Tuggerah Lakes Estuary Modelling

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Final Report

Contract Number: CPA/157279

Grantee: Department of Environment, Climate Change and Water

Reporting Period: 01 August 2009 – 29 July 2010

NSW GOVERNMENT | Environment, Climate Change & Water

Executive Summary

Tuggerah Lakes is a coastal lagoon system consisting of three shallow interconnecting lagoons. From north to south the lakes are Lake Munmorah, Budgewoi Lake and Tuggerah Lake with Tuggerah Lake having the only connection with the ocean at The Entrance. The lakes are fed by four major tributaries – Wyong River and Ourimbah, Wallarah and Tumbi creeks. The catchment has undergone substantial urban development and shoreline alterations over past century which have changed the ecological components and processes within the estuary. There is a potential risk in deterioration of the health of the lakes if catchment runoff exceeds the buffering capabilities of the ecosystem. The NSW Department of Environment, Climate Change and Water (DECCW) have been subcontracted by Wyong Shire Council to fulfil some of the knowledge gaps in the Estuary Management Plan and to identify potential risks within the catchment.

A series of integrated catchment, hydrodynamic and estuary response models have been developed to represent the Tuggerah Lakes catchment. These models simulate the processes occurring within the system to predict nutrient and sediment loads entering the lakes and the likely effect these loads have on the ecosystem.

Catchment modelling suggests that the larger rural subcatchments deliver the largest amount of nutrients and sediments per year and dominate the loading in the lakes. The fringing lake catchments are highly developed and contribute frequent and concentrated flows. Flows from urban fringing catchments impact the local nearshore zone by creating a build-up of nutrients and sediments, especially in sheltered bays. Weir extractions can stop upstream flows making flows from the urban catchments the main source for the lakes during drier periods.

Overall, the lakes are well mixed basins mainly due to their shallow nature allowing vertical mixing by wind. Wind and current driven resuspension plays an important role in the ecology of the lakes as it influences the light climate and therefore growth of autotrophic species such as seagrass. In the summer months, resuspension in the lakes is the main driver of turbidity over catchment discharge as it is generally windier and drier.

A number of land use and management scenarios have implied that the urban catchments have had the biggest increase in nutrient and sediment discharge compared with the rural catchments since being developed, sometimes upwards of 400% increase. With water treatment devices such as water sensitive urban design, bioretention systems and constructed wetlands, discharge can be greatly reduced.

The ecological response model indicates that Tuggerah Lakes is a highly productive system with autotrophic production supporting a diverse foodweb. This suggests that the system has a relatively large buffering capacity in terms of nutrient and sediment input. The shallowness of the lakes, and therefore good light climate, enables such a high productivity level. The large contributions of nutrients and sediments made by rural catchments create a moderate risk of phytoplankton blooms during high rainfall years.

The potential risk of macroalgae blooms within the lakes is high if there is an excess of nutrients in the water column as these conditions favour macroalgae over seagrass growth. Macroalgae blooms are more likely to be associated with inputs from urban catchments, especially within sheltered areas. Excessive macroalgae growth can potentially cause detrimental effects to the ecosystem by creating anaerobic conditions unsuitable for seagrass growth.

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Project Milestones

Table 1 describes the main objectives of the project and completion dates for each. Deliverables 3, 4 and 5 have been allowed an extension from 31 May to 30 June 2010 due to the delay in deciding on the various scenarios and receiving appropriate information to carry them out. This report therefore describes the scope of each of the catchment, hydrodynamic and estuary response models and how they are integrated to form a better representation of the catchment. This report will be updated with results from deliverables 3, 4 and 5 by 30 June 2010. Tables 2 to 4 provide a more detailed summary of the steps taken in completing each deliverable and what is expected to occur for the future deliverables.

Table 1 Summary of the expected deliverables and due dates

Letter of Acceptance issue to the Consultant by Council		Monday 2 February 2009	
Consultation/ Liaison between Council and the Consultant		Ongoing through project	
Deliverable 1	Establish a hydrodynamic model for the Tuggerah Lakes and major tributaries	Monday 2-Feb-2009	Monday 31-Aug-2009
Deliverable 2	Establish an ecological response model to assess critical processes within the Tuggerah Lakes, describe the impact of nutrient and sediments loads from the catchment on the Lakes' ecosystems	Monday 2-Feb-2009	Wednesday 31-Mar-2010
Deliverable 3	Model effects of various land use/management scenarios on nutrient reductions to receiving waters	Wednesday 14-Apr-2010	Wednesday 31-Jul-2010
Deliverable 4	Develop load targets that would be needed to protect no net increase for the Tuggerah Lakes	Monday 31-May-2009	Wednesday 31-Jul-2010
Deliverable 5	Revise modelling and reporting based on feasibility testing to establish the effectiveness of planning guidelines to meeting the ecological condition targets of the receiving waters	Monday 31-May-2010	Wednesday 31-Jul-2010

Note: Completed tasks highlighted in green

Table 2 The milestones and a summary of work undertaken to complete deliverable 1

Milestone	Progress/Completion (summary of work undertaken)	Date Completed
Letter of Acceptance issued	Head agreements/contracts signed & accepted	3rd March 2009
Project Administration (Recruit project staff)	Project team established: Sonia Claus – Project Manager, Jocelyn Dela-Cruz and Angus Ferguson – Senior Scientist	February 2009
Scope of models - Initial site visits	Lake tour, DECCW staff (Peter Scanes, Geoff Coade, Sonia Claus and Angus Ferguson) with Danny Roberts (consultant that developed Tuggerah Lakes EMP) Catchment tour to determine appropriate sites for installing runoff monitoring equipment (rising stage samplers and water level sensors), DECCW staff (Greg Pullinger, Max Carpenter, Sonia Claus, Peter Scanes, Gus Porter)	3rd March 2009
Recruit technical staff	Aaron Wright and Gus Porter – Technicians.	June 2009
Scope of hydrodynamic modelling	Discussion between DECCW staff and Brian Sanderson (Contractor) The temporal & spatial scales of model application determined Develop conceptual & numerical framework for model (e.g. 1D, 2D, 3D model or combination; mixing between lake basins)	April - June 2009
Scope of catchment modelling	Discussions between Jocelyn Dela-Cruz and iCAM (Contractor) Existing 'Whole of catchment models' (e.g. AEAM) developed specifically for Tuggerah Lakes were considered inappropriate for integrating with the hydrodynamic models. Input data for the existing models were also outdated. A new whole of catchment model (IHACRES) that predicts daily subcatchment flows and exports is being developed for the project. The type of existing 'high (temporal & spatial) resolution catchment models' (MUSIC) developed for Tuggerah Lakes was considered to be appropriate but the input data, calibration and application of the existing models will be revised substantially for this project to account for specific management scenarios.	May 2009
Scope of ecological response modelling	Discussion between Angus Ferguson and Brian Sanderson The temporal & spatial scales of model application determined Develop conceptual & numerical framework for model	March - August 2009
Data & knowledge gap analysis	Assessed data needs for all model development, calibration & verification Desktop analysis of existing data was carried out to determine data & knowledge gaps for model development, calibration and testing The analyses showed a lack of data input, calibration and test data for calibrating catchment models around the periphery of the lakes, as well as a distinct lack of runoff water quality data. Much of the existing data was unsuitable due to incomplete metadata (i.e. time and/or of sampling).	June 2009

Milestone	Progress/Completion (summary of work undertaken)	Date Completed
Field monitoring for hydrodynamic, ecological response and catchment models	Established water quality sampling program at 21 sites within the lakes and tributaries for model development, calibration & testing. Installed in situ monitoring equipment to collect flow data and/or runoff water quality data- • Rising stage samplers at Wyong River, Ourimbah Creek and Jilliby Creek • Water level sensors in stormwater drains at Munmorah, Canton Beach, Long Jetty and Craigie Park • Salinity loggers at the entrance	April 2009 14th May 2009 11th June 2009 12th June – 12th August 2009
Project Administration (Sub-contracts)	Development of sub-contract for hydrodynamic and catchment modeling Sub-contract for catchment modelling let to iCAM Sub-contract for hydrodynamic modelling let to Brian Sanderson of Newcastle Innovations	May 2009 27th May 2009 4th June 2009
Scope of models - Follow up site visit	Catchment tour – DECCW (Jocelyn Dela-Cruz, Gus Porter) with subcontractors (Barry Croke, Natasha Herron and Chaturangi Wickramaratne from the Integrated Catchment Assessment and Management Centre, iCAM) visited rising stage samplers, Ourimbah and Wyong Weirs, stormwater drains level sensors and areas of different land use in the catchment to gain a perspective on the condition of the catchments and how the weirs potentially affect stream flows into the lakes. Lake tour – Brian Sanderson and Angus Ferguson to investigate inflows to the lake, bottom sediments, macrophyte and seagrass distribution.	21st August 2009
Catchment modelling	Main subcatchments identified. Developed IHACRES 'whole of catchment model' using current local data & information to predict a daily streamflows from the main subcatchments for the period between February 1950 and December 2008. The predicted streamflows will be refined and updated (to include 09/10 FY) once the catchment monitoring program has been completed. Integration of daily streamflows from IHACRES with hydrodynamic model(s) completed. Annual current nutrient and sediments loads from main subcatchments have been modeled to generate a 'whole of catchment' nutrient and sediment map. Runoff water quality, which was required to estimate nutrient and sediment loads, were obtained from a review of existing literature. The loads will be refined upon completion of the catchment monitoring program.	July 2009
Hydrodynamic model established	2D hydrodynamic model established. Needs further development with field data being collected	August 2009
Deliverable 1 completed	Prepare and submit progress report	August 2009

Table 3 The milestones and a summary of work undertaken to complete deliverable 2 & 3

Milestone	Progress/Completion (summary of work undertaken)	Date Completed
Catchment Modelling	From the catchment model flow, TP, TN and TSS loads for Wyong, Ourimbah and inflows to the Tuggerah Lakes system have been determined. Wyong and Ourimbah into Tuggerah and Wallarah Creek into Budgewoi. The recommended TP, TN and TSS concentrations (distributions) for the various land uses from the NSW guidelines have been adopted in the urban catchments using the MUSIC model. For upper catchments, available WQ data was used to inform the calculation of loads in the IHACRES model.	January 2010
Progress report	**Submitted**	**31 March 2010**
Field monitoring for model development	Analysis of samples and compilation of data arising from field program.	April 2010
Catchment Modelling	Appoint BMT WBM (Tony Weber) as sub-contractor to carry out catchment modelling for the land use/management scenarios and to redefine the MUSIC models of urban catchments	1 April 2010
Land use/management scenarios identified	Meeting at Wyong Shire Council with council representatives (Sian Fawcett, Vanessa McCann, Kristy Martin and David Ryan), DECCW (Kirsty Brennan), iCAM (Natasha Herron) and BMT WBM (Tony Weber) to discuss land use/management scenarios and to fill data gaps needed to complete scenarios Land use/management scenarios have been identified as: • Pre-settlement • Future development • Retrofit • Optimal wetland function With a final scenario putting together a number of the above treatments	14 April 2010
Catchment modelling	Refine whole of catchment and high resolution (MUSIC) models	14 May 2010
Hydrodynamic & Ecological Response Model couple/integration	Refine hydrodynamic models and ecological response model with data from the monitoring program. Integrate the hydrodynamic models and the ecological response models	31 May 2010
Deliverable 2	**Completed**	**31 May 2010**

Table 4 The milestones and work to be completed for future deliverables

Milestone	Progress/Completion (summary of work to be undertaken)	Deadline
Field monitoring for model development	Analysis of samples and compilation of data arising from field program	April 2010
Catchment modelling	Refine whole of catchment and high resolution (MUSIC) models upon completion of the catchment monitoring program	14 May 2010
Scenarios for catchment model(s)	Advise consultant(s) on modelling the catchment scenarios using their high resolution catchment model (e.g. MUSIC)	14 May 2010
Scenarios for hydrodynamic model(s)	Use high resolution catchment model outputs to model changes in the hydrodynamic regime of Tuggerah Lakes	28 June 2010
Scenarios for ecological response model(s)	Use hydrodynamic model outputs to model the ecological response of Tuggerah Lakes to identified land use/management scenarios	26 July 2010
Hydrodynamic modelling phase 2	Develop 3D hydrodynamic and wind wave model for further inputs into ecological response model if favourable lake and weather conditions occur	Continuing
Management areas identified	Identify areas in the Lakes that are at high risk of degradation from activities in the catchment. Identify ecological condition targets for high risk areas, as well as other distinct hydrological zones in the lakes	Continuing
Load targets developed	Run coupled/integrated hydrodynamic & ecological response models in high risk areas & other distinct hydrological zones to optimise land use/management scenarios that achieve ‘no net increase’ for Tuggerah Lakes &/or achieve ecological condition targets	Continuing
Feasibility testing of load & ecological condition targets	Use coupled/integrated hydrodynamic & ecological response models to assess the feasibility of implementing broad (large zones &/or subcatchment scale) planning guidelines. The number and types of feasibility tests will be agreed between DECC & WSC.	Continuing
Revise Models and final report	Revise modeling and reporting based on feasibility testing to establish the effectiveness of planning guidelines to meeting the ecological condition targets on receiving waters	Continuing
Deliverables completed	**Prepare and submit Final Report**	**31 July 2010**

Summary of Catchment, Hydrodynamic and Ecological Response modelling

A series of catchment, hydrodynamic and ecological response models have been developed and integrated to simulate the ecological processes occurring within the Tuggerah Lakes catchment in order to predict the impact of changes to land use and/or management.

The catchment model uses rainfall and potential evapotranspiration data to simulate the flow of water over the landscape in a catchment. Land use maps along with soil maps are used to inform the amount of runoff from each land use category, with hard surfaces such as roads and urban landscapes having a larger runoff coefficient that forested or farmed land uses where water is allowed to penetrate. The land use maps are also used to predict the concentrations of sediments and nutrients exported to the receiving waters in both dry and storm conditions. This model indicates the impact each subcatchment has on the receiving waters and can suggest focus areas for management efforts.

The hydrodynamic model uses bathymetry, water level, rainfall, water quality measurements and outputs from the catchment model to simulate the movement of water, sediments and nutrients around the entire system, including the major tributaries and lakes. This model provides the linkages between catchment discharge and ecological impact.

The ecological response model (ERM) uses outputs from both the catchment and hydrodynamic models to predict the biogeochemical processes and seagrass growth in the lakes. Using the current situation in the lakes as well as knowledge from literature, this model will predict the ecological consequences of changed catchment and/or hydrodynamic situations. The ERM will be an important management tool as it will provide threshold levels of sediment and nutrient concentrations to trigger intervention of management.

Data from the field sampling and monitoring program are used to calibrate and validate each of the models.

Field sampling and monitoring

Between April 2009 and March 2010 an extensive field sampling and monitoring program was carried out fortnightly at 21 sites within the Tuggerah Lakes and tributaries as well as monthly grab samples at a number of sites within the catchment including DECCW gauging stations, weirs and drains. Field data has been used to validate each of the models.

Lake water quality sampling and monitoring

Water quality within Tuggerah, Budgewoi and Munmorah lakes as well as Wyong River and Ourimbah, Wallarah and Tumbi creeks was sampled on a fortnightly basis, weather depending (Figure 1).

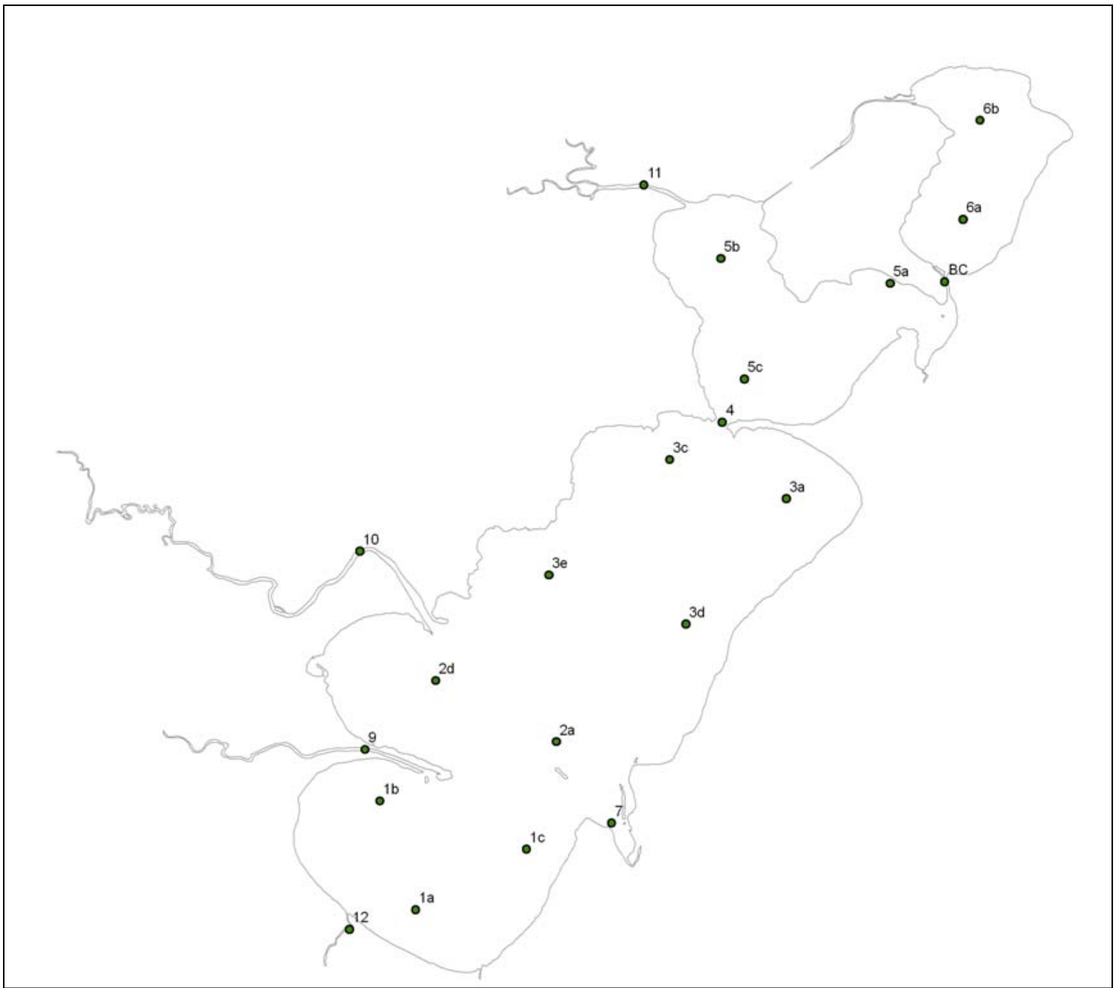


Figure 1 Water quality sampling sites in Tuggerah Lakes and tributaries

The samples collected were analysed for chlorophyll-*a*, colour, salinity, turbidity, TSS, nutrients (Silica, Ammonia, NO_x, Phosphate, Total dissolved Phosphorus, Total Dissolved Nitrogen, Total Phosphorus and Total Nitrogen) and light. Chlorophyll-*a* concentrations were measured as proxies for benthic and pelagic microalgal biomass. Colour, Turbidity, Secchi depth and total suspended solids were measured to assess their contribution to water column light attenuation. A summary of water quality results for the lakes and tributaries is presented in Table 5.

Table 5 Summary of water quality results for Tuggerah Lakes (annual means and standard deviations)

	Chlorophyll-*a* (ug/L)	Colour (true at 400nm) (x10^-3)	Salinity (ppt)	Turbidity (NTU)	TSS (105oC) mg/L	TP (ugP/L)	TN (ugN/L)
Tuggerah Lake	4.24 ± 1.96	4.30 ± 0.98	30.58 ± 2.42	5.47 ± 5.80	7.81 ± 7.66	16.87 ± 7.62	353 ± 64
Budgewoi Lake	4.06 ± 2.23	5.37 ± 1.13	29.96 ± 3.74	6.35 ± 8.29	11.92 ± 15.35	21.12 ± 11.12	472 ± 114
Lake Munmorah	3.97 ± 3.50	5.38 ± 1.22	29.94 ± 3.21	4.98 ± 2.58	9.28 ± 7.86	21.44 ± 9.51	504 ± 109
The Entrance	3.40 ± 1.93	3.48 ± 1.22	31.47 ± 3.03	2.58 ± 1.69	5.01 ± 4.56	15.20 ± 5.13	288 ± 69
Ourimbah Creek	8.42 ± 4.48	7.15 ± 2.38	24.63 ± 5.60	3.14 ± 2.06	6.84 ± 6.79	30.37 ± 14.28	459 ± 89
Wyong River	7.48 ± 3.80	10.70 ± 7.26	22.21±10.23	4.99 ± 8.67	7.36 ± 8.69	36.72 ± 28.67	486 ± 183
Wallarah Creek	5.88 ± 2.15	8.70 ± 2.96	27.92 ± 4.08	3.62 ± 1.13	10.04 ± 13.02	24.56 ± 10.32	542 ± 102
Tumbi Creek	13.29 ± 7.39	13.25 ± 7.60	25.36 ± 7.70	6.51 ± 3.31	12.56 ± 10.04	41.09 ± 20.06	571 ±140

Chlorophyll-*a*

Chlorophyll-*a* concentration is an important water quality measurement as it indicates the abundance and biomass of phytoplankton in the waterway. In the Tuggerah Lakes system, chlorophyll-*a* is likely to be influenced by catchment discharge, wind-driven resuspension of benthic micro-algae and shallow, stable embayments. Resuspension plays a significant role in chlorophyll concentrations and is discussed further in this report. Figure 2 shows a summary of the field data for chlorophyll-*a* for the time period April 2009 to March 2010. The changing patterns of chlorophyll-*a* concentrations are discussed in the Ecological Response modelling section.

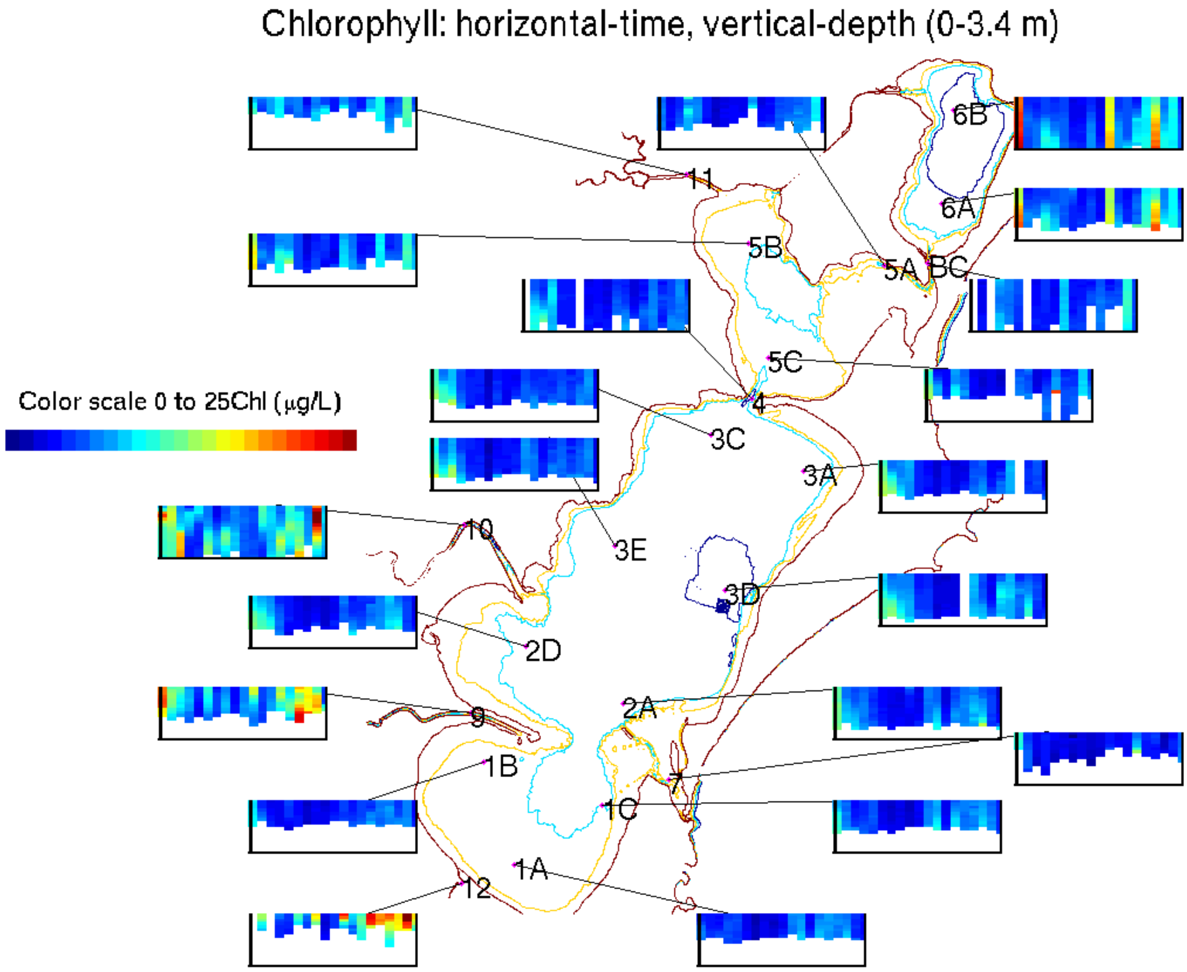


Figure 2 Chlorophyll-*a* in Tuggerah Lakes and tributaries from 24 April 2009 till 18 March 2010.

Colour

Colour in waters of coastal estuaries is measured by the concentration of coloured dissolved organic matter (CDOM) and is influenced by catchment discharge, plant tannins and the decay of organic material. CDOM is an important water quality indicator as it affects the absorption of sunlight in the waters, which is the main factor for photosynthesis.

From the field data, the river and creeks of the Tuggerah Lakes system showed the highest values of colour which is expected due to the runoff from rural catchments being higher in dissolved organic matter than the urban catchments. There was little variation in CDOM among the lakes.

Salinity

Salinity in Tuggerah Lakes and its tributaries from the field data obtained between April 2009 and March 2010 is summarised in Figure 3. Salinity within Tuggerah, Budegewoi and Munmorah lakes are more or less vertically homogenous. This may be attributed to both intermittent freshwater inputs and the fact that the lakes are broad and shallow thereby allowing effective vertical mixing by the wind. The main tributaries of the Tuggerah Lakes (Wyong River and Ourimbah, Wallarah and Tumbi creeks) are narrow and deep preventing effective mixing by the wind and causing vertical stratification to occur. Some vertical stratification occurs in the channels connecting Tuggerah Lake to Budgewoi Lake and Budgewoi Lake to Lake Munmorah due to differences in pressure and temperature (baroclinicity).

The observed salinity range over the sampling period was 3.1-36 ppt. Higher salinity concentrations over the summer months relate to low catchment discharge as a result of low rainfall, high evaporation and ocean exchange.

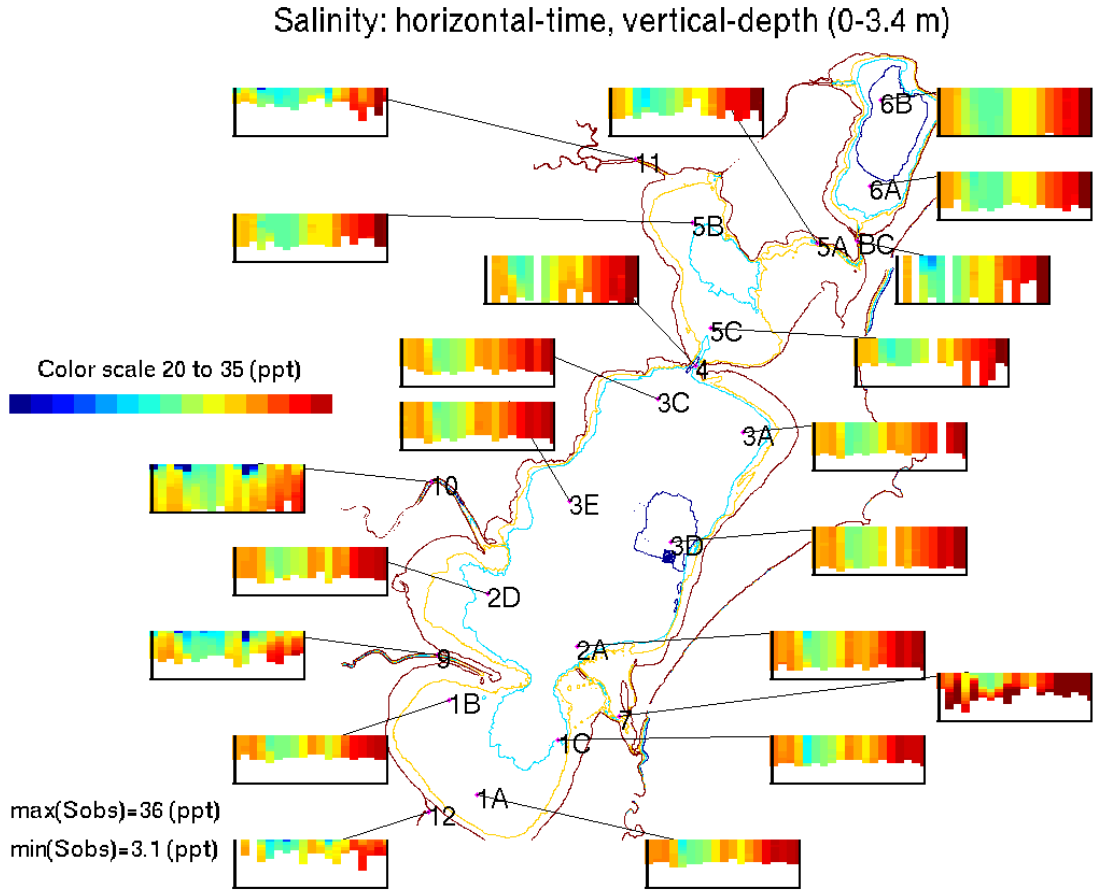


Figure 3 Salinity in Tuggerah Lakes and tributaries from 24 April 2009 till 18 March 2010.

Turbidity

Turbidity is a measure of water clarity. In Tuggerah Lakes and its tributaries, turbidity is generally influenced by catchment discharge and resuspension of bottom sediments by wind. Turbidity is the amount of suspended sediments in the water column which affects the ability of light to penetrate. Water quality greatly influences seagrass growth and sustained periods of turbidity may be detrimental to the seagrass beds.

Due to the shallow nature of the lakes, resuspension plays a large role in the function of the lakes and is a major factor in turbidity. Figure 4 shows the turbidity at each of the sampling sites from April 2009 to March 2010. Resuspension is characterised by the increase in turbidity going down the water column.

Higher turbidity observations over the summer months are likely due to the higher wind speeds that generally occur when compared with winter.

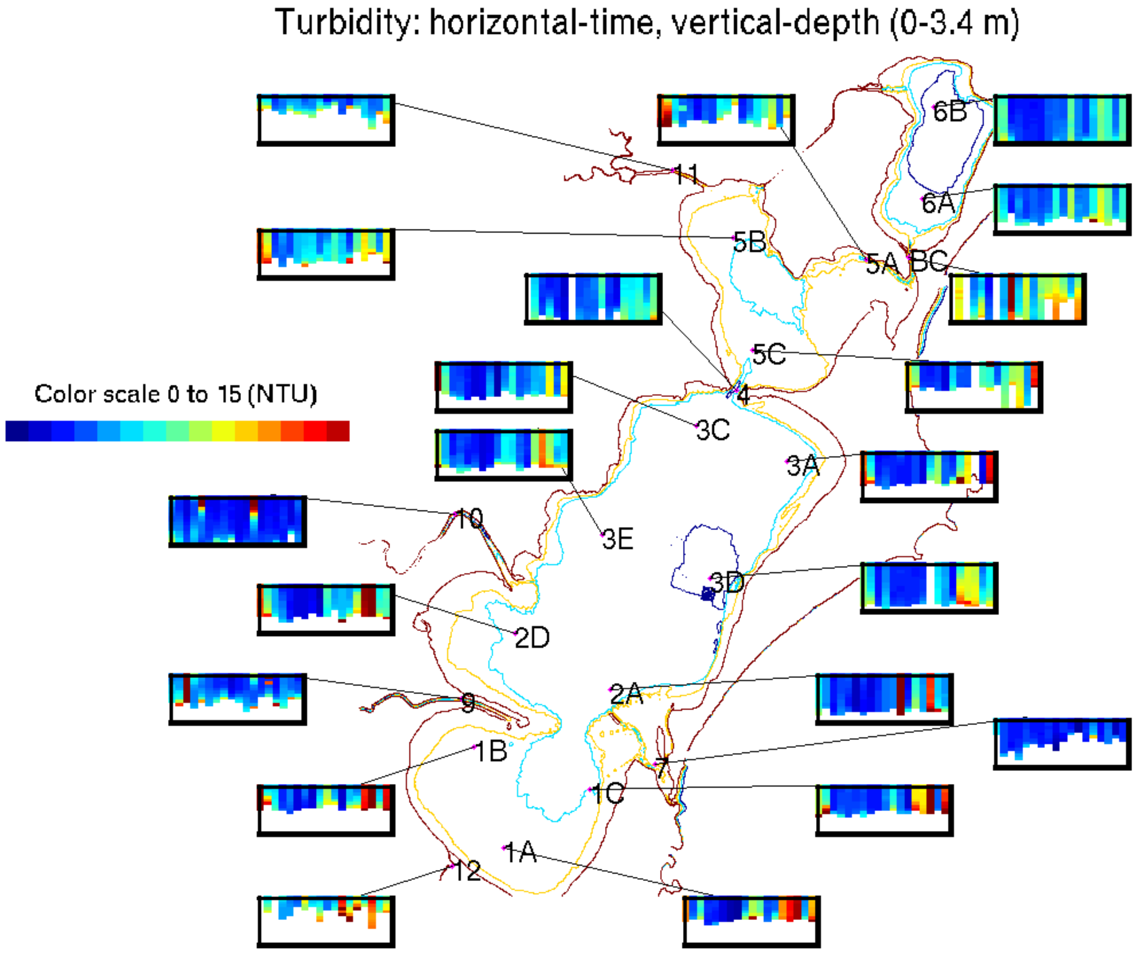


Figure 4 Turbidity in Tuggerah Lakes and tributaries from 24 April 2009 till 18 March 2010.

Total suspended solids and nutrients

Total suspended solids (TSS) and nutrients (TP and TN) were sampled to validate the various models and to gain an understanding of the processes within and between the lakes and the influences of catchment runoff. As would be expected, the field data reflect higher concentrations of TSS and nutrients in the rivers and creeks, and concentrations in the lakes decreasing with distance from the discharge point. Nutrients can be dissolved in the water column or adsorbed onto sediments and are required for ecological processes including seagrass growth. Too much of these components sustained over a period of time may have detrimental effects on the ecosystem and water quality.

Catchment sampling and monitoring

Rising stage samplers

Rising stage samplers have been installed at three existing DECCW (previously Department of Water and Energy) gauging stations, 211014 Wyong River at Yarramalong, 211015 Ourimbah Creek and 211010 Jilliby Creek (Figure 5). The rising stage samplers collect water during a rainfall event at a number of points in the flow peak. The falling stage water sample is then collected through manual sampling and dry/base flow is sampled every month also through a manual sample.

The samples collected at these locations were analysed for TSS, turbidity, conductivity and nutrients. These samples give an indication of the concentrations in runoff from different land uses in the upper catchment and are used to calibrate and validate the models. Results from the stage samplers are presented in Figures 6 to 8.

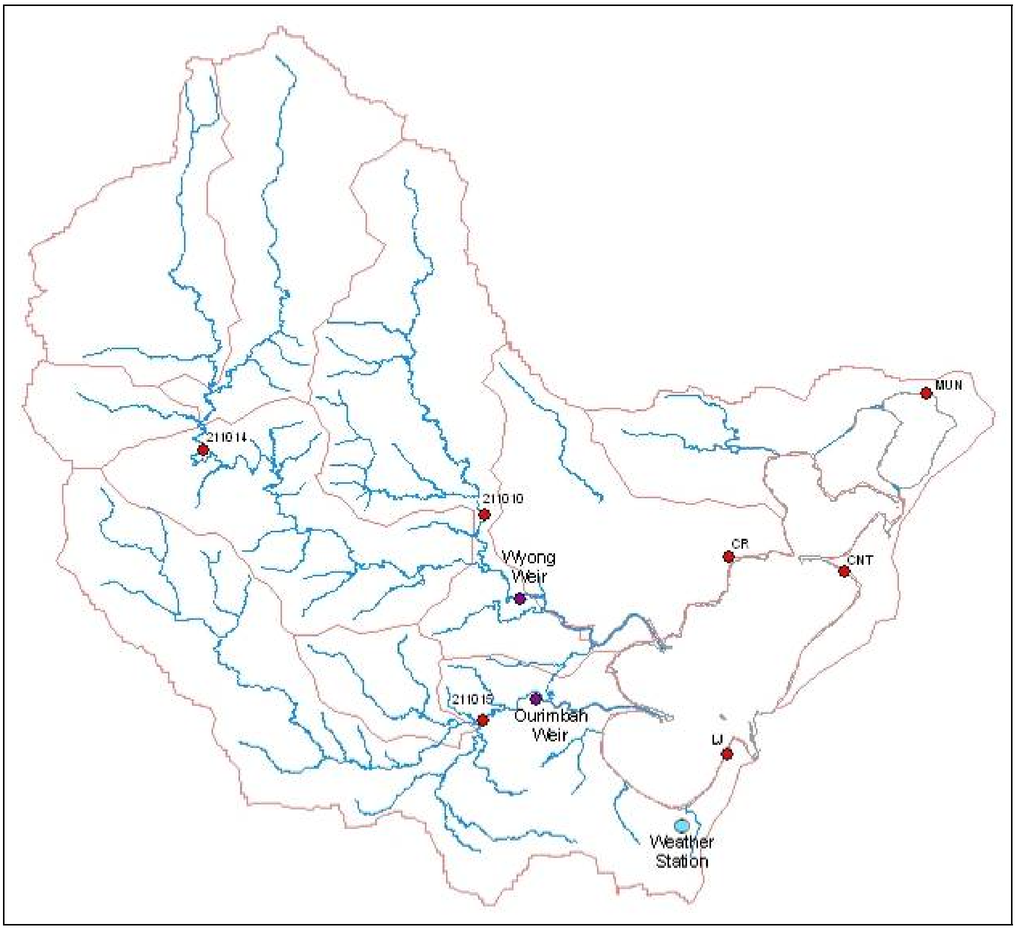


Figure 5 Location of stage samplers (211010, 211014 and 211015), stormwater drains(MUN – Munmorah, CNT – Canton Beach, CR – Craigie and LJ – Long Jetty) and weirs (Ourimbah and Wyong)

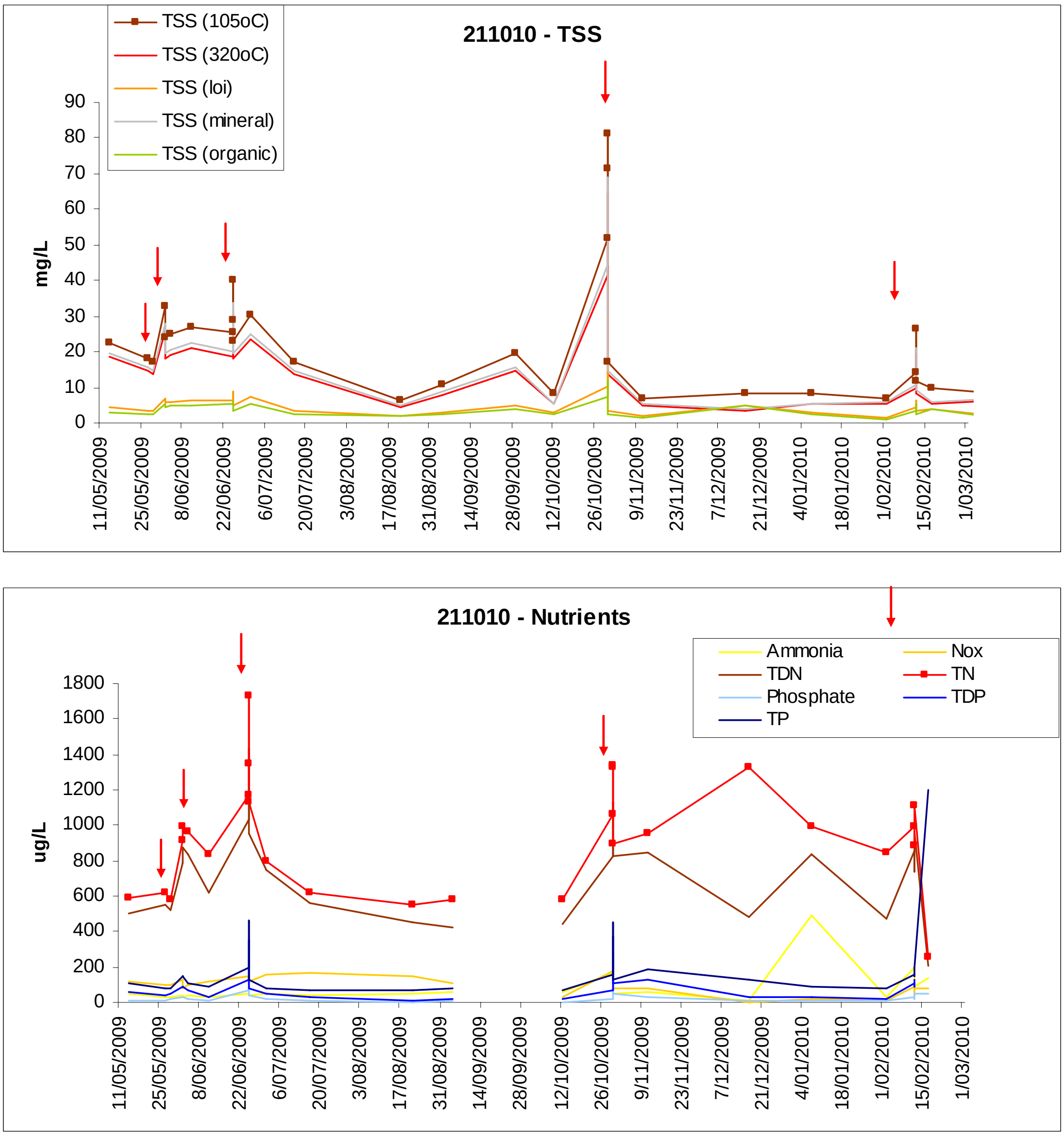


Figure 6 Total suspended solids (top) and nutrients (bottom) for the Jilliby Creek stage sampler. The red arrows indicate a peak flow event

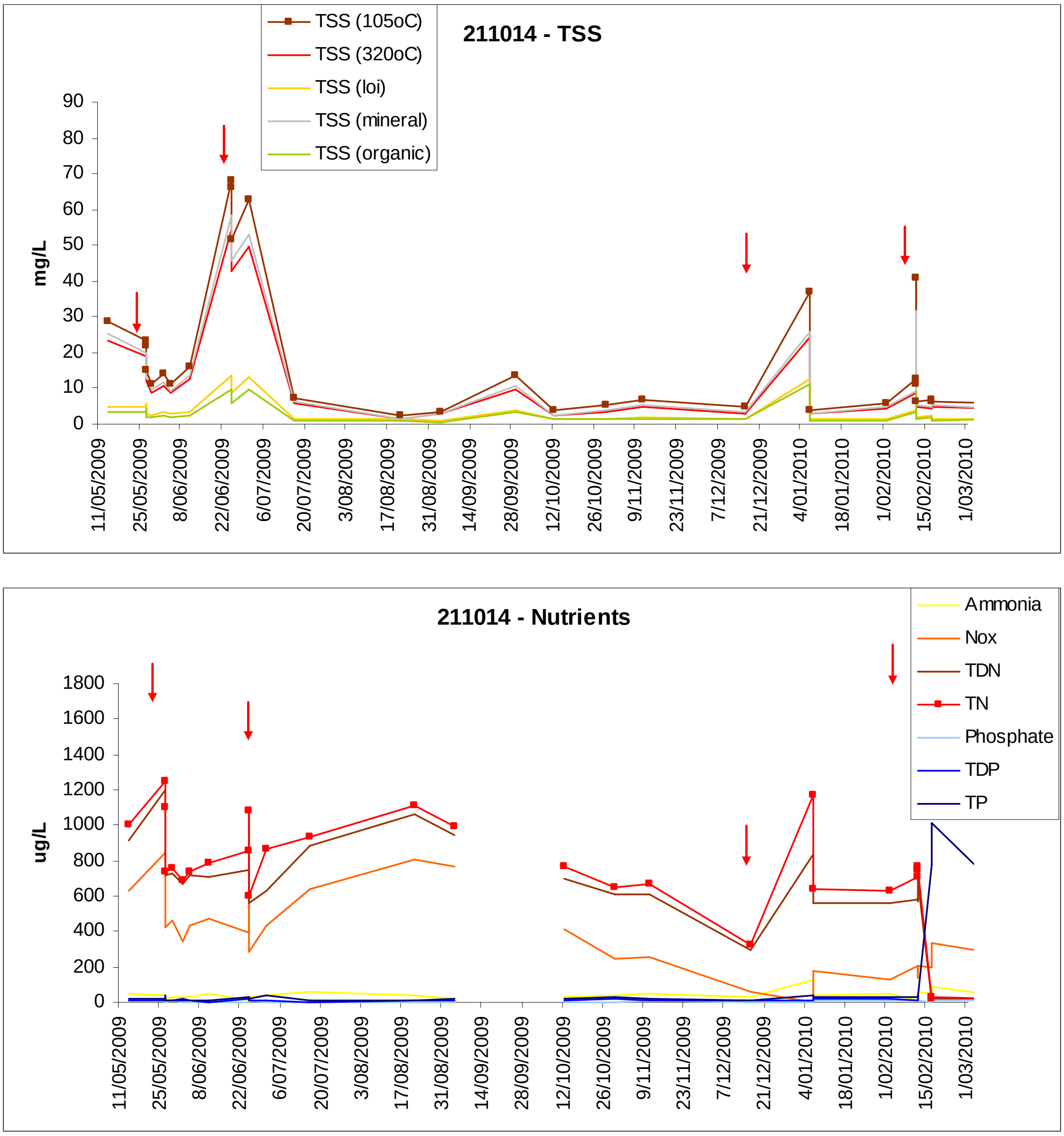
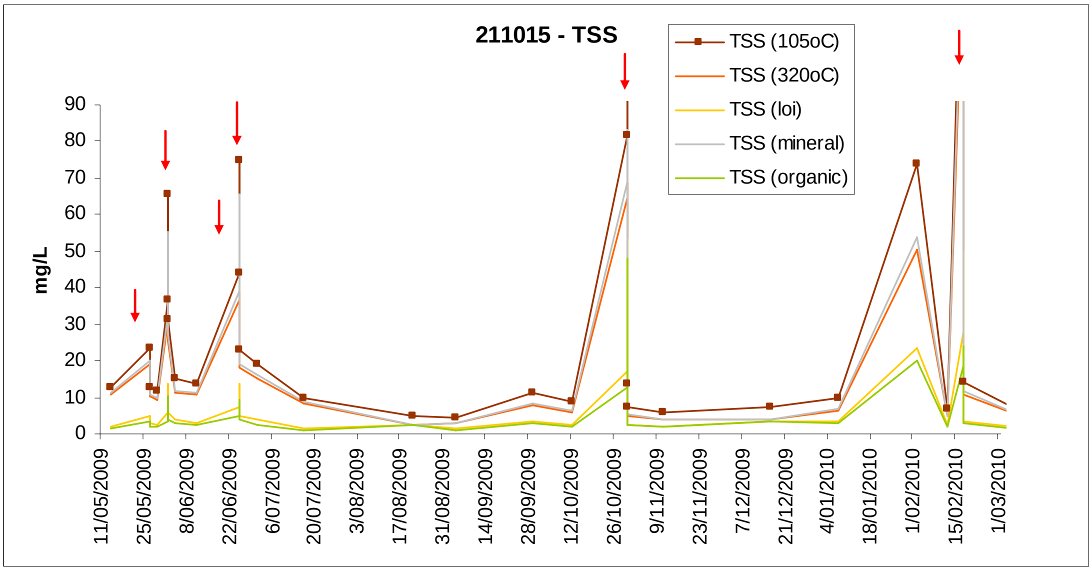


Figure 7 Total suspended solids (top) and nutrients (bottom) for the Wyong River stage sampler. The red arrows indicate a peak flow event



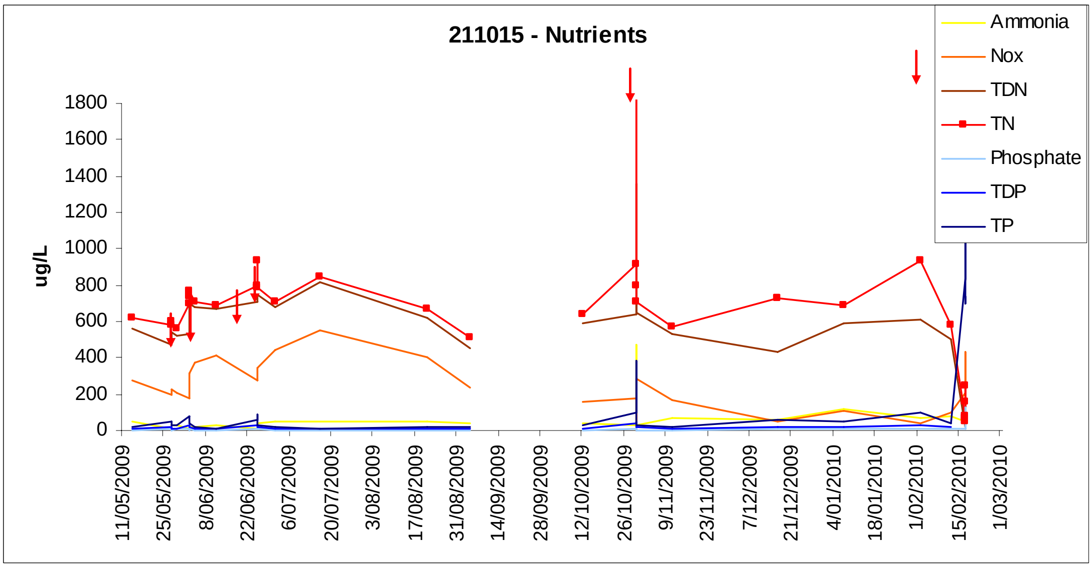


Figure 8 Total suspended solids (top) and nutrients (bottom) for the Ourimbah Creek stage sampler. The red arrows indicate a peak flow event

Weir Sampling

Monthly samples from Ourimbah and Wyong Weirs were collected from August 2009 to March 2010 (Figure 5). As with the stage sampler, the weir samples were analysed for TSS, turbidity, conductivity and nutrients. The sample analyses allow better representation of the upper catchment by the catchment and hydrodynamic models.

Stormwater Runoff

Water level sensors were installed in four stormwater drains (Munmorah - MUN, Canton Beach - CNT, Long Jetty - LJ and Craigie Park - CR) that flow directly into Tuggerah Lakes (Figure 5). These sensors gave an estimate of the amount of rainfall that flows off the urban areas directly to the lakes. Water samples were collected from these drains monthly if there was flow. If there was a rainfall event the samples were analysed for TSS, turbidity, conductivity and nutrients.

Catchment Modelling

BMT WBM Pty Ltd in conjunction with the Integrated Catchment Assessment and Management Centre at the Australian National University have developed a detailed representation of the sediment and nutrient runoff from the Tuggerah Lakes catchment. The catchment model is being used to provide source area maps and daily catchment inflows of TN, TP and TSS to Tuggerah Lakes from the subcatchments to inform the Hydrodynamic and Ecological Response models.

Methods

The catchment of Tuggerah Lake was subdivided into 32 subcatchments for detailed catchment modelling. Discharge from these subcatchments can be modelled, as entering Tuggerah Lakes at 25 locations around the shores of Tuggerah Lakes; these are represented as dots in Figure 9.

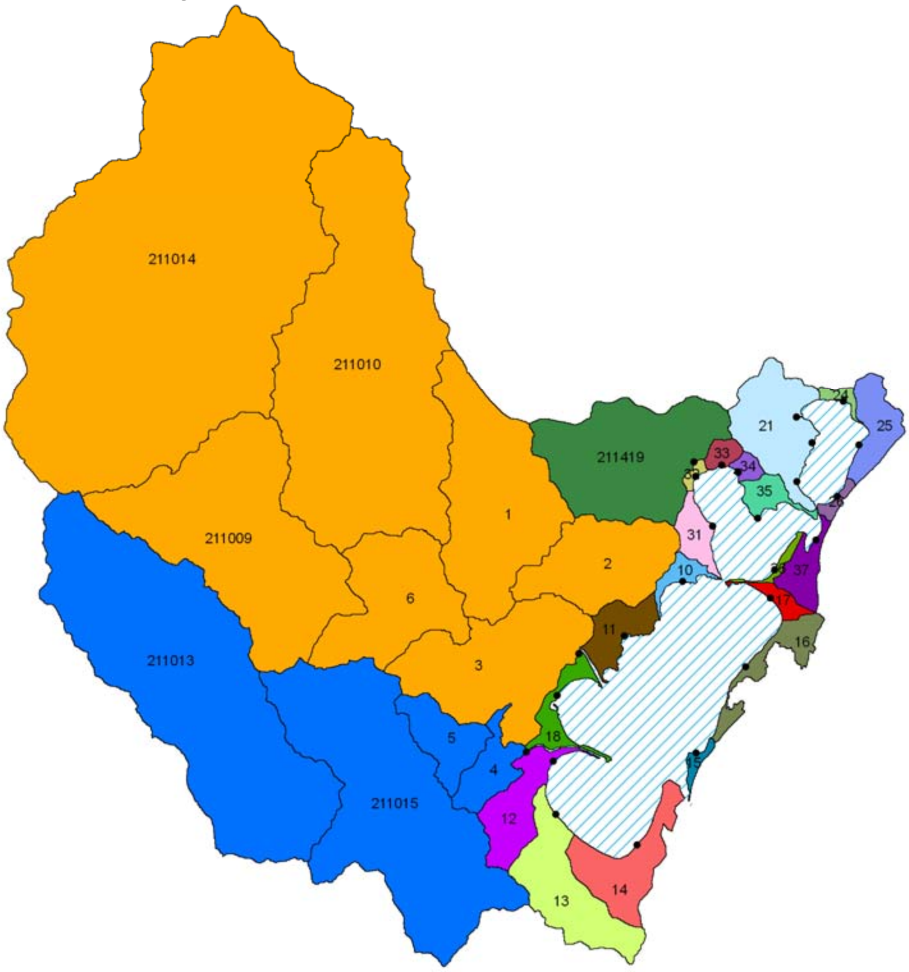


Figure 9 Subcatchments of Tuggerah Lakes. Discharge locations are indicated with dots.

Catchment model selection

Two different models were used to represent the Tuggerah Lakes catchment due to distinctly different land uses. An IHACRES rainfall-runoff model was used for the larger, predominately non-urban headwater subcatchments and the MUSIC urban stormwater model was used for the smaller, predominately urban subcatchments fringing the lake (Figure 10). For a detailed report on the model selection and setup, refer to the appended document BMT WBM 2010.

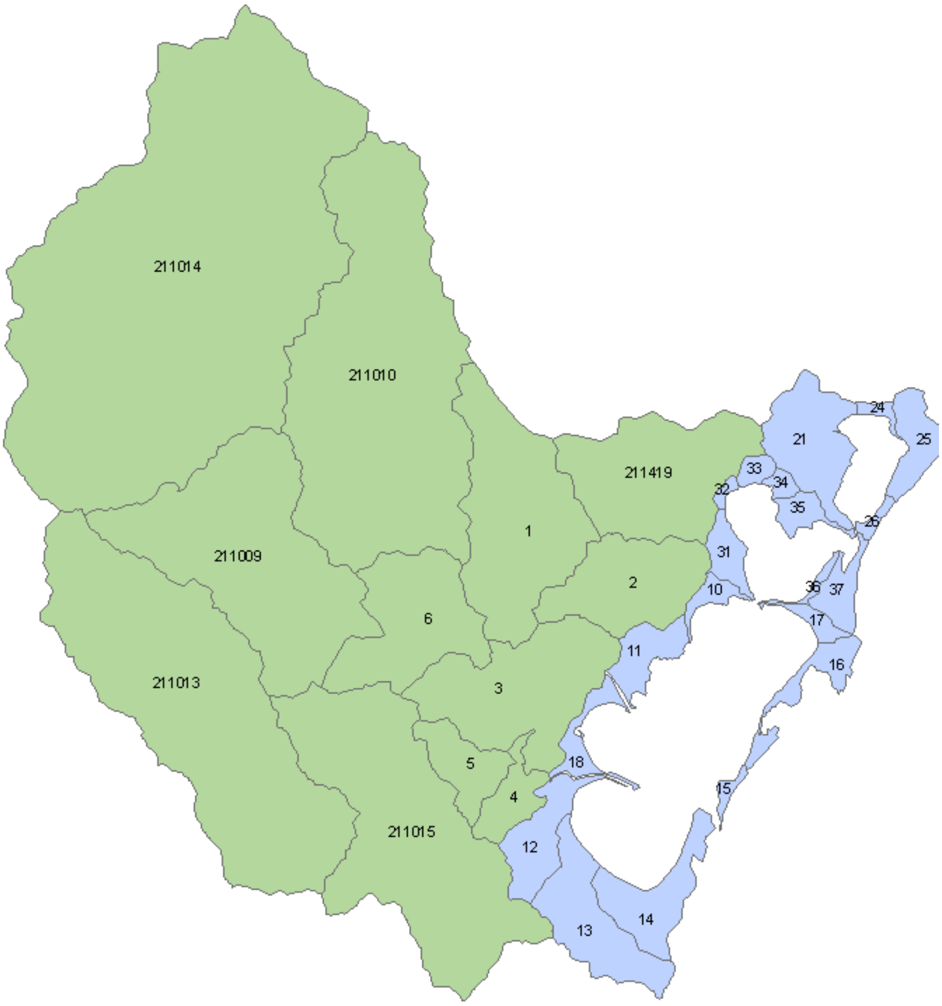


Figure 10 Subcatchments in the Tuggerah Lakes catchment – areas shaded green are modelled with IHACRES and the blue areas are modelled with MUSIC.

IHACRES model

Water quality data for the upper catchment area was used to develop concentration-flow relationships at a couple of locations in the Wyong River and Ourimbah Creek catchments, which were then used to calculate daily time-series of TN and TP loads to Tuggerah Lake. TSS data was generally lacking and the time-series of TSS loads was based on the field data as described in the previous section. Inflows and loads for Wallarah Creek, which flows into Budgewoi Lake, were based on regionalisation of the runoff models and water quality information from near-by catchments.

Figure 11 shows a link-node schematic of the Tuggerah Lakes system, with the subcatchments modelled using IHACRES, identified as nodes within the network. In terms of inflows to the lakes, there are only three inflow points, two into Tuggerah Lake – Wyong River and Ourimbah Creek and one into Budgewoi Lake – Wallarah Lake.

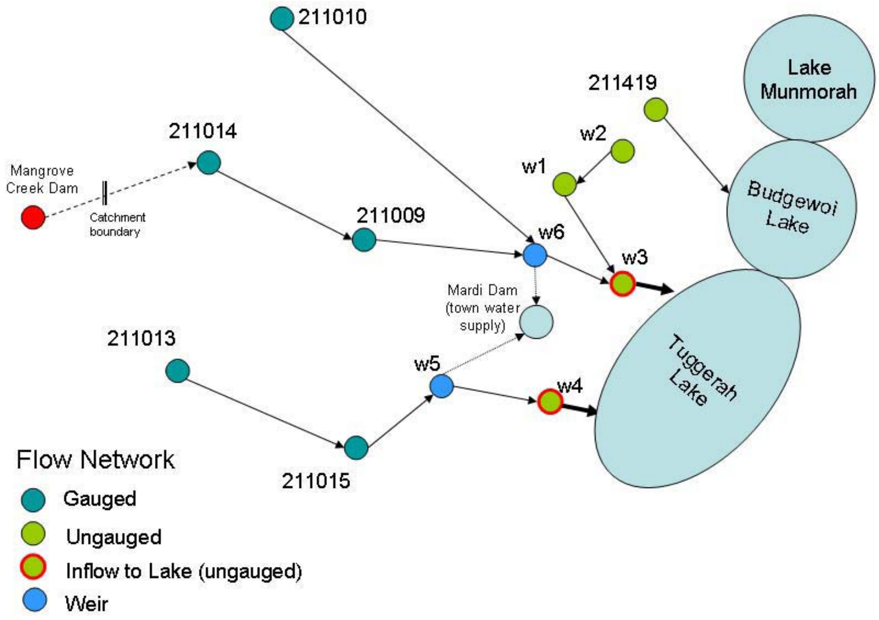


Figure 11 Link-node representation of the catchment-stream network, modelled using IHACRES

The link-node figure also shows a pipe from Mangrove Creek Dam, located in an adjoining catchment to the southwest, which transfers water into the Tuggerah Creek catchment when necessary to meet the town water supply requirements of the Gosford-Wyong area. These contributions have been modelled for the period with data (note that the data supplied is only up to 2006, and the modelling for more recent years does not include any supplement). It is worth noting that the contributions are specifically for town water supply, and therefore do not contribute to Tuggerah Lake via Wyong River.

MUSIC model

The MUSIC modelling has been developed for each blue shaded subcatchment in Figure 10 and has been run using daily rainfall inputs. Pluviometer data at a 6-minute time-step is available and some preliminary models have been set up with these meteorological templates. This model also uses a link-node structure with 25 discharge points around the lakes as shown in Figure 9. Each of these discharge points have been parameterised for the generation of runoff, TSS, TP and TN. The key runoff parameter is the percentage of impervious surface within a catchment, and then there are various soil and groundwater related parameters to account for soil storage capacity and fluxes of water into subsurface pathways. The MUSIC Modelling Guidelines for NSW (BMT WBM 2008) have been used to inform the parameterisation of each model.

Rainfall and evaporation

Daily rainfall data used for the model was sourced from Bureau of Meteorology gauging stations for the period 1/1/80 to 30/4/10. The gauging stations include Alstonville (058131), Gosford (061087), Mangrove Mountain (061375), Newcastle (061055), Norah Head (061366), Peats Ridge (061351), Sydney Airport (066037) and Williamtown RAAF (061078).

Land use

The land use layer used for the Tuggerah catchment was mapped in 1998 at a scale of 1:50 000. From the land use classes, percentages of imperviousness were assumed and incorporated into the model (Table 6).

Table 6 Land use classes and imperviousness

Class	%impervious
State Forest	0
Grazing Natural	0
Grazing Improved	0
Turf Farm	0
Orchard	0
Vegetable Crops	0
Native Veg	0
Intensive Animal Production	0
Water	0
Wetland	0
Beach	0
Rural Residential	5
Urban Residential	25
Industrial Commercial	65
Transport	90
Urban Disturbed	65
Future Urban	35

Source: BMT WBM 2010

Water quality

The baseline catchment model allows for constant values to be set for base flow and event flow conditions. This approach requires values for the Event Mean Concentration (EMC) and Dry Weather Concentration (DWC) to be input into the model for each land use (BMT WBM 2010).

The constituents modelled and their respective EMC and DWC values for each land use are presented in Tables 7 and 8 and were obtained from the draft NSW MUSIC Modelling Guidelines as there are insufficient long term water quality datasets.

Table 7 EMC Parameterisation (mg/L)

Concentration (mg/L)			
	TSS	TP	TN
	mean	mean	mean
Land use/zoning			
Residential	141.3	0.251	2.00
Commercial	141.3	0.251	2.00
Industrial	141.3	0.251	2.00
Rural residential	89.1	0.219	2.00
Agricultural	141.3	0.603	3.02
Forest	39.81	0.079	0.89

Table 8 DWC Parameterisation (mg/L)

Concentration (mg/L)			
	TSS	**TP**	**TN**
	mean	**mean**	**mean**
Land use/zoning			
Residential	15.8	0.141	1.29
Commercial	15.8	0.141	1.29
Industrial	15.8	0.141	1.29
Rural residential	14.1	0.060	0.89
Agricultural	20.0	0.089	1.10
Forest	6.03	0.030	0.30

Water quality data from the field sampling program was used to calibrate the model to make it more specific to Tuggerah Lakes.

Results

Baseline catchment model

The following results represent the predicted loads and export rates of nutrients and sediments from the Tuggerah Lakes catchment in its current state. The current state is defined as the land use from 1998 mapping, rainfall data for the period 01 January 1980 to 31 October 2009, and a drainage system in which there are no water treatment devices.

From the IHACRES and MUSIC modelling, streamflow (mm/y) from each subcatchment (Figure 12) and Total nitrogen (kg/y), Total Phosphorus (kg/y) and Total Suspended Solids (t/y) exported from each subcatchment was determined (Figures 13, 14, 15). The export rate of TN, TP and TSS is also expressed per unit area (kg/ha/y) in Figures 16, 17 and 18.

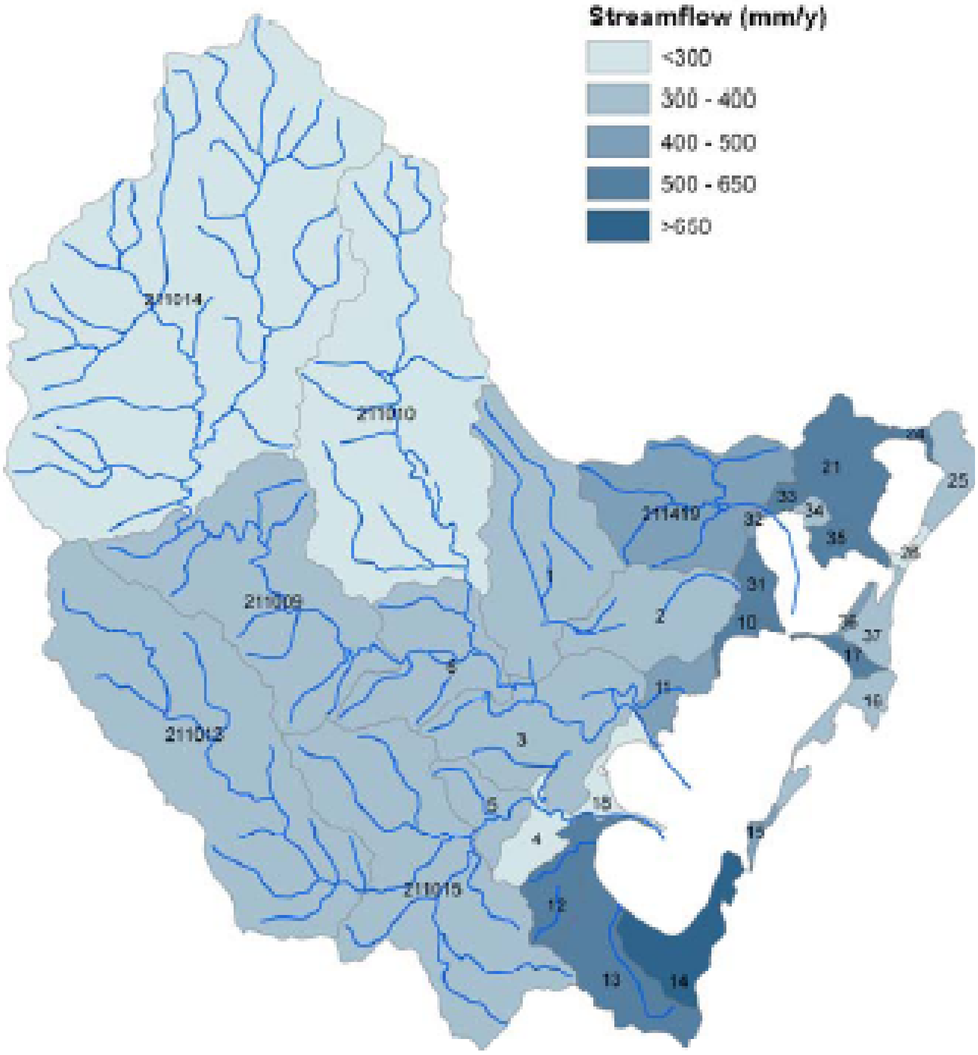


Figure 12 Mean annual runoff (mm/y) by subcatchment

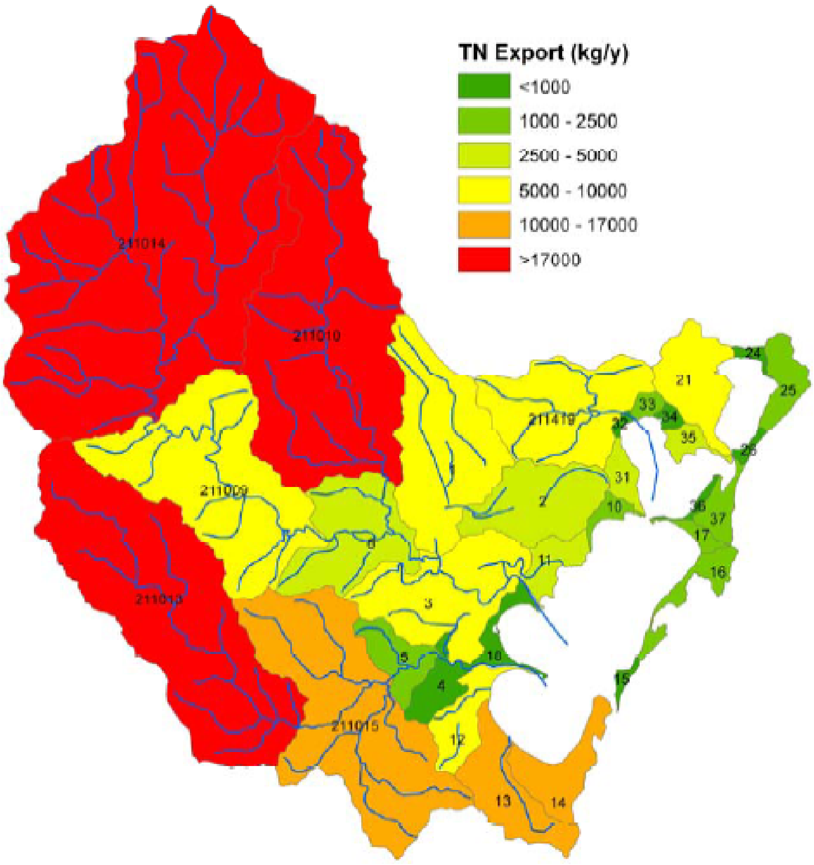


Figure 13 Mean annual TN loads (kg/y) by subcatchment

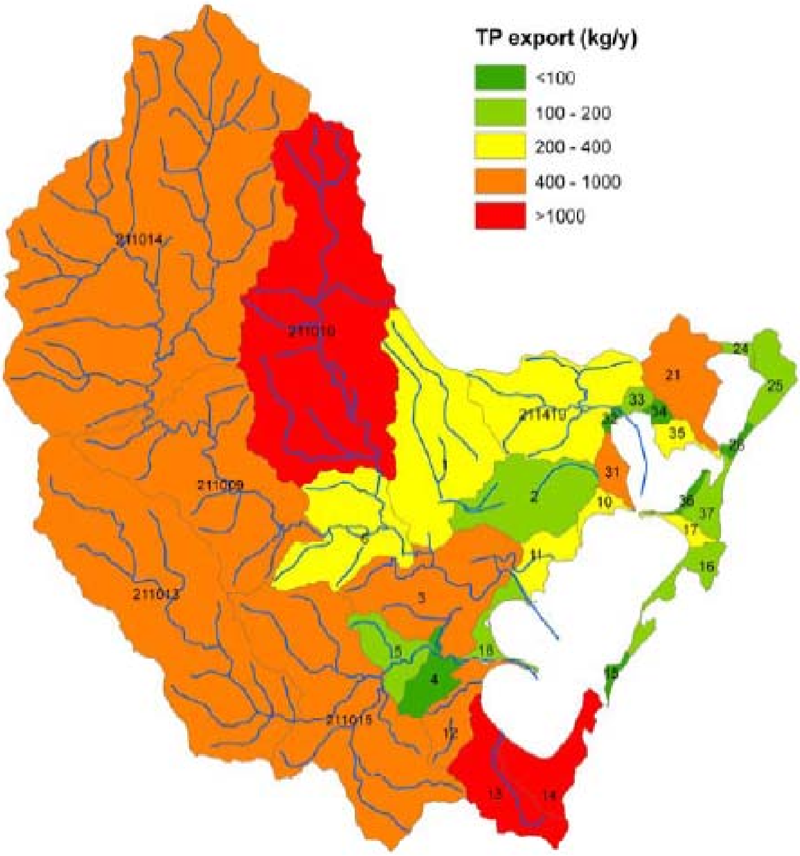


Figure 14 Mean annual TP exports (kg/y) for each subcatchment

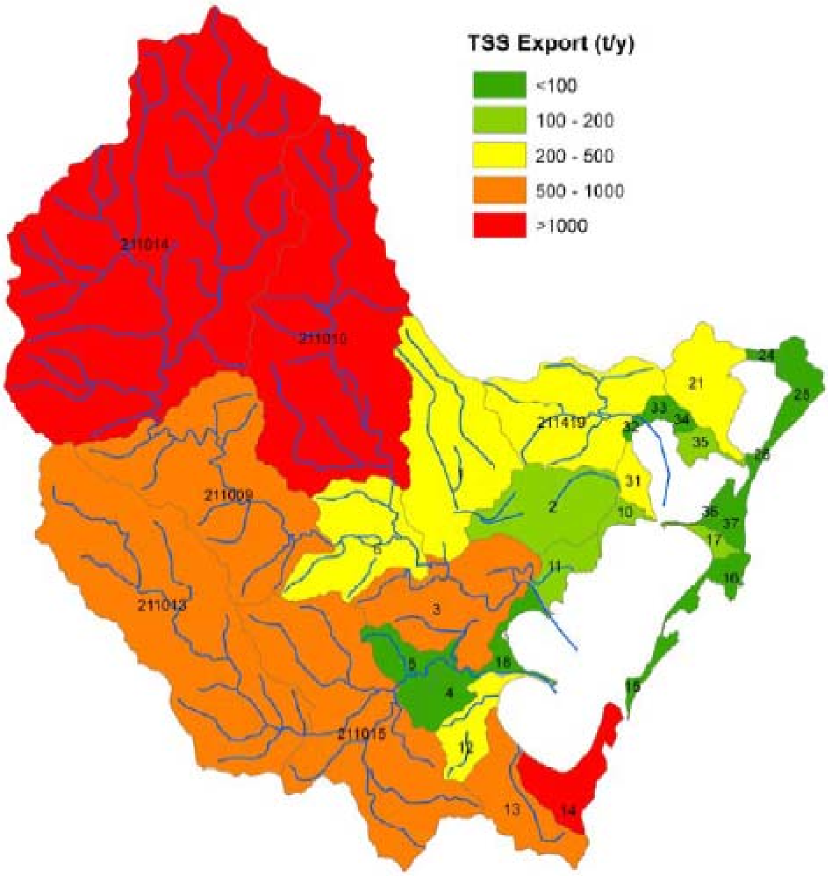


Figure 15 Mean annual TSS loads (t/y) by subcatchment.

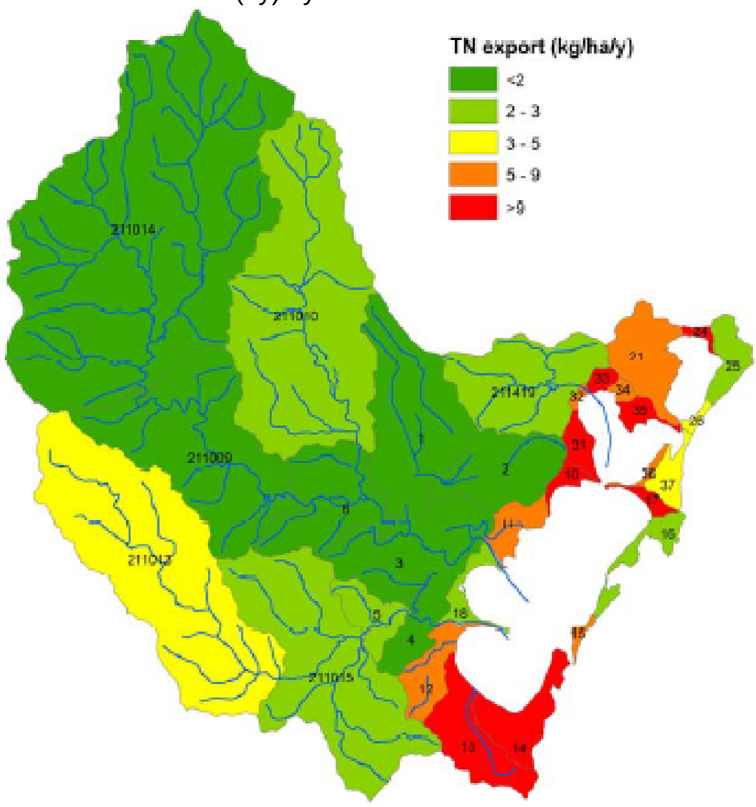


Figure 16 Mean annual TN export rate (kg/ha/y) by subcatchment

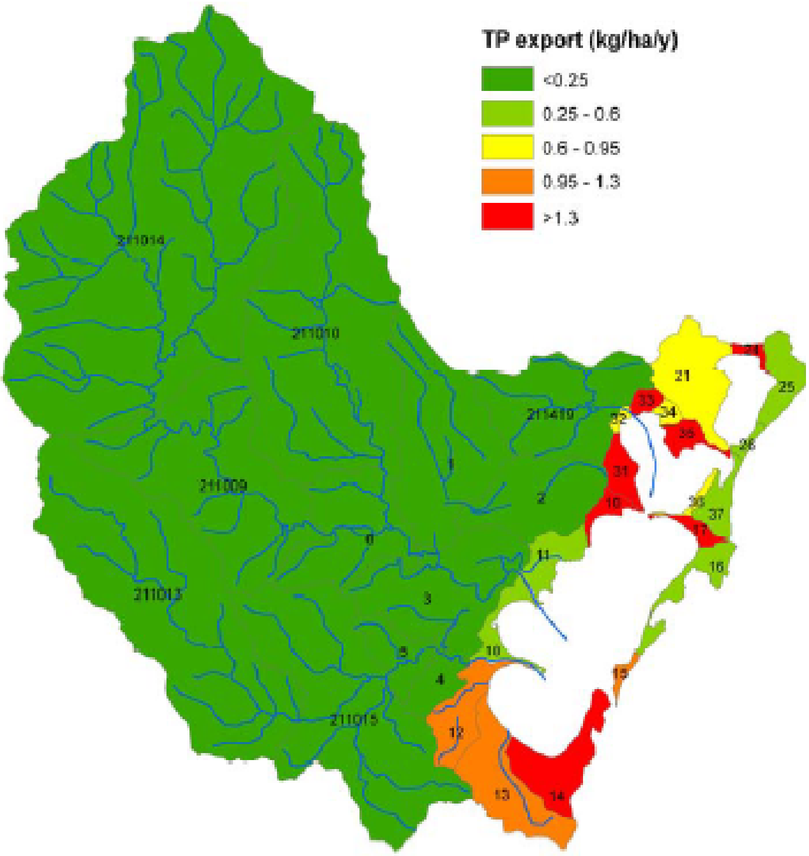


Figure 17 Mean annual TP export rate (kg/ha/y) for each subcatchment

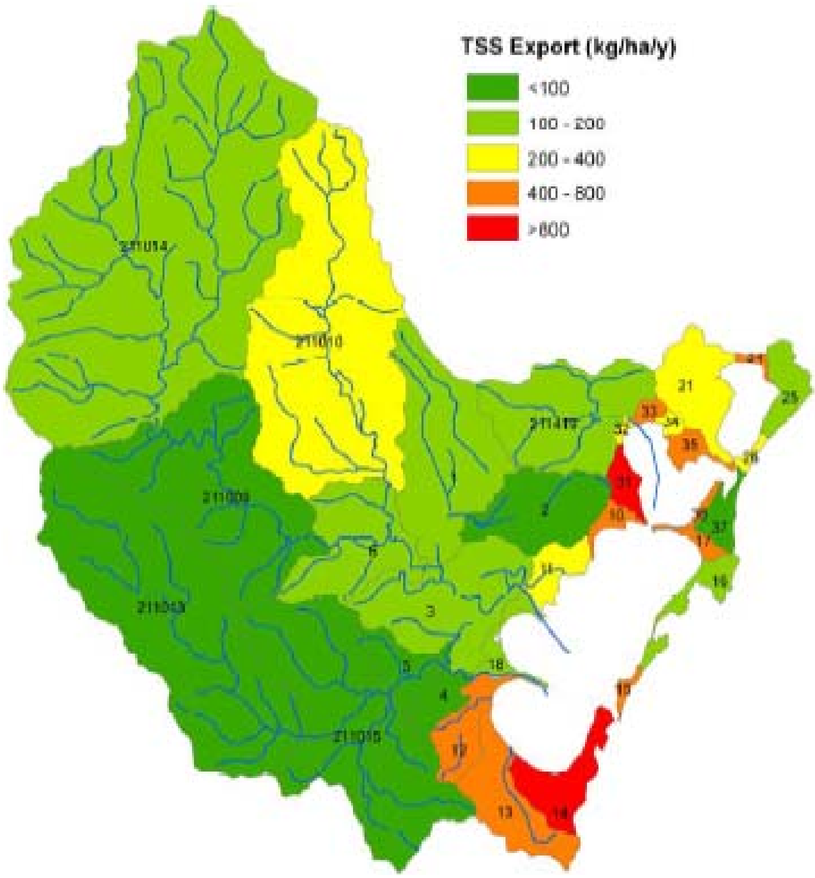


Figure 18 Mean annual TSS export rate (kg/ha/y) by subcatchment

Summary of catchment modelling

A summary of the results of the catchment model for the current scenario indicate:

- The upper catchment is the main contributor of TN and TSS to the Lakes system, although contributions from the fringing catchments are certainly significant (~36% and 33%, respectively).
- Flow dominates the load response, so while concentrations of constituents in the upper catchments are generally lower than from urban catchments, they dominate the loading to the lake.
- The fringing lake catchments, modelled using the MUSIC model, contribute more TP than the upper catchment, despite making up 12% of the total contributing area (and ~20% of runoff).
- Caution in the interpretation of these results is advised, since they could be an artefact of the two different sources of water quality information used in the modelling. Further work/data is required to confirm this finding.
- Jilliby Creek catchment (211010) appears to be a more significant source of TN, TP and TSS than the other upper catchments, both in terms of concentrations and loads.
- Ourimbah Creek (211013) has relatively high TN exports.
- Of the catchments' fringing the lakes, watersheds 12, 13 and 14 on the southern end of Tuggerah Lake, watershed 31 on the southwest side of Budgewoi Lake and watershed 21 to the west of Munmorah Lake come out as being the most significant contributors of TP, TN and TSS to their receiving waters.
- Other fringing catchments of potential concern are watersheds 10 and 17 (Tuggerah Lake), 33, 35 and 36 on Budgewoi Lake and 24 to the north of Munmorah Lake.
- Extractions from Wyong Weir and Ourimbah Weir for town water supply can cause flow from the weirs to cease, such that inflows to the lakes come only from areas downstream of the weirs and the fringing lake catchments. At these times urban runoff will be the main source of inflows the lake, although in absolute terms they will be small.

Hydrodynamic Modelling

The catchment of Tuggerah Lake was divided into 32 subcatchments for the purposes of catchment modelling. Discharge from these subcatchments can be modelled as entering Tuggerah Lakes at 25 locations around the shores of Tuggerah Lakes (Figure 9). A number of hydrodynamic models have been developed to address a range of mechanisms that have been identified to be important at different localities and times for different ecological functions.

In order to determine the impact of each subcatchment in the Tuggerah Lakes system, the transport of a passive scalar tracer was modelled at each of the 25 discharge points around the lakes. This is to show the path of movement of a substance which remains unchanged over time, and will indicate the degree of impact each subcatchment has on the system.

Material (nutrients and suspended solids) discharged into Tuggerah Lakes will be transported with currents. A two-dimensional X-Y model (shallow water equations) was used to calculate currents and suspended material within Tuggerah Lake, Budgewoi Lake, and Munmorah Lake. The constricted channels between lakes are modelled using a two-dimensional X-Z model which determines motion integrated across the channel. The X-Z model is also used to model currents and suspended material within the estuarine portions of: Ourimbah Creek, Wyong River, and Wallarah Creek.

Methods

Existing Data

Bathymetry

Bathymetric and coastline data from the most recent survey in 1979 were used create depths on a 12.5 m rectangular grid. The bathymetry was integrated with an existing digital elevation model of topography (Figure 19). Higher cross-channel resolution was obtained using a channel-following strained coordinate system for: Wyong River, Ourimbah Creek, and Wallarah River. Hypsometry was determined for various localities of interest.

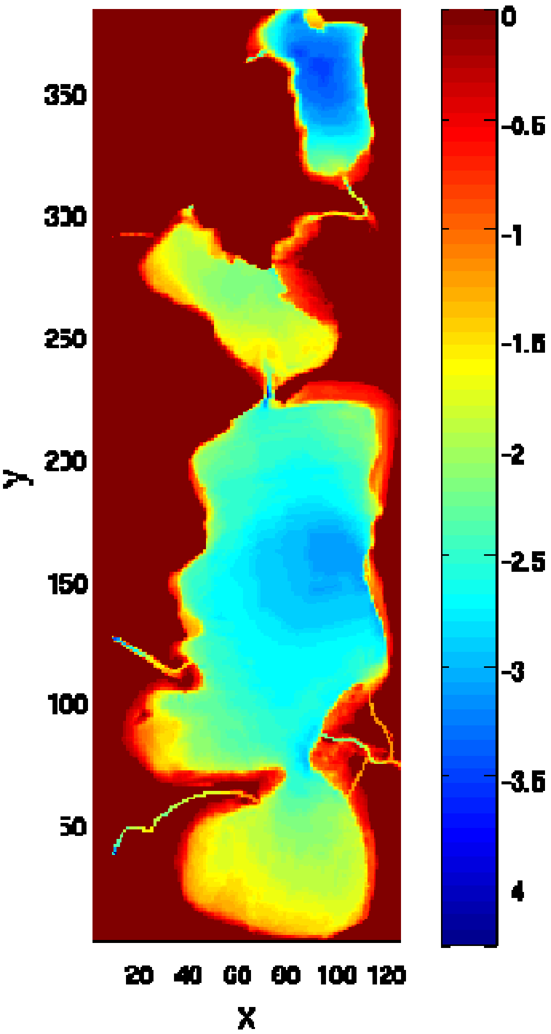


Figure 19 Bathymetry of Tuggerah Lakes and Tributaries

Water Level

Water level measurements have been compiled and analysed to provide an independent estimate of catchment discharge into the head of Wyong River estuary (Sanderson 2009d).

Hydrodynamic model development

The models that have been developed and will be, to some extent, coupled to the Ecological Response Model. They include:

- Box-model for Tuggerah Lakes for quickly calculating properties of the three main basins over long periods (eg for ecological scenario-testing). See Sanderson 2010b for the full report.
- X-Z hydrodynamic model for managing estuarine sections of rivers and narrow channels connecting basins. The along-channel and vertical dimensions are of primary importance in creeks, rivers, and connecting channels. Creeks and rivers are an important buffer between the catchment and lakes when catchment discharge is small or moderate. Larger discharge events flush the creeks as well as directly transport runoff from the catchment into the lakes.
- The X-Z hydrodynamic model has been created and coupled to the box model and 2D (X-Y) model (Sanderson 2010f). The 2D X-Y model is used for obtaining wind-driven currents and redistribution of catchment discharge throughout the main basins.
- A high-resolution 3D model used for case-studies of relatively short-term events. See Sanderson 2009a for the full report.
- A lower resolution 3D model (Tuggerah Lake only) in the horizontal and higher resolution in the vertical has also been developed. This model would include a seagrass parameterization to study interactions of seagrass with wind-driven currents and buoyancy effects.
- A new model for vertical turbulence that is appropriate for application in shallow water that is sometimes stratified by catchment discharge and sometimes well-mixed by wind-stress.
- A Young-Verhagen wind-wave model for running within the X-Y dynamical model to study turbidity and TSS within the major basins.
- A coupled 3D hydrodynamic wind-wave model for calculating bottom stress.

A comparison of the 3D model versus the 2D model to capture the transport of material within Tuggerah Lakes has shown that the 2D model will be adequate to represent this parameter. See Sanderson 2010a for the full report. A summary of justifications are presented below:

- When the water column is not strongly stratified the transport of material by a 3D (xyz) hydrodynamic model of Tuggerah Lakes will be very similar to that calculated by a 2D (xy) hydrodynamic model. The one thing that the 2D model can't resolve directly is the the along-wind shear-diffusion. However, the shear-diffusion can be parameterized.
- Warming heat fluxes can sometimes stabilize the water column under low-wind conditions and this might somewhat modify the overalll transport of material within the basin of a lake. Given that transport will not be great under low-wind conditions, a 2D model will still give a reasonable result.
- Cooling heat fluxes will more strengthen vertical mixing of the water column. This will cause the 3D model to transport material in a way that even more closely corresponds to the transport caused by a 2D model.

An appropriate vertical mixing model has been created. Two cases are considered with very different mixing signatures

- the response to a pressure gradient relating to water column density. The entire water column is accelerated by the pressure gradient but bottom drag retards the water motion at depth. It takes a long time for bottom drag to cause sufficient velocity shear at the density discontinuity and thereby mix the salinity gradient. However, once the mixing of salt begins, it is rapidly mixed to depth and the water column destratifies.

- the response to a wind stress. Only the top layer is accelerated at first. The stable stratification prevents motion at depth, for a time. Early on, salt is entrained into the surface layer. Only later does the surface layer deepen until eventually it extends through the water column.

Once the salt has been mixed throughout the water column, the salinity profiles become quite similar (Sanderson 2009b).

Wind stress calculations have also been carried out. Figure 20 shows an example of fetch for a wind blowing from 345°. Fetch was tabulated at a spatial resolution of 100 m in Tuggerah Lakes and with respect to wind direction at 15° resolution.

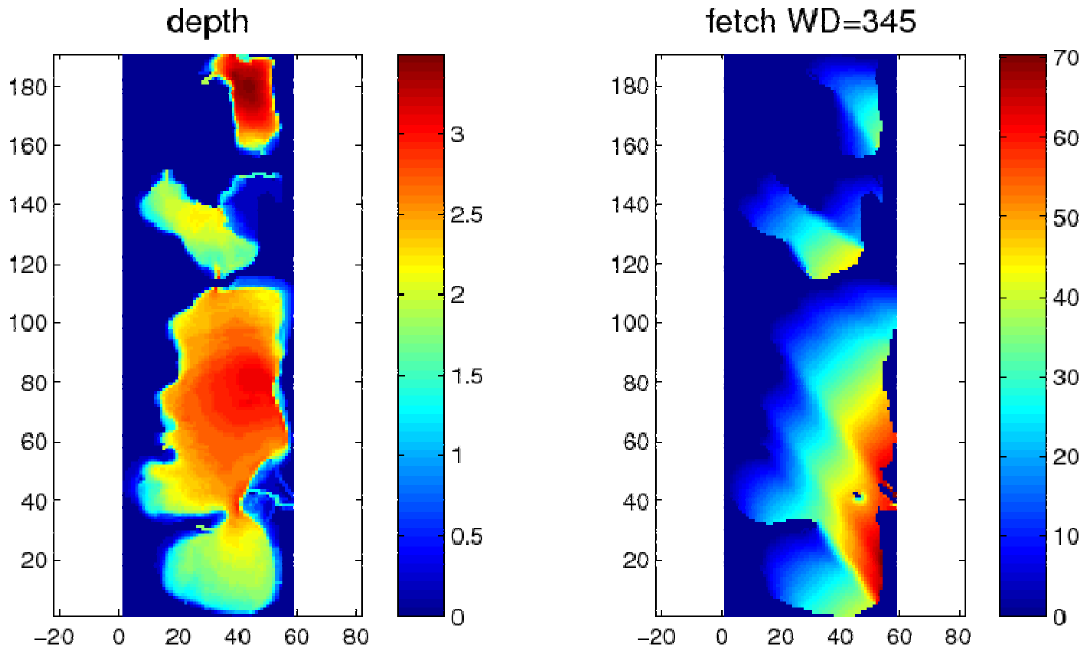


Figure 20 Left: bathymetry of Tuggerah Lakes. Right: fetch for a NNW wind. Distances (including fetch) have been normalized by the gird scale (ie 100 m).

Results

Lake hydrodynamics

Simulations of salinity were used to represent the hydrodynamics of the Tuggerah Lakes system as it is a measurable component which is conserved within the system (ie it remains chemically intact). Salinity is influenced by lake-ocean exchange, lake-lake exchange, catchment discharge, evaporation and direct rainfall. Due to the shallowness of the lakes, wind mixing is effective in preventing vertical stratification in the water column. However, under calm conditions, the lakes can become stratified with catchment flows. The results of the field sampling program support these simulations.
The Entrance conditions change greatly over time. In this version of the model, exchange through The Entrance is a broadly averaged representation using tides and salinity (Sanderson 2010d).

Nutrients and sediment are represented in the hydrodynamic model as conservative tracers moving from the catchment to the lakes. The outputs of the catchment model compared with observed water quality data show that the lakes act as a sink for TN, TP and TSS. Settling and resuspension also play a role in TN and TP concentrations within the lakes (Sanderson 2010c).

Resuspension of bottom sediments has a large impact on water column concentrations of TN and TP due to the frequency of occurrence (Sanderson 2010e).
Munmorah Lake is the deepest of the three lakes which allows more sediments to settle and a reduced resuspension frequency. TN, TP and TSS concentrations show a similar annual cycle to resuspension; higher in the warmer months and lower in the calmer winter months (Sanderson 2010e).

Although Lake Munmorah has a relatively small catchment area, its has high sedimentation. This is likely attributed to the exchange of water and sediments from Budgewoi Lake via pumping by the Power Station (Sanderson 2010e).

Discharge impact

Wyong River, Ourimbah Creek and Wallarah Creek have the largest impact on the lakes in terms of discharge. The hydrodynamic model can represent the spatial impact a particular discharge point has on the receiving waters. Figures 21 to 23 below show the spatial structure of the impact of a concentration of a material from each major tributary averaged over a two month period, 1 September 2009 to 28 October 2009.

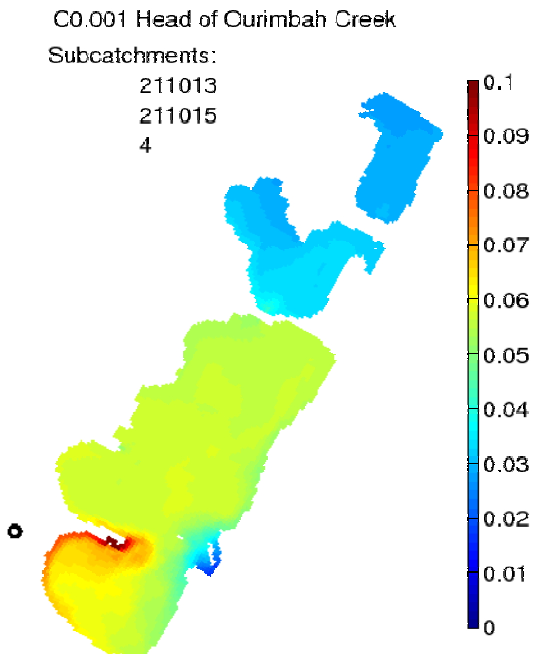


Figure 21 Discharge from subcatchments affecting Ourimbah Creek causes high concentrations close to shore in Chittaway Bay.
Note, the lower concentrations in Budgewoi Lake and Munmorah Lake are, at least in part, an artifact of the brevity of the simulation period.

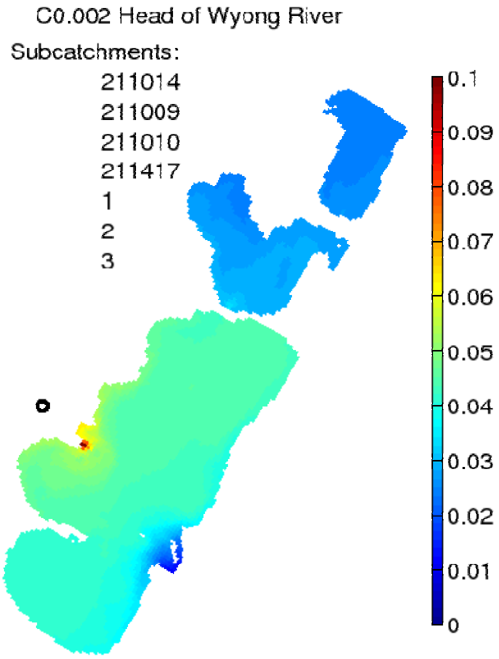


Figure 22 Wyong River discharges to a relatively exposed location within Tuggerah Lake and so highest concentrations are only found very near the mouth of the river.
Note, the lower concentrations in Budgewoi Lake and Munmorah Lake are, at least in part, an artifact of the brevity of the simulation period.

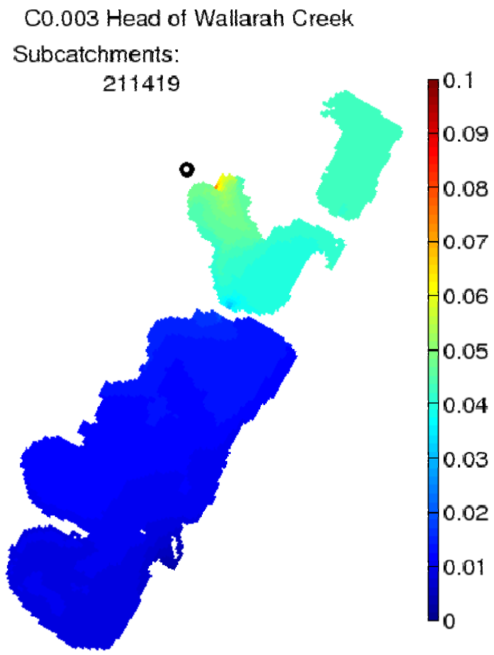


Figure 23 Wallarah Creek discharges to a location near the Power Station canal.
Circulation caused by the Power Station acts to mix material throughout Budgewoi Lake and Munmorah Lake, so highest concentrations are only found very near the mouth of the creek.

Discharge impact from each fringing subcatchment has also been estimated by the hydrodynamic model. While the concentrations of discharge are much lower, the impact within a localised area is high, especially in sheltered bays. The effect of localised discharge impact in the near-shore zone is discussed later. The spatial representation of the impact of each fringing subcatchment on the lakes over a two month period (1 September 2009 to 28 October 2009) can be found in Appendix 2.

Summary of Hydrodynamic Modelling

Preliminary results indicate the following:

- The lakes are well-mixed basins with vertical stratification occurring during relatively calm conditions
- Tuggerah Lakes act as a nutrient and sediment sink with sediment accumulation being greater than removal, with Lake Munmorah having the greatest amount of sedimentation
- Settling and resuspension plays an important role in water column concentrations because resuspension has a higher frequency of occurrence than catchment discharge events
- Discharge points associated with higher discharge (larger subcatchment area) have by far the biggest impact on Tuggerah Lakes. Thus, particular attention should focus upon material discharged from Ourimbah Creek, Wyong Creek and Wallarah Creek
- Localised nearshore areas are impacted as follows:
    1. Chittaway Bay is impacted by discharge from Ourimbah Creek and to a lesser extent by local discharge at Chittaway Bay
    2. The shallow waters in the sheltered embayment near the Golf Course seem to be impacted by local sources
    3. Water at the mouths of Saltwater Creek and Tumbi Creek is somewhat impacted by local discharge
- The work above is centred around concentrations averaged with respect to time. Different results might be obtained if we looked at short-term peak values. The important point to remember is that discharge is very intermittent and there are long periods between discharge events. Material within the lakes can be substantially mixed during those long intervening periods
- Discharge from fringing catchments is more frequent and may remain in the near-shore zone until sufficient mixing occurs. This may result in localised build up of excess nutrients and sediments in these areas.

Ecological Response Modelling

Aims

The Tuggerah Lakes ecosystem response model (ERM) is intended to provide a tool that reproduces the response of key biogeochemical processes at the base of the foodweb in response to catchment pressures. It aims to provide a detailed understanding of system function, and to identify sensitivity / thresholds to pressures. The ERM will be used to assess the likely impacts of management scenarios, and to provide insights into historical trends in the ecology of Tuggerah Lakes.

Scope

The ERM is based on a hybrid mechanistic / empirical approach developed for NSW riverine estuaries. The ERM consists of three main tiers: 1) a detailed biogeochemical model that predicts pelagic and benthic processes on daily to seasonal timescales, 2) a seagrass / wrack model which predicts processes at seasonal timescales; and 3) an empirical risk assessment model that estimates longer term (i.e. decadal) shifts in biological communities (e.g. seagrasses and macroalgae).

The ERM architecture is being adapted to two levels of hydrodynamic model: 1) a 1D approach which considers each lake basin as a single box; and 2) a 2D hydrodynamic resolved at a spatial resolution of 600m. The final choice of model used to test management scenarios will depend on a sensitivity analysis of the two model setups, their ability to reproduce routine monitoring results under the current management scenario, and an assessment of computational cost.

Methods

Overview

The current ERM was developed for the 1-D box model representation of the Tuggerah Lake system, treating each lake basin (Tuggerah, Budgewoi and Munmorah) as separate, well mixed boxes. Inputs and exchanges between lake basins and the ocean have been taken from the finer resolution hydrodynamic models described previously. The bathymetry of each lake basin is included as the total area within depth ranges of 0.1m intervals allowing quantification of light dependent processes. The ERM has been developed to allow either daily or hourly timesteps.

The results discussed in this report are existing scenario simulations, which are limited to the time period of the current catchment export estimations.

Model Layout

Biogeochemical model

This sub-model predicts the growth, death and breakdown of microalgal biomass in the water column and sediments Pelagic and benthic light climate is modelled as a function of incident irradiation, light attenuation and depth. Coupling between pelagic and benthic processes is described dynamically, and varies as a function of light, organic matter supply, hydrodynamic mixing and resuspension. Benthic productivity and nutrient cycling are described in detail, with rates calibrated against extensive field data from estuaries and nearby lakes (e.g. Wallis Lake).

Resuspension model

Due to the importance of wind-driven resuspension and circulation in Tuggerah Lake, these processes are explicitly modelled using a 2D hydrodynamic model coupled to a wind wave model. The current ERM uses estimations of daily average bottom stress for each lake basin to calculate resuspension, and literature values for material-specific settling speeds have been applied as default values. It is anticipated that these values will be updated in the near future with data obtained from a proposed field campaign in Tuggerah Lake.

Seagrass and macroalgae models

The seagrass model predicts the probability distribution of change in seagrass coverage at fortnightly timesteps based on the integration of light climate, salinity, temperature, organic matter deposition, nutrient concentrations, and bed stress over this timeframe. The model is based on measurements of seagrass productivity in NSW south coast lagoons made by DECCW. The production of seagrass wrack is based on measured rates of biomass loss during the same study, and is based on productivity and the integration of a suite of stress factors (light climate, temperature, salinity) over a 1 month timeframe. The fate of wrack is considered using a standalone model which takes wrack production rates and precomputed flows from a 3D hydrodynamic model and predicts the likely distribution of wrack along shorelines and sediments.

Long term impacts

Decadal shifts in macroalgae and seagrass will be assessed using an empirical risk assessment model. This is based on matching rainfall, hindcast salinity and urban development patterns with the presence / absence of macrophytes in the lake (based on available distribution maps, anecdotal evidence and aerial photo interpretation). The influence of episodic drivers (such as major floods) will be considered, as will the influence of positive feedbacks (e.g. the build up of organic matter content in sediments colonised by macrophtyes).

Results

Rainfall and catchment inputs

The baseline ERM simulation covers the period 5/5/09 to 31/10/09 based on the availability of preliminary catchment model results and field sampling data. This period encompasses the annual wet season and the progression into an extended dry period from late winter to spring (Figure 24). The wet season was characterised by a succession of rainfall events in late autumn – early winter which caused a depression of salinity in the Tuggerah Lakes to approximately 25 PSU, after which there was a gradual recovery to a salinity of 32 PSU by October (Figure 24). Two rainfall events during October 2009 caused a slight depression of salinity to approximately 30 PSU. The ERM predicted the broad trends in salinity variation in all three lakes, however it slightly underestimated the magnitude of salinity depression in Budgewoi Lake and Lake Munmorah following rainfall events (Figure 25).

Water level in the lakes increased by approximately 10cm in response to freshwater inputs, and subsequently decreased steadily by about 35 cm throughout the dry period as salinity increased (Figure 24). The model indicates that water levels in the three lakes are closely coupled through time. Average water depth during the existing scenario simulation was greatest in Lake Munmorah (mean = 2.52m), followed by Tuggerah Lake (mean = 2.14m), and Lake Budgewoi (mean = 1.45m), reflecting the differences in bathymetry between the basins.

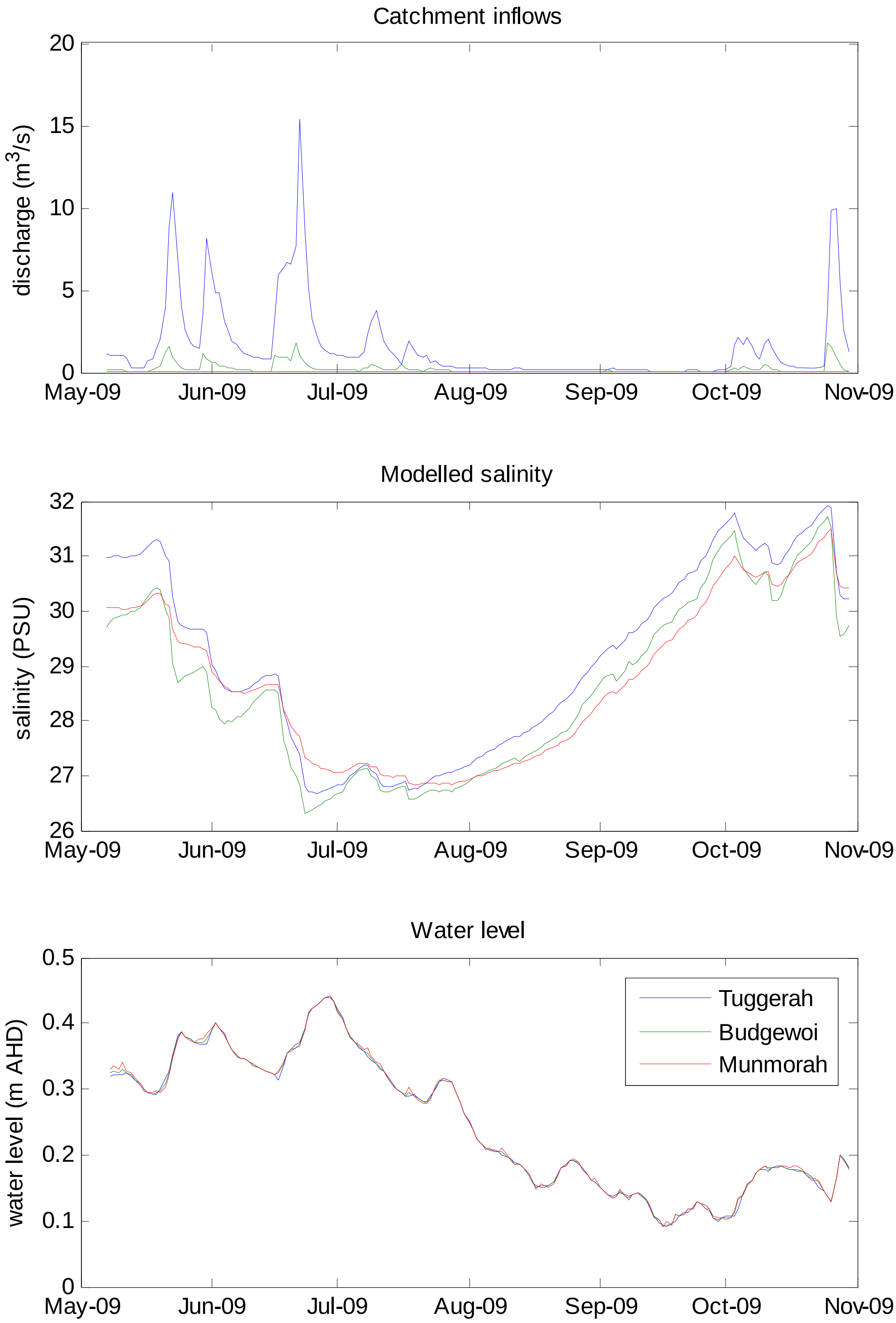


Figure 24 Timeseries plots of freshwater discharge (top), salinity (middle) and water level (bottom).

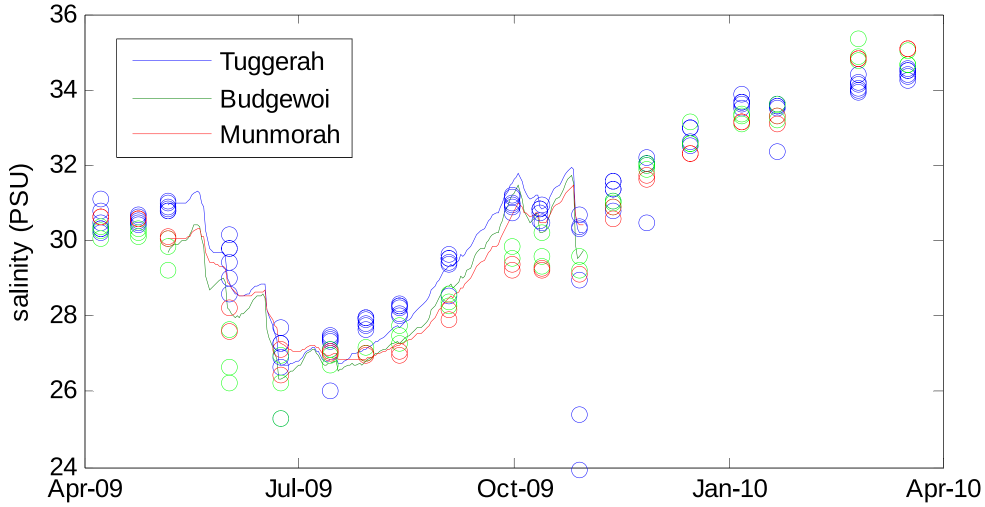


Figure 25 Comparison of modelled (line) and observed (circles) salinity in the Tuggerah Lakes system.

Total Suspended Solids (TSS)

The ERM results confirm that seasonal variation in TSS_mineral (e.g. soil particles) and particulate nutrient concentrations in all three lake basins is primarily driven by wind / wave resuspension. Due to limited exchange at the ocean entrance, the primary fate for particulate material delivered from the catchment is deposition in the lake basins, followed by repeated cycles of resuspension and settling. This dominant physical mechanism has important implications for light climate and various aspects of the lakes biogeochemistry which are discussed in more detail below.

In general, suspended particulate material concentrations follow the seasonal pattern in predominant wind strengths and direction, being greatest during the summer-autumn period when the occurrence of strong northeast and southeasterly events is highest, and greatly diminishing during winter when winds tend to be lighter and from the west. Short term increases in TSS_mineral and particulate nutrient concentrations are also observed immediately following large freshwater inputs, however these are relatively short lived due to the settling of material in the lake basins. Some of the observed spatial variation in TSS within sample runs was not captured by the ERM due to the non-spatial representation of the resuspension term within the model (Figure 26).

TSS_organic (e.g. algae and detritus) concentrations in the lakes are less clearly coupled to resuspension/settling dynamics than TSS_mineral fractions, implicating internal biological processes as a partial control. There was a weak positive relationship between chlorophyll and TSS_organic concentrations (measured data) indicating that phytoplankton cells and potentially phyto-detritus made partial contributions to the TSS_organic faction. The ERM reproduces TSS_organic concentrations within the range of observations, however some of the shorter term variability (i.e. monthly) is not captured by the model (Figure 26). The reasons for this are unclear at this point. Sensitivity analyses show that this variation is unlikely to be due to resuspension/settling dynamics, therefore it is more likely due to internal biological processes. This will be further investigated in the ongoing model development.

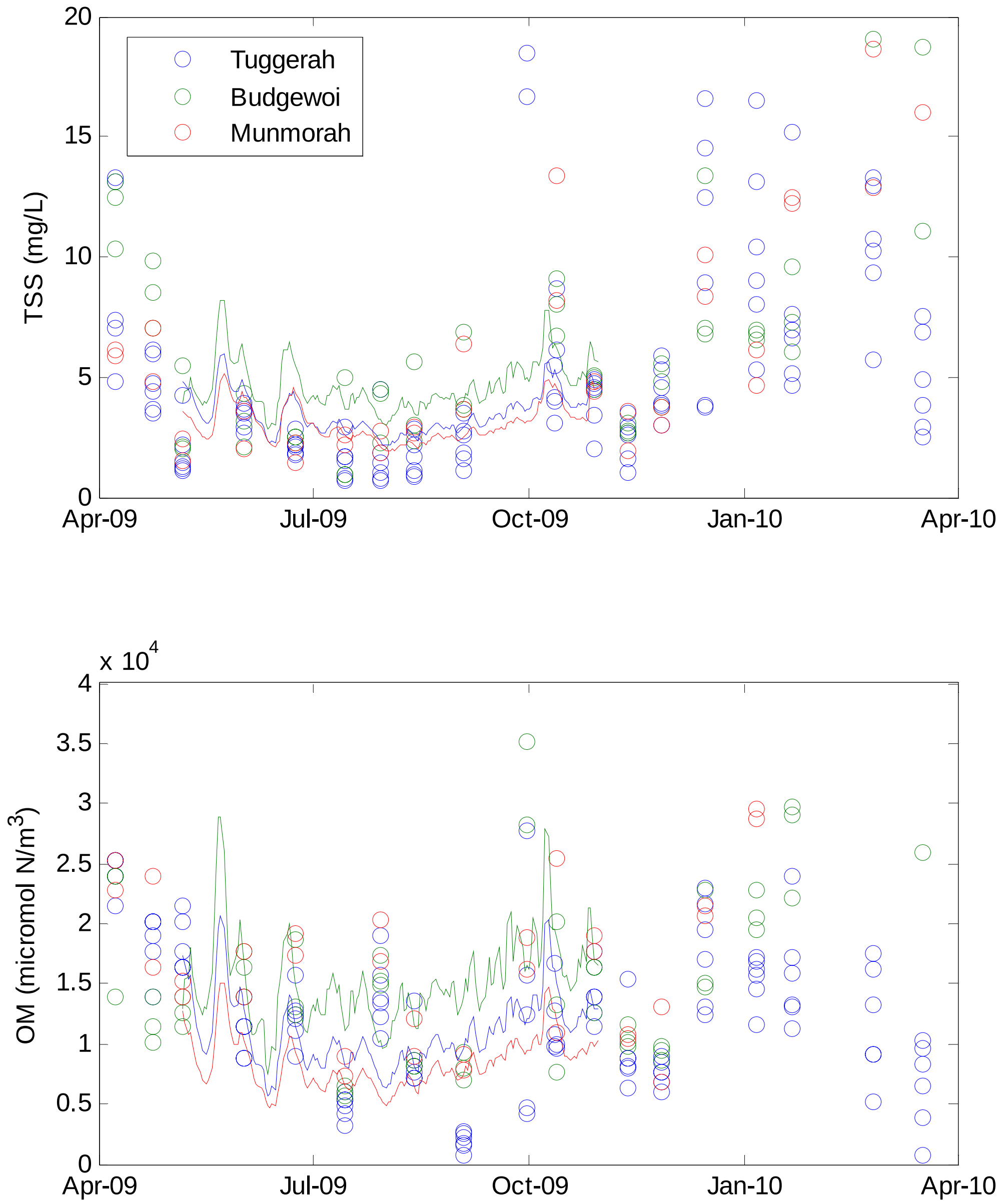


Figure 26 Comparison of modelled (line) and observed (circles) TSS_mineral (top) and TSS_organic (bottom) in the Tuggerah Lakes system.
Note that TSS_organic has been converted to nitrogen equivalents for inclusion in the ERM as a dynamic stock.

Nutrients

Total nitrogen concentrations in the Tuggerah Lakes comprise three major fractions: dissolved inorganic nitrogen (DIN); dissolved organic nitrogen (DON); and total particulate nitrogen (TPN). The relative contribution of these different fractions varies as a function of flow, catchment type (e.g. upland forest, rural, swamp), and instream biogeochemical processing. In general, DIN (itself comprising the sum of ammonium [NH_4^+], nitrite [NO_3^-] and nitrate [NO_2^-]) is regarded the most bio-available fraction and generally limiting primary production in coastal and marine waters. DON comprises various compounds depending on its source, however the dominant paradigm has regarded DON as largely refractory (i.e. unavailable for uptake by plants and microbes). TPN comprises mostly biogenic material such as phytoplankton cells and phyto-detritus, and may be regarded as bio-available upon remineralisation by microbial activity.

Total phosphorus concentrations also comprises three major fractions: dissolved inorganic phosphorus (DIP); dissolved organic phosphorus (DOP); and total particulate phosphorus (TPP). The bio-availability of these fractions is generally regarded to be similar to nitrogen. Phosphorus is widely held to be of secondary importance as a limiting nutrient for primary productivity in coastal and marine waters, however this paradigm is being challenged in certain cases where N fixation by organisms such as cyanobacteria may occur. At this stage phosphorus has only been included as a passive tracer in the Tuggerah Lakes ERM (i.e. is subject only to physical transport and resuspension/settling and not included in biological cycling). Work is ongoing to upgrade the ERM to include phosphorus in biological cycles.

Observations of nutrient concentrations across the catchment-weir pool-estuarine creek continuum for the major catchment inputs show that there is significant attenuation and transformation of the catchment nutrient load as it passes into the lake systems (Figure 27). No attempt has been made to model processes along this continuum, rather estimates of total nutrient export from catchment models have been multiplied by appropriate factors (based on observed DIN:TN, TPN:TN, and DIP:TP ratios in the estuarine creeks) to provide valid estimates of dissolved inorganic and particulate nutrient inputs to the lake system.

Observations of TN and its constituent parts in Tuggerah Lakes are presented in Figure 28. The ERM results indicate that TN concentrations are also closely controlled by resuspension/settling dynamics and follow similar seasonal trends observed and modelled for TSS. The ERM reproduces TN concentrations within the range of observations for the Tuggerah and Budgewoi lake basins, but slightly underestimates concentrations in Lake Munmorah most likely due to the higher DON fraction in this lake. As a dissolved constituent, DON is prone to concentration increases arising from resuspension of porewaters, however it is obviously unaffected by settling. Work is ongoing to further refine the ERM so that it tracks only TPN.

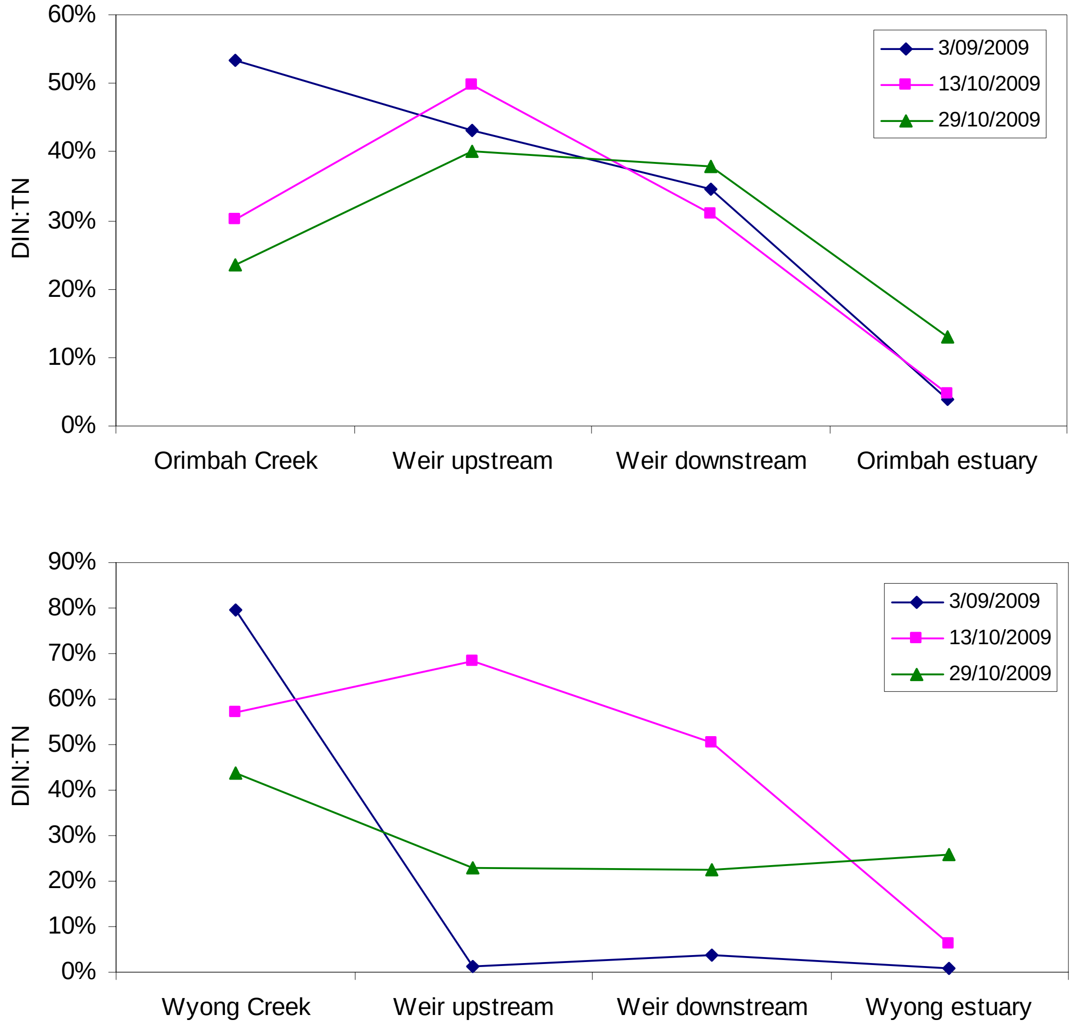


Figure 27 The DIN:TN fraction of water quality samples collected across the catchment-weir pool-estuarine creek continuum in Ourimbah and Wyong creeks during the current study.

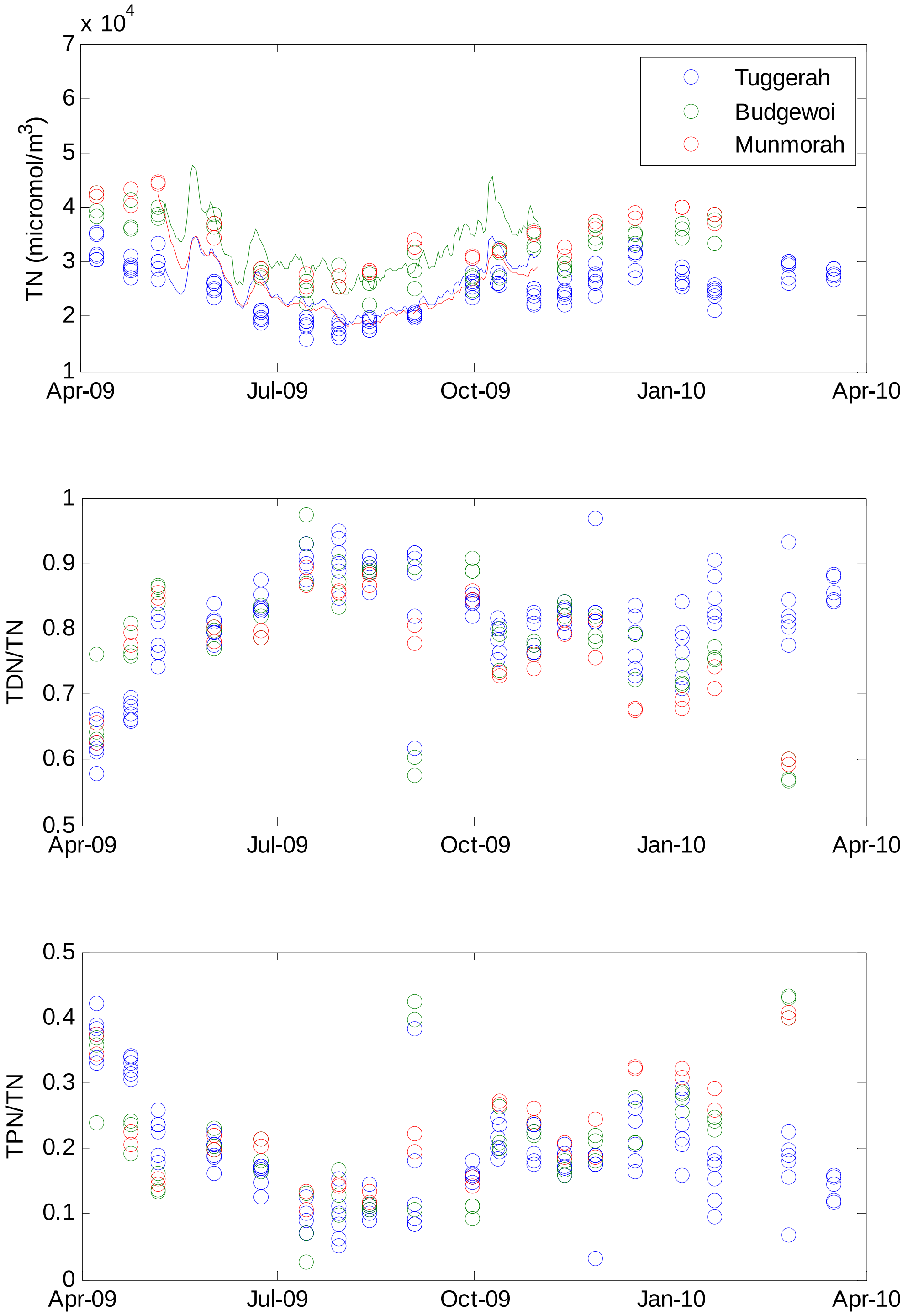


Figure 28 Comparison of modelled (line) and observed (circles) total nitrogen in the Tuggerah Lakes system (top).
Also shown are the relative contributions of total particulate (TPN) and total dissolved (TDN) fractions to the total nitrogen pool over time.

Light climate

The light climate (defined here as the daily average quanta of photosynthetically active radiation [PAR] in the water column or reaching the sediment surface) is a critical driver of aquatic ecosystem processes. The light climate determines the rate of primary productivity by micro and macroalgae in the water column and sediments. Light climate is determined by the attenuation of PAR with depth through the water column, which is due to particulate and dissolved constituents in the water. The ERM explicitly models light climate as a function of daily irradiance at the water surface and attenuation due to TSS, phytoplankton, and coloured dissolved organic matter. Routine water quality data collected as part of this study were analysed to determine the light attenuation properties of different water quality constituents in Tuggerah Lakes (DECCW 2010).

Light attenuation (Kd) in Tuggerah Lakes broadly follows the seasonal trends in suspended particulate material, reflecting the controlling influences of these materials. The ERM reproduces Kd within the range of observations (Figure 29), with the exception of a minority of observations where TSS was significantly higher than model estimations (see discussion above for details).

Due to the predominantly shallow nature of the lakes, light was not generally limiting to pelagic productivity under average incident light conditions (Figures 29 and 30). However, extended periods of heavy cloud significantly increase light limitation in both the pelagic and benthic zones of the lake. It is likely light limitation during the wet season (when cloud cover is relatively increased) will be greater than indicated by the initial period of the simulation shown in Figure 30. The impacts of cloud induced light limitation have significant implications for ecosystem function which are discussed in following sections.

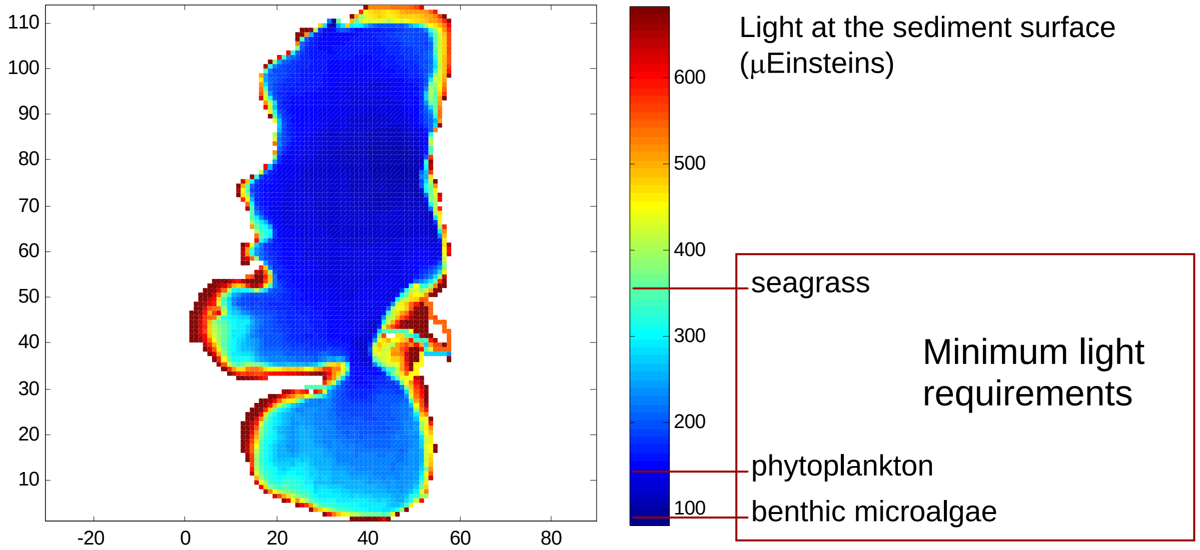


Figure 29 Modelled distribution of benthic light climate in Tuggerah Lake (mean for April to October 2009).
These results indicate that light was not limiting for phytoplankton and benthic microalgae, while seagrass was limited to the fringing sediments.

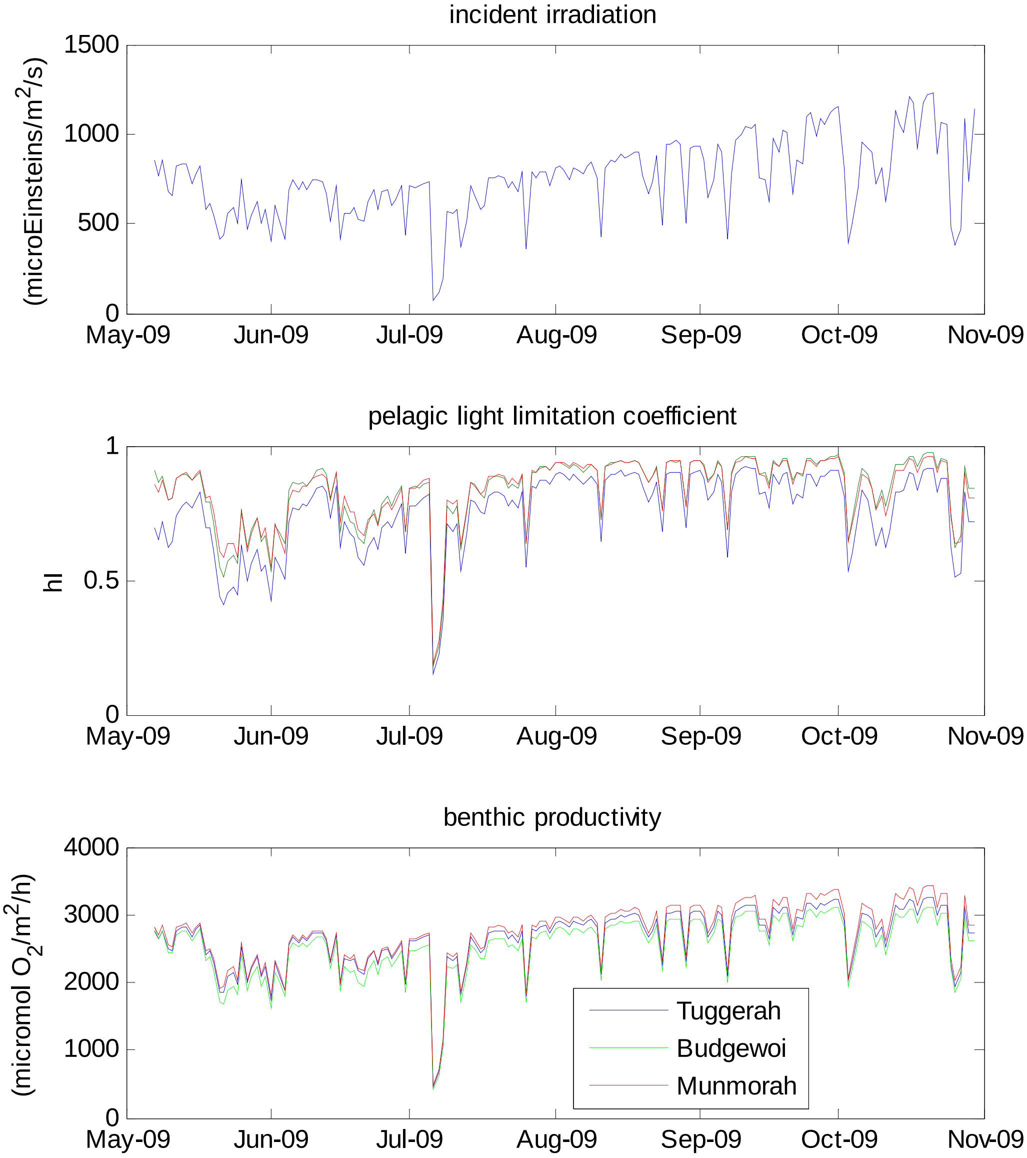


Figure 30 Timeseries plots of incident irradiation (top), pelagic light limitation coefficient (hl; middle) and benthic productivity (bottom).
The hl coefficient is derived from the average light climate in the water column (based on incident irradiation and attenuation). An hl coefficient = 1 is not limiting.

Phytoplankton, benthic microalgae and dissolved inorganic nutrients

Phytoplankton and benthic microalgae (BMA) represent two of the major primary producers at the base of most aquatic foodwebs. The excessive growth of phytoplankton in aquatic systems represents one of the most immediate and obvious impacts of eutrophication arising from nutrient pollution. Impacts include hypoxia (low dissolved oxygen), harmful algal blooms, and loss of benthic microalgae, seagrass and macrophyte beds due to shading. An understanding of the controls over phytoplankton growth is central to prioritising catchment management investments.

Resuspension of benthic microalgae

Chlorophyll-*a* concentrations in Tuggerah Lakes followed the same seasonal trends observed for all suspended particulate material indicating that resuspension of microalgal cells from the sediments is a primary control over phytoplankton populations in the lakes (Figure 31). The benthic stock of viable microalgal cells was maintained in the model by BMA production (with resuspension set to zero once this stock was exhausted). Hence the maintenance of a good light climate on the sediments was crucial to maintaining the observed trends in pelagic chlorophyll-*a*. Due to the predominantly shallow nature of the lakes, BMA production was a significant contribution to overall system production throughout the simulation period, therefore the BMA stock was rarely depleted. BMA stocks tended to increase through the model simulation due to the improvement in light climate (Figure 32).

The ERM results indicate that grazing of phytoplankton by microzooplankton plays a primary role in controlling phytoplankton (chlorophyll-*a*) concentrations once cells are resuspended. This has been confirmed by field measurements of primary productivity and grazing which showed extremely close coupling between production and grazing.

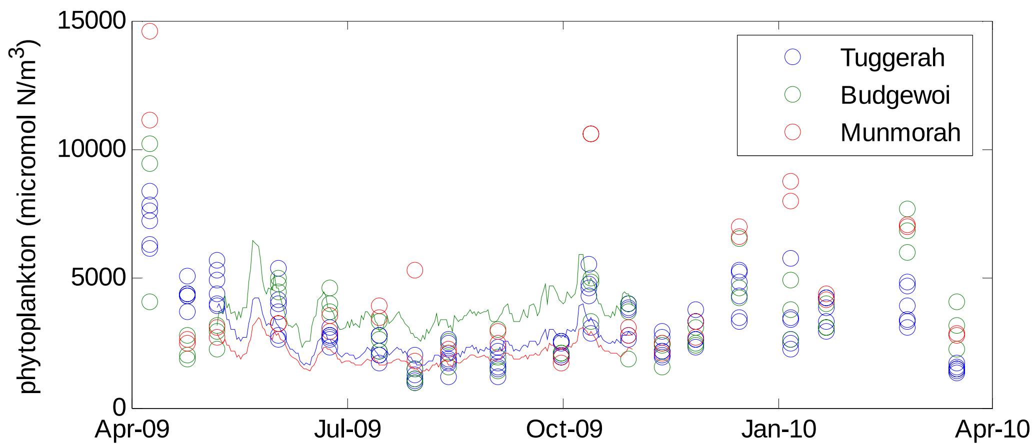


Figure 31 Comparison of modelled (line) and observed (circles) phytoplankton biomass.

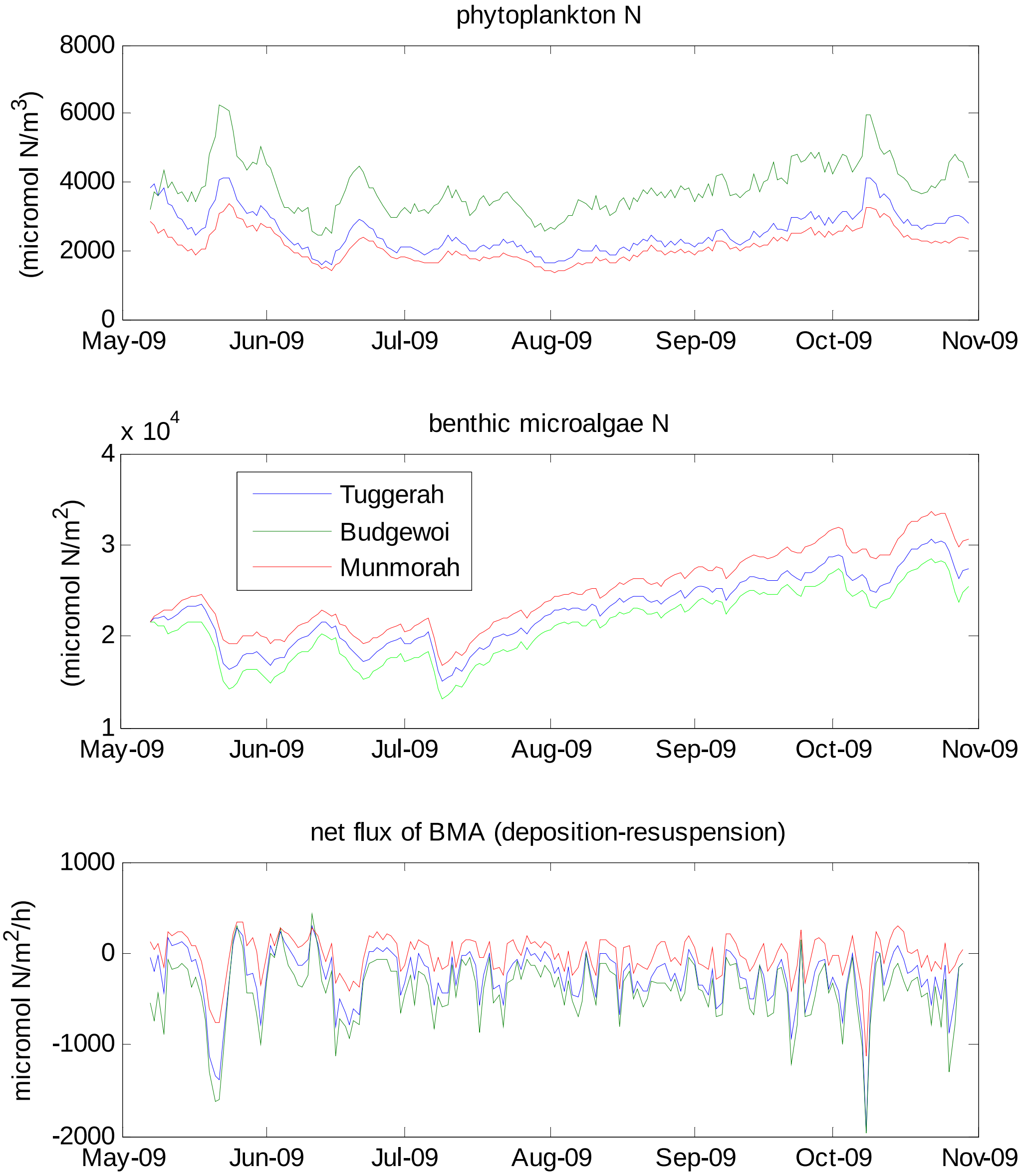


Figure 32 ERM timeseries plots of phytoplankton_N, BMA_N, and the net resuspension flux of BMA_N due to wind wave bottom stress (negative = net loss to the pelagic zone and positive = net deposition).

Due to a combination of difference in mean depth and circulation induced by the operation of the power station there is a net transport of material from Lake Budgewoi to Lake Munmorah.

Nutrient recycling

The ERM indicated that inputs of dissolved inorganic nitrogen (DIN) from the catchment were insufficient to maintain the observed phytoplankton biomass and productivity in the lakes. As such, internal recycling of nutrients via the remineralisation of organic matter in the sediments and pelagic zone was the principal DIN source for primary productivity. BMA played an important role in regulating the flux of remineralised DIN from the sediments. Due to high rates of BMA productivity DIN flux from the sediments is reduced to zero (or uptake) during the light, and only replenishes pelagic stocks during the night (Figure 33). This mechanism effectively maintained nutrient limitation in the pelagic zone throughout the simulation period.

Net benthic fluxes of DIN to the pelagic zone were important throughout the simulation period, but tended to be greatest during the wet season. As the light climate improved during the latter part of the simulation, the relative influence of BMA as a temporary nutrient sink increased, resulting in the net uptake of DIN from the pelagic zone. The dramatic impact on benthic DIN fluxes resulting from variation in light climate due to clouds is clearly illustrated in Figure 33. Sediments can quickly revert to a source of DIN to the pelagic zone during cloudy periods, and it is likely that this may explain some of the higher DIN concentrations measured in Lake Munmorah.

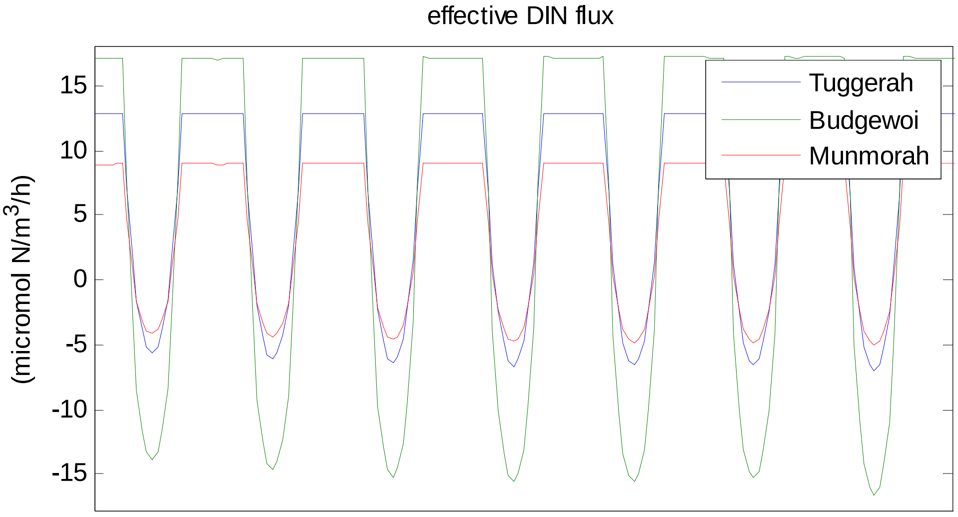


Figure 33 Daily variation in effective benthic DIN flux over a seven day period from the existing scenario simulation.
Fluxes switch to uptake from the pelagic zone (i.e. become negative) in response to productivity by BMA. Note: 'effective DIN flux' refers to the change in pelagic DIN concentrations due to benthic DIN flux.

<u>Denitrification</u>

Denitrification refers to the conversion of bio-available nitrate to atmospheric N_2 gas during the breakdown of organic matter in the sediments by anaerobic bacteria. Denitrification represents one of the major sinks of bio-available nitrogen in aquatic systems and can help to alleviate the impacts of nutrient pollution in coastal environments.

Denitrification represented the major sink of bio-available N in the lake system, and is responsible for the steady decline in sediment nitrogen throughout the simulation period (Figure 34). Note that the different rates of decline in N remineralisation shown in Figure 34 reflect the winnowing and net transport of material from Lake Budgewoi to Lake Munmorah. As such, the rate shown for Tuggerah Lake more accurately reflects the net decline in material due to denitrification alone. The current simulation run ends with the dry season, hence it would be expected that benthic stocks of organic matter (and nutrients) would be replenished during the wet season. Given the inter-annual variability in rainfall along the eastern Australian coastline there is likely to be annual to decadal trends in organic matter supply to the Tuggerah Lakes system. This will be further assessed in subsequent longer term simulations.

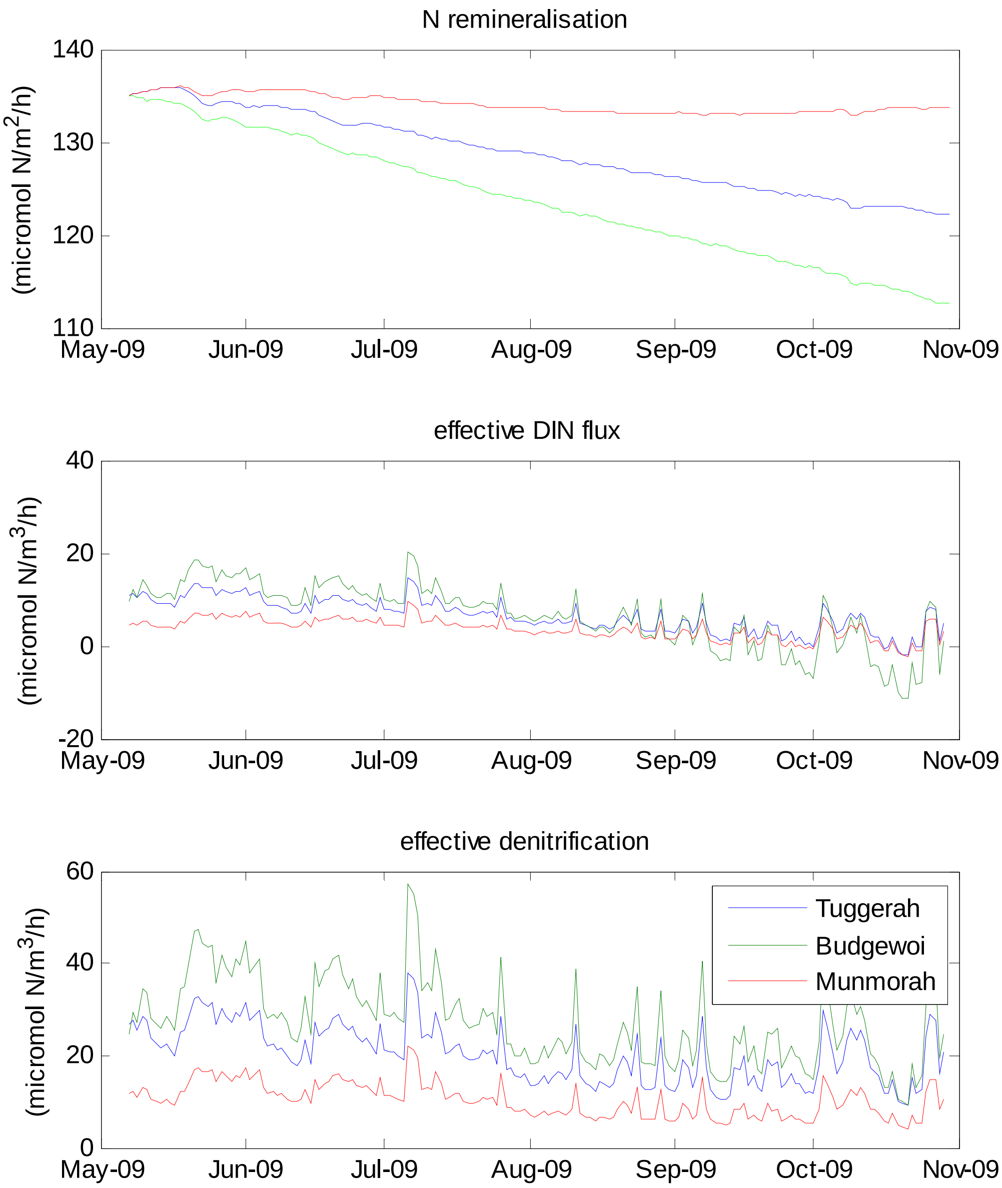


Figure 34 Rates of N mineralisation in the three lakes (top) and the relative impact of benthic DIN fluxes (=effective DIN fluxes: middle plot) on pelagic DIN concentrations.
The differences in effective fluxes are primarily controlled by the surface area to volume ratio (i.e. mean depth) of the lake basins. While denitrification is a nitrogen sink and does not directly influence pelagic N concentrations, it has been scaled in a similar way (bottom plot) to show the relative importance of this pathway in the Tuggerah Lakes system.

The results of the ERM simulations highlight the significant negative interactions between DIN assimilation by BMA (Figure 35). This interaction reflects to main mechanisms: 1) the competition between denitrifiers and BMA for DIN substrates, and 2) the reduction in potential denitrification sites due to oxygen production by BMA. Within the ERM results this is reflected by close mirroring of the two processes over time, and their opposing trends with respect to depth (and therefore light availability).

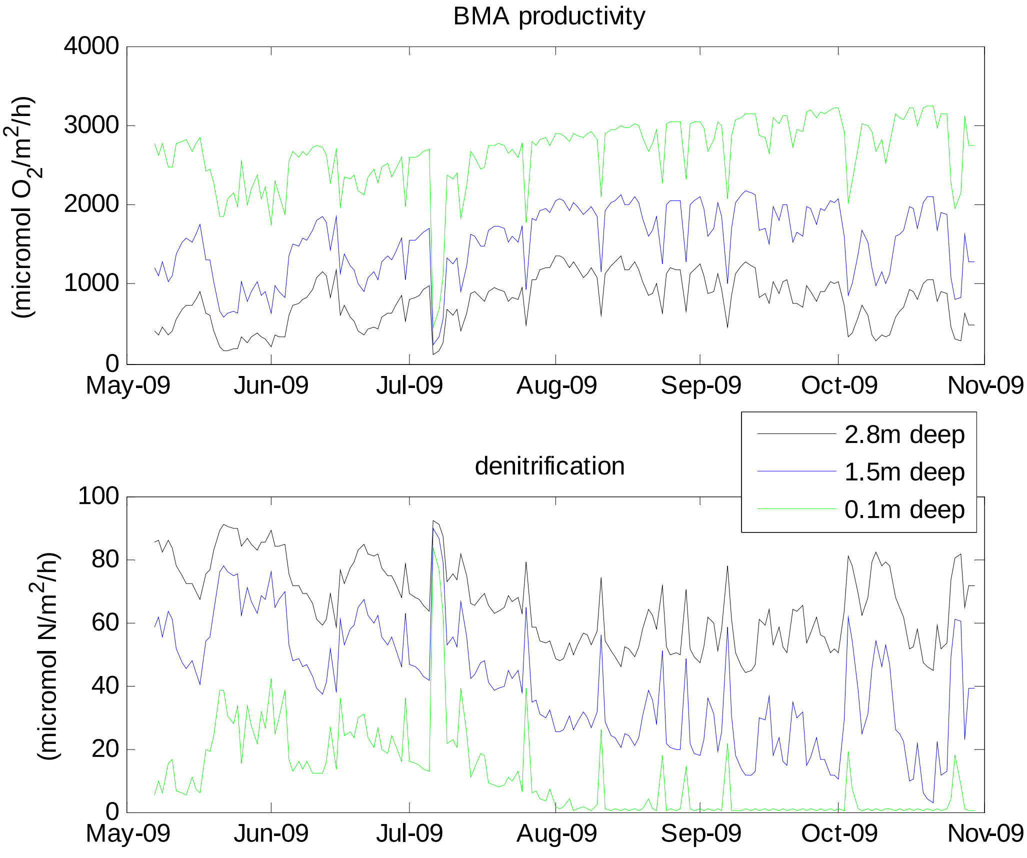


Figure 35 Timeseries traces of BMA productivity and denitrification at three depths in Tuggerah Lake.

Limitations and further work

The biogeochemical module of the ERM will undergo continual refinement throughout the duration of the project. Specific areas of improvement include:

1) Inclusion of phosphorus in the biogeochemical model.
2) Calibration / verification of model performance against the full year of observations from the routine monitoring program once updated catchment inputs are available.
3) Updating of resuspension coefficients and settling speeds for phytoplankton and TSS using field measurements.
4) Full integration of the ERM with a 2-D hydrodynamic model.
5) The current scenario simulation represents only a limited window of time and hydrological conditions. Upon completion of catchment models we anticipate carrying out much longer simulations across a range of climatic extremes (e.g. El Nino / La Nina cycles) to investigate inter-annual trends in ecosystem responses and the impacts of wet, median and dry years.

Net Ecosystem Metabolism (NEM)

Background

Net ecosystem metabolism provides an estimation of whether an ecosystem is a net consumer or producer of organic matter. NEM is defined as the sum of organic matter production via photosynthesis in the pelagic and benthic zones minus the sum of organic matter breakdown in these zones. A positive NEM is termed net autotrophic (producer), while a negative NEM is termed net heterotrophic (consumer). It is also useful to calculate NEM in the pelagic and benthic zones in isolation, and also to consider the pelagic/benthic productivity ratio (i.e. the ratio of photosynthetic production in the pelagic and benthic zones). NEM is important for determining ecosystem function (e.g. oxygen status, nutrient cycling), and specifically shapes the nature of foodwebs (ultimately impacting on the species diversity and abundance of higher order commercial and recreational fish).

NEM in Tuggerah Lakes

The ERM results for Tuggerah Lakes indicate that all three lake systems are highly net autotrophic (Figure 36), with the autotrophic productivity sustained by the internal recycling of nutrients between the pelagic and benthic zones. The different levels of NEM between the lake basins largely reflects their relative sizes, however results do indicate that Lake Munmorah is more heterotrophic per unit area than the other basins due to the net transport of organic material to Lake Munmorah sediments. The depression in NEM shown for Tuggerah Lake during the June to August period reflects the increase in heterotrophic breakdown in the sediments as relatively larger catchment inputs of organic material to this basin are processed. This trend is also influenced by reduced benthic light climate and hence benthic productivity.

Pelagic/benthic productivity ratios

The relative importance of primary production in the pelagic and benthic zones to overall NEM is compared as the pelagic/benthic productivity ratio in Figure 36. Pelagic productivity dominates autotrophic carbon fixation in all lake basins throughout the simulation period. The predominance of pelagic productivity is more pronounced during the wet season when nutrient and organic matter inputs are greatest and benthic light climate is reduced due to greater attenuation. The relative influence of benthic productivity increases into the dry season as catchment inputs and resuspension of BMA diminish, and benthic light climate improves.

Implications of NEM in Tuggerah Lakes

The ERM results for NEM in Tuggerah Lakes indicate a highly productive system, with autotrophic production potentially supporting a diverse foodweb. The results suggest that pelagic foodchains are important in this system, although it is unclear at this stage how much trophic transfer of energy occurs past the microzooplankton level (i.e. is passed up the foodchain to higher order fish). The highly autotrophic NEM indicates that the Tuggerah Lake system was not sensitive to hypoxia due to excessive organic matter breakdown during the current scenario simulation.

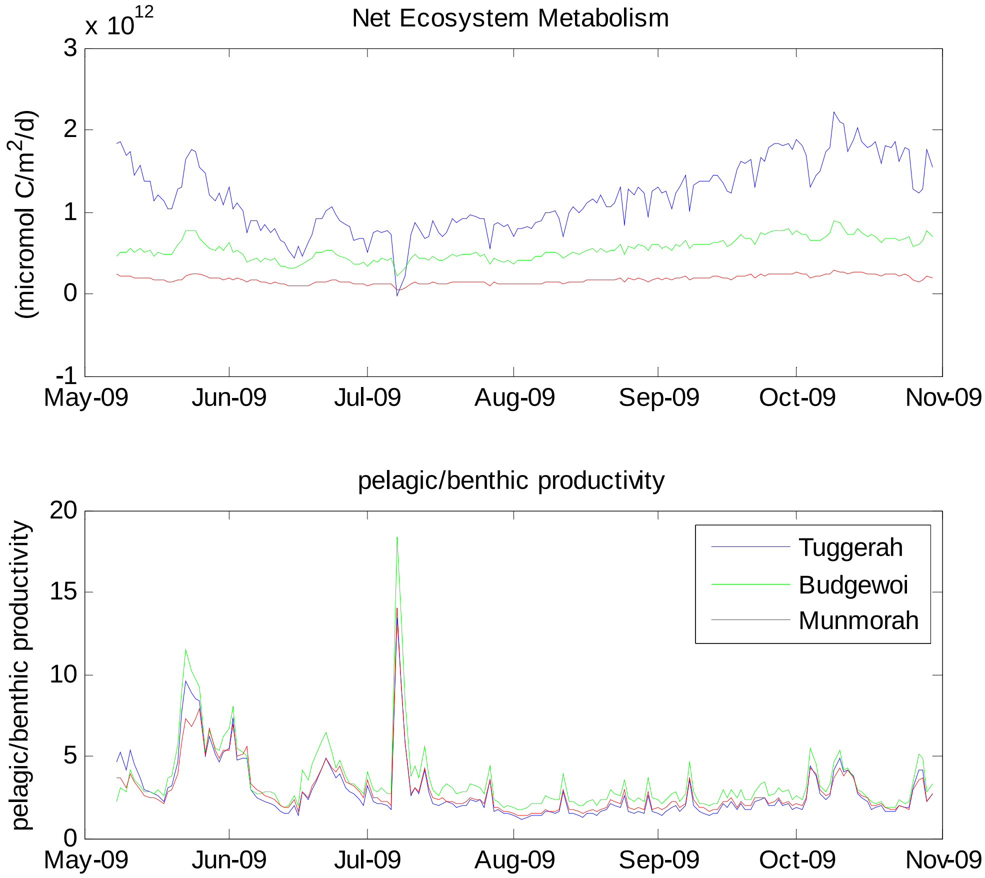


Figure 36 Estimations of total NEM for the three Tuggerah Lake basins (top) during the simulation period.
The relative contribution of pelagic and benthic primary productivity (bottom) shows a predominance of pelagic productivity (i.e. pelagic/benthic productivity >1) during the wet season, progressing to a relative increase in benthic productivity during the dry season as light climate improves and the pelagic zone becomes nutrient limited.

<u>Limitations and Further work</u>

The current ERM setup does not include feedbacks from seagrass and macroalgae to NEM calculations, therefore the current results should be regarded as representing microalgal process only. We are currently working on including these feedbacks to quantify the contributions of seagrass, seagrass rack and macroalgae to the organic matter balance of the lake systems. It is anticipated that results will vary significantly during extended wet year cycles, and with significant implications for seagrass health and macroalgal abundance.

Seagrass and macroalgae

<u>Observed trends in seagrass distribution</u>

Seagrass surveys from 1963-2005 were analysed in the context of determining their distributions relative to bathymetry (Figure 37, 38 and 39). Trends show a general decline in the overall coverage of Zostera (*Zostera capricornii*) and Ruppia (*Ruppia megacarpa*) in Tuggerah Lakes, and a significant increase in the coverage of Halophila (*Halophila Ovalis*) (see Appendix 1 for data sources). There has been progressive shoreward migration of all seagrass species (i.e. reduction in depth range). The significant reduction in depth range for seagrass suggests that there has been an increase in turbidity (i.e. reduction in water clarity) in Tuggerah Lakes over the past 50 years. However, available data (1973 – 1974 and 1990 – present) do not support this hypothesis, and is likely that other mechanisms may be more important. Possible alternative mechanisms are discussed in more detail in following sections of this report.

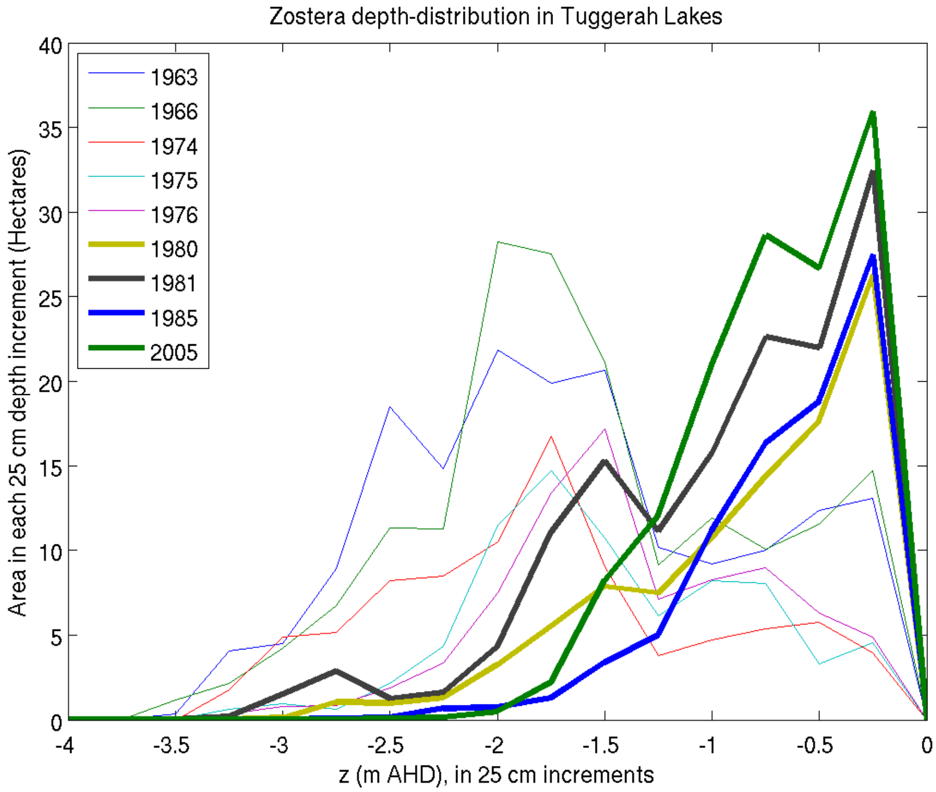


Figure 37 Area of Zostera at 0 - 4 m depth within Tuggerah Lake from 1963 – 2005

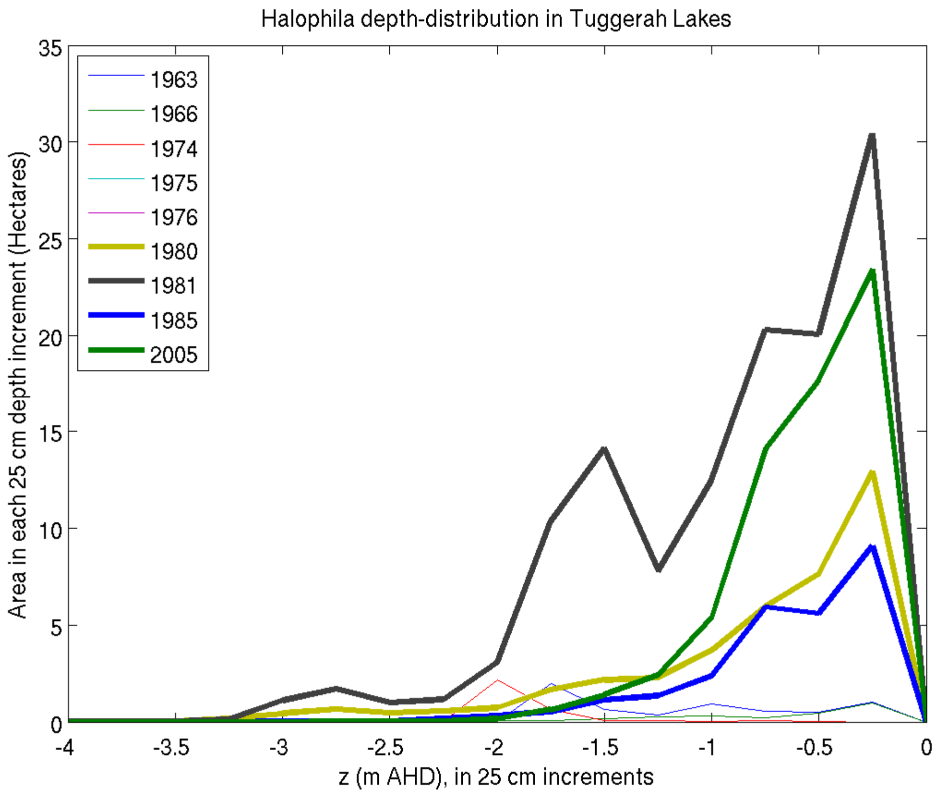


Figure 38 Area of Halophilia at 0 - 4 m depth within Tuggerah Lake from 1963 – 2005.

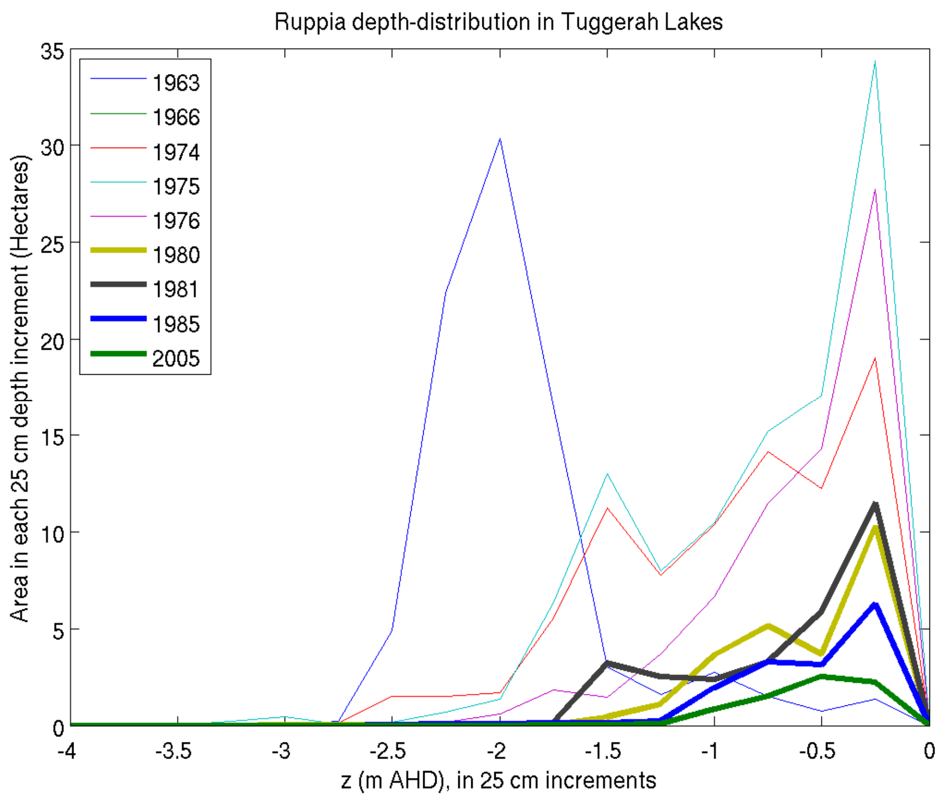


Figure 39 Area of Ruppia at 0 - 4 m depth within Tuggerah Lake from 1963 – 2005.

Hydrodynamic impacts of seagrass

A hydrodynamic analysis was undertaken for seagrass-current interactions. The full report can be found within Sanderson 2009c. This analysis indicates:

1) Emergent seagrass may reduce the transmission of wind stress to the water column.
2) Emergent seagrass can reduce the water level setup/down associated with wind stress.
3) Seagrass prevents resuspension of benthic sediments by hampering bottom and surface currents

Prediction model for seagrass and macroalgal distribution

Due to limitations in the understanding of processes determining the health and abundance of seagrasses it is extremely difficult to construct realistic mechanistic models of seagrass growth. Instead we have opted to develop a probability model which will predict the likely trajectory of seagrass response to more easily predicted variables known to influence seagrass distribution. A probability model for the prediction of seagrass distribution has been developed for *Zostera capricornii* as a post processor for outputs from the hydrodynamic, wrack transport and ecosystem response models (Figure 40).

The seagrass model predicts the probability of seagrass increase/decline in a given area (100m X 100m grid cell) as a function of fortnightly-integrated values for key drivers including: light climate, substrate stability (i.e. bottom stress due to wave and current energy), salinity, nutrient concentrations, temperature and sediment organic matter content. An impact weighting scale has been developed for each of the drivers and is currently being fine-tuned using existing data on seagrass distributions in NSW, and using expert opinion on critical thresholds. Information was collected at a special workshop on seagrass processes convened by DECCW in March of this year. The workshop was attended by leaders in seagrass research from across Australia. A working conceptual draft of the Tuggerah Lakes seagrass probability model coded in Microsoft Excel is provided as supplementary material to this report.

The macroalgae model is constructed in the same way as the seagrass model, with impact weighting scales amended to reflect macroalgae specific responses. As seagrass and macroalgae compete for similar niches within Tuggerah Lakes the outputs of the seagrass and macroalgae models will be passed to a competition model to allow the assessment of competitive advantage between the two macrophytes.

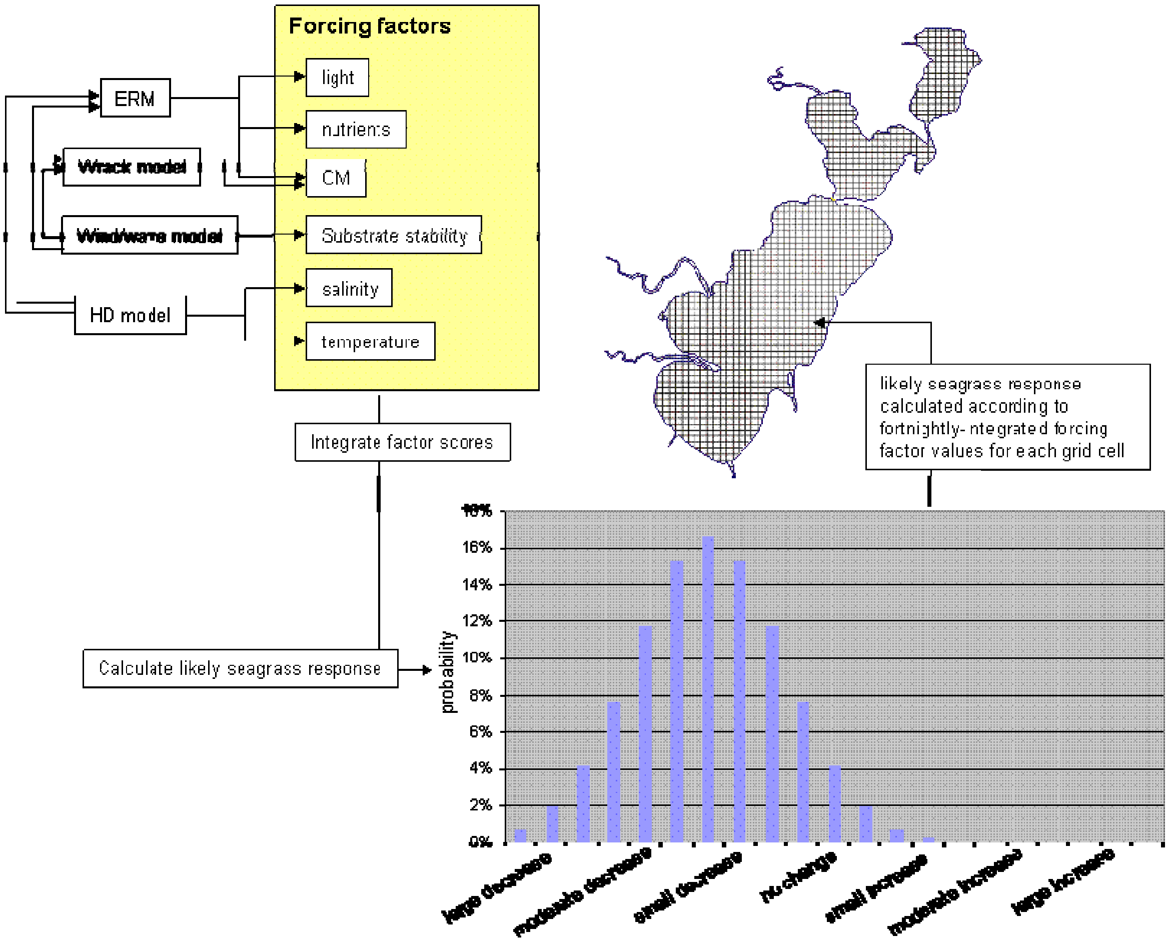


Figure 40 Conceptual layout of the seagrass response model.

Seagrass model predictions

The results of the seagrass model predictions show that optimal conditions for seagrass occurrence in Tuggerah Lakes are highly variable on a timescale of weeks to months, however integrated over a six month timeframe the model predictions closely match observed distributions (Figure 41 to 45). Hence, changes in seagrass cover respond to seasonal and inter-annual variations in environmental conditions (e.g. water clarity, wind stress, salinity and temperature). As such, it is expected that some of the observed shifts in seagrass distributions over the last century can be explained by decadal cycles in weather patterns (e.g. ENSO cycles). We are currently undertaking further long term modelling to investigate this hypothesis. However, not all of the observed trends can be explained by the current model, and an alternative model of the nearshore zone is posed below to help understand the shoreward migration of seagrass over the last 50 years.

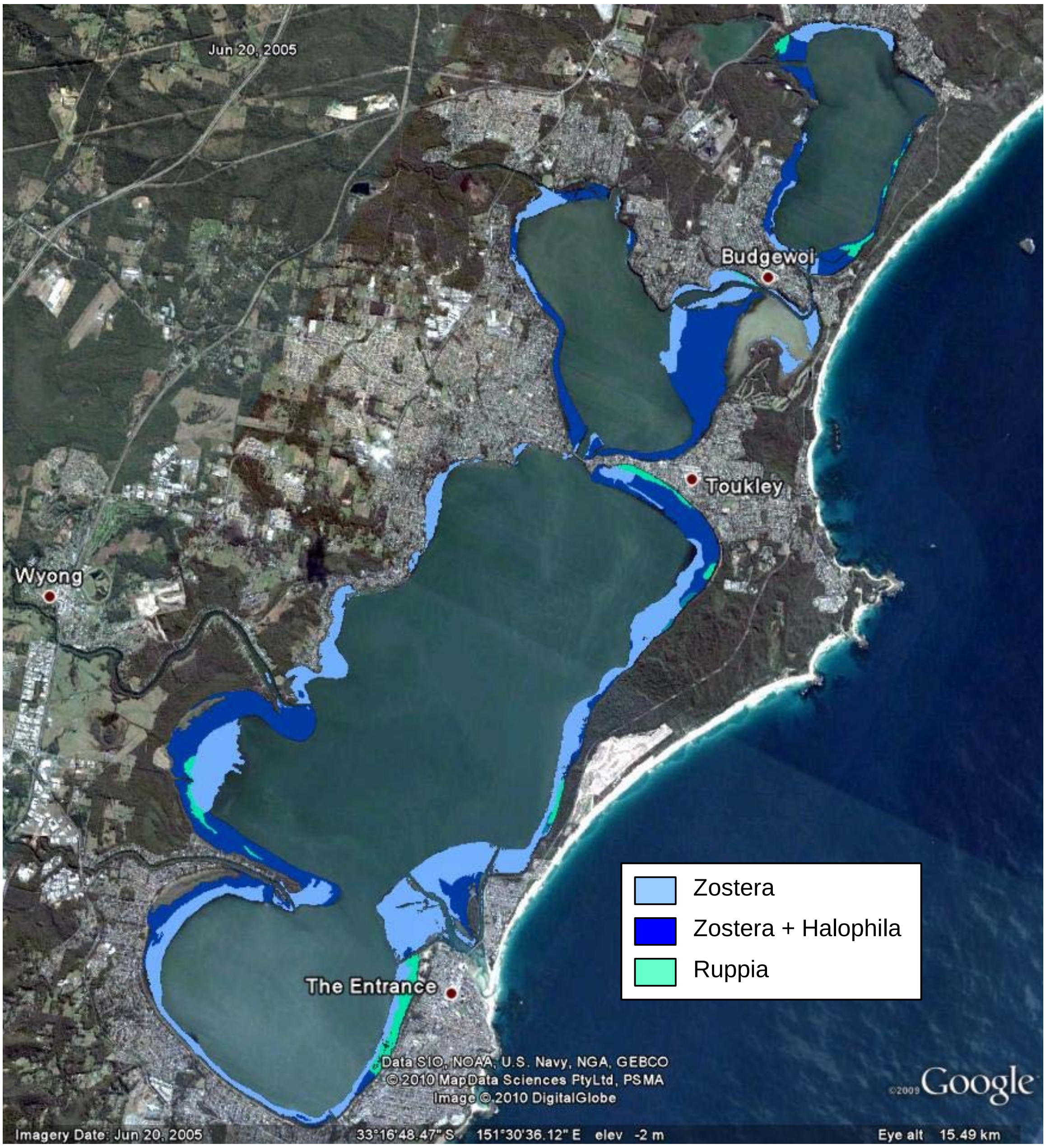


Figure 41 The distribution of seagrasses in Tuggerah Lakes in 2005.
These distributions have been used as overlays in subsequent figures showing seagrass model outputs.

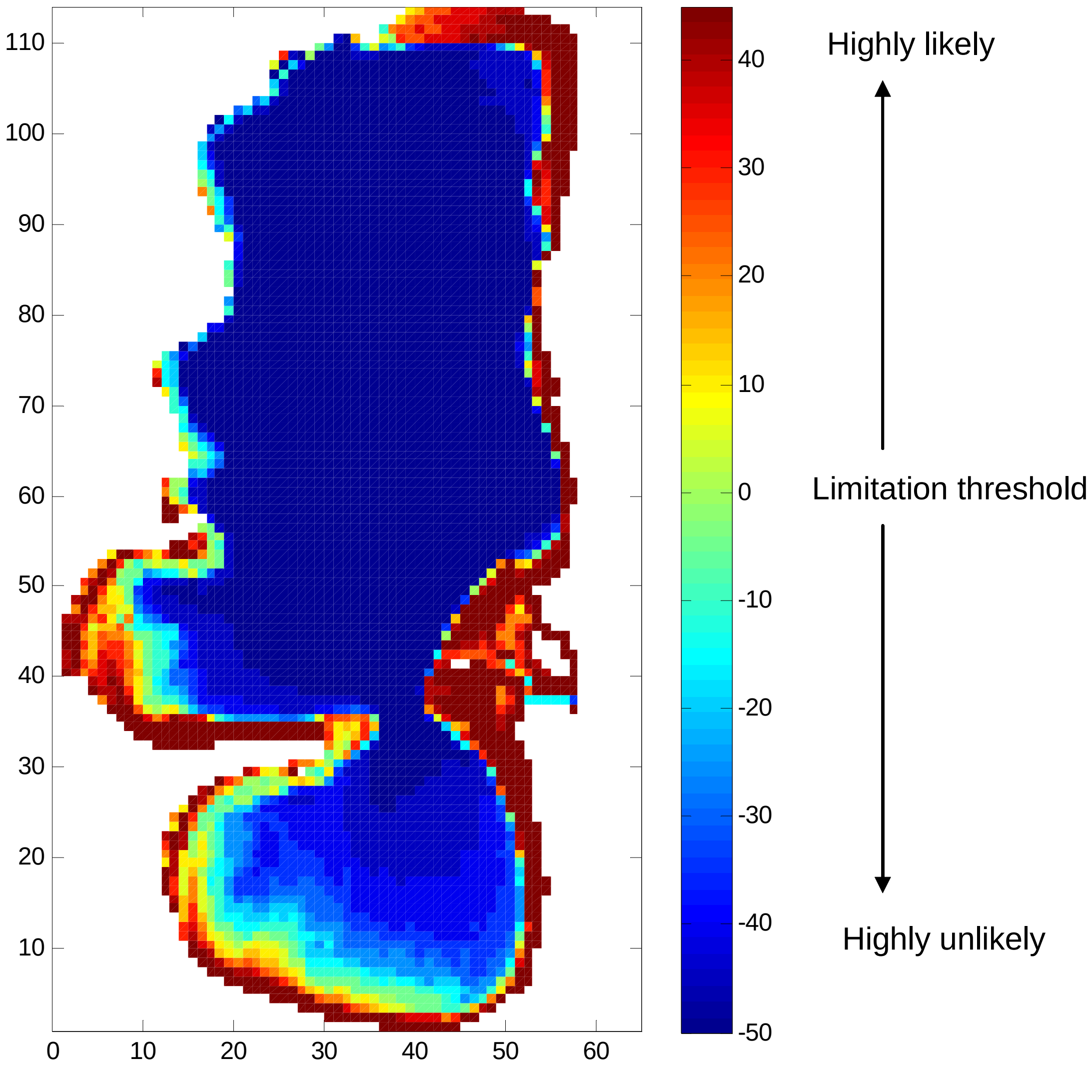


Figure 42 Probability of seagrass occurrence in Tuggerah Lake over the period April 2009 – October 2009.

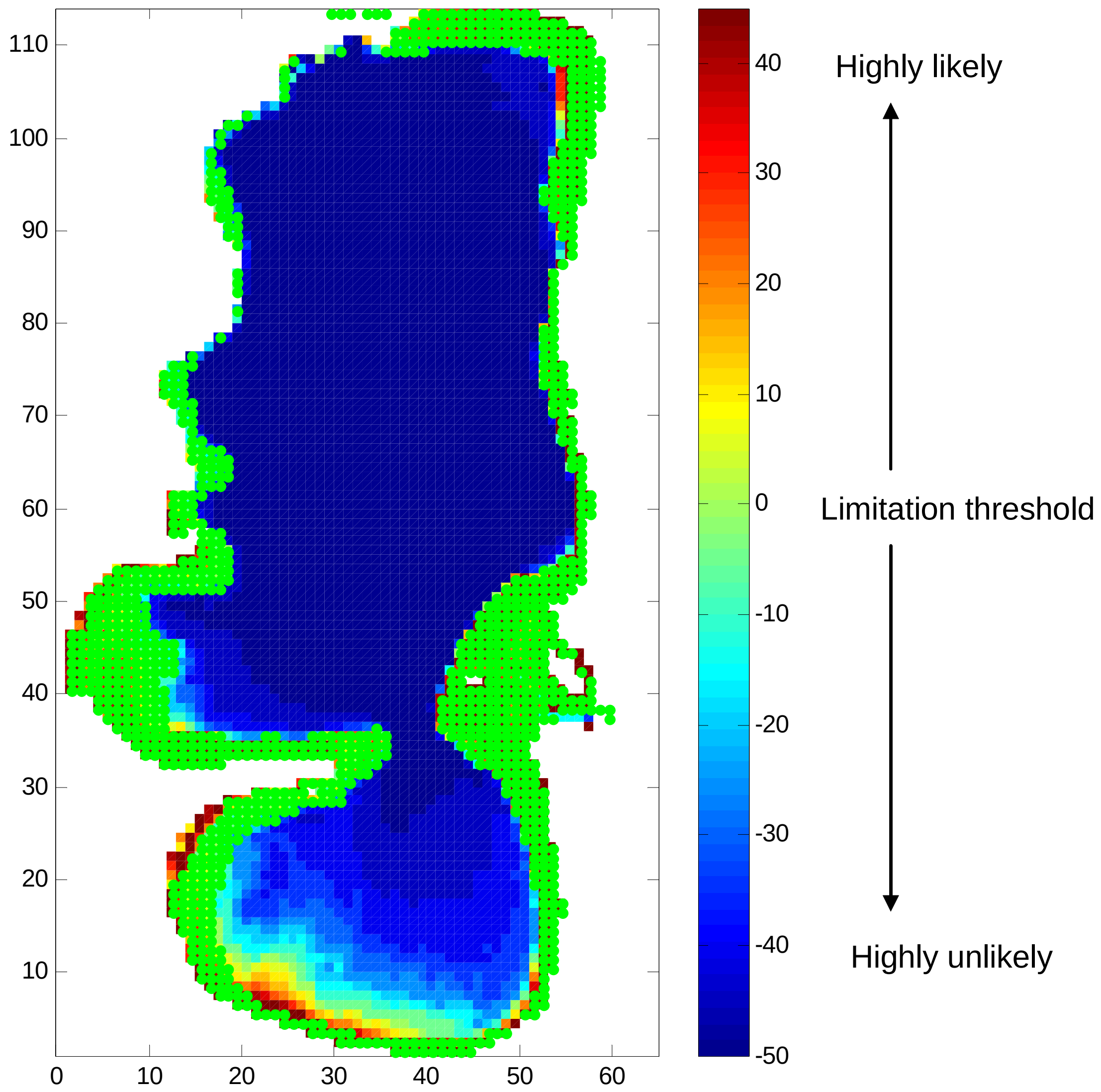


Figure 43 Observed seagrass occurrence in Tuggerah Lake over the period April 2009 – October 2009.
Green dots indicate the measured coverage of Zostera in 2005 (refer to Figure XX).

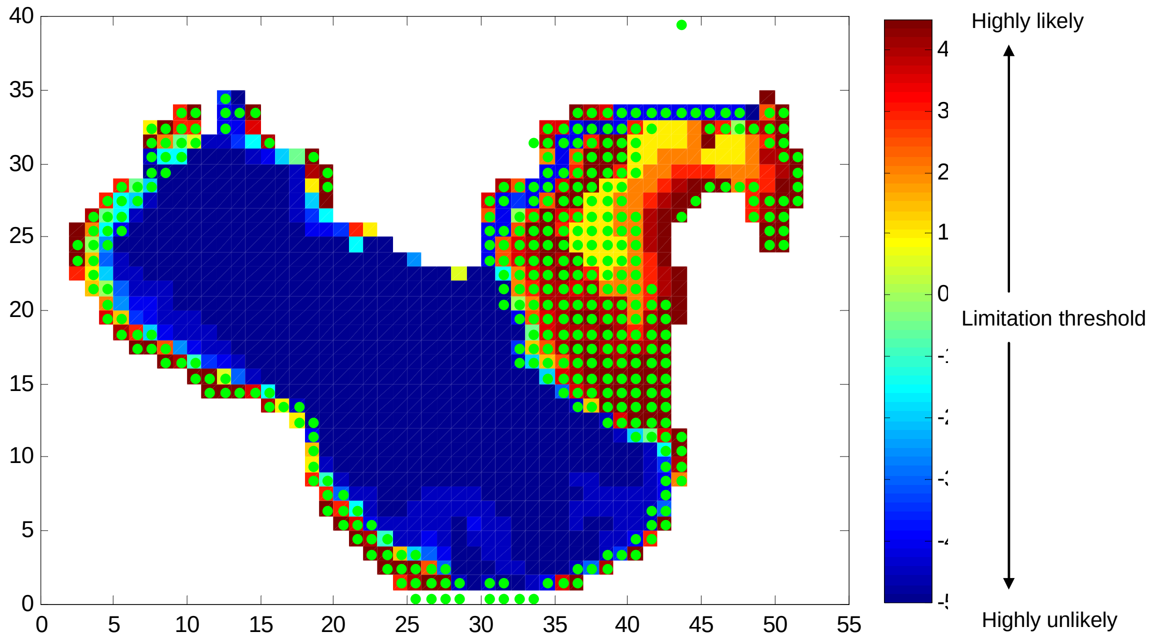


Figure 44 Probability of seagrass occurrence in Budgewoi Lake over the period April 2009 – October 2009.
Green dots indicate the measured coverage of Zostera.

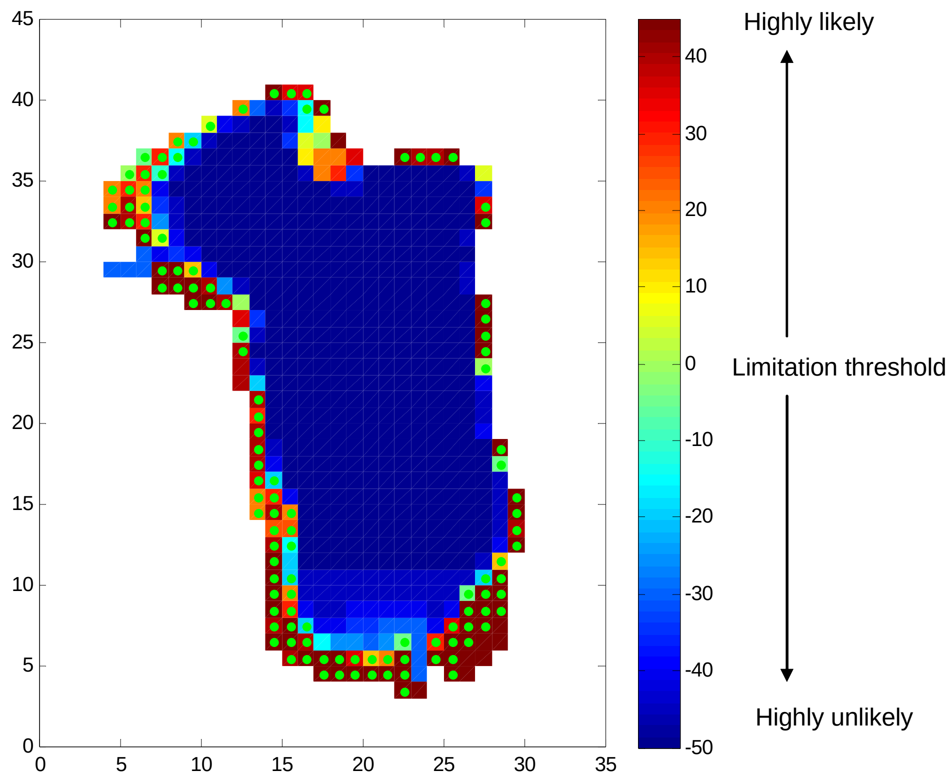


Figure 45 Probability of seagrass occurrence in Lake Munmorah over the period April 2009 – October 2009.
Green dots indicate the measured coverage of Zostera.

Nearshore zone conceptual model

There have been fundamental changes to the function and ecology of the nearshore zone along extensive parts of the Tuggerah Lakes over the past 60 years. These changes to nearshore sediments are characterised by:

1) More stable water levels and a marked decrease in high water events
2) Conversion of low-grade shoreline profiles to armouring
3) increase in the fine particle fractions
4) Increase in the organic content
5) Increase in sub-tidal wrack accumulation
6) Increase in seagrass and macroalgae cover

These changes can be explained by considering interactions and feedbacks between a number of physical and biological processes. These are discussed below.

Entrance management

Under natural conditions, the entrance conditions were characterised by closure or restricted exchange during extended dry weather periods, and scouring during major floods. Model simulations of this regime indicated that water levels in the lake were characterised by a bi-modal distribution (Figure 46 and 47): a low water state during low flow conditions; and a high water state when flood waters backed up behind the partially closed entrance. Over the last 30 years, the entrance of Tuggerah Lakes has been routinely dredged to improve tidal exchange and to reduce the occurrence of flooding in low lying areas surrounding the lakes. Observations and model results show that this has resulted in a marked decrease in water level and waterway area variation in the lakes (Figure 48).

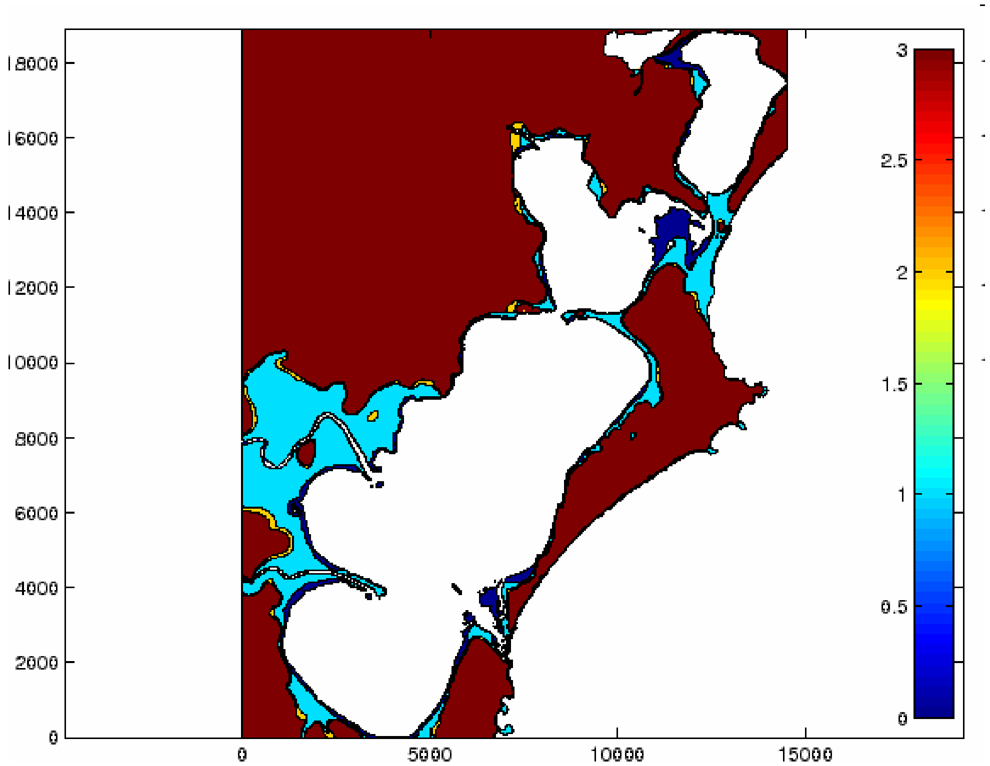


Figure 46 Distribution of low lying lands subject to inundation during flood events in the Tuggerah Lakes system.
This analysis was used as input into the analysis of water level variation below.

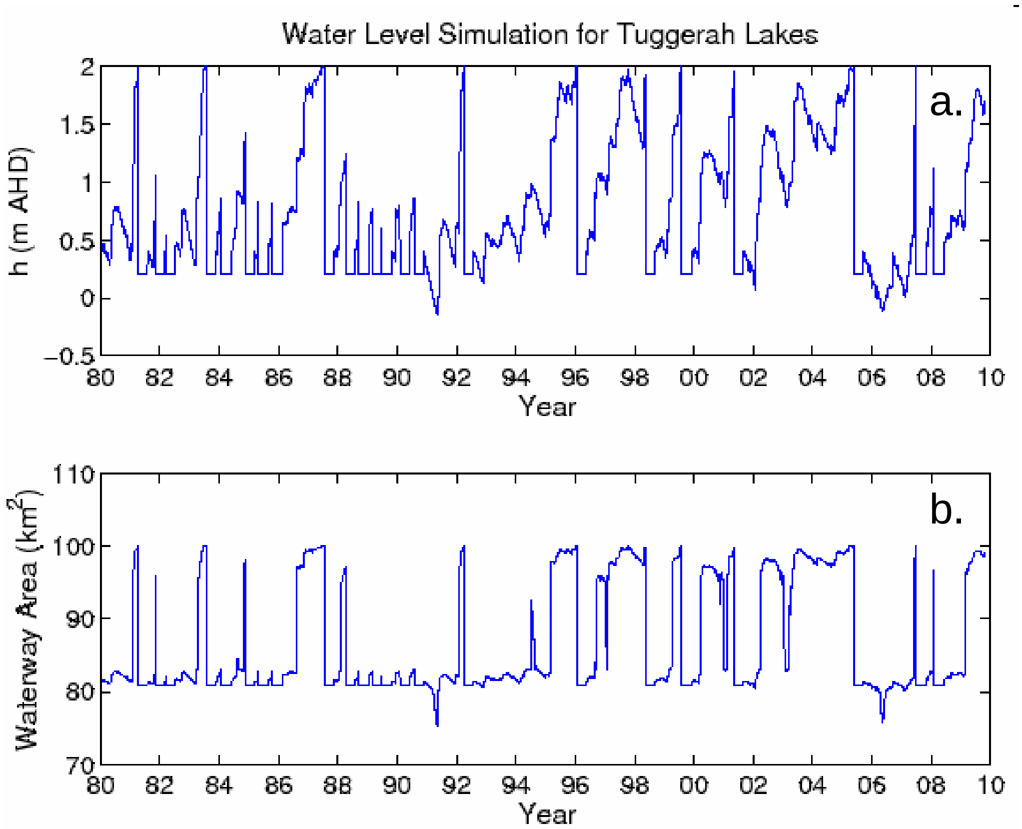


Figure 47 Water level and inundation for Tuggerah Lakes
a) Simulated water level variation in Tuggerah Lakes under natural entrance conditions. **b)** Resultant changes in the area of inundation over the simulation period.

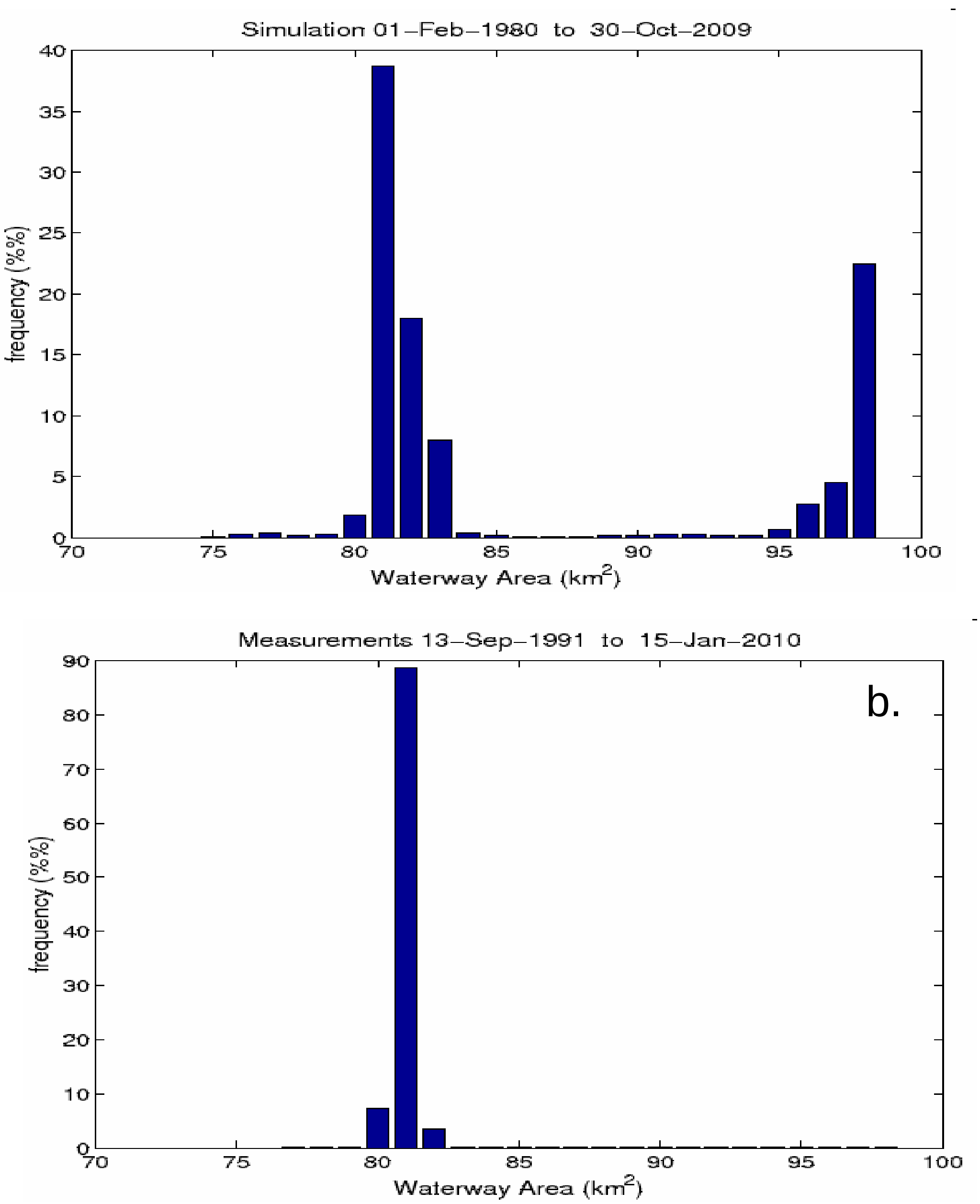


Figure 48 Observed versus modelled water way area
a) Frequency analysis of water way area under natural entrance conditions. **b)** Frequency analysis of observed water way area under current entrance management conditions showing a relatively stable water level / waterway area state.

Changes in wrack accumulation and breakdown pathways

Under the natural shoreline profiles and variable water levels, seagrass wrack tended to accumulate along the shoreline and was periodically deposited higher up the profile in fringing saltmarsh areas by high water events. As such, the primary fate of wrack was decomposition under aerobic conditions in fringing saltmarsh areas (Figure 49 and 50). A combination of shoreline modification and entrance management (more stable water levels) resulted in a shift toward the accumulation of wrack sub-tidally in the nearshore zone. The rate of accumulation in these areas now far out weighs the rate of breakdown, resulting in the build up of organic material in the sediments. These conditions favour a predominance of sulfate reduction (anaerobic bacterial breakdown of organic matter) over aerobic processes. The by-products of sulfate reduction are sulfide gas (“rotten egg gas”), iron monosulfides (potential acid sulfate soils), and high rates of nutrient regeneration to the overlying water (Figure 51).

Figure 49 The accumulation of wrack in the inter-tidal zone of a natural low-grade shoreline on the western shore of Tuggerah Lake.
The red-orange colour is characteristic of a predominance of aerobic breakdown.

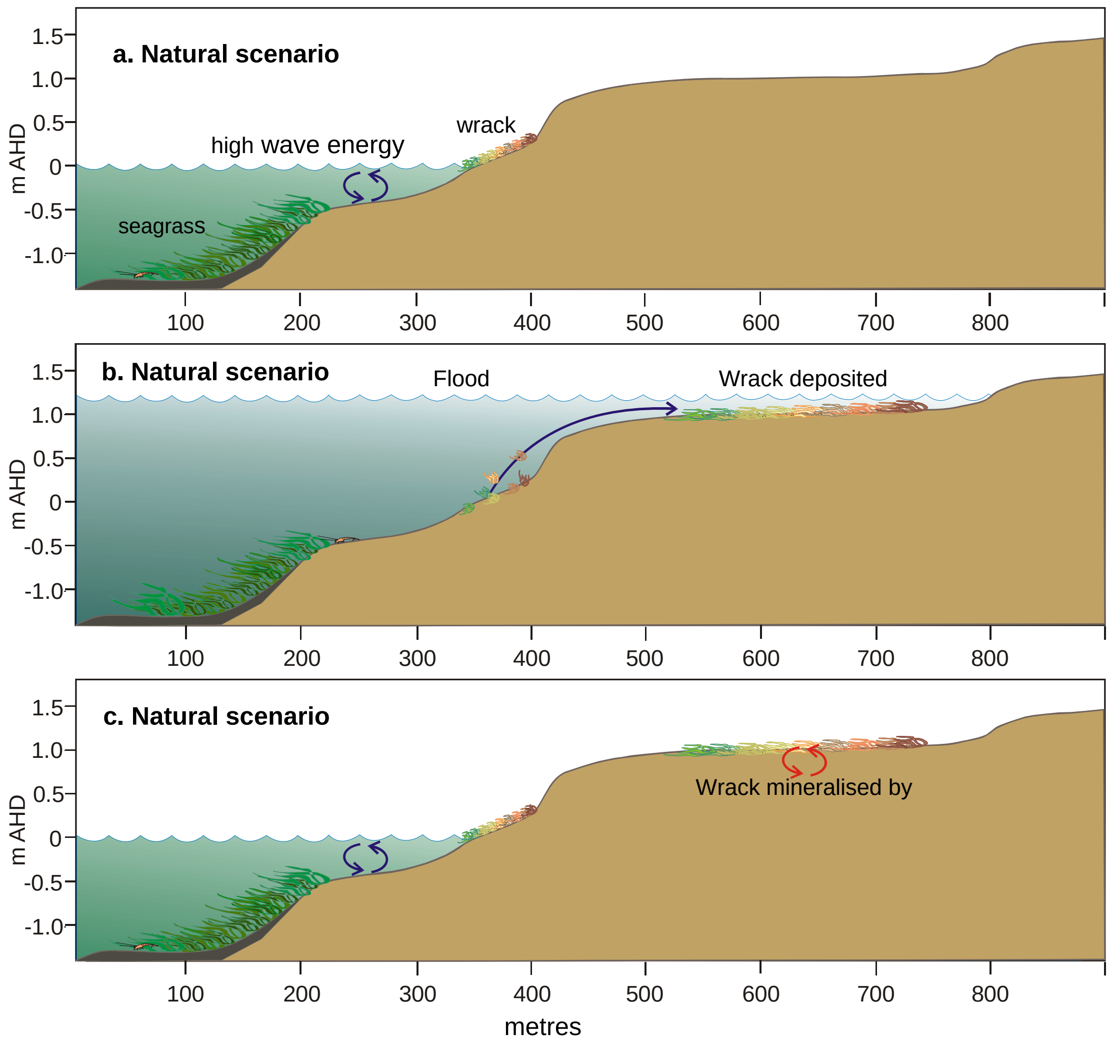


Figure 50 Conceptual model of processes in the nearshore zone under natural variations in water levels
a) High wave energy and water currents tend to limit colonisation and wrack accumulation in the nearshore sediments, with wrack accumulating in the inter-tidal zone. **b)** Wrack is transported and deposited inland during flood events. **c)** Once water levels recede, wrack is left to breakdown under aerobic conditions, thereby providing an important carbon and nutrient source for saltmarsh and various invertebrate foodchains.

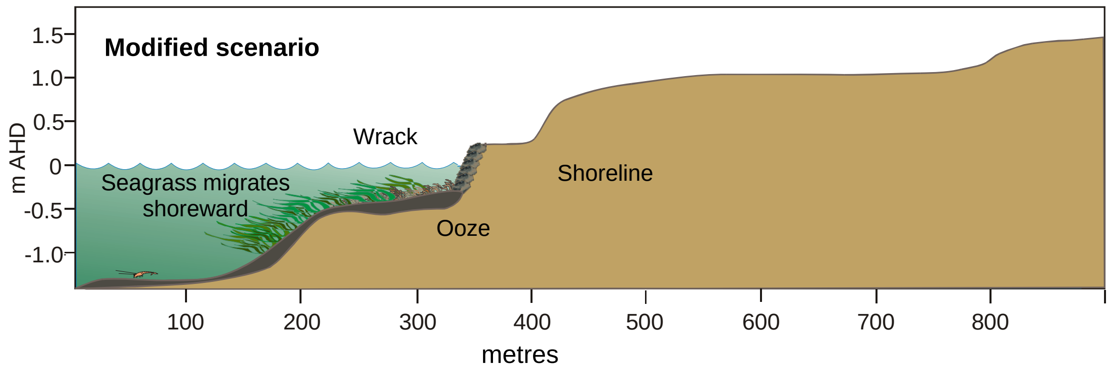


Figure 51 Conceptual model of the current, modified shoreline scenario.
A combination of shoreline armouring and stable water levels allows wrack to accumulate sub-tidally. The excessive build up in organic matter leads to a predominance of breakdown by sulfate reduction resulting in the production of potential acid sulfate soils and offensive sulfidic odours.

Increased urbanisation of the lake fringes

There has been considerable infilling of the lake margins with urban development over the last century, resulting in an increase in nutrient-rich urban runoff to the nearshore zone. Prior to the 1990s when there was an extensive conversion to reticulated sewerage, the bulk of urban development was serviced by septic tanks which resulted in significant nutrient-enrichment of nearshore groundwater. This served to increase the localised enrichment of the nearshore zone, and has been implicated as a major factor in the development of macroalgae blooms prior to the 1990s.

Colonisation of the nearshore zone by seagrass/macroalgae

The observed shoreward migration of seagrass and macroalgae into the nearshore zone can be explained by a gradual progression resulting from the combination of direct stimulus effects and positive feedbacks. Under natural conditions, the nearshore zone most likely kept clear of submerged macrophytes primarily by the action of high variations in water level (as described above) and the predominance of high bottom stress caused by wind driven currents (Figure 50). A combination of the mechanisms described above have allowed gradual macrophyte colonisation of the nearshore zones in recent times (Figure 52). Once established, macrophytes serve to reduce the severity of nearshore currents, thereby providing a positive feedback promoting further colonisation. In addition, the presence of macrophyte canopies tends to promote the trapping of particulate organic material thereby promoting the enrichment of sediments and forming a positive feedback through increased nutrient recycling (Figure 53).

Figure 52 Two views of the Long Jetty shoreline (1941 and 2006)
This shows the dramatic change due to colonisation by macrophytes over the past 60 years. The effects of wave energy and water currents on the sediments can be seen as mega ripples (sand ridges perpendicular to the shoreline) in the 1941 image.

The potential increase in ambient nutrient concentrations in the water column of the nearshore zone (resulting from a combination of urban inputs and enhanced internal recycling) would tend to favour macroalgae blooms over seagrass. This is because macroalgae source nutrients from the water column whereas seagrasses source their nutrients via rhizome structures in the sediments. Excessive macroalgae growth can potentially cause negative feedbacks for seagrass due to the build up of organic matter and the development of anaerobic (reducing) conditions in underlying sediments.

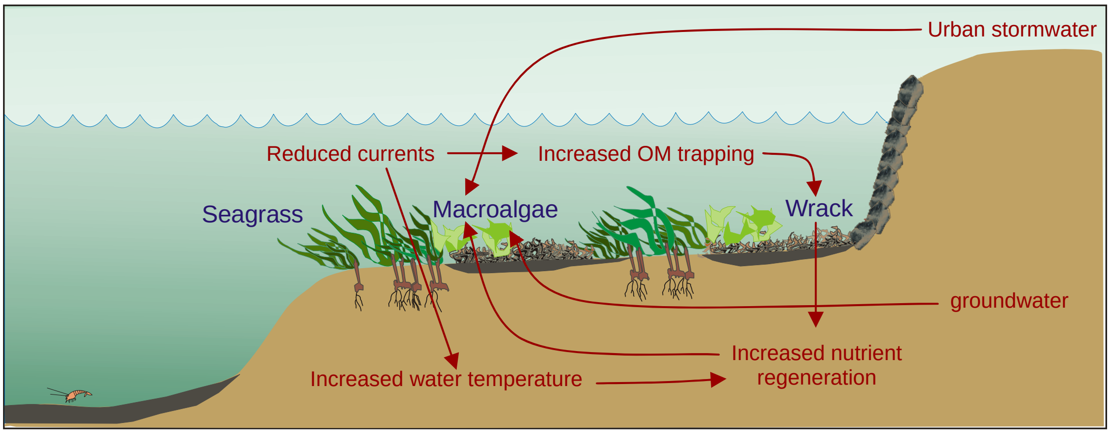


Figure 53 Conceptual model of feedbacks associated with the progressive colonisation of the nearshore zone by macrophytes.

Limitations and further work

1) The validity of the seagrass model will be tested in a 20 year simulation (1990 – present) with outputs compared against measured trends in seagrass distribution.

Summary of Ecosystem Response Modelling

A summary of the ERM results to date indicate that:

- There is significant attenuation and transformation of nutrient loads across the catchment-weir pool-estuarine creek continuum of major catchment inputs to the lake system.
- Seasonal variation in TSS and particulate nutrient concentrations in the lakes are controlled by wind driven resuspension which peaks during the summer – autumn period.
- TSS and nutrient concentrations are also briefly elevated immediately post high flow events.
- Due to the predominantly shallow nature of the lakes light penetration is sufficient to maintain good light climate for both pelagic and benthic productivity.
- Seasonal variation in phytoplankton (indicated by chlorophyll concentrations) is also controlled by wind driven resuspension of benthic microalgae.
- Catchment inputs of DIN are insufficient to account for the estimated pelagic productivity of phytoplankton indicating that productivity in the system is sustained by the internal recycling of nutrients via breakdown of organic matter in the sediments.
- The major fate of phytoplankton productivity is grazing by microzooplankton which delivers most of the grazed material to the sediments as faecal pellets.
- Production by BMA exerts a strong control over the recycling of nutrients back to the pelagic zone, especially during the dry season when the benthic light climate improves.
- Denitrification constitutes a major sink of nitrogen in the lake system, however BMA productivity can temporarily quarantine some nitrogen from loss via denitrification.
- The NEM results show that the lake system is net autotrophic (a net producer of organic matter), with most productivity occurring in the pelagic zone.
- The highly autotrophic NEM indicates that the Tuggerah Lake system was not sensitive to hypoxia due to excessive organic matter breakdown during the current scenario simulation.

Foodweb implications

The results from the ERM provide a detailed quantification of potential energy flows that support higher order fish and bird species in Tuggerah Lakes (Figure 54). Due to its shallow nature and resultant good light climate, catchment nutrients are rapidly assimilated by phytoplankton and benthic microalgae. Despite highly efficient grazing rates by zooplankton, phytoplankton biomass is maintained relatively constant through time by the physical resuspension of viable benthic microalgae cells. Internal recycling of nutrients due to breakdown of organic matter in the sediments is important for maintaining productivity throughout low flow periods. A significant fraction of the annual nitrogen load to the lake system is lost via denitrification. In contrast, there is relatively little export of material across the ocean boundary due top the relatively small ocean entrance.

Seagrass productivity is relatively small in comparison to phytoplankton and benthic microalgae. Nutrients supporting seagrass are most likely sourced from the breakdown of organic matter (e.g. phyto-detritus) trapped and deposited in the seagrass beds. Despite its secondary role in the overall carbon budget of the system, seagrass has a number of direct and indirect implications for the Tuggerah Lake foodweb. It directly supports a range of detritivorous and herbivorous invertebrate, fish and bird species. It provides physical habitat for numerous juvenile fish species. Wrack represents an important carbon source for various sub- and inter-tidal invertebrate species, and wrack has also been shown to be important for maintaining healthy saltmarsh communities.

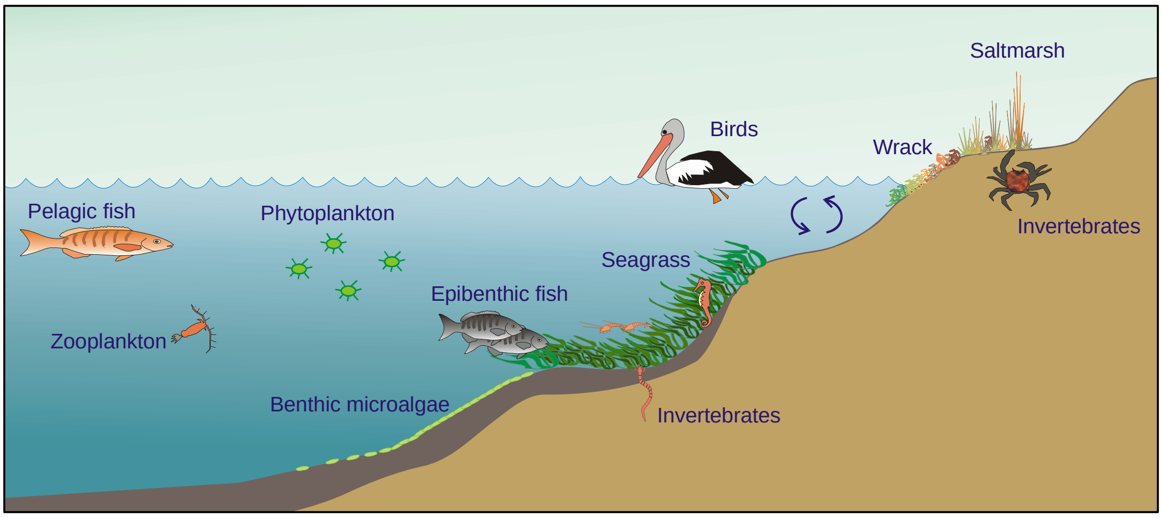


Figure 54 Foodweb example for Tuggerah Lakes

Ecosystem risks

This section provides a qualitative assessment of risks to key ecosystem components, based on current outputs from the ERM. We are currently updating the ERM for a long term simulation (1980 – present), and will run simulations for all management scenarios in the near future.

Phytoplankton blooms

The ERM results indicate a moderate risk of phytoplankton blooms with minor hypoxia during high rainfall years. This risk is primarily associated with rural catchment inputs due to their relatively large contribution to overall freshwater inputs to the system. Fringing urban catchments pose a much lower risk of triggering phytoplankton blooms due to their relatively minor contribution (and hence high dilution factor). The risk of phytoplankton blooms is considerably less during low to median rainfall years due to relatively higher diversion of catchment nitrogen to benthic microalgae production and denitrification.

Macroalgae blooms

Due to its relatively shallow nature (and the resultant good benthic light climate), severe macroalgae blooms represent a major risk and most likely the primary expression of eutrophication in the Tuggerah Lakes system. In contrast to phytoplankton, macroalgae blooms are more likely to be associated with inputs from fringing urban catchments (see Nearshore processes below).

Seagrass loss

Seagrass in Tuggerah Lakes has undergone a marked shoreward shift in distribution in response to alterations in controlling factors. Further opportunities for migration (e.g. in response to sea level rise) are now limited, and any further changes to controlling factors (in particular increased turbidity and water depth) will result in a net loss of seagrass coverage. The seagrass model was used to perform a sensitivity analysis of seagrass response to increases in phytoplankton biomass (and the subsequent decreases in water clarity). Results of this analysis show that seagrass in Tuggerah Lake is the most sensitive to increases in phytoplankton, followed by Budgewoi Lake and finally Lake Munmorah (Figure 55).

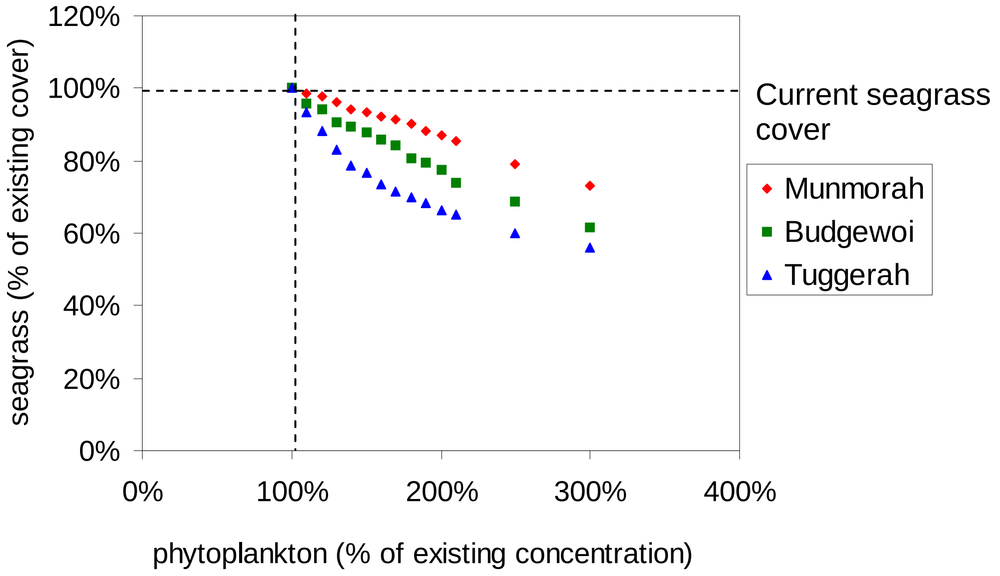


Figure 55 Impact of relative increases in the 6 month average phytoplankton concentration on seagrass coverage.
This analysis describes the effects of phytoplankton on light attenuation and hence shading of seagrass at the lower limits of its current depth range.

Nearshore processes

The ecology of the nearshore zone in many areas of Tuggerah Lake has been significantly altered in recent times, and it is unclear whether this change is permanent or there is potential for rehabilitation. In its current state, the nearshore zone is highly sensitive to increased nutrient inputs from urban runoff, with a high likelihood of macroalgal blooms and loss of seagrass. This relates particularly to reduced circulation/flushing of this zone due to the dampening effects of macrophytes on currents. Reduced flushing in the nearshore zone means that localised nutrient inputs from stormwater, nutrient rich groundwater and underlying sediments will not be subject to immediate dilution in the wider lake and will therefore exacerbate the probability of macroalgal blooms. The connectivity between the waterway and the fringing saltmarsh communities has been greatly reduced due to alterations in water level regimes and shoreline regrading. Rehabilitation of the nearshore sediments must address this issue of connectivity in order to achieve a low maintenance and sustainable solution. A good example of such rehabilitation is the saltmarsh rehabilitation program Wyong Council are carrying out.

Land use and management scenarios

Using the baseline set of models, a number of scenarios were introduced to answer key questions as directed by Wyong Council. The scenarios are:

1. **Pre-settlement** – Using the baseline catchment model and hydrodynamic model, run the same parameters with the land use as 100% forested. The results can be compared to the current situation in the Tuggerah Lakes catchment to indicate how far the system has deviated from a natural state
2. **Future development** – To show the likely changes in nutrient and sediment loads to the lakes system and potential ecological effects when proposed developments are in place
3. **Retrofit** – To determine the extent of water quality treatments needed in each of the lake fringing sub-catchments to meet the load targets advised by the ERM. Retrofit may include constructed wetlands and bio-retention systems. There will be three parts to this scenario; the effect of 25%, 50% and 100% retrofit enabling council to decide on the most cost effective outcome

An extra scenario **optimal wetland function** was discussed with Wyong Council. It proposed to investigate the cost and ecological benefit to repair and maintain the existing constructed wetlands in the catchment. However, not enough information on the wetlands exists and timeframes did not allow collection of this information.

Pre-settlement

The catchment was assumed to be completely vegetated for this scenario. Land-use in the baseline catchment model was set to 100% vegetated, therefore being 0% impervious. The TN, TP and TSS outputs have been compared to the concentrations from the current scenario, providing the percentage increase from natural (Figure 56 to 58).

The change in land use from forested to urban means that there is an increase in loads and concentrations of nutrients and sediments entering the lakes. This can largely be attributed to the presence of hard surfaces such as driveways, roads, car parks and buildings where rainfall cannot reach the soil and filter through; rather it is taken directly through the stormwater system and into the lakes. Around the perimeter of Tuggerah Lakes is a large number of drains which connect urban stormwater to the adjacent lake via an unmaintained vegetation strip (Wyong Council pers. comm.). This direct linkage provides a frequent source of nutrients and sediments to the near-shore zones.

The loss of plants in an urban environment means there is a reduction in uptake of water and nutrients and a lack of sediment trapping allowing discharge of higher concentrations and flows. In a forested environment, nutrient cycling and evapotranspiration reduces the output.

The results indicate that even though the larger subcatchments produce the largest amounts of total nutrients and sediments (Figures 13-15), this is due to their size rather than a proportionally greater change in land use over time. It is in the urban catchments fringing the lakes where the biggest changes have occurred since settlement. These results can be used to identify hot spot areas where the biggest increase in change has occurred to the likely natural processes and therefore areas where the environment may be under the most stress.

There are differences between TN, TP and TSS within subcatchments due to the land use type. The main source of TN as modelled here is dissolved inorganic nitrogen (DIN) which is dissolved in the water column. The greatest increases in TN from presettlement can be seen where there is a large increase in runoff. Subcatchments 10 and 31 in the Gorokan and Lake Haven areas showed the biggest increase from presettlement, upwards of 400% increase. The other fringing catchments showed a large increase of between 150-400% from presettlement with the exception of subcatchments 16, 18 and 25 where land use is classed as *conservation area* or *trees and shrubs*. The increase in TN in the upper catchments is moderate, a 50-150% increase. Agricultural land allows rainfall to seep into the ground however it is not as efficient at capturing nutrients and sediments as a forested landscape. Fertiliser is a major contributor of nitrogen and poor farming practices can mean nitrogen-rich runoff into the receiving waters.

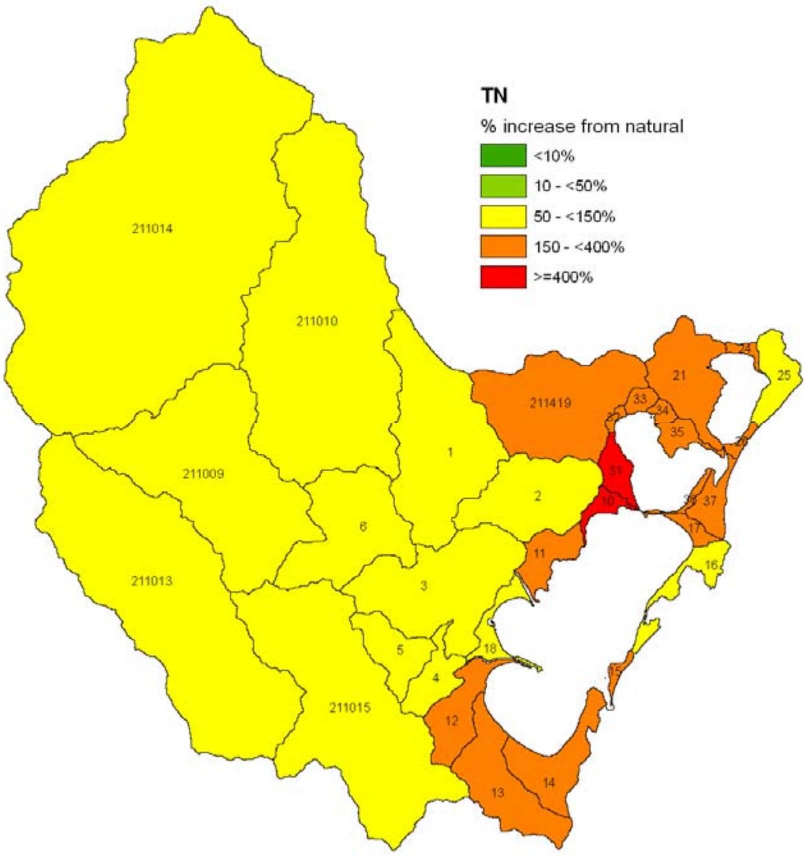


Figure 56 Percent increase in TN from natural

Sources of TP include both dissolved and particulate forms; delivered in the water column as well as being adsorbed on sediments. The similarities in percent increase for each subcatchment between TP and TSS suggest that the main source of increased TP is from sediment. For both TP and TSS a larger percent increase in the upper rural catchments compared with TN indicates that agricultural lands are a source of particulate phosphorus. The fringing catchments around Budgewoi Lake all show a very high to extremely high increase in TP and TSS from presettlement. This area of the catchment is densely populated to the water's edge, which increases direct runoff entering the lake. Other hot spots for TP and TSS include Long Jetty (14), Gorokan (10) and Toukley (17) subcatchments. The Colongra subcatchment (21) containing the power station also shows an extremely high increase in TP and TSS from natural.

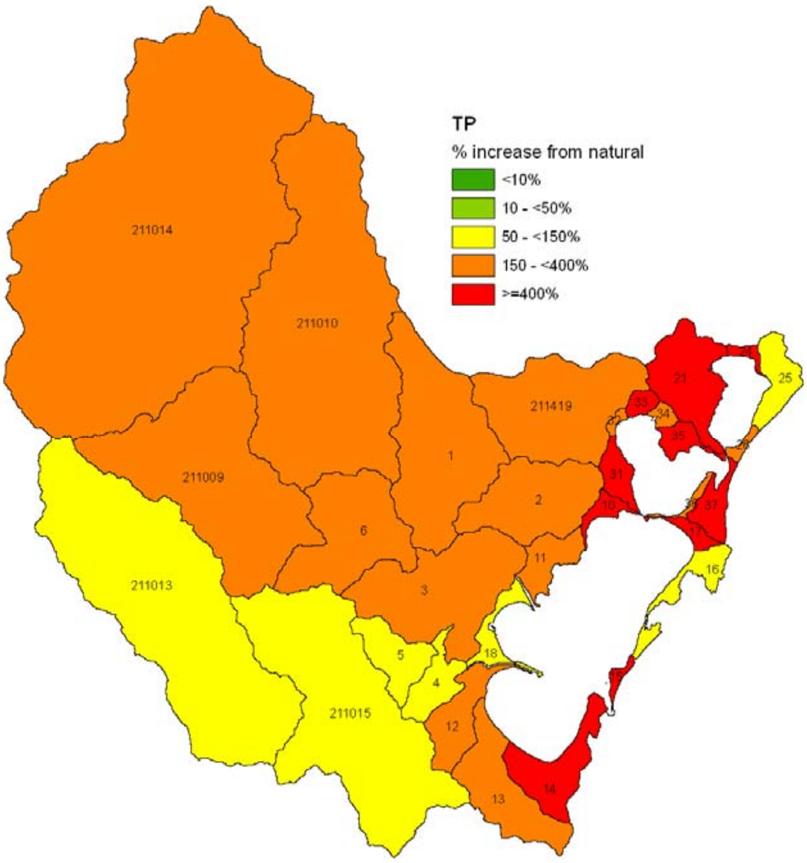


Figure 57 Percent increase in TP from natural

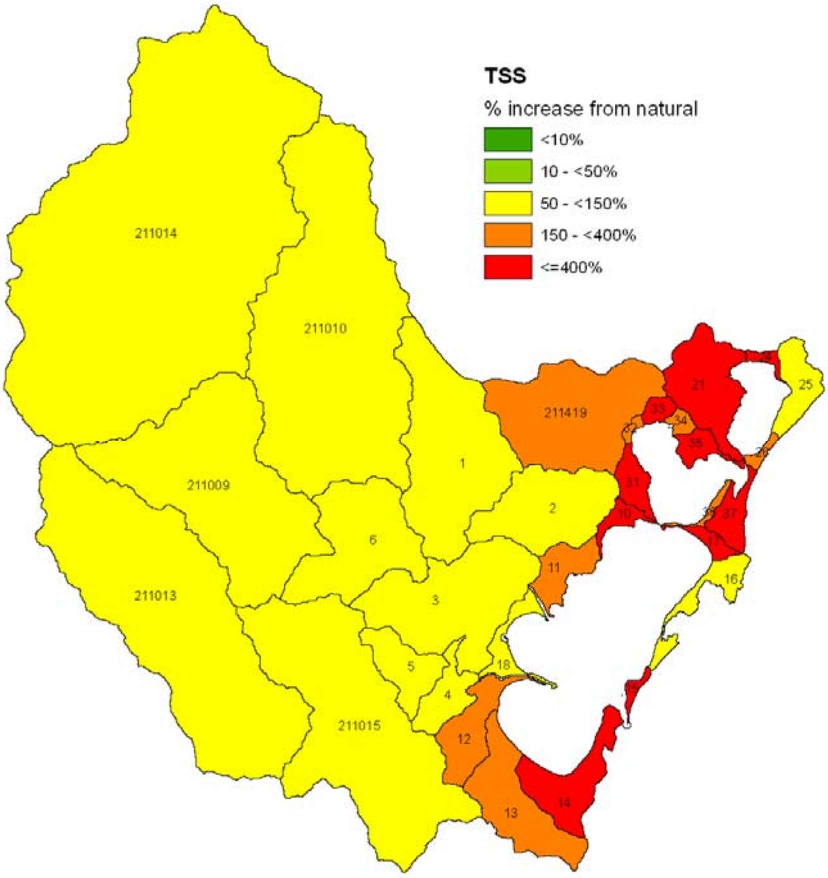


Figure 58 Percent increase in TSS from natural

The main consequence of increased discharge of nutrients and sediments from the fringing catchments is highly concentrated nutrients and sediments in lake water along the shoreline. This is mainly a result of a higher frequency of runoff due to a high proportion of impervious surfaces, a lack of retention and a short flow-path to the lake. Waters around the lake shoreline are shallow and sheltered creating favourable conditions for algal growth stimulated by the trapping of the nutrient rich run-off.

By increasing the area of forested land around the fringes of the lakes, this creates a buffer from the urban edge and helps to filter the discharge by reducing flows and trapping sediments and nutrients. However, this is not always possible in highly developed urban areas. Water treatment devices such as biofiltration systems and constructed wetlands can be placed within an existing urban environment capturing the bulk of stormwater flow and filtering it before it enters the lakes. Better farm management practices in agricultural areas are important to reduce excess nutrients and sediments

Future development

Wyong Council provided proposed development plans for the catchment and while they are not yet finalised and will change slightly, they give a good indication of the extent and density of what is likely to be approved. The proposed areas (Figure 59) were added to the current land use layer.

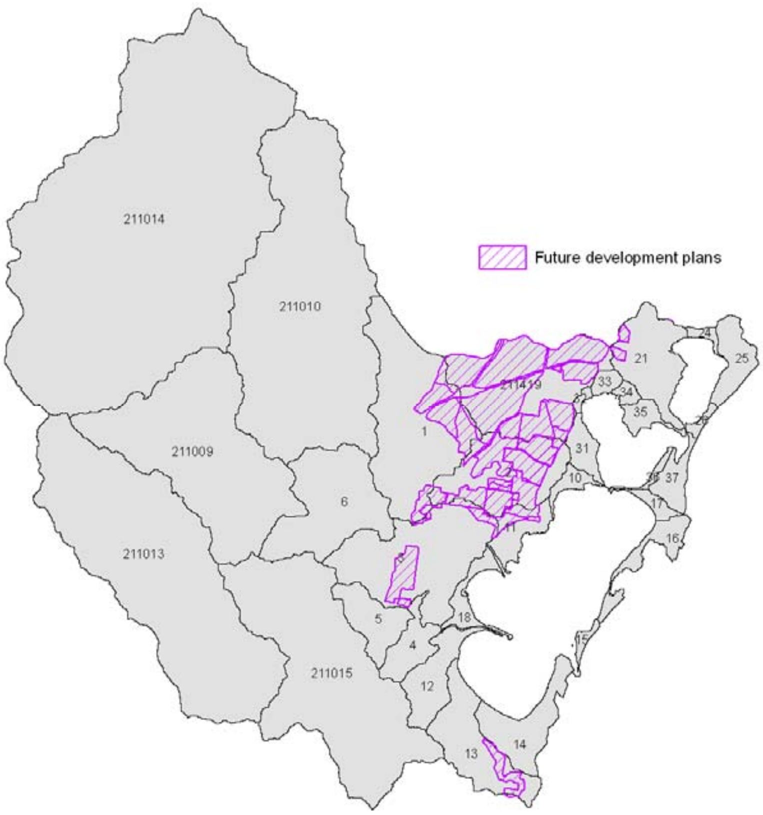


Figure 59 Areas of proposed development

In most cases, the new land use covers vegetated lands however in some cases the proposed areas overlay existing urban residential areas. In the cases where urban density is proposed to be increasing, imperviousness was assumed to increase from 25% to 35% imperviousness.

NOTE: The results of these scenarios are not yet available in a form acceptable for this report. These results will be provided as an addendum as soon as possible

Retrofit

The ecological response model will suggest catchment load targets that need to be achieved to maintain the health of the lakes. These targets are then used to compare the outputs of the future scenario to determine whether a reduction in nutrients and sediments is required to improve lake water quality. It allows individual assessment of each subcatchment to then tailor water quality improvements to suit.

By retrofitting a subcatchment with water treatment systems, nutrients and sediments can be trapped and removed. Such systems include water sensitive urban design, biofiltration systems and constructed wetlands. Three scenarios have been developed showing the effect of 100%, 50% and 25% retrofit on each subcatchment (Figure 60, 61 and 62). Using the percentage reduction of TN, TP and TSS for each retrofit scenario, a decision on the extent of retrofit needed to meet the target can be made for each subcatchment. Having a comparison for different retrofit extent allows decisions to be cost effective on a subcatchment scale.

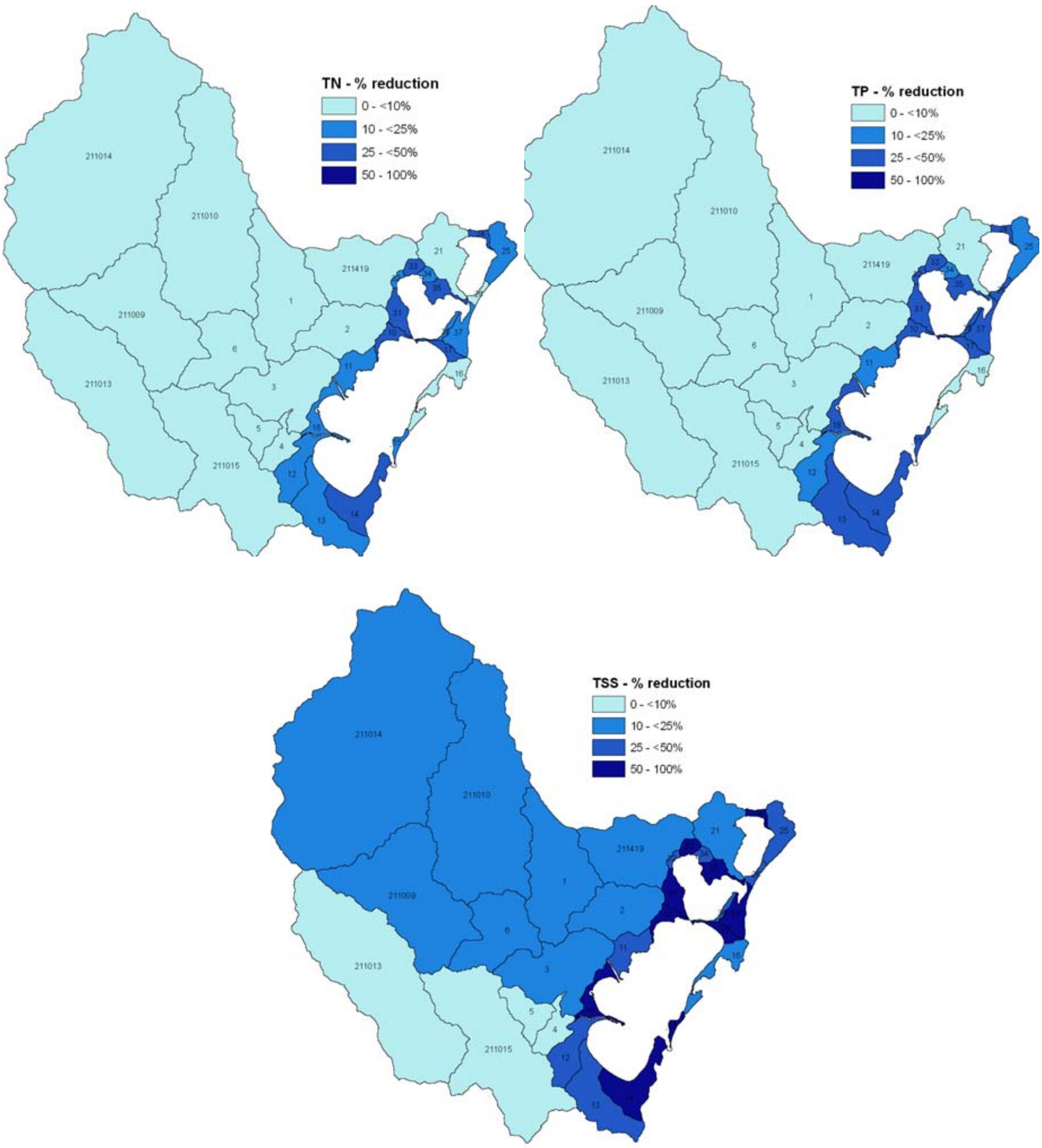


Figure 60 Percent reduction in TN, TP and TSS from future scenario by 100% retrofit with WSUD

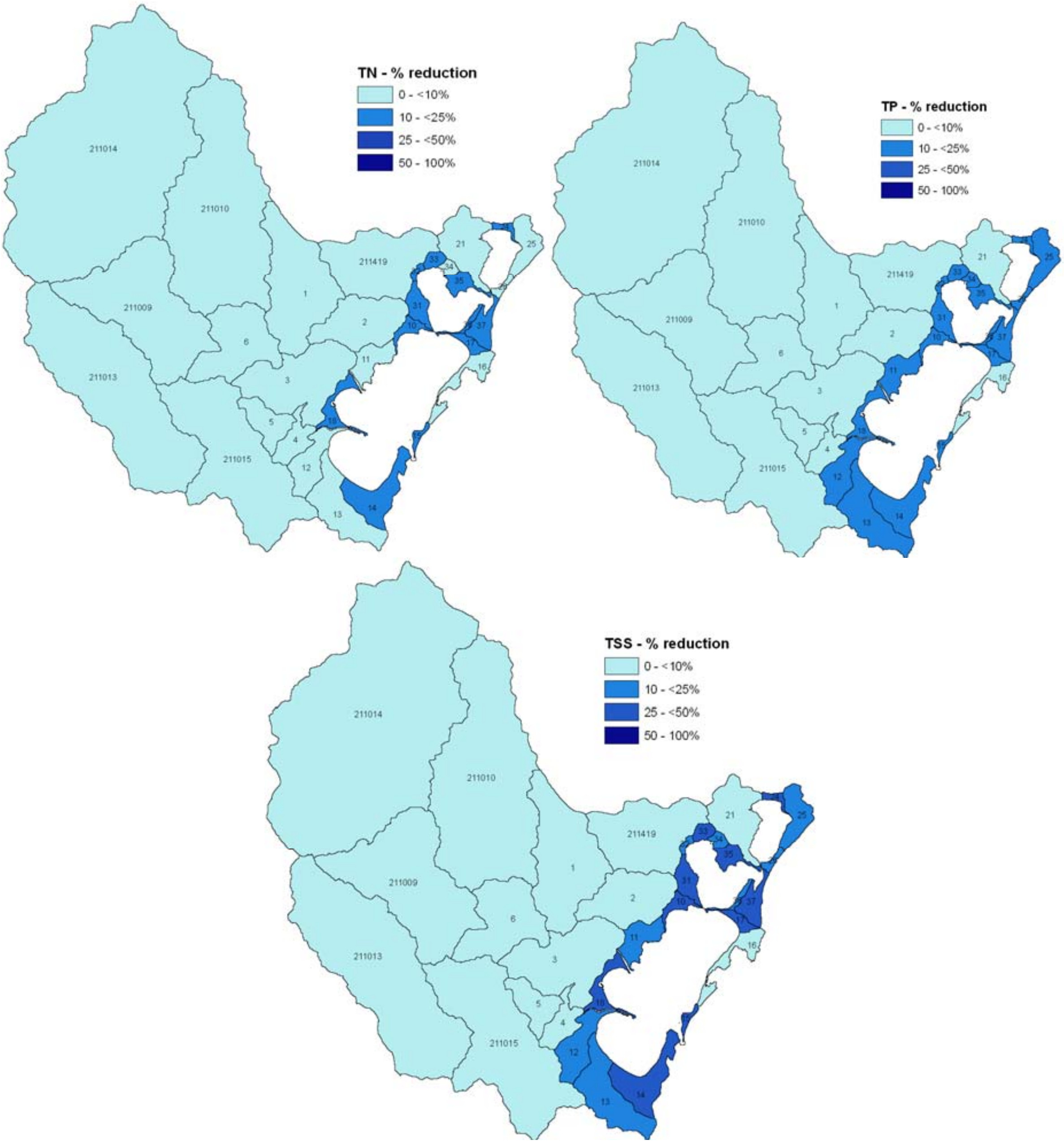


Figure 61 Percent reduction in TN, TP and TSS from future scenario by 50% retrofit with WSUD

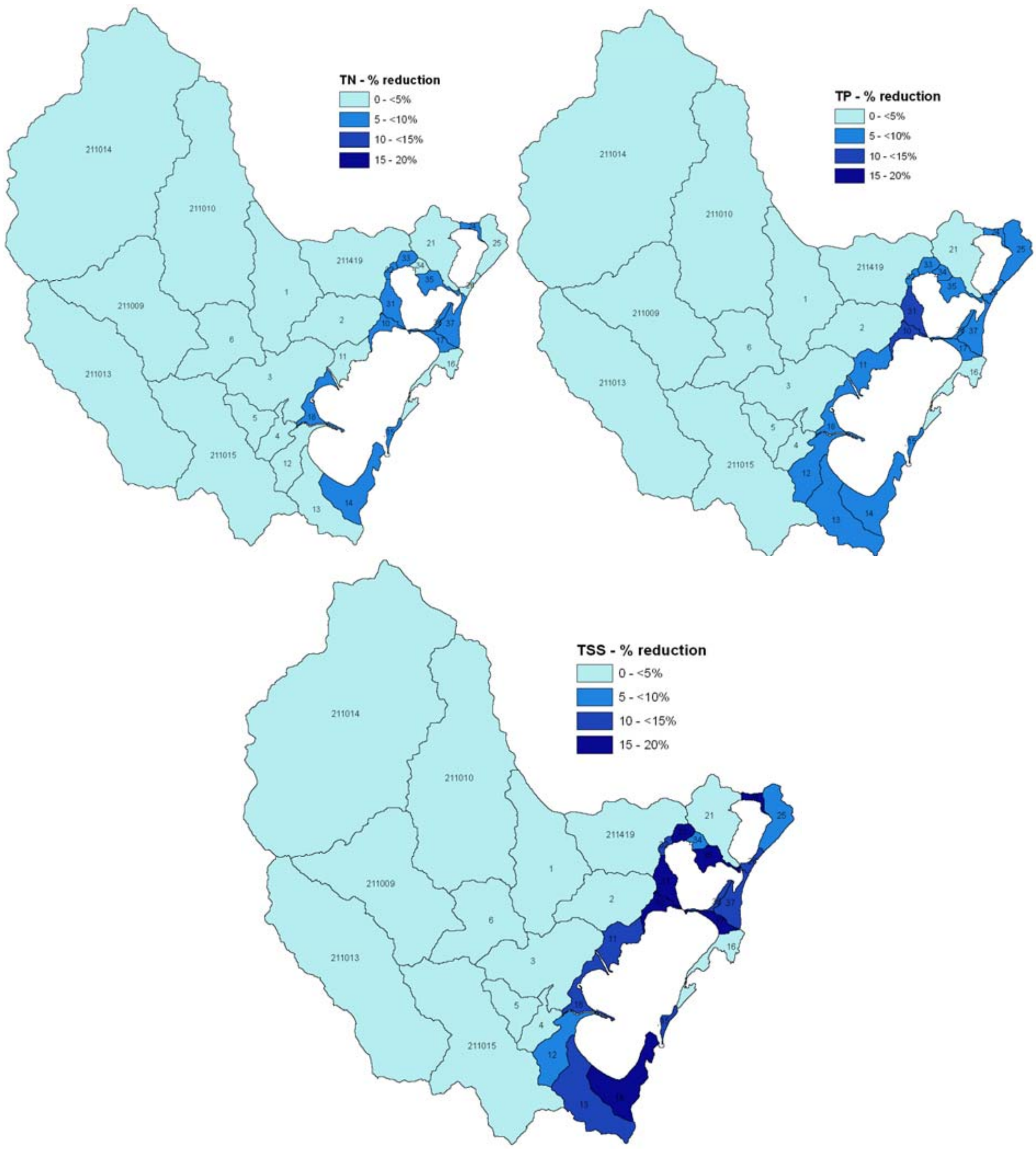


Figure 62 Percent reduction in TN, TP and TSS from future scenario by 25% retrofit with WSUD Note the different scale used.

Deliverables

Project deliverables 4 and 5 and parts of 3 as outlined below are still to be met. At the time of writing this report all components of the project were unable to be completed due to fundamental inconsistencies found in the catchment modelling. We are currently working on correcting these errors so that the models will more accurately represent the Tuggerah Lakes ecosystem for reliable results.

Deliverables still to be reported on:

- Deliverable 3: Model effects of various land use/management scenarios on nutrient reductions to receiving waters
- Deliverable 4: Develop Load Targets That Would be Needed to Protect No Net Increase for the Tuggerah Lakes
- Deliverable 5: Revise Modelling and Reporting Based on Feasibility Testing

References

BMT WBM 2008. MUSIC Modelling Guidelines for New South Wales. Prepared for the Sydney Metropolitan Catchment Management Authority, April 2008

BMT WBM 2010. Tuggerah Lakes Catchment Scenario Assessment: Draft Report. Prepared for DECCW, June 2010

DECCW 2010. Water quality data for the Tuggerah Lakes catchment. April 2009-March 2010

Sanderson, B.G. 2009a. Preliminary 3D Modelling for Tuggerah Lakes

Sanderson, B.G. 2009b. A Simple Model for Vertical Mixing

Sanderson, B.G. 2009c. Water Currents and Seagrass

Sanderson, B.G. 2009d. Water level in Tuggerah Lakes and Associated Rivers

Sanderson, B.G. 2010a. 3D Modelling of Passive Scalar Tracers in Tuggerah Lakes

Sanderson, B.G. 2010b. A Box Model for Tuggerah Lakes

Sanderson, B.G. 2010c. Box Model Simulation of Conservative TN and TP in Tuggerah Lakes

Sanderson, B.G. 2010d. Box Model Simulation of Salinity in Tuggerah Lakes

Sanderson, B.G. 2010e. Box Model Simulation with Resuspension and Settling of Conservative TN, TP and TSS in Tuggerah Lakes

Sanderson, B.G. 2010f. Salinity in Tuggerah Lakes and Associated Creeks

Appendix 1 - Tuggerah Lakes Seagrass GIS files

1963 (May)
1966 (August)
1974 (July)

Shapefile created from Jpeg images scanned from Roberts (2001) Tuggerah Lakes Estuary Process Study. Original images from Inter-departmental Committee 1975. Tuggerah Lakes Investigation.

1975 (Jan)
1976 (Jan)
1980 (July)
1981 (July)

Shapefile created from Jpeg images scanned from Electricity Commission of NSW. 1983. Report on the effect of heated water discharges from power stations on the environments of Lake Macquarie and Tuggerah Lakes.

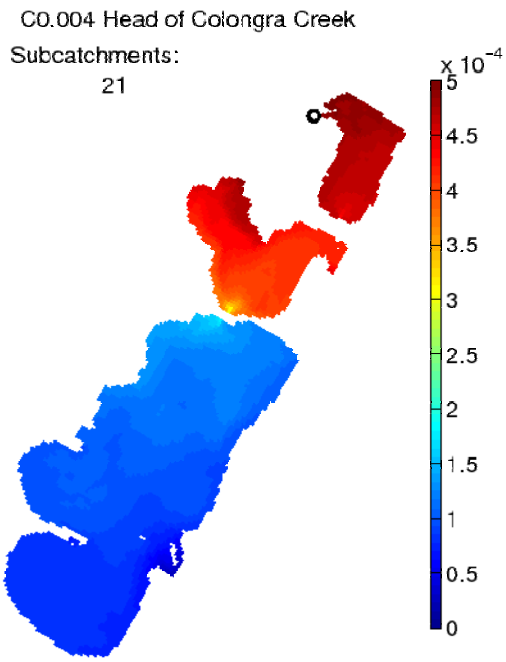
1985

Shapefile created from Jpeg images scanned from West, Thorogood, Walford and Williams. 1985. An estuarine inventory for NSW, Australia.

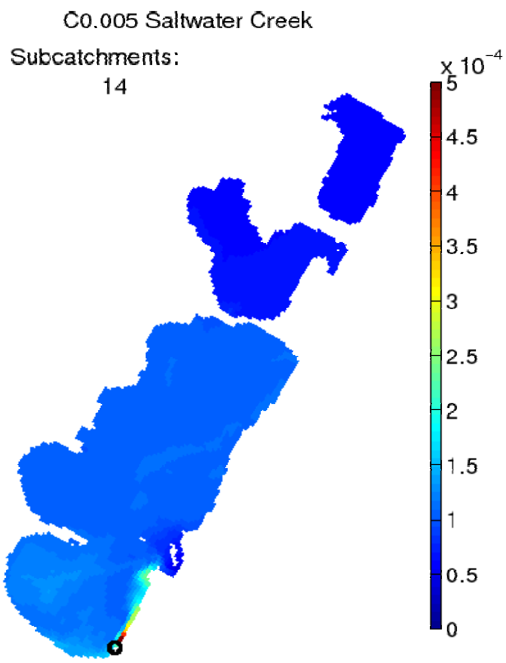
2005

Shapefiles from Estuarine Macrophytes of New South Wales, Australia. NSW Fisheries 2008. See metadata file NSW Estuarine Macrophytes_240608.doc

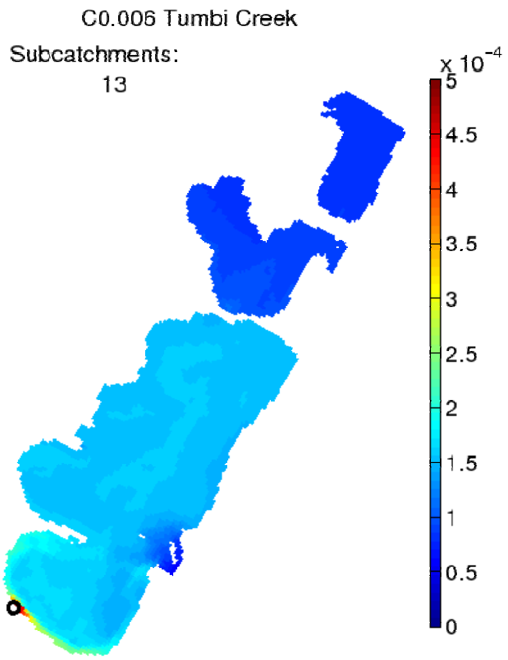
Appendix 2 – Discharge impact of fringing subcatchments on Tuggerah Lakes



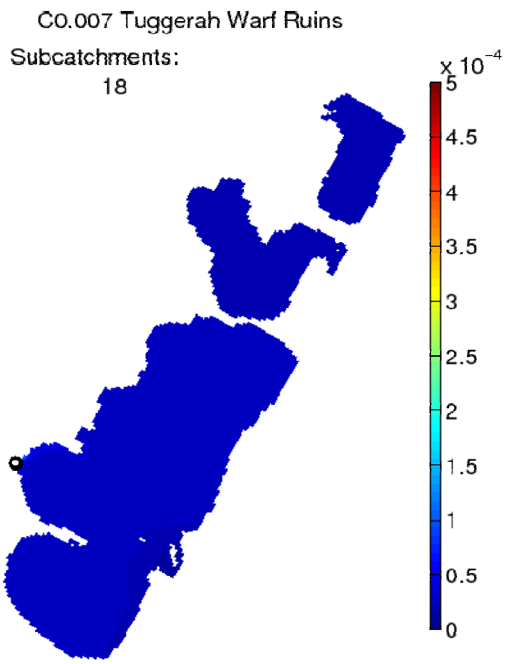
Discharge from Colongra Creek is also well-circulated throughout Munmorah and Budgewoi Lakes due to flow in the Power Station Canal. The catchment for Colongra Creek is relatively small and so concentrations are much smaller than those due to discharge from Ourimbah Creek, Wyong River and Wallarah Creek.



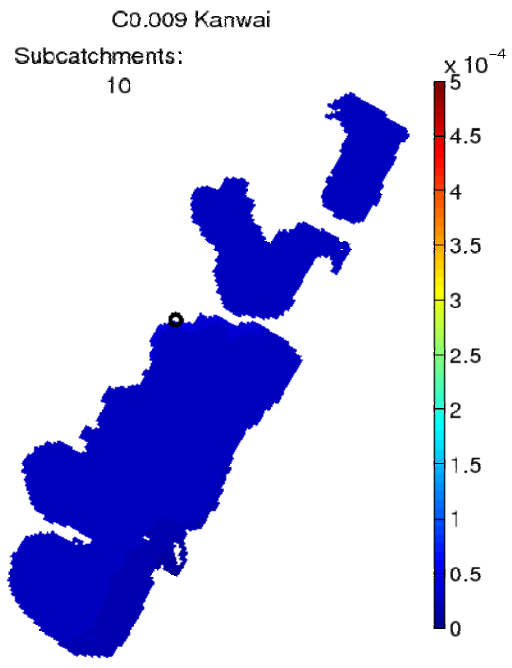
Discharge from Saltwater Creek increases concentrations near its mouth and along the coast towards Long Jetty. Except, perhaps, at its mouth, the `impact' of Saltwater Creek is substantially less than Ourimbah Creek, Wyong River and Wallarah Creek.



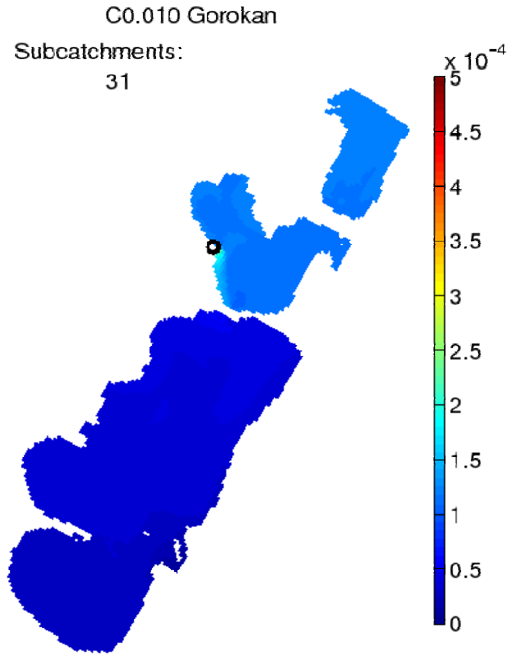
Discharge from Tumbi Creek increases concentrations near its mouth and, somewhat, throughout Tuggerah Lake. Except, perhaps, at its mouth, the `impact' of Tumbi Creek is substantially less than Ourimbah Creek, Wyong River and Wallarah Creek.



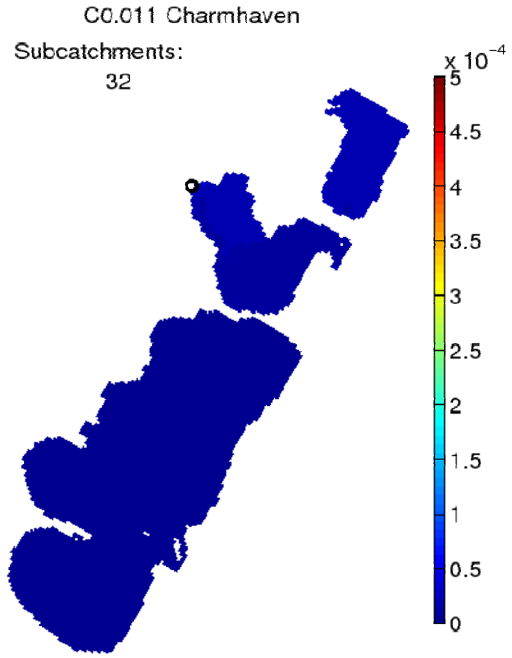
Discharge from near the Tuggerah Wharf Ruins has a low impact on the Lakes



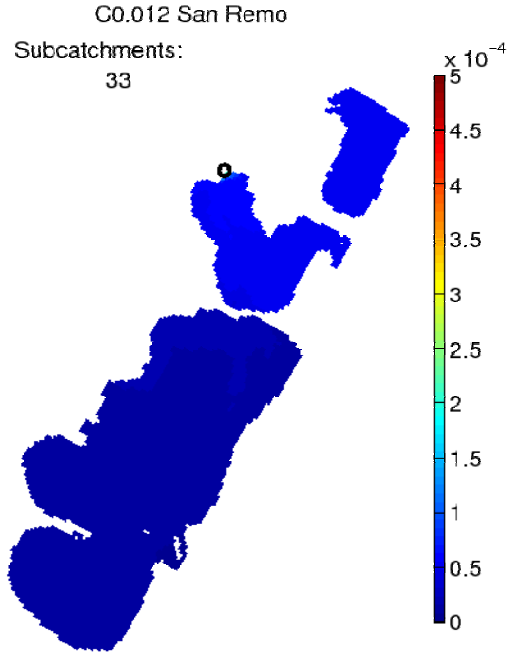
Discharge at Kanwai has a low impact on the Lakes.



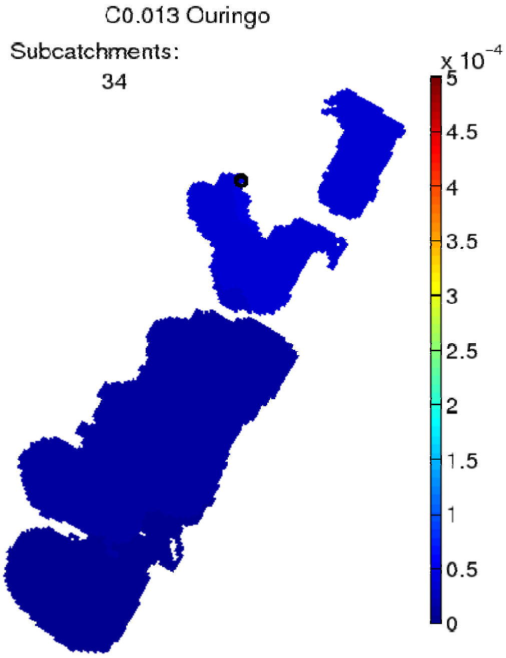
Discharge at Gorokan has an impact throughout Budgewoi Lake and Munmorah Lake. However, this is substantially less than Ourimbah Creek, Wyong River and Wallarah Creek.



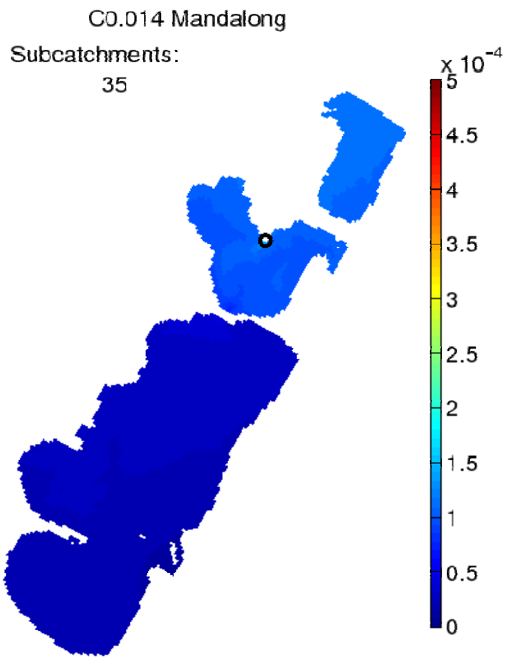
Discharge from Charmhaven has a low impact on the Lakes.



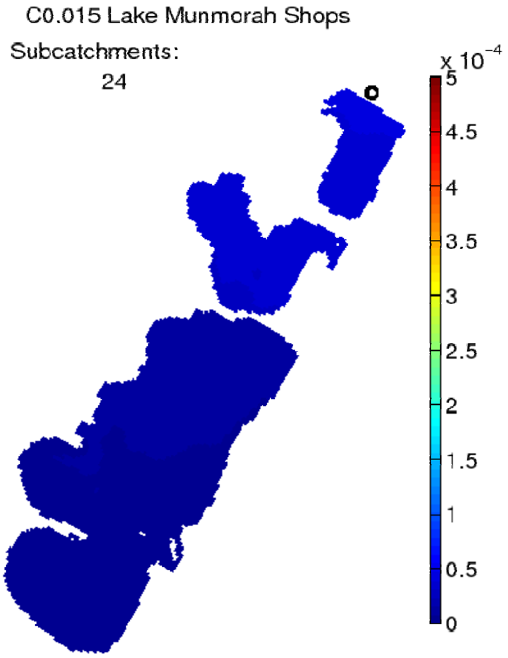
Discharge from San Remo has a greater impact than that from Charmhaven, but still has a low impact on the Lakes.



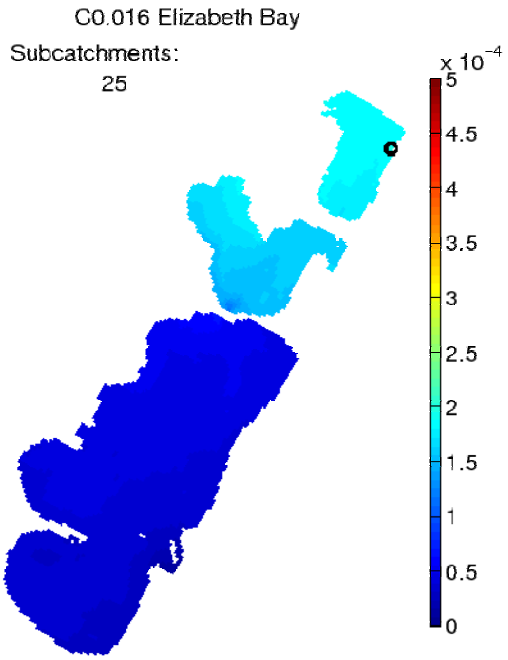
Discharge from Ouringo has a greater impact than that from Charmhaven, but still has a low impact on the Lakes.



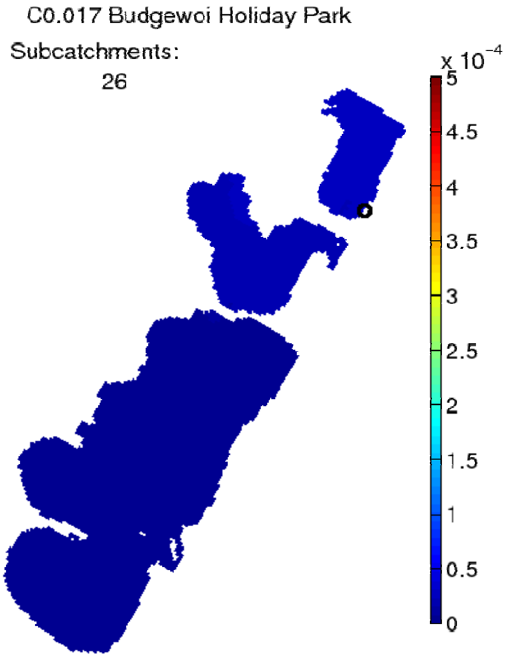
Discharge at Mandalong has an impact throughout Budgewoi Lake and Munmorah Lake. But has a low impact on the Lakes compared to Wallarah Creek, Wyong River and Ourimbah Creek.



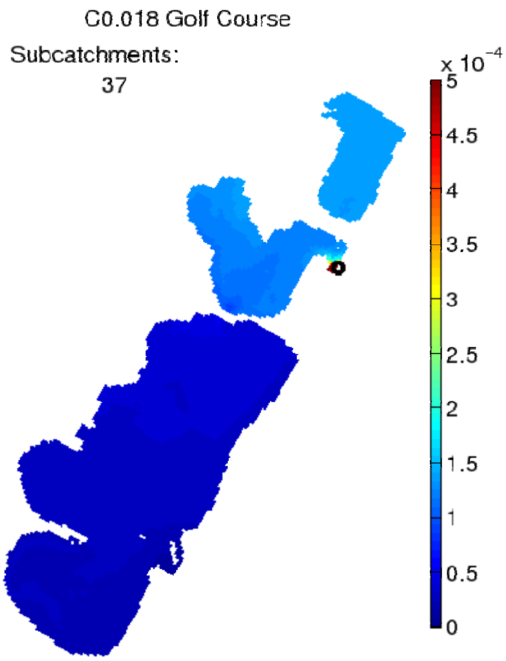
Discharge from Lake Munmorah Shops has a low impact on the Lakes.



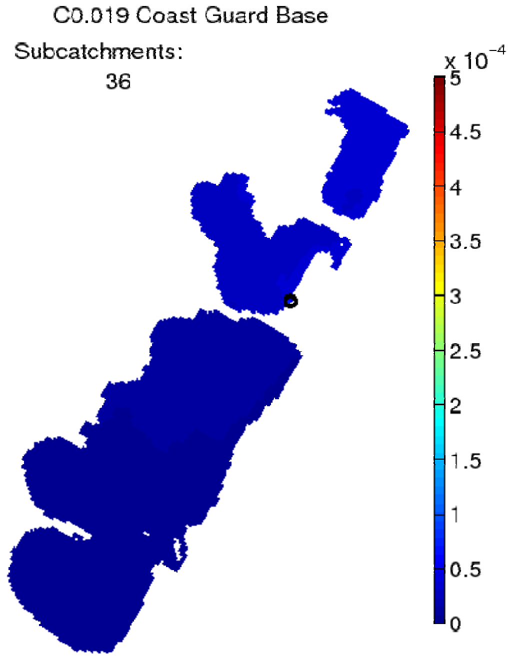
Discharge from Elizabeth Bay has an impact throughout Budgewoi Lake and Munmorah Lake. But has a low impact on the Lakes compared to Wallarah Creek, Wyong River and Ourimbah Creek.



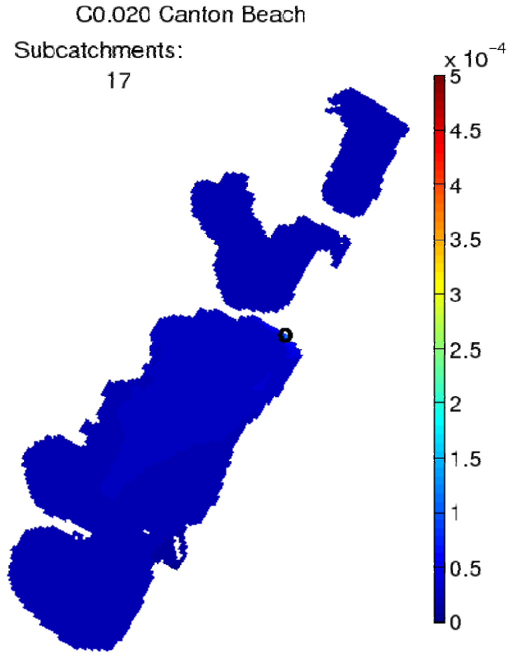
Discharge near Budgewoi Holiday Park has a low impact on the Lakes.



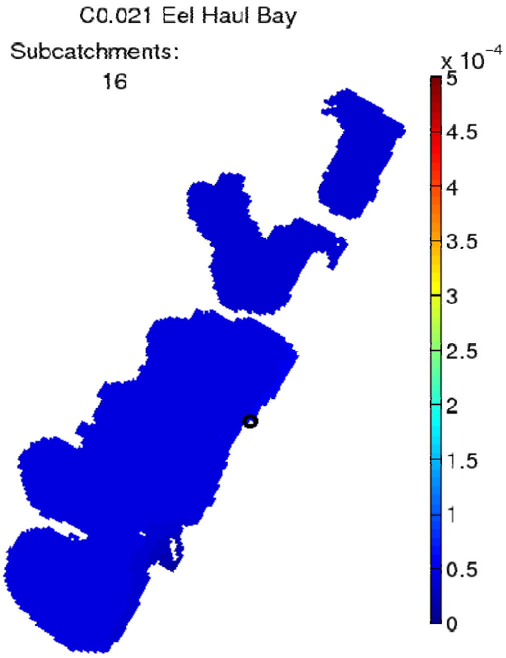
Discharge at the Golf Course has an impact throughout Budgewoi Lake and Munmorah Lake. But has a low impact on the Lakes compared to Wallarah Creek, Wyong River and Ourimbah Creek. However, the impact may be of importance in the embayment near the discharge location.



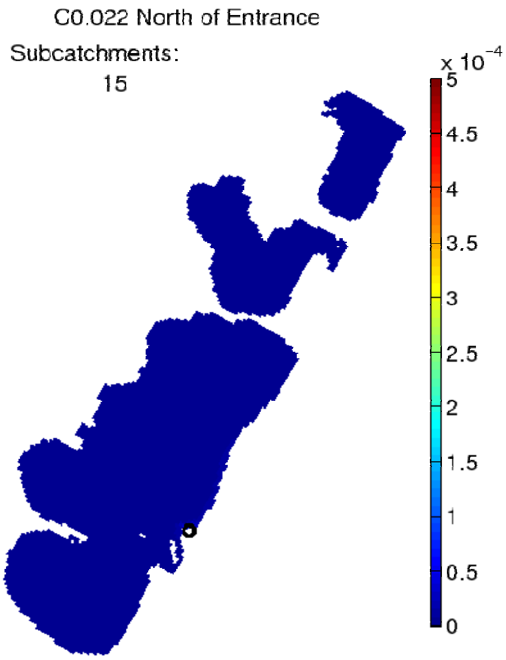
Discharge at the Coast Guard Base has a low impact on the Lakes.



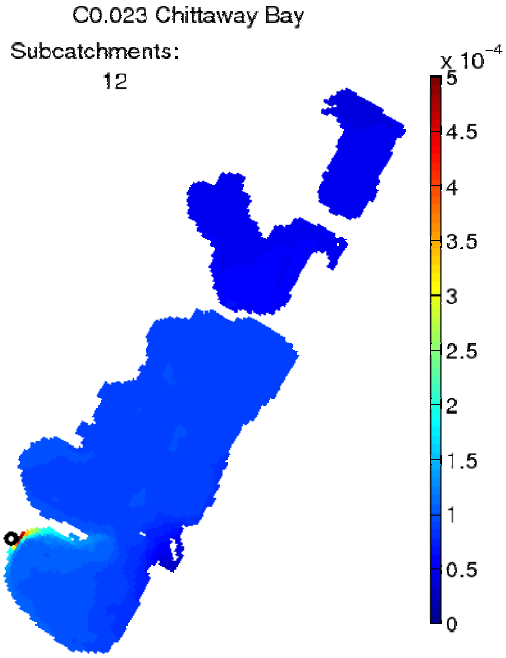
Discharge at Canton Beach has a low impact on the Lakes



Discharge from Eel Haul Bay has a low impact on the Lakes



Discharge from north of The Entrance has a low impact on the Lakes



Discharge from Chittaway Bay affects the nearshore but to a much lesser extent than discharge from Ourimbah Creek.