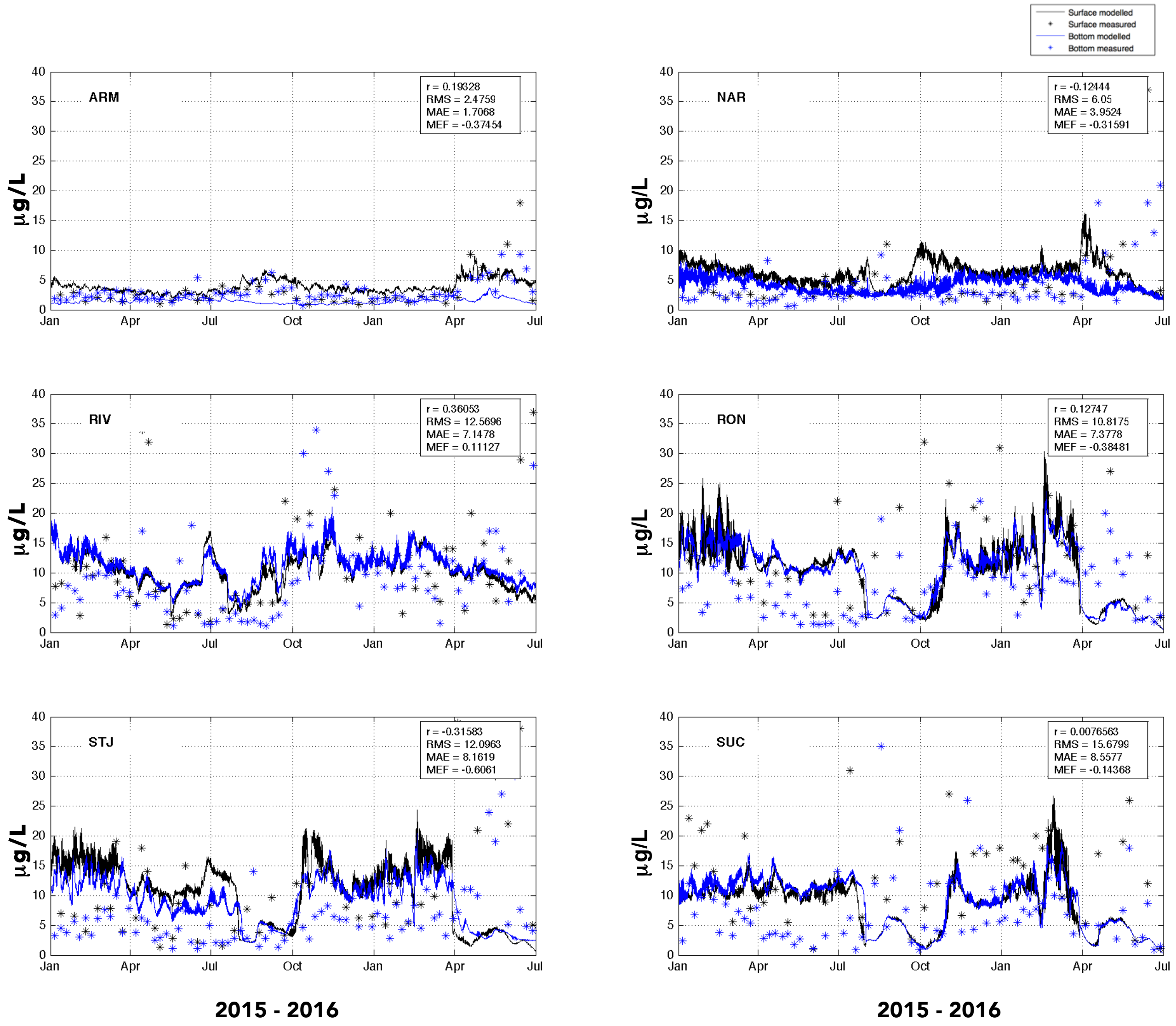


Figure 13. Total Chlorophyll-a concentration at six representative sites.

3.2 Transect thalweg (whole river view) of selected variables

Transect thalweg plots of surface waters

- The modelled surface salinity shows a gradual decrease from Lower Swan to Upper Swan, well matched the field measurements; while the surface temperature doesn't show much variety across the estuary;
- The model captured the spatial variety of TN, Nitrate, and DON, although the TN tends to be overestimated and Nitrate tends to be underestimated. This matches the statistics results in Chapter 3.1 that the modelled TN and Nitrate have a good regression coefficients against the measured TN and Nitrate, but big deviations are found.
- The spatial variation of TP and Phosphate are well captured, although the TP is tended to be overestimated;
- The surface dissolved oxygen doesn't show much variety across the estuary;
- The surface TCHLA is underestimated in the Upper Swan;

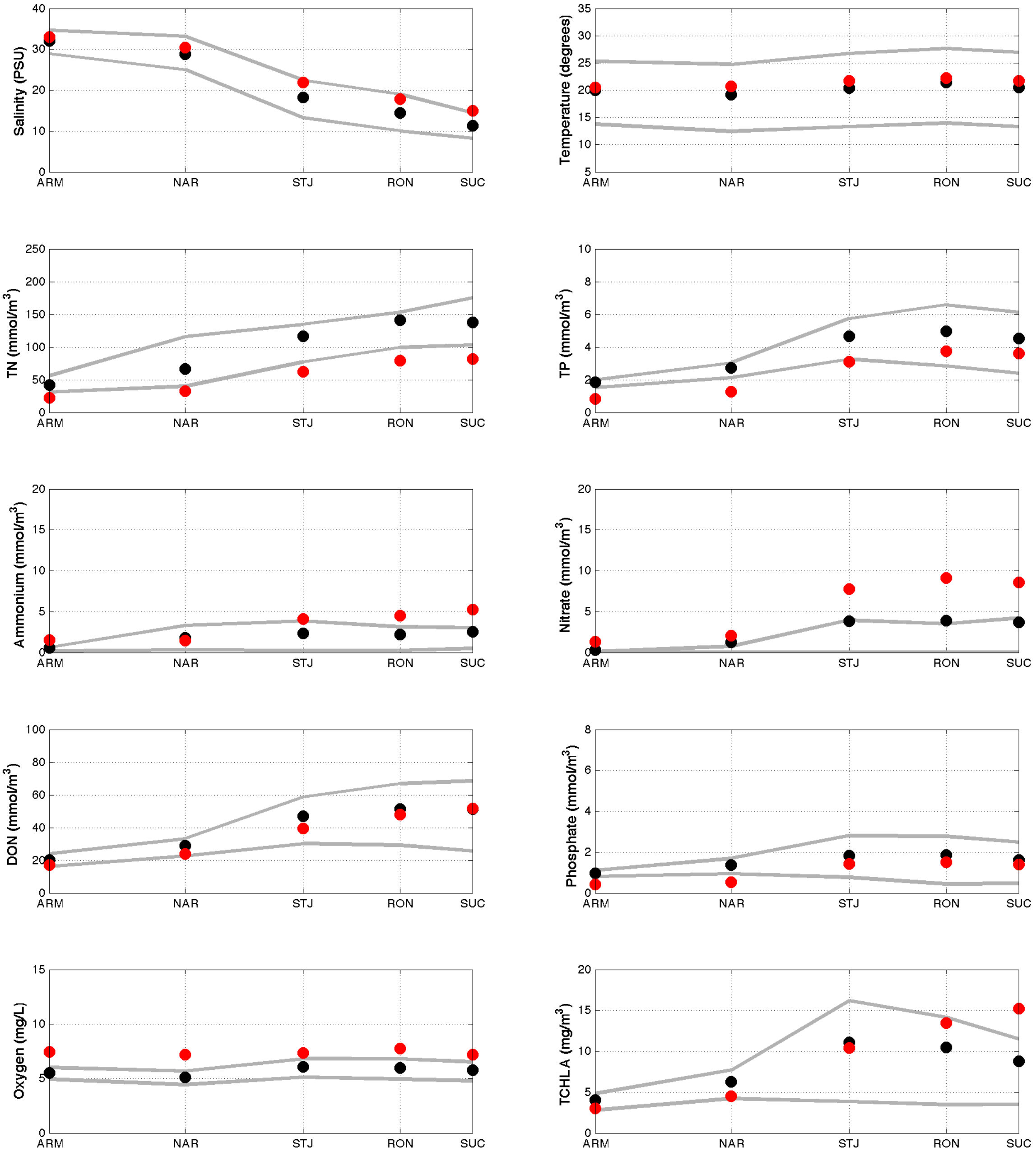


Figure 14. Thalweg plots of the spatial distribution of surface water properties and model performance along the Swan River from Lower Swan to Upper Swan (except RIV which is at Canning River). Grey lines indicate the 20 – 80% modelled envelope; black dots represent the mean modelled value, while red dots represent the mean measured value.

Transect thalweg plots of bottom waters

- Similar to the plots of surface water, the modelled bottom salinity shows a gradual decrease from Lower Swan to Upper Swan, while the bottom temperature at ARM and NAR is a bit lower than other sites doesn't due to deeper water depths;
- The model captured the spatial variety of bottom TN, Nitrate, and DON, but again the TN tends to be overestimated and Nitrate tends to be underestimated. The Ammonium performance is good in lower and middle Swan while under-predicted in upper Swan;
- The spatial variation of bottom TP and Phosphate are well captured;
- The spatial variation of the bottom DO is well captured; the lowest bottom DO is found in the middle Swan;
- The bottom TCHLA increase from lower Swan to Upper Swan;

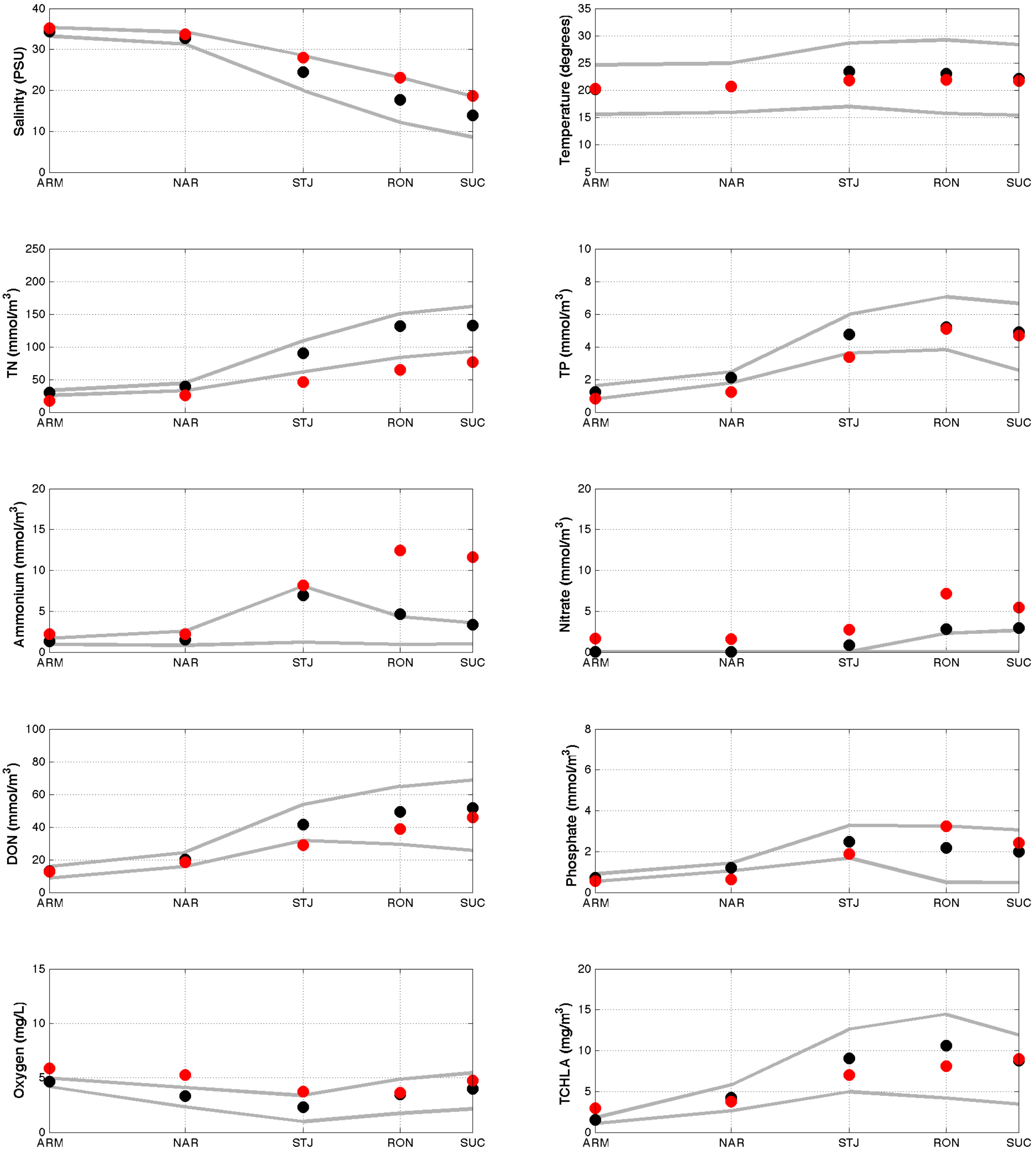


Figure 15. Similar to figure 14 except for properties in bottom water.

3.3 Error assessment by region

Lower Swan + Canning River – include sites of ARM, HEA, BLA, RIV

- The physical properties (salinity and temperature) are well captured;
- The modelled nitrogens (TN and nitrogen components) have good regression coefficients against the measurements, except ammonium that has medium performance values;
- The distributions of TP, Phosphate, and DO are well captured;
- The model reasonably captures TCHLA variations in the Lower Swan

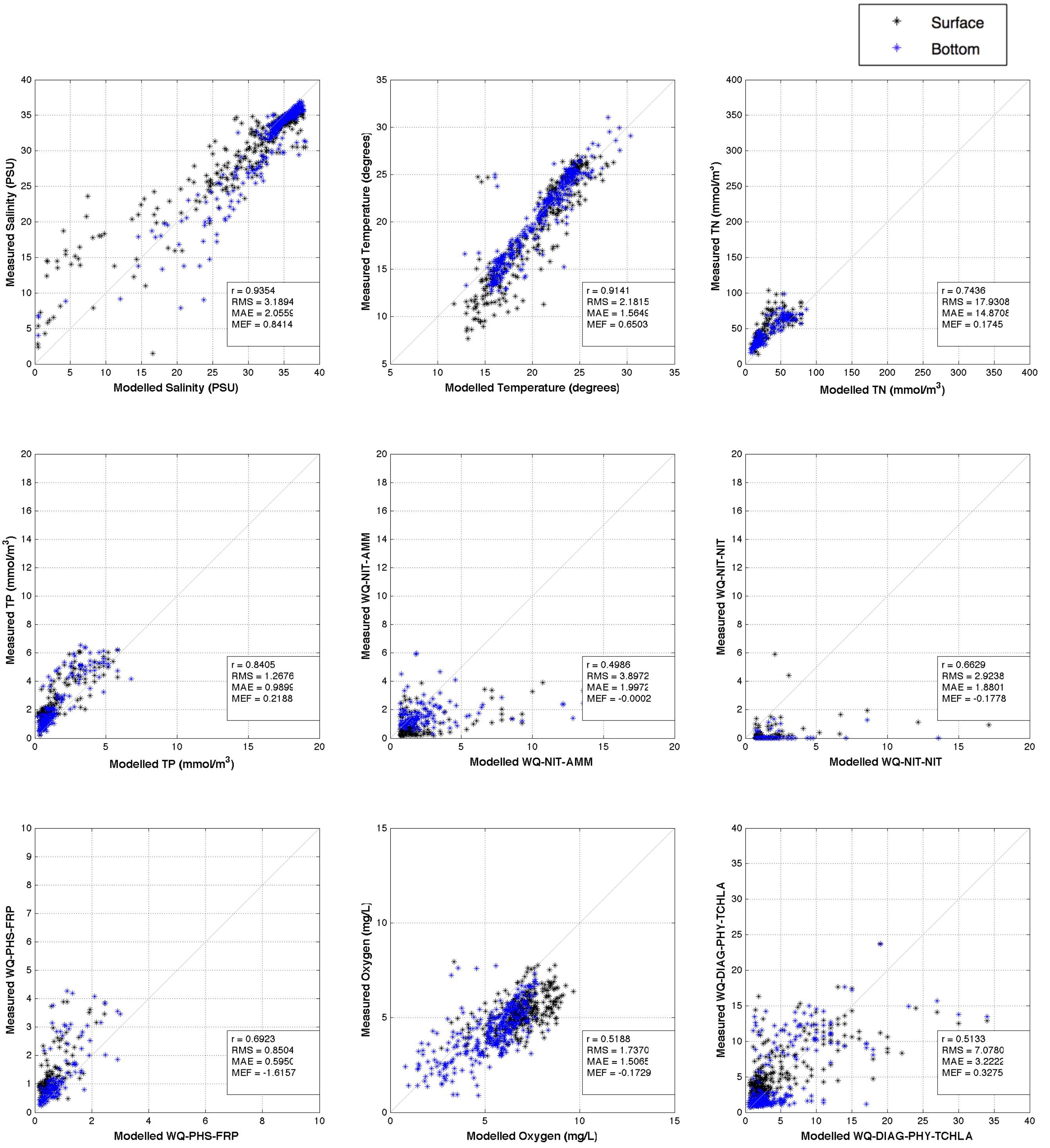


Figure 16. Scatter plots with model performance metrics in Lower Swan.

Middle Swan – include sites of MAY, NAR, NIL, STJ

- The physical properties (salinity and temperature) are well captured;
- The modelled nitrogens (TN and nitrate) have good regression coefficients against the measurements, but large deviations were found, indicating the nitrogen variations are captured but there is a systematic error that might come from the boundary inputs;
- The distributions of TP, Phosphate, and DO are reasonably captured;
- The low regression and MEF values for TCHLA indicate the complexity of phytoplankton activities as well as the necessary to increase the phytoplankton monitoring frequency in Middle Swan (further discussion is provided in Chapter 5).

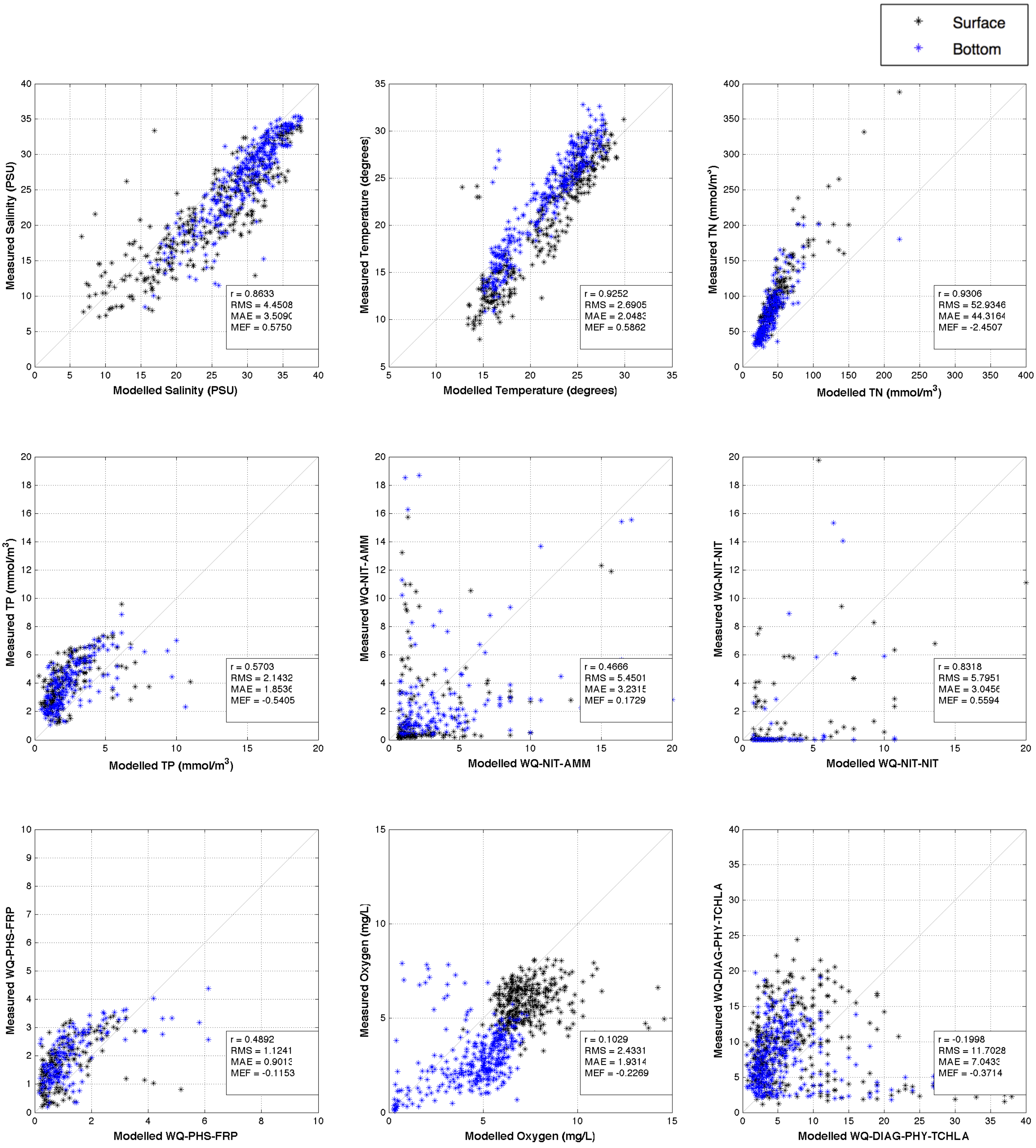


Figure 17. Scatter plots with model performance metrics in Middle Swan.

Upper Swan – include sites of KIN, MSB, RON, SUC

- The physical properties (salinity and temperature) are well captured, although both the surface and bottom salinity tends to be slightly overestimated;
- Similar to Middle Swan, the modelled nitrogens (TN and nitrogen components) have good regression coefficients against the measurements, but large deviations were found;
- The distributions of TP, Phosphate, and DO are well captured;
- The performance of TCHLA in Upper Swan is better than Middle Swan, but low regression and MEF values are still found.

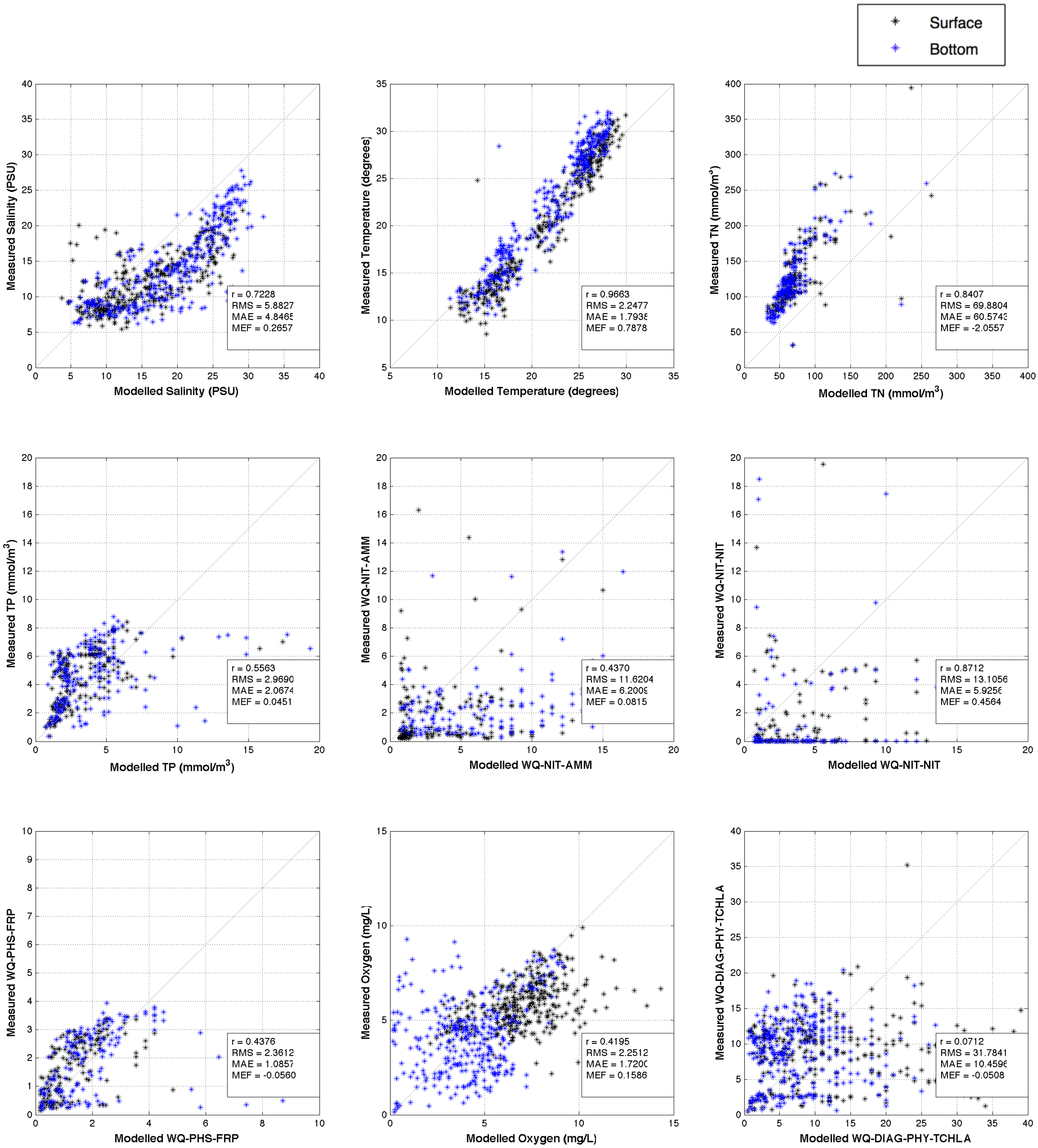


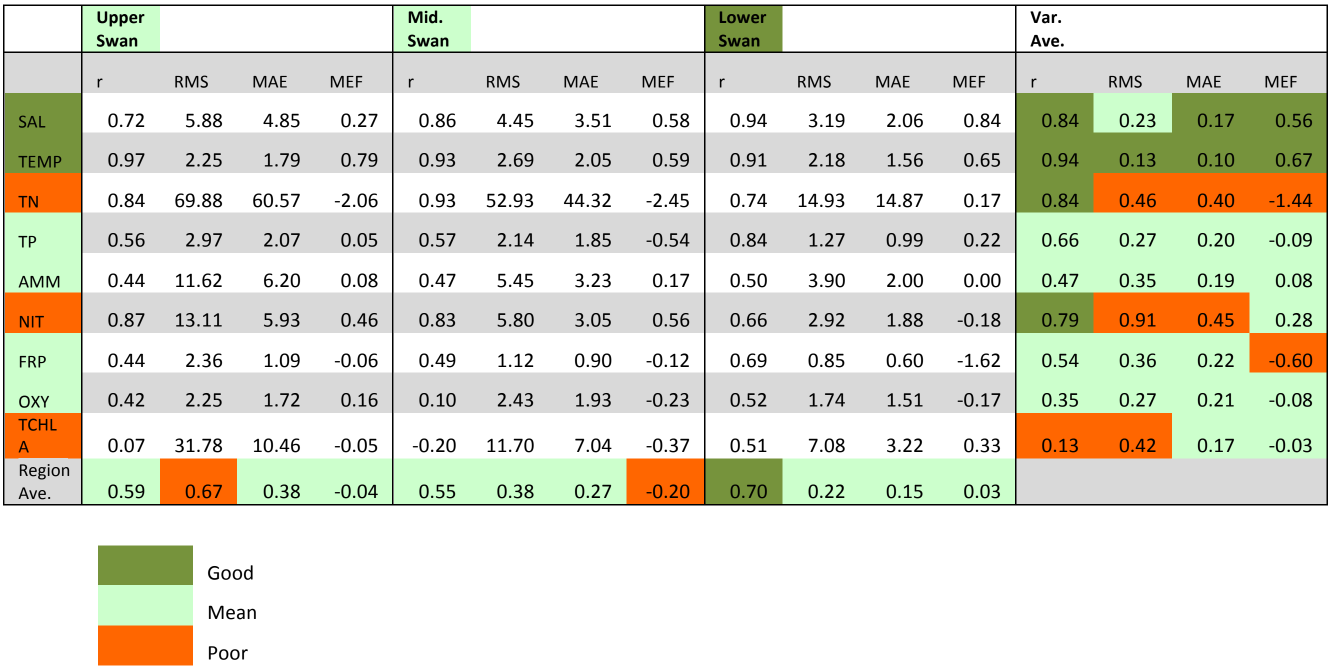
Figure 18. Scatter plots with model performance metrics in Middle Swan.

Summary

The model performance in three regions as well as for each variable is summarised in Table 3, which suggest:

- Lower Swan has the best performance in three regions, maybe due to the fact that other two regions (Middle Swan and Upper Swan) were more affected by boundary inflows that had not been well set up in the model due to insufficient monitoring data;
- Salinity and Temperature have the best performance in all the variables, indicate the physics of the estuary are well captured;
- The good regression but poor deviation values of TN and Nitrate suggest the model captures the nitrogen variations but there are systematic errors that might come from boundary inputs or parameter settings in the water quality model. Poor performance of TCHLA suggests more attention to phytoplankton biology and monitoring is required in future work by enhancing boundary monitoring, improving water quality model algorithms, and increasing monitoring frequency inside the estuary.

Table 3: Summary of model performance at three regions and for each variable. The RMSE and MAE have been normalized with background values of each variable when average variable and region performance are considered.

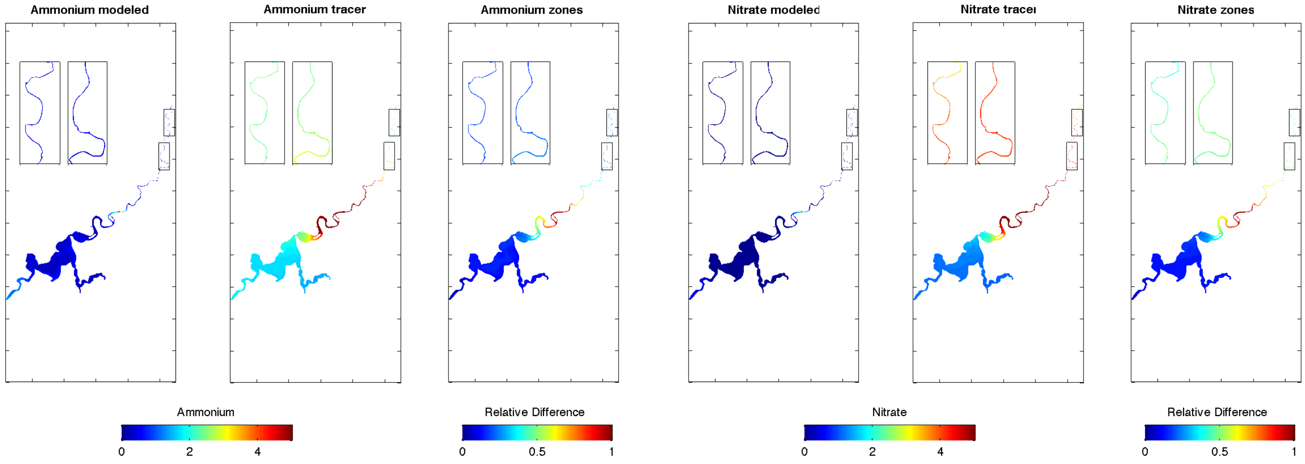


	Upper Swan				**Mid. Swan**				**Lower Swan**				**Var. Ave.**			
	r	RMS	MAE	MEF	r	RMS	MAE	MEF	r	RMS	MAE	MEF	r	RMS	MAE	MEF
SAL	0.72	5.88	4.85	0.27	0.86	4.45	3.51	0.58	0.94	3.19	2.06	0.84	0.84	0.23	0.17	0.56
TEMP	0.97	2.25	1.79	0.79	0.93	2.69	2.05	0.59	0.91	2.18	1.56	0.65	0.94	0.13	0.10	0.67
TN	0.84	69.88	60.57	-2.06	0.93	52.93	44.32	-2.45	0.74	14.93	14.87	0.17	0.84	0.46	0.40	-1.44
TP	0.56	2.97	2.07	0.05	0.57	2.14	1.85	-0.54	0.84	1.27	0.99	0.22	0.66	0.27	0.20	-0.09
AMM	0.44	11.62	6.20	0.08	0.47	5.45	3.23	0.17	0.50	3.90	2.00	0.00	0.47	0.35	0.19	0.08
NIT	0.87	13.11	5.93	0.46	0.83	5.80	3.05	0.56	0.66	2.92	1.88	-0.18	0.79	0.91	0.45	0.28
FRP	0.44	2.36	1.09	-0.06	0.49	1.12	0.90	-0.12	0.69	0.85	0.60	-1.62	0.54	0.36	0.22	-0.60
OXY	0.42	2.25	1.72	0.16	0.10	2.43	1.93	-0.23	0.52	1.74	1.51	-0.17	0.35	0.27	0.21	-0.08
TCHLA	0.07	31.78	10.46	-0.05	-0.20	11.70	7.04	-0.37	0.51	7.08	3.22	0.33	0.13	0.42	0.17	-0.03
Region Ave.	0.59	0.67	0.38	-0.04	0.55	0.38	0.27	-0.20	0.70	0.22	0.15	0.03				

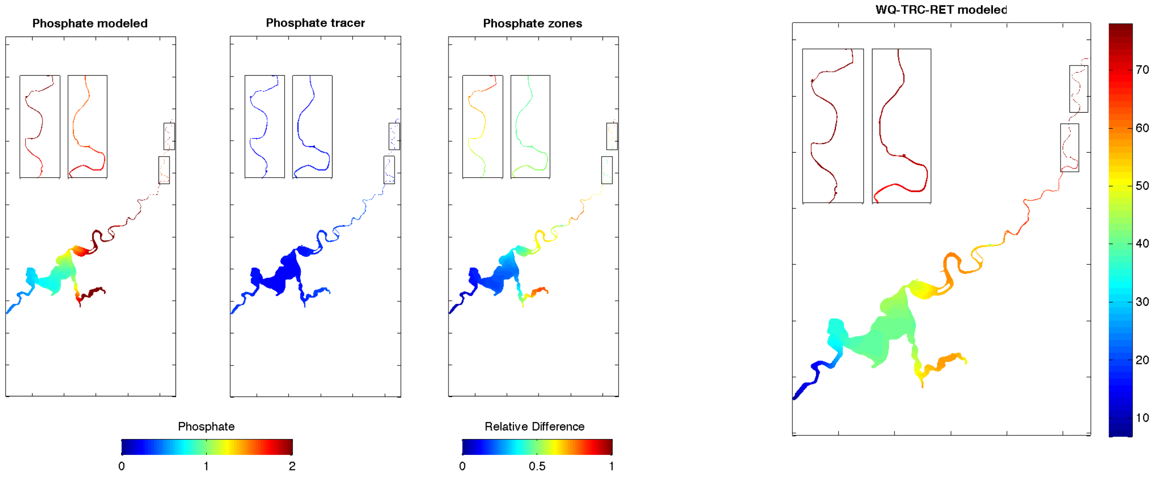
4. Hotspot analysis: tracer model assessment

4.1 Hotspot in dry season (February 2015)

- The biogeochemical "hotspots" (where with intensive biogeochemical activities) are found in the north Middle Swan, and upper part of the Canning branch;
- The biogeochemical intensity in the Upper Swan is medium, although the Upper Swan has the highest water retention time during the dry month;
- Water close to Fremantle has both low biogeochemical intensity and low water retention time, due to the high flushing by tidal currents.


(1) Ammonium

(2) Nitrate


(3) Phosphate

(4) Retention Time

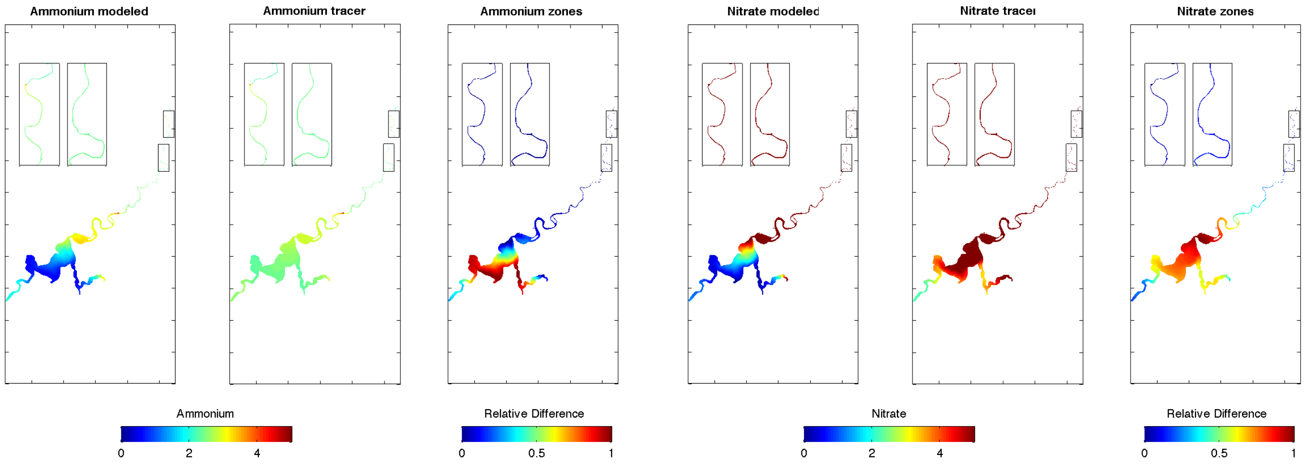
Figure 19. Spatial distributions of "hotspots" (1 - ammonium, 2 - nitrate, 3 - phosphate) and water retention time (4) in dry seasons within estuary domain. For each variable the first panel is the monthly-averaged concentration from the estuarine response model, the second panel is the monthly-averaged concentration from the tracer model, and the third panel is degree of difference between two models.

4.2 Hotspot in wet season (August 2015)

- The biogeochemical "hotspots" are found in Lower Swan and south part of Middle Swan, in corresponding to the high water retention time in these areas;
- The biogeochemical intensity and water retention time in the Upper Swan are both low, due to the high flushing effect created by high inflows;
- Water close to Fremantle still has both low biogeochemical intensity and low water retention time due to the high flushing by tidal currents.

(1) Ammonium

(2) Nitrate



(3) Phosphate

(4) Retention Time

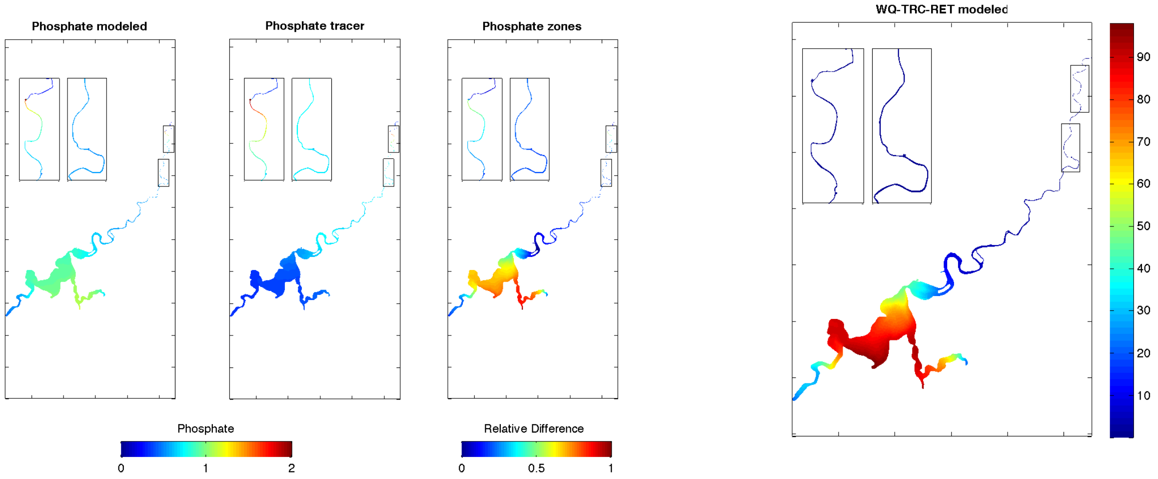


Figure 20. Similar to figure 19 except for the period of wet season.

5. Assessing Monitoring Data Worth

5.1 Is the current monitoring program capturing areas in the domain that are more biogeochemically active?

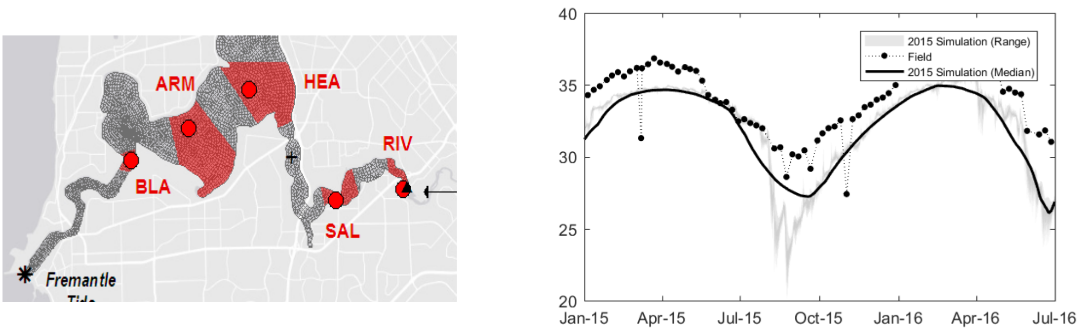
The analysis of our tracer modelling results in Chapter 4 indicated that the biogeochemical 'hotspots' dynamically response to the inflow rates. In the dry seasons when inflow rate is low, biogeochemical activities mostly focus in north Middle Swan and upper part of the Canning branch; while in wet seasons when inflow rate is high, biogeochemical activities mostly focus in Lower Swan and south part of Middle Swan. Bear in mind that these hotspots represents where the change rates, not the absolute concentrations, of nutrients are high, so the distribution of these spots might differ to that of the eutrophic states of the waters. From an aquatic system point of view, monitoring data at these hotspots provide more details of how nutrients and energy transfer inside the ecosystem, therefore are more valuable to understand the Swan-Canning ecosystem and improve the model settings and performance. We recommend taking the biogeochemical hotspots into account when design monitoring programs.

5.2 Are there strong cross-stream gradients that are not picked up? – Needs for transect monitoring

Current monitoring sites in Lower Swan are set along the central line. In the narrow branch near Fremantle, the water doesn't show much variation across transect, while in the main body of Lower Swan where the length of transect is up to 2km, some water quality show large variety between shallow and deep waters. Figure 21 shows the range of modelled salinity, DO, and TCHLA across a section of ARM in Lower Swan. The daily-median value of DO across the section is ~6 mg/L with variations of ~2 mg/L, while for TCHLA the median value is 3-6 μg/L but the variations are up to ~3 μg/L. The deviations of modelled data across the section almost account for the deviations between median modelled data and measurements, indicating the need for monitoring across the section at ARM.

(1) ARM transect map

(2) SAL



(3) DO

(4) TCHLA

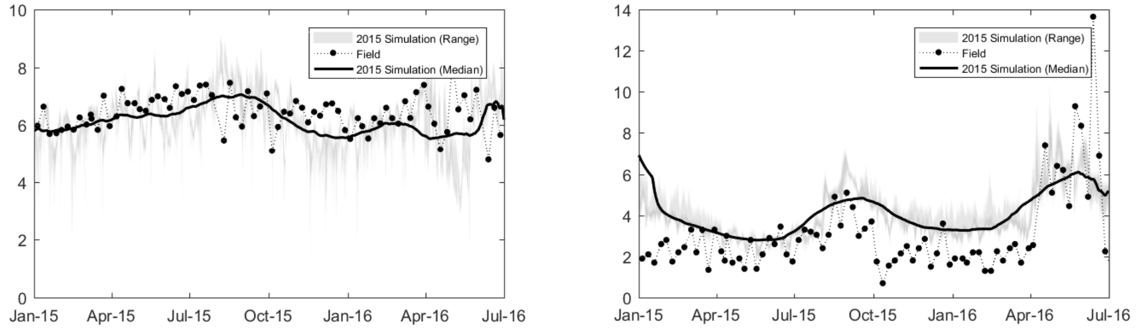
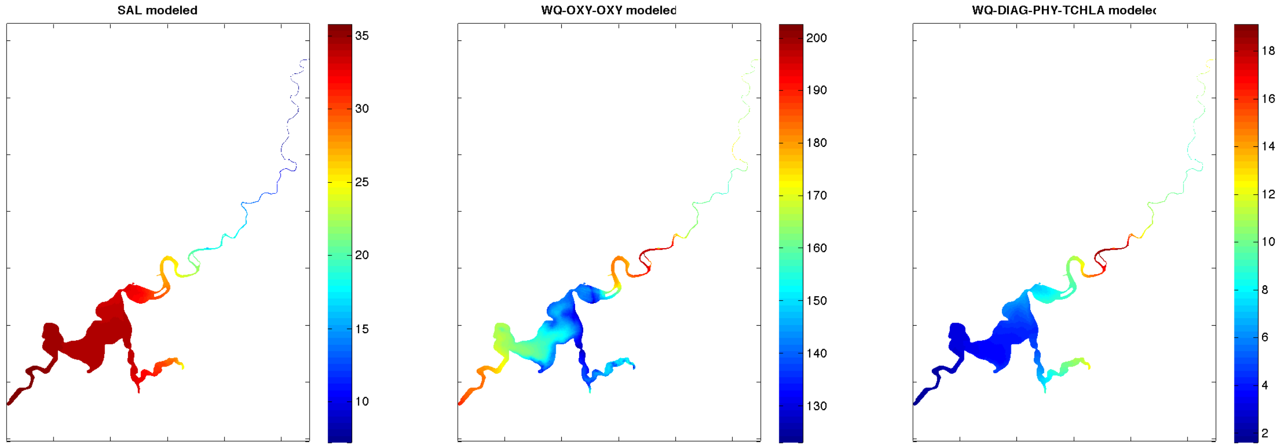


Figure 21. (1) Transect area around ARM site for comparison; (2) time-series of daily-median and range (99 percentile) of modelled salinity against measurements in the transect area; (3) similar to 2 except for DO; and (4) similar to 2 except for TCHLA.

Figure 22 also shows that uneven distribution of salinity, DO and TCHLA along transects in Lower Swan and part of the Middle Swan are found in both wet and dry seasons. The reasons for the transect variety could be (1) the water circulation caused by flushing and mixing in shallow near-shore area is different to that in the deep central water and (2) sediment and seagrass could play important roles in modifying water quality in shallow waters.

(1) Feb 2015



(2) Aug 2015

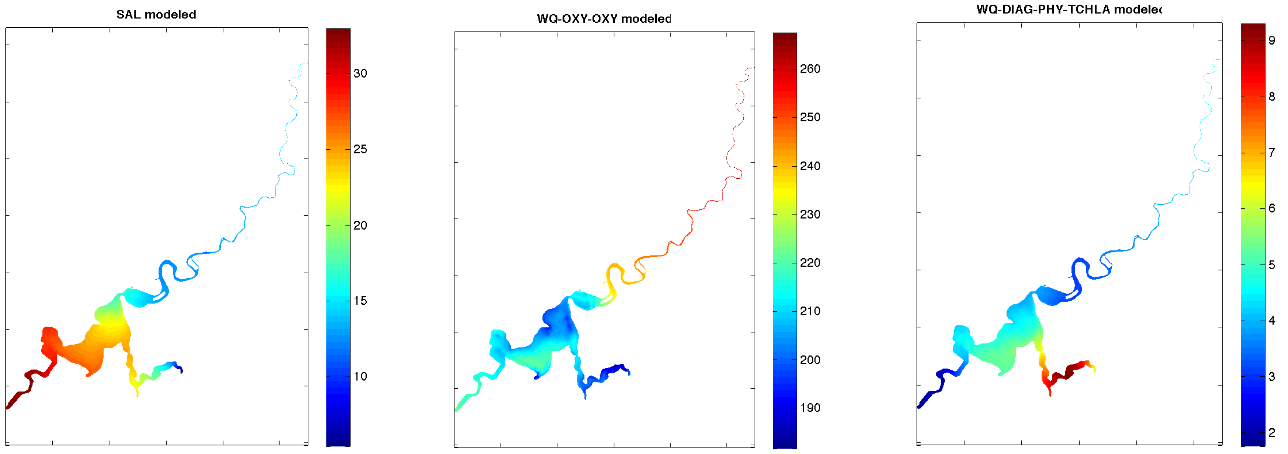


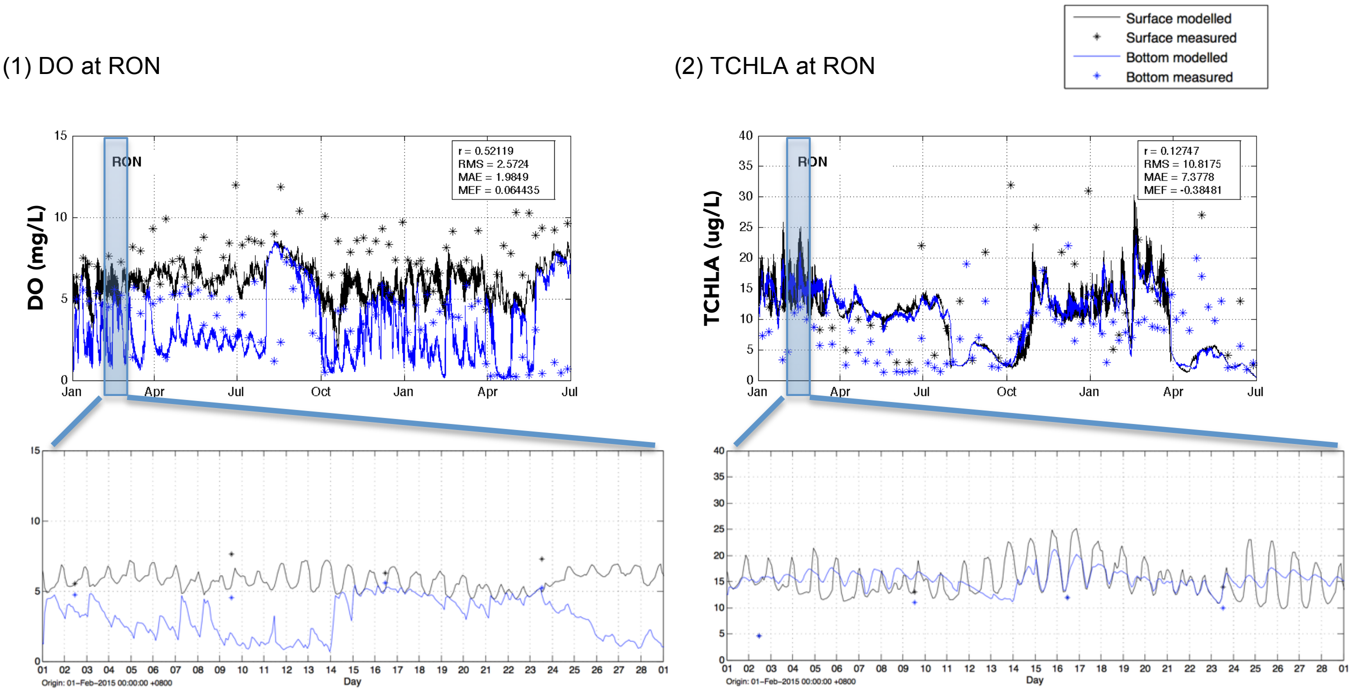
Figure 22. Spatial distributions of monthly-averaged salinity, DO, and TCHLA in (1) Feb 2015, and (2) Aug 2015.

5.3 Does the regular monitoring adequately capture events and daily variations? - Needs for dynamic monitoring and high-frequency monitoring

The sampling time interval of current water quality data available for model validation is generally weekly. This coarse time interval is fine for monitoring the estuary eutrophic states or the seasonal variation of estuary aquatic ecosystem. However, it might not be enough if a better understanding of some key water quality variables such as DO and TCHLA is needed. As shown in Figure 23, both the DO and TCHLA present a clear daily variation that is impossible to be captured by the weekly sampling campaigns. The reasons for the daily variation could be that light radiations have a direct impact of water temperature and phytoplankton metabolism, which subsequently change the DO concentration. This, from another point of view, indicates the difficulty of validating model performance when sparse weekly field data is used while strong temporal variations is modelled.

We therefore recommend that higher-frequency data of DO and TCHLA in consistent days are required in order to capture their variations and provide more information for model settings and validations.

There is also a concern that the low-frequency sampling program would have a bias to non-extreme environmental conditions. That is, the field trips of sampling are done on the 'calmer weather' dates to avoid extreme weather conditions, although the extreme weather conditions such as storms could cause significant changes to the estuarine ecosystem in a short time. We therefore recommend setting up a dynamic monitoring program to capture the events with assistance of the estuarine response model to predict the changes in response to different environmental condition scenarios.


(1) DO at RON

(2) TCHLA at RON

Figure 23. Example daily variations of (1) DO, and (2) TCHLA at RON.

5.4 Do we adequately monitor what is coming into the estuary? - Need to improve boundary monitoring

Figure 24 shows the inflow rates and some of the water quality variables recorded in boundary rivers that were used to force the estuary model. The time interval of inflow rate is daily, but of water quality varies from fortnightly to monthly. This coarse sampling frequency results in poor boundary inputs to the estuary model, especially when the river flow rate changes quickly over a short time period while the water quality information is lost. In that case the water quality is interpolated between data measured at close events, but systematic errors are unavoidable. For example, there are strong inflows coming from river at north Upper Swan in August and September 2015 (figure 24, panel 1) when nitrate concentration varied quickly in same period (figure 24, panel 3) maybe due to being brought from soil to the river by flushing. The large amount of water coming into the estuary with coarse nitrate data likely cause a systematic error in the performance of nitrate and TN (as shown in Chapter 3.1 and Chapter 3.3). Therefore we recommend to enhance the boundary monitoring of water quality by increasing sampling frequency to weekly, or set up a dynamic monitoring program in response to high flow events to catch the high variety of nutrient concentrations at that short-term periods.

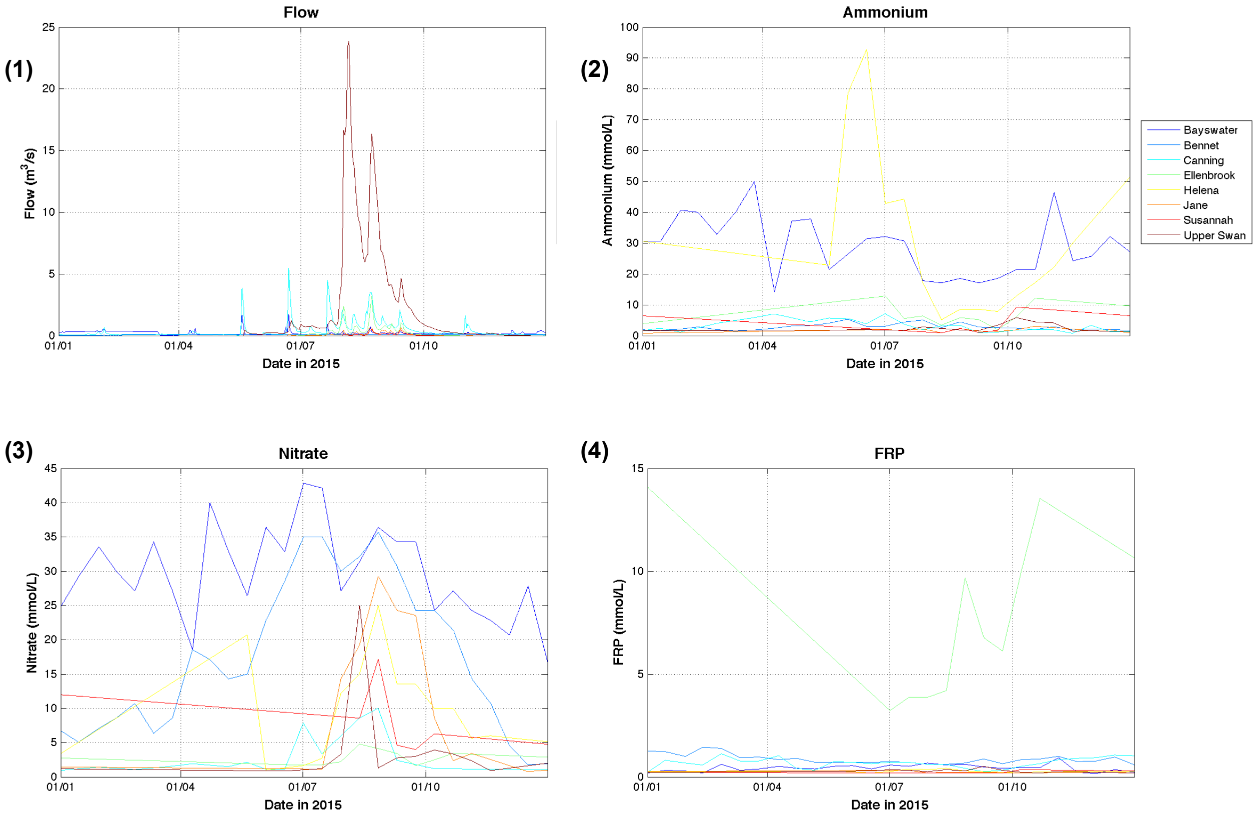


Figure 24. (1) Daily records of flow rates vs weekly-monthly records of (2) ammonium, (3) nitrate, and (4) filterable reactive phosphorus at 8 inflow rivers.

5.5 Would reducing sampling frequency affect the model validation?

Given the field water quality data is expensive to obtain, one last question we want to know is that if we change the field sampling frequency to reduce the number of field data, how would that affect the model validation? To answer this question and illustrate the impacts of sampling frequency on model validations, we reduced the field measurement data numbers to 1/2, 1/4, 1/6, and 1/8 of their original numbers (e.g. only used every second, forth, sixth, and eighth data in validation), and then used these “new” datasets to do the same statistics of the model performance and compare their differences.

Figure 25 shows the validation results of two key physical variables (salinity and temperature) and two key biogeochemical variables (TCHLA and DO) with different sampling frequencies. To our surprise, the sampling frequency, even when it is reduced to 1/8, doesn’t significantly affect the model validation. For salinity and temperature that are well captured by the model, the validation is still good even when the sampling frequency reduced to 1/8; while for TCHLA and DO, the validation shows small variations but no significantly worse performance is found with reduced sampling frequencies. So reducing sampling frequency does not seem to affect the model validation. However, we do not recommend reducing the sampling frequency because (1) we need enough number of validation data to make the result statistically significant; (2) the current sampling frequency of weekly is low already. As shown in the discussion of Chapter 5.3, a higher-frequency monitoring program is needed to capture the daily variations of TCHLA and DO.

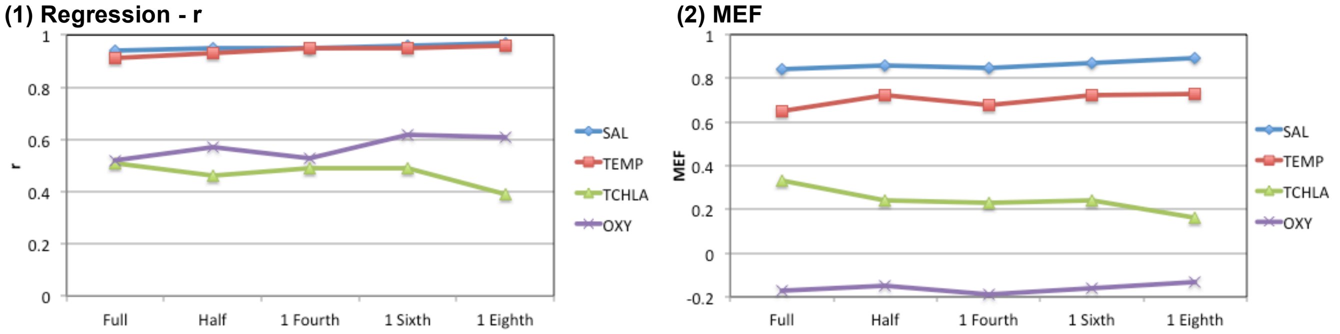


Figure 25. Variations of (1) regression coefficient and (2) MEF with the reduction of sampling frequency.

6. Real-time Model Operation

SCEVO model automation framework

SCEVO (Swan-Canning Estuary Visual Observatory) is an online platform providing real-time water quality prediction for Swan-Canning Estuary, based on the water quality model that has been well calibrated with field data since 2008. The model is able to provide water quality hind-cast for the past 5 days and fore-cast for the next 5 days. Key facts of the SCEVO model automation framework (Figure 26) include:

- Tidal forcing is provided by the ROMS coastal model that is set up by UWA Ocean Institute (http:// http://coastaloceanography.org) and has been well calibrated with tidal measurement at Fremantle by DoT;
- Meteorological inputs (wind speeds, air temperature, humidity, precipitation, cloud cover) are provided by WRF weather model;
- Due to the time lap (up to ~1 month) of the field measurement at boundary rivers, we are using average water quality data recorded at the same dates (obtained from DoW and DPaW) in the past 8 years to force the model;
- The data pre-processing, mode runs, and post-processing of model outputs are undertaken by ARMS (Aquatic Real-time management System) on a daily basis;
- The model outputs are presented online (http://swan.science.uwa.edu.au, this website will be ready for viewing soon) in formats of time series plots and animations.

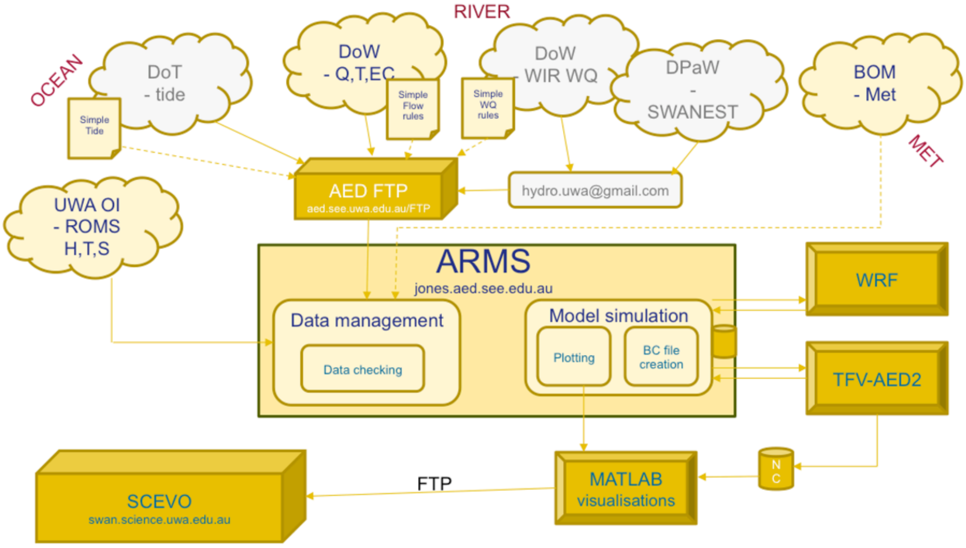


Figure 26. SCEVO model automation framework.

Link to SCEVO website

The real-time results from SCEVO and other relative information can be viewed at the website - http://swan.science.uwa.edu.au.

7. Key Points and Recommendations

Model Performance

Performance of the Swan-Canning Estuarine Response Model over simulation period from 01/2015 to 07/2016 is evaluated using various statistics methods. The performance analysis results suggest that, the model performed well in capturing salinity, temperature, oxygen, and for some of the nutrient pools such as TP, PO_4, and RSi. Reasonable predictions were obtained for other nutrient pools and chlorophyll-a. Among three estuary regions (Lower, Middle, and Upper Swan), the Lower Swan has the best performance, while Middle and upper Swan less performed, maybe because these two regions are more affected by inflows that were not well monitored. Overall, the model performance is consistent to previous simulation in 2008 – 2012 with same model parameters, suggesting in its present form the model is suitable for assessing the management scenarios associated with oxygenation variations, nutrient load management and/or climate change, bearing in mind deficiencies in the predictions outlined in the previous sections. Further work is specifically required on to improve the predictions of TN, Nitrate, TCHLA, sediment resuspension and seagrass in the next round of model calibration. Priority areas for work on model improvement include:

- Sediment resuspension and Suspended solid particle size distribution
- Sediment nutrient flux predictions
- DOM reactivity and photolysis
- Boundary nutrient inputs
- Dinoflagellate and cyanobacteria vertical migration
- Seagrass biomass variation and sensitivity to water column turbidity
- Macroalgal dynamics, and hotspot locations for wrack formation
- Fish-kill risk index

Recommendations to water quality monitoring from a modelling point-of-view

A "Tracer Model" has been set up to reveal the biogeochemical "hotspots", e.g. where more intensive biogeochemical activities occurred, within the estuary domain. The results from the tracer model, together with the Thalweg analysis, regional analysis, and boundary data analysis, suggests:

- In dry seasons the Middle Swan and south part of Upper Swan are biogeochemical hotspots; while in wet seasons, the hotspot is being brought further to Lower Swan;
- The water close to Fremantle is always not a biogeochemical hotspot due to high flushing rate;
- Predicted water quality variables generally have higher deviations in Middle and Upper Swan, indicating more complex biogeochemistry and the needs of improving monitoring and modelling abilities in these areas.
- Higher-frequency (up to hourly) monitoring of DO and TCHLA is recommended to gain better understanding and prediction of the variation of these variables;
- Dynamic monitoring program to capture the events (e.g. storms) with assistance of the estuarine response model to predict the changes in response to different environmental condition scenarios
- Spatial difference along transect in Lower Swan is observed, suggesting the needs of monitoring along transect in shallow and deep waters.
- Coarse temporal sampling frequency at boundary rivers together with quick change of flow rate suggest the needs to improve the boundary water quality monitoring, which could be critical to the performance of estuary models.

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