Cobaki – Terranora Broadwaters and Terranora Creek

Water Quality Assessment

Draft Report

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Prepared on behalf of Tweed Shire Council by Hydrosphere Consulting.

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Cover photo: Clockwise from top left: Aerial image of the Cobaki-Terranora Broadwater system (Source: Google Maps, 2017)

PROJECT 16-051 – TWEED RIVER ESTUARY CMP: COBAKI-TERRANORA BROADWATERS AND TERRANORA CREEK WATER QUALITY ASSESSMENT

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EXECUTIVE SUMMARY

Tweed Shire Council (TSC) monitors water quality at a number of sites in the Cobaki-Terranora Broadwater system to assess estuary health. The objective of this study is the review of water quality data collected by the program over 5 years from 2012 to 2016 to assess the following: compliance with water quality guidelines for aquatic ecosystem and human health; temporal and spatial trends; identification of the likely controlling processes (both natural and man-made); any major changes in water quality compared to the previous 5 years; and discuss the potential ecological implications and associated management considerations. A summary of key findings is provided below:

Water Quality Compliance

Overall compliance with water quality objectives for aquatic ecosystem and human health was assessed at each sample site (refer Table 5, page 13 and Figure 8, page 14). Compliance with water quality guidelines was greatest in the lower estuary and generally deteriorated with distance upstream. Sites with an ‘A’ score achieved over 76% compliance across all parameters and were located in the lower estuary, Terranora Inlet, Terranora Creek and nexus functional zones, reflecting a generally well-flushed and healthy functioning estuarine system. Both the Cobaki and Terranora Broadwater sites (TES1 and TES5) received a “B” grade (between 66-75% overall compliance) reflecting increasing influence of urban stormwater and upstream agricultural runoff and the shallow morphology of the broadwaters affecting water clarity (susceptible to resuspension of bottom sediments through wind and wave turbulence). The upper tributaries to both broadwaters (Cobaki, Bilambil and Duroby Creeks) displayed the poorest water quality, all receiving ‘D’ grades (<50% overall compliance). In the upper tributaries frequently eutrophic conditions with poor water clarity, high levels of bacteria, low dissolved oxygen (DO) and low pH episodes indicate poor ecosystem health and a high level of disturbance from natural state.

Identified Water Quality Management Issues

Through the analysis of water quality data and assessment of spatial and temporal trends, the following management issues were identified:

- The upper tributary sites (Cobaki, Bilambil and Duroby Creeks) are susceptible to hypoxia and this is linked to high nutrient and chlorophyll *a* levels indicating eutrophic conditions and a poorly functioning aquatic ecosystem. Low DO runoff from Cobaki Creek also appears to be contributing to reduced DO in the Cobaki Broadwater.
- Total nitrogen (TN) concentrations were consistently elevated at the upper tributary sites. The data suggest that catchment import of TN to the Cobaki-Terranora Broadwater system is occurring during high flows. This is supported by previous analysis completed by ABER (2012) indicating a consistent trend through time of rural runoff impacting the aquatic ecosystem health of the estuary. The data indicate that the Banora Point WWTP is having minimal influence on nutrient concentrations in Terranora Creek. Bioavailable nitrogen (i.e. ammonium and NOx) is the primary factor influencing phytoplankton blooms in the estuary and levels of ammonium and NOx observed during 2012-2016 were elevated throughout the Cobaki-Broadwater system and particularly at the upper tributary sites.
- There was a general trend of low total phosphorus (TP) concentrations in the lower estuary increasing with distance upstream rising to a peak in the upper tributary sites. TP concentrations in the upper tributary sites were consistently high throughout all flows. There was a trend of increasing TP concentrations with flow at most sites, particularly the upper tributary sites corresponding to peaks in TSS and indicating export of TP with eroded sediment from upper catchment areas.
- Results indicate the Tweed River Estuary currently tends toward nitrogen limitation meaning that nitrogen (particularly in bioavailable forms) is a key risk factor in development of phytoplankton blooms and related impacts (e.g. increased turbidity, fluctuation in DO, disruption of chemical and biological processes etc.).

- The upper tributaries of the Cobaki Terranora Broadwater system (Cobaki, Bilambil and Duroby Creeks) experience relatively severe phytoplankton blooms during dry and moderate flow periods suggesting moderate eutrophication. The Cobaki and Terranora Broadwaters both experience periodic phytoplankton blooms. These results are consistent with the previous 5 years monitoring and indicate ongoing trends.
- The Cobaki and Terranora Broadwaters and the upper tributaries experience poor water clarity (i.e. high total suspended solids) during most flow conditions. Erosion of sediments from the catchment during runoff events, resuspension of bottom sediments and in some locations algal blooms all contribute to reduced clarity.
- Currently, enterococci levels in the Cobaki-Terranora Broadwater system are in excess of human health guidelines at many sites during high flow (i.e. freshwater dominated) conditions.
- While no severe low pH events were recorded by the present study, some minor acid runoff impacts were observed emanating from the upper tributaries (Cobaki, Bilambil and Duroby Creeks). The present monitoring program design does not adequately capture high risk times (rainfall events) and it is therefore highly likely that low pH episodes in the Cobaki-Terranora Broadwater have been missed during 2012-2016. Acid sulfate soils remain a constant risk to water quality, particularly in the event of major rainfall events.

Recommended Management Actions for consideration

- Reduce nutrient inputs to the system by:
    - Reducing diffuse inputs through catchment management throughout rural areas. The focus of management is to reduce export of sediment and nutrients during rainfall/runoff events; and
    - Stormwater control and treatment in urban areas.
- It is recommended that any management actions aimed at the reduction of nutrients to the system consider both N and P.
- Management of agricultural land and drains to minimise low DO floodwaters developing and reaching the estuary.
- Reduce sediment inputs to the system by:
    - Reducing TSS in catchment runoff during high and moderate flows by employing soil conservation strategies;
    - Reducing phytoplankton blooms which will also reduce TSS concentrations in the middle and upper reaches of the estuary; and
    - Stormwater control and treatment in urban areas.
- Manage the human health risk of exposure to faecal contamination by:
    - Community education about high risk periods and locations for swimming;
    - Investigate sources of pathogen inputs (i.e. human or animal sources and key locations) to better assess the risk to human health and to direct management effort to specific areas of the estuary;
    - Stormwater controls in urban areas and education regarding pet droppings, illegal sewer connections etc.; and
    - Restricting direct stock access to waterways.

- Continued management effort working with floodplain landholders to reduce acid runoff wherever possible. Management should seek to reduce acid runoff during key risk periods (i.e. following major rainfall events).

Review of the monitoring program and recommendations for improvement

Review of the existing water quality monitoring program identified key recommendations for improvement including:

1. Targeted rainfall event sampling to better assess high risk events;
2. Discontinue monitoring sites with limited value (2 sites);
3. Sampling methods - consideration of tidal state; discontinue depth profiles;
4. Sampling parameters – replace secchi disk depth with turbidity as a more reliable and comparable measure of water clarity and include analysis of ortho-phosphate; and
5. Simplified annual reporting of water quality results to the community and detailed technical analysis to occur at longer intervals (e.g. every 5 years).

CONTENTS

EXECUTIVE SUMMARY III
1. INTRODUCTION 1
  1.1 Study Area 1
    1.1.1 Functional Zones 2
  1.2 Background 2
    1.2.1 Review of water quality in the Cobaki-Terranora Broadwaters 2007 – 2011 (ABER, 2012) 2
    1.2.2 Coastal Zone Management Plan for the Cobaki and Terranora Broadwater (Australian Wetlands, 2010) 5
    1.2.3 Tweed River Estuary Ecosystem Health Monitoring Program 2000-2001 (University of Queensland, 2003) 5
2. SAMPLING PROGRAM 6
  2.1 Monitoring sites 6
  2.2 Sample Collection 9
  2.3 Rainfall data 9
  2.4 Rainfall and River Flows 11
  2.5 Tidal Influence 12
3. WATER QUALITY COMPLIANCE 12
4. WATER QUALITY RESULTS 15
  4.1 Salinity 15
    4.1.1 Spatial Trends 15
    4.1.2 Temporal Trends 15
    4.1.3 Inter-annual variation 16
  4.2 Temperature 16
    4.2.1 Spatial Trends 17
    4.2.2 Temporal Trends 17
    4.2.3 Inter-annual variation 18
  4.3 pH 18
    4.3.1 Spatial Trends 19
    4.3.2 Temporal Trends 19
    4.3.3 Inter-annual variation 20
    4.3.4 Comparison with water quality objectives 20
    4.3.5 Management Implications 21
  4.4 Dissolved Oxygen 21
    4.4.1 Spatial Trends 21

4.4.2 Temporal Trends 22
4.4.3 Inter-annual variation 22
4.4.4 Comparison with water quality objectives 23
4.4.5 Management Implications 23
4.5 Total Nitrogen 23
4.5.1 Spatial Trends 24
4.5.2 Temporal Trends 24
4.5.3 Inter-annual variation 25
4.5.4 Comparison with water quality objectives 25
4.5.5 Management Implications 26
4.6 Total Phosphorus 26
4.6.1 Spatial Trends 26
4.6.2 Temporal Trends 27
4.6.3 Inter-annual variation 27
4.6.4 Comparison with water quality objectives 28
4.6.5 Management Implications 28
4.7 Ammonium 28
4.7.1 Spatial Trends 28
4.7.2 Temporal Trends 29
4.7.3 Inter-annual variation 29
4.7.4 Comparison with water quality objectives 30
4.7.5 Management Implications 30
4.8 Oxidised Nitrogen 30
4.8.1 Spatial Trends 30
4.8.2 Temporal Trends 31
4.8.3 Inter-annual variation 31
4.8.4 Comparison with water quality objectives 31
4.8.5 Management Implications 32
4.9 Dissolved Organic Nitrogen 32
4.9.1 Spatial Trends 32
4.9.2 Temporal Trends 32
4.9.3 Inter-annual variation 33
4.9.4 Management Implications 33
4.10 TN:TP ratios 34
4.10.1 Spatial Trends 34

4.10.2 Management Implications ... 34
4.11 Chlorophyll *a* ... 34
4.11.1 Spatial Trends ... 35
4.11.2 Temporal Trends ... 35
4.11.3 Inter-annual variation ... 36
4.11.4 Comparison with water quality objectives ... 36
4.11.5 Management Implications ... 37
4.12 Total Suspended Solids ... 37
4.12.1 Spatial Trends ... 37
4.12.2 Temporal Trends ... 38
4.12.3 Inter-annual variation ... 38
4.12.4 Comparison with water quality objectives ... 39
4.12.5 Management Implications ... 39
4.13 Water Clarity (Secchi Depth) ... 39
4.13.1 Spatial Trends ... 39
4.13.2 Temporal Trends ... 40
4.13.3 Inter-annual variation ... 41
4.14 Faecal Indicator Bacteria (enterococci) ... 41
4.14.1 Spatial Trends ... 41
4.14.2 Temporal Trends ... 42
4.14.3 Inter-annual variation ... 42
4.14.4 Comparison with water quality objectives ... 43
4.14.5 Management Implications ... 43
4.15 Stratification ... 43
4.16 Wastewater Treatment Plants ... 47
4.17 TSC WWTP Effluent Monitoring 2012-2016 ... 47
4.17.1 Banora Point WWTP ... 47
5. RECOMMENDATIONS FOR ONGOING MONITORING ... 49
5.1 Targeted event sampling ... 49
5.2 Sample sites ... 49
5.3 Consideration of tidal state ... 49
5.4 Parameters ... 50
5.5 Depth profiles ... 50
5.6 Reporting of water quality results ... 50
6. REFERENCES ... 51

7. GLOSSARY AND ABBREVIATIONS 52

APPENDIX 1: WATER QUALITY COMPLIANCE MAPS 54

TABLES

Table 1: Summary of ecosystem health of Cobaki and Terranora Broadwater and catchment (Source: EHMP, IWC 2009, cited in Australian Wetlands, 2010) 5

Table 2: Details of water quality sampling sites 6

Table 3: Parameters assessed as part of this study 9

Table 4: Sample counts at each site classified by rainfall condition compared to all days from 2012-2016 ...11

Table 5: Water quality % compliance for each site broken down by parameter 13

Table 6: Details of Banora Point WWTP (Source: TSC, 2016 & Hydrosphere Consulting, 2014) 47

Table 7: Banora Point WWTP Point 1 - % compliance with EPA licence limits (red cells show non-compliances with the licence) 48

FIGURES

Figure 1: Cobaki-Terranora Broadwater study area 1

Figure 2: Conceptual model of the Cobaki-Terranora Broadwater system (Source: ABER, 2012) 4

Figure 3: Conceptual model of Cobaki-Terranora Broadwater catchment (University of Queensland, 2003)...5

Figure 4: Water Quality sampling sites within the Cobaki-Terranora Broadwater study area 8

Figure 5: Annual rainfall for each year of the study period (2012-2016) at Tweed Heads and Murwillumbah showing the long-term average annual rainfall (Source: BOM, 2016 and Silo Data Drill, 2016) 10

Figure 6: Average monthly rainfall Tweeds Heads from 2012-2016 showing the long-term averages 10

Figure 7: Daily rainfall at Tweeds Heads 2012-2016 10

Figure 8: Overall water quality compliance scores at each site 14

Figure 9: Spatial variation in salinity throughout the Cobaki Terranora Broadwater system during low, moderate and high rainfall conditions 15

Figure 10: Temporal variation in salinity during the study period 16

Figure 11: Inter-annual variation in mean estuary salinity over the study period 16

Figure 12: Spatial variation in temperature throughout the Cobaki Terranora Broadwater system during low, moderate and high rainfall conditions 17

Figure 13: Temporal variation in temperature during the study period 18

Figure 14: Inter-annual variation in mean estuary water temperature over the study period 18

Figure 15: Spatial variation in pH throughout the Cobaki Terranora Broadwater system during low, moderate and high rainfall conditions 19

Figure 16: Temporal variation in pH during the study period 20

Figure 17: Inter-annual variation in mean estuary pH over the study period 20

Figure 18: Spatial variation in dissolved oxygen throughout the Cobaki Terranora Broadwater system during low, moderate and high rainfall conditions 22

Figure 19: Temporal variation in dissolved oxygen during the study period 22

Figure 20: Inter-annual variation in mean estuary dissolved oxygen over the study period 23

Figure 21: Spatial variation in total nitrogen throughout the Cobaki Terranora Broadwater system during low, moderate and high rainfall conditions 24

Figure 22: Temporal variation in TN during the study period 25

Figure 23: Inter-annual variation in mean estuary total nitrogen over the study period 25

Figure 24: Spatial variation in total phosphorus throughout the Cobaki Terranora Broadwater system during low, moderate and high rainfall conditions 26

Figure 25: Temporal variation in total phosphorus during the study period 27

Figure 26: Inter-annual variation in mean estuary total phosphorus over the study period 27

Figure 27: Spatial variation in ammonium throughout the Cobaki Terranora Broadwater system during low, moderate and high rainfall conditions 29

Figure 28: Temporal variation in ammonium during the study period 29

Figure 29: Inter-annual variation in mean estuary ammonium over the study period 29

Figure 30: Spatial variation in Oxidised Nitrogen throughout the Cobaki Terranora Broadwater system during low, moderate and high rainfall conditions 30

Figure 31: Temporal variation in oxidised nitrogen during the study period 31

Figure 32: Inter-annual variation in mean estuary oxidised nitrogen over the study period 31

Figure 33: Spatial variation in Dissolved Organic Nitrogen throughout the Cobaki Terranora Broadwater system during low, moderate and high rainfall conditions 32

Figure 34: Temporal variation in dissolved organic nitrogen during the study period 33

Figure 35: Inter-annual variation in mean estuary dissolved organic nitrogen over the study period 33

Figure 36: Spatial variation in TN:TP ratios throughout the Cobaki Terranora Broadwater system during low, moderate and high rainfall conditions 34

Figure 37: Spatial variation in Chlorophyll *a* throughout the Cobaki Terranora Broadwater system during low, moderate and high rainfall conditions 35

Figure 38: Temporal variation in Chlorophyll *a* during the study period 36

Figure 39: Inter-annual variation in mean estuary Chlorophyll *a* over the study period 36

Figure 40: Spatial variation in total suspended solids throughout the Cobaki Terranora Broadwater system during low, moderate and high rainfall conditions 38

Figure 41: Temporal variation in TSS during the study period 38

Figure 42: Inter-annual variation in mean estuary total suspended solids over the study period 39

Figure 43: Spatial variation in Secchi disk depth throughout the Cobaki Terranora Broadwater system during low, moderate and high rainfall conditions 40

Figure 44: Temporal variation in secchi depth during the study period 40

Figure 45: Inter-annual variation in mean estuary secchi depth over the study period 41

Figure 46: Spatial variation in enterococci throughout the Cobaki Terranora Broadwater system during low, moderate and high rainfall conditions. 42

Figure 47: Temporal variation in enterococci during the study period 42

Figure 48: Inter-annual variation in mean estuary enterococci over the study period 43

Figure 49: Boxplot summaries of physico-chemical profiles at sites TES6 and TES7 (all data from 2012-2016)...45

Figure 50: Depth profiles of DO, salinity and temperature at sites TES6 and TES7 under low flow conditions on 6/6/2012...46

Figure 51: Banora Point WWTP Point 1 monitoring results from 2012-2016..48

Figure 52: Changes to location of TES12 and TES10 49

Figure 53: Lower estuary functional zone water quality compliance scores 55

Figure 54: Terranora Inlet functional zone water quality compliance scores 56

Figure 55: Terranora Creek functional zone water quality compliance scores 57

Figure 56:Nexus and Cobaki Broadwater functional zone water quality compliance scores...........................58

Figure 57: Cobaki Creek functional zone water quality compliance scores 59

Figure 58: Nexus and Terranora Broadwater functional zone water quality compliance scores 60

Figure 59: Bilambil Creek and Duroby Creek functional zone water quality compliance scores 61

1. INTRODUCTION

Water quality monitoring has been undertaken within the Cobaki-Terranora Broadwaters and Terranora Creek for a number of years to assess estuary health. The last systematic review of estuarine water quality data was completed in 2012. This assessment focuses on water quality data collected over 5 years from 2007-2011 (ABER, 2012).

The current study analyses and assesses water quality data collected since the ABER (2012) report and spans the last 5 years from 2012 to 2016. The study updates the analysis and interpretation completed by ABER (2012) to provide: an assessment of compliance with water quality guidelines for the Tweed River Estuary; an analysis of temporal and spatial trends in water quality; identification of the likely controlling processes (both natural and man-made); any major changes in water quality compared to the previous 5 years; and discussion of the potential ecological implications and management considerations. The analyses considers water quality results in terms of the overall data set as well as discretely for low, moderate and high flow conditions and separated into the five functional zones (refer section 1.1.1). This study aims to identify key processes, problems and threats to water quality.

1.1 Study Area

The Cobaki-Terranora Broadwater is a shallow water ecosystem adjoining the lower Tweed River Estuary approximately 1.5km upstream of the estuary mouth. It is located on the NSW north coast within the Tweed Shire Council (TSC) local government area (LGA). The boundary of the study area follows the topographical catchment for the Cobaki-Terranora Broadwaters as shown in Figure 1, including Terranora Creek and the lower extent of the Tweed River Estuary to the ocean entrance. A separate assessment of water quality in the Tweed River Estuary has been completed in parallel to this report.

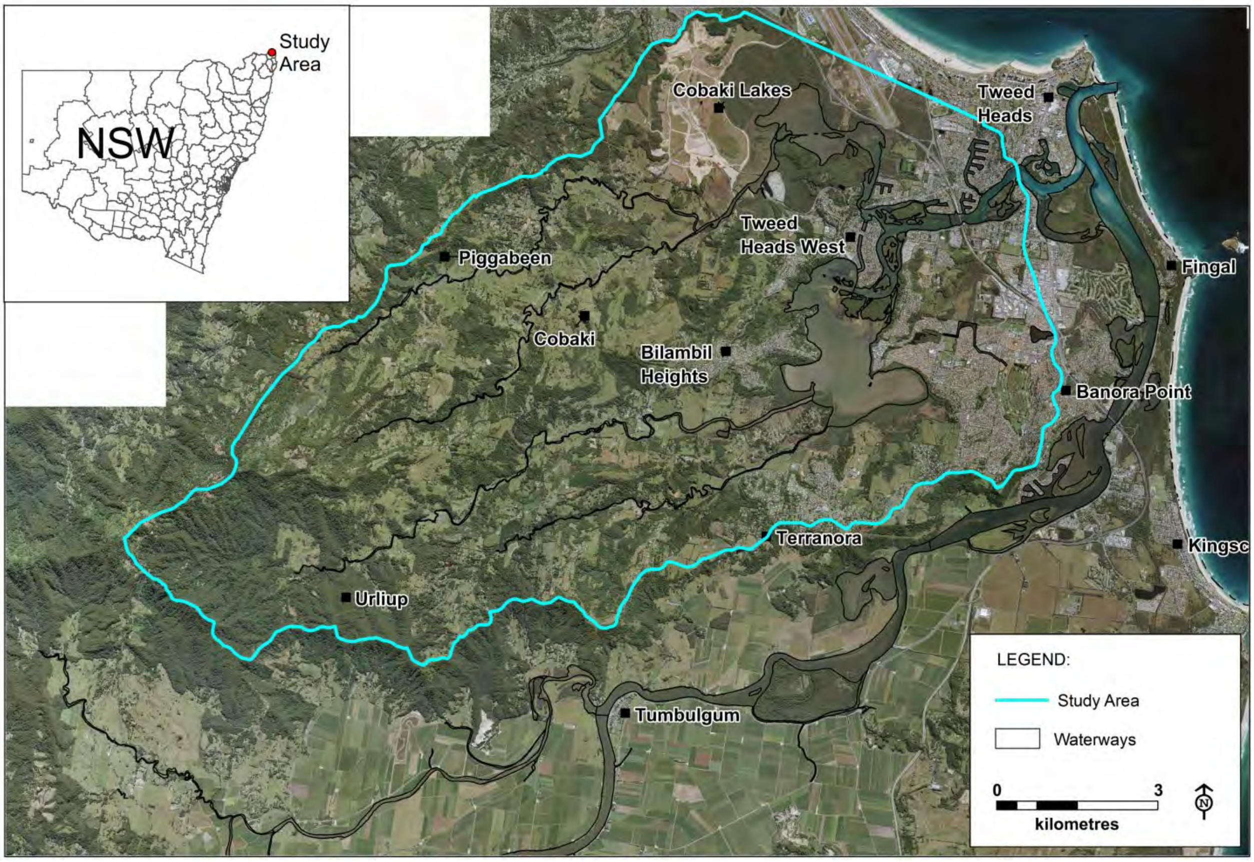


Figure 1: Cobaki-Terranora Broadwater study area

1.1.1 Functional Zones

Previous study of water quality in the Tweed River Estuary (ABER, 2012) divided the Cobaki-Terranora Broadwater system into six functional zones based on morphology, sediment type, hydrodynamics, salinity regime and water residence times. The broad functional zones described below and shown in Figure 4 are used throughout this water quality assessment to divide the study area. The zones include the ABER (2012) defined zones with the addition of Terranora Inlet and the lower tweed Estuary which forms part of the Tweed River Estuary Coastal Management Program study area. Functional zones are as follows:

- Lower estuary – from the ocean entrance to Shallow Bay, upstream to Fingal (the portion included in this study is downstream of Terranora Inlet only);
- Terranora Inlet – from the confluence of Terranora Creek with the Tweed River at Tweed Heads upstream to Boyds Bay Bridge and including Ukerebagh Passage and Tweed Heads Marina.
- Nexus – two zones with the north zone a transition between Terranora Creek and the Cobaki Broadwater and the south zone a transition between Terranora Creek and the Terranora Broadwater;
- Cobaki Broadwater – large shallow embayment (approx. 0.5-1.5m deep) bordered by Cobaki Lakes development areas to the west and the Gold Coast Airport to the north and fed by Cobaki and Piggabeen Creeks draining upstream catchments;
- Terranora Broadwater- large shallow embayment (approx. 0.5-1.5m deep) bordered by Bilambil Heights development areas to the west and Banora Point to the east and fed by Bilambil and Duroby Creeks draining upstream catchments ;
- Cobaki Creek – drains upper catchment areas providing freshwater input to the Cobaki Broadwater. Pigabeen Creek joins Cobaki Creek approx. 2.5kms upstream of the Cobaki Broadwater.
- Bilambil Creek - drains upper catchment areas providing freshwater input to the Terranora Broadwater.
- Duroby Creek - drains upper catchment areas providing freshwater input to the Terranora Broadwater.

1.2 Background

Water quality in the Cobaki-Terranora Broadwater system and broader Tweed River system is continuously monitored by TSC, and the collected data has been comprehensively assessed several times. Other water quality assessments have been carried out within the study area either as part of State-wide investigations or localised study by TSC or other stakeholders. The following section describes the available water quality studies completed in the Cobaki-Terranora Broadwater including details of the data collected, timeframes, modelling undertaken and key conclusions drawn from reporting of results. This information provides detailed information on the function of the system including seasonal changes, response to flooding, physical and biological processes, key risk factors and threats and ecological implications.

1.2.1 Review of water quality in the Cobaki-Terranora Broadwaters 2007 – 2011 (ABER, 2012)

ABER (2012) is the most recent review of estuarine water quality in the Cobaki-Terranora Broadwaters. The review assessed water quality data from 2007-2012, presented results and provided management recommendations. Key conclusions were:

- TN concentrations exceeded the ANZECC guidelines for the maintenance of aquatic ecosystems for more than 75% of the time at the estuarine creek sites. TN in the Broadwaters exceeded guidelines ~50% of the time during median flow and more than 75% of the time during high flow. TN only exceeded guidelines in Terranora Creek during high flow times.

- Total Nitrogen (TN) concentrations in the Cobaki – Terranora system are highest during high flow reflecting freshwater inputs from the estuarine creeks. There was no impact on TN concentrations due to effluent from the Banora Point STP. TN concentrations decreased with diminishing flow due to the influence of marine water and uptake by benthic microalgae.
- Total Phosphorus (TP) concentrations increase with flow. Bio-available P concentrations become very low during low flow due to biological processing and binding with sediments. There was a strong correlation between TP and suspended sediments.
- Phytoplankton productivity is generally low in Terranora Creek, due to a combination of low ambient nutrient concentrations and short residence times. Chlorophyll *a* concentrations in the creek are highest during high flows. In contrast, the Broadwaters and estuarine creeks experience moderately severe phytoplankton blooms during low to median flow conditions.
- Dissolved oxygen saturation was consistently poorest at the estuarine and Broadwater sites and best at the lower Terranora Creek and Tweed entrance sites. There was a general decrease in DO saturation with increasing flow throughout the Broadwater and Terranora Creek sites, reflecting the influence of freshwater inflows. In contrast, flow dependence was not as clear at the estuary sites most likely due to the relatively greater influence of internal processes which influence DO saturation (e.g. phytoplankton O_2 production and sediment O_2 consumption). Internal processes are more important in reaches where residence times are longer.
- High turbidity (TSS) in the Cobaki – Terranora Broadwater system occurs in response to wind / tide driven resuspension events (mainly in the Terranora Broadwater), and during high flow runoff events.
- Catchment runoff, urban runoff (particularly from construction sites) and discharge of treated sewage effluent are identified as the primary causes of poor water quality.
- Recommended management actions included: reduce catchment nutrient exports; regenerate riparian zone along estuarine creeks; reduce fine grained catchment TSS exports from rural land and urban construction sites; implement WSUD; improve performance of the Western Drainage Scheme; and reducing nutrient export through STP management (e.g. ebb tide discharge, discharge during high and median flow, reuse during low flow)

Conceptual Model of the Cobaki-Terranora Broadwater

ABER (2012) developed a conceptual model of estuarine function for the Cobaki-Terranora Broadwater based on evidence provided by the water quality study, preliminary analysis of morphometrics, biogeochemical process measurements and preliminary modelling of the estuary. Figure 2 shows the conceptual model divided into different flow conditions and four broad functional zones each with its own set of primary attributes including morphology, sediment types, salinity regime, and water residence times. The ecology and resilience to disturbance (e.g. eutrophication) of each zone varies due to interactions between these attributes (ABER, 2012). Temporal and spatial variation in water quality can be broadly explained by considering the processes represented in Figure 2. In general, the degree of internal processes and transformation of nutrients depends on the water residence times. During floods and high flow conditions when flushing times are less than 1 day, internal estuarine processes are bypassed and dissolved and particulate materials are delivered to the nearshore coastal zone. The system recovers quickly after floods to estuarine conditions due to highly efficient tidal flushing. During median flows Terranora Creek and the nexus reaches become marine dominated and the broadwaters are ¾ seawater. Light climate improves throughout the system, resulting in bioavailable nutrients being rapidly assimilated by benthic microalgae and seagrass. This leads to nutrient limitation of phytoplankton productivity, except in the estuarine creeks where recycling of nutrients occurs from light limited sediments. During the dry season the braodwaters become marine dominated and salinity in the estuarine creeks approaches ¾ seawater. Phytoplankton becomes N limited and DIN concentrations in the water column approach zero. The Broadwaters experience high turbidity events due to resuspension of sediments caused by tidal flows and wind waves (ABER, 2012).

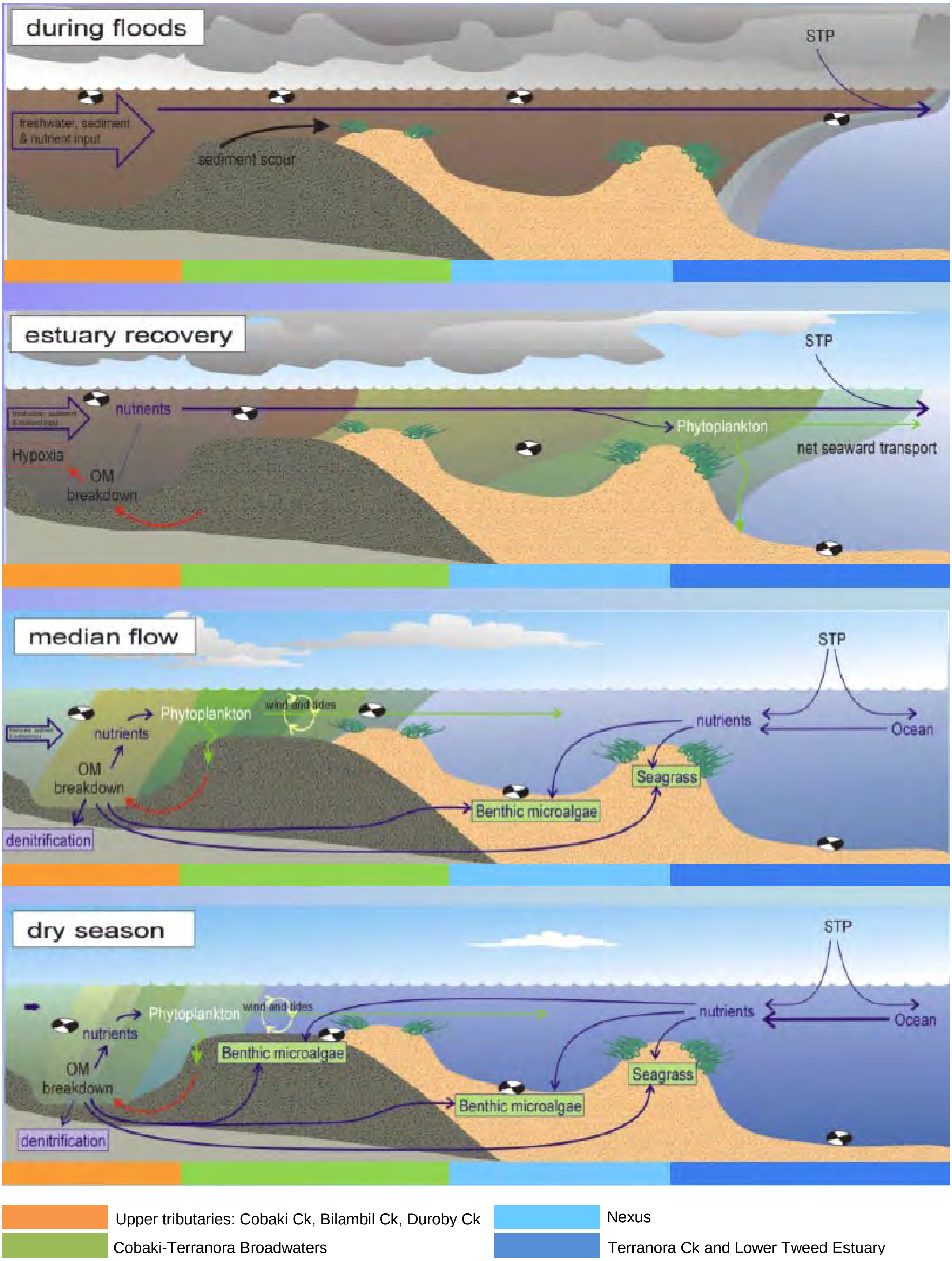


Figure 2: Conceptual model of the Cobaki-Terranora Broadwater system (Source: ABER, 2012)

1.2.2 Coastal Zone Management Plan for the Cobaki and Terranora Broadwater (Australian Wetlands, 2010)

The Coastal Zone Management Plan for the Cobaki and Terranora Broadwater (Australian Wetlands, 2010) provided a summary of ecosystem health (Table 1).

Table 1: Summary of ecosystem health of Cobaki and Terranora Broadwater and catchment (Source: EHMP, IWC 2009, cited in Australian Wetlands, 2010)

Water Body	EHMP Score	Ecosystem Health Summary	Key Ecosystem Health Issues
Piggabeen Creek	C- (Fair)	Ecological health is compromised by high levels of nutrients and the loss of streamside vegetation. There is evidence of a breakdown of nutrient cycling processes.	• There is a significant source of nitrogen likely from on-site wastewater treatment systems and/or manure from livestock within the catchment. • Clearing of riparian vegetation and proliferation of weeds can significantly alter ecosystem processes. • High silt loads – often contributed to by livestock. • Large number of fish passage barriers.
Cobaki Creek	C- (Fair)		
Bilambil Creek	C- (Fair)		
Duroby Creek	D (Poor)	Duroby Creek has the poorest health condition of all four freshwater creeks due to elevated levels of nutrients and low biological indicator scores.	• Low dissolved oxygen • Poor aquatic macroinvertebrate and fish populations.
Terranora Broadwater	D+ (Poor)	The water quality in the broadwater deteriorates during the wetter months due to sediment and nutrient inputs from the catchment. Water quality improves with distance away from the two creeks. The riparian vegetation is in good to very good condition.	The particulate load (with associated organic and nutrient load) during rainfall events is likely to be the main driver affecting water quality in the estuary.
Cobaki Broadwater	C (Fair)	The water quality in the broadwater deteriorates during the wetter months due to sediment and nutrient inputs from the catchment. The riparian vegetation is in good to very good condition.	
Terranora Creek	C+ (Fair)	Water quality is influenced by the two broadwaters and tends to improve with distance towards the Tweed River mouth. Wastewater discharges into the creek don't appear to have influenced the results of monthly water quality monitoring. However the presence of sewage related nitrogen has been mapped and occurs along the entire length of the creek. The riparian vegetation has been assessed as fair to good condition.	
Tweed River Mouth	B- (Good)	Water quality is good to excellent due to the high level of ocean exchange. This riparian condition is poor due to development along much of the river banks.	This area is beyond the extent of the catchment.

1.2.3 Tweed River Estuary Ecosystem Health Monitoring Program 2000-2001 (University of Queensland, 2003)

The University of Queensland Marine Botany Unit conducted an ecosystem health assessment of the Tweed River Estuary in 2000 and 2001. The seasonal surveys involved measuring a suite of factors including water and sediment quality; algal blooms; phytoplankton counts; seagrass depths; and estuarine and riparian vegetation mapping. They also conducted nutrient tracing studies to identify major sources. Community consultation materials were produced as part of the work to communicate findings including a report card and conceptual models (Figure 3). The 2001 Report Card assigned an overall grade of B- to the Cobaki-Terranora Broadwaters with the following summary points of ecosystem health status:

- High sediment loads;
- Low nutrient levels;
- Medium capacity for algal blooms;
- Patchy seagrass (Terranora);
- Low wastewater impacts; and
- Healthy mangrove forests.

Figure 3: Conceptual model of Cobaki-Terranora Broadwater catchment (University of Queensland, 2003)

2. SAMPLING PROGRAM

2.1 Monitoring sites

The Cobaki-Terranora Broadwater water quality monitoring program involves *in situ* monitoring and collection of samples for laboratory analysis. There are a total of 17 water quality sampling sites within the Cobaki-Terranora Broadwater study area including Terranora Inlet and the lower Tweed Estuary. Table 2 provides details of sampling sites. Figure 4 shows the location of sites within the catchment.

Table 2: Details of water quality sampling sites

Site Code	Waterway	Functional Zone	Surrounding landuse	Site Description
TES13	Cobaki Creek	Cobaki Creek	Grazing/pasture, bushland	Located approx. 1.8km upstream of the Cobaki Broadwater and just downstream of confluence with Piggabeen Creek. Drains rural catchment.
TES14	Cobaki Creek	Cobaki Creek	Grazing/pasture, bushland, cleared land, urban residential	Located approx. 400m upstream of the Cobaki Broadwater and downstream of where the drainage channel draining the Cobaki Lakes urban development site joins Cobaki Creek.
TES1	Cobaki Broadwater	Cobaki Broadwater	Bushland, grazing/pasture, cleared land, urban residential, Gold Coast Airport	Middle of the Cobaki Broadwater
TES2	Cobaki Creek	Nexus	Gold Coast Airport, Bushland, Grazing/pasture, cleared land, urban residential,	At downstream outlet of Cobaki Broadwater. Mangroves border site.
TES3	Cobaki Creek	Nexus	Urban residential, bushland, roads	Located adjacent to urban areas of Tweed Heads West. Several stormwater outlets in the vicinity.
TES15	Bilambil Creek	Bilambil Creek	Agriculture, grazing/pasture, bushland	Located approx. 2.9km upstream of the Terranora Broadwater. Drains rural catchment.
TES16	Duroby Creek	Duroby Creek	Rural residential, bushland, grazing/pasture	Located approx. 150m upstream of the Terranora Broadwater. Drains rural catchment. Some urban and rural residential development nearby.
TES5	Terranora Broadwater	Terranora Broadwater	Urban residential, bushland, roads	Middle of the Terranora Broadwater, bordered by a mixture of urban residential development and mangrove forest. Several stormwater outlets in the vicinity.
TES4	Terranora Creek	Nexus	Urban residential, bushland, roads	Located adjacent to urban areas of Tweed Heads West. Several stormwater outlets in the vicinity.
TES6	Terranora Creek	Terranora Creek	Urban residential, urban recreational, roads	Located approx. 200m upstream of the Pacific Motorway and the Banora Point discharge location. Several stormwater outlets in the vicinity.
TES7	Terranora Creek	Terranora Creek	Urban residential, urban recreational, roads	Located just downstream of the Pacific Motorway and adjacent to the Banora Point discharge location. Several stormwater outlets in the vicinity.
TES8	Tweed Heads Marina	Terranora Inlet	Urban residential, commercial and industrial, transport and communication	Located at northern end of Tweed Heads Marina. Several stormwater outlets in the vicinity.

Site Code	Waterway	Functional Zone	Surrounding landuse	Site Description
TES9	Terranora Creek	Terranora Inlet	Urban residential, urban recreational, bushland	Located in Terranora Creek approx. 200m downstream of Boyds Bay Bridge. Boat mooring location.
TES10	Terranora Creek	Terranora Inlet	Urban residential, commercial and industrial, bushland	Located at the outlet of Ukerebagh Passage approx. 500m from confluence with the tweed River. Urban and commercial areas of Tweed Heads on west side and Ukerebagh Island Nature Reserve on east side. Several stormwater outlets in the vicinity.
TWE1	Tweed River	Lower	Urban residential, commercial and industrial, pasture, bushland	Adjacent to urban and commercial areas of Tweed Heads. Just downstream on confluence with Terranora Inlet to the west and Kerosene Inlet to the east. Several stormwater outlets in the vicinity.
TES12	Tweed River	Lower	Bushland, sand/beach	Lower Tweed River adjacent to outlet of Kerosene Inlet. Urban residential and commercial areas upstream. Several stormwater outlets in the vicinity.
TES11	Jack Evans Boat Harbour	Lower	Urban residential, urban recreational, commercial and industrial	Jack Evans Boat Harbour, surrounded by parklands, urban areas and shops. Several stormwater outlets in the vicinity.

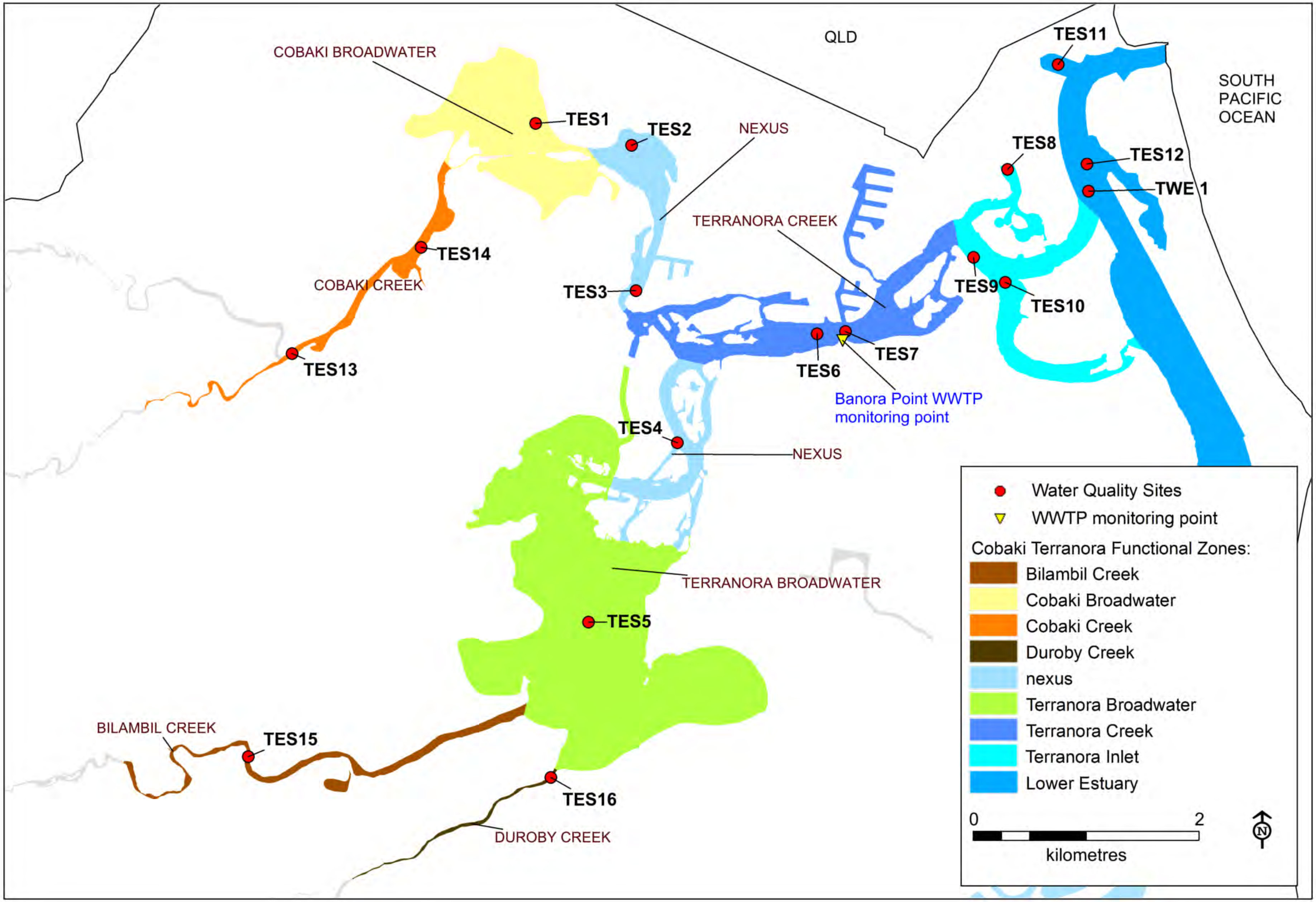


Figure 4: Water Quality sampling sites within the Cobaki-Terranora Broadwater study area

2.2 Sample Collection

Routine sampling of the Cobaki-Terranora Broadwaters has been undertaken by TSC continuously since 2007. The sampling period currently under review is from Jan 2012 – Nov 2016 (5 years). During this time sampling was carried out on a monthly basis at all sites.

No allowance is made for tidal state except at shallow sites, when timing of sampling must be according to tide to allow boat access (e.g. the shallow broadwaters). ABER (2012) discussed the error introduced by not accounting for tidal state in an estuary is significant (refer Section 2.5) and this remains as a source of error for the current sampling period.

Water quality sampling and analysis is undertaken by Tweed Laboratory Centre. All samples are collected mid-stream by boat. At each site physico-chemical properties (salinity, temperature, pH, dissolved oxygen) were measured in surface water via a handheld data unit and sonde. Depth profiles of physico-chemical properties were also measured at sites TES 6 and TES7 in Terranora Creek upstream and downstream of the Banora Point WWTP monitoring location. Samples for nutrients, total suspended solids, colour, and chlorophyll *a* were collected from a depth of approx. 20cm at each site. Dissolved organic and inorganic nutrient samples were filtered immediately through a 0.45µm cellulose acetate filter, and all samples were stored on ice until return to the laboratory for analysis. Nutrient, chlorophyll *a* and TSS analyses were undertaken by the TSC laboratory within 3 days of sample collection. Ortho-phosphorus (dissolved inorganic form of phosphorus) was not assessed as part of the monitoring program in 2012-2016 and this has created a gap in understanding of bioavailable phosphorus in the estuary and potential ecological implications. Duplicate samples were taken at some sites to assess within-site variation.

Table 3: Parameters assessed as part of this study

Group	Parameter
Physico-chemical (ecosystem health)	pH, Salinity, Dissolved Oxygen (DO), Temperature, TSS, Secchi Disc Depth, Biological Oxygen Demand (BOD), True Colour, Apparent Colour
Nutrients (ecosystem health)	Chlorophyll *a*, Total Nitrogen (TN), Nitrate (NO_3-N), Nitrite (NO_2-N),Oxidised Nitrogen (NOx) [calculated from Nitrate (NO_3-N) + Nitrite (NO_2-N)], Ammonia (NH_4-N), Total Phosphorus (TP),
Biological (ecosystem health)	Chlorophyll *a*
Pathogens (human health)	Thermotolerant coliforms, enterococci

2.3 Rainfall data

Rainfall data obtained from the Bureau of Meteorology (BOM) and Silo Data Drill at Tweed Heads (Golf Course station). The Silo data provides a patched dataset for any given location by interpolating rainfall data from nearby BOM rainfall stations. Figure 5, Figure 6 and Figure 7 show the annual, average monthly and daily rainfall totals for Tweeds Heads from 2012-2016 as compared to long term averages. Variation in annual rainfall is apparent over the period of this study with 2012, 2013 and 2015 all recording above average rainfall and below average rainfall experienced in 2014 and 2016. Average monthly rainfall for 2012-2016 (Figure 6) compared well with long-term averages, shows that the majority of rain falls in summer and autumn with driest months in late winter and early spring. Figure 6 also indicates that the last 5 years have experienced greater extremes in rainfall compared to the long-term averages with higher than average rainfall in January and June and below average rainfall in October. Despite this, there were no major flooding events occurring in the study period such as the January 2008 flood recorded by ABER (2012). Daily rainfall also shows considerable variation with maximum daily rainfall typically falling in summer (up to 200mm per day) and one uncharacteristic event on 5th June 2016 which recorded the highest daily rainfall for the sampling period of 295mm in Tweed Heads (Figure 7).

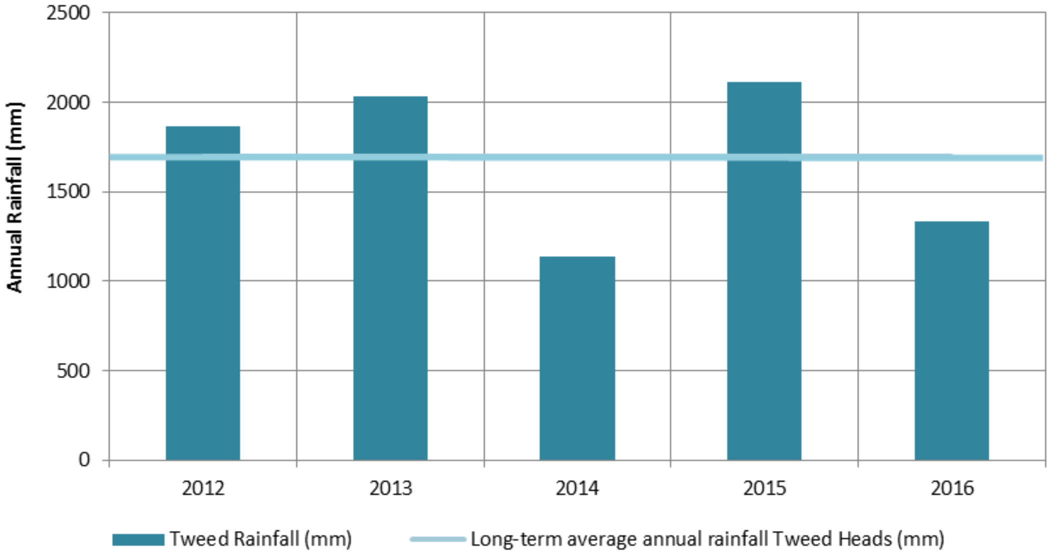


Figure 5: Annual rainfall for each year of the study period (2012-2016) at Tweed Heads and Murwillumbah showing the long-term average annual rainfall (Source: BOM, 2016 and Silo Data Drill, 2016)

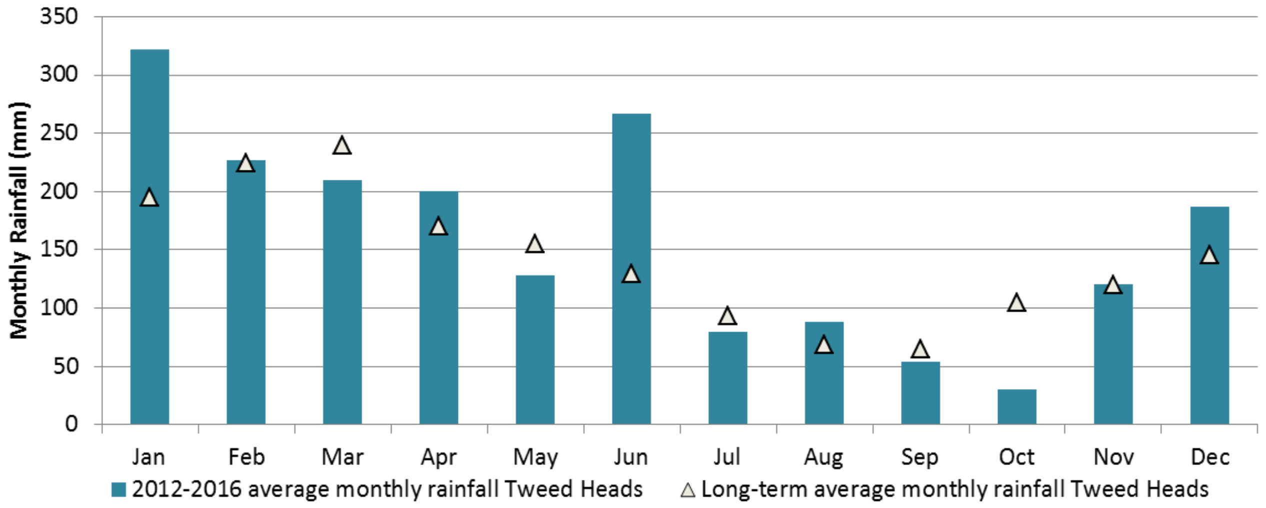


Figure 6: Average monthly rainfall Tweeds Heads from 2012-2016 showing the long-term averages

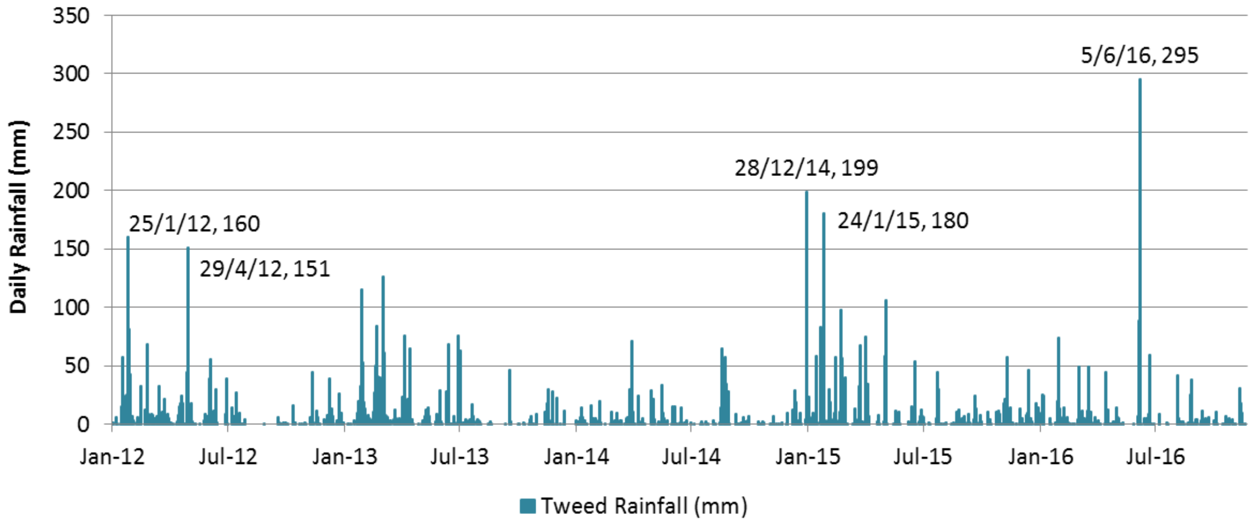


Figure 7: Daily rainfall at Tweeds Heads 2012-2016

2.4 Rainfall and River Flows

In natural river systems, water quality is supported by a variable flow regime whereby each flow component (e.g. high flows, low flows, cease to flows) fulfils particular functions to restore or maintain water quality and a range of ecological and geomorphological functions (Bunn and Arthington, 2002). For instance, low flows provide warm, clear conditions suitable for nutrient cycling and primary production. Higher flows provide dilution of ions and toxins and entrainment of a fresh supply of nutrients and carbon to support ecological functions. Cease to flow periods in temporary streams can dry out the sediments, releasing carbon and nutrients that enables new life to flourish when flows return.

Extremes in flow variability, which occur during severe droughts and major floods, often cause extremes in water quality. Although such extreme events have a low frequency of occurrence, when they do occur, they often have major consequences for water quality in aquatic systems. Water quality impacts from such extreme events can compromise the availability and suitability of water resources for its environmental values and beneficial uses.

Rainfall information was assigned to the Cobaki-Terranora Broadwater dataset retrospectively by calculating three-day rainfall leading up to each sampling event. Three-day rainfall prior to sampling is considered to be a good indicator of the occurrence of runoff generation and river flows. The samples were then categorised using the following method:

- Low: <10mL of rainfall in three days prior to sampling;
- Moderate: between 10mL and 50mL of rainfall in three days prior to sampling; and
- High: >50mL of rainfall in three days prior to sampling.

Table 4 shows the percentage of samples in each rainfall category based on this classification. Also included in the table is the percentage breakdown of rainfall conditions over the entire sampling period (2012-2016). Most samples (66%) have been collected during low rainfall conditions, with 27% collected during moderate rainfall conditions. High rainfall or ‘event’ samples comprise approximately 8% of the dataset. Based on this classification, it appears that overall the program has sampled water quality under a range of rainfall conditions that aligns well with the ratio of rainfall conditions experienced over the whole period. However, because the occurrence of ‘wet’ conditions was only around 6%, the chances of capturing these conditions were low when sites are sampled on routine monthly basis. This is evident in data collected where a total of only 4-6 ‘event’ samples were collected over the whole 5 year period (close to one event per year) (Table 4). This highlights a need to target wet events in future sampling to adequately represent water quality under a range of hydrologic conditions.

Table 4: Sample counts at each site classified by rainfall condition compared to all days from 2012-2016

Site	High	Moderate	Low
TES13	6	13	40
TES14	6	13	40
TES1	4	17	38
TES2	5	22	44
TES3	4	18	39
TES15	6	13	40
TES16	6	13	40
TES5	5	19	42
TES4	4	19	38
TES6	4	17	38

Site	High	Moderate	Low
TES7	4	17	38
TES8	6	23	63
TES9	4	17	40
TES10	4	17	38
TWE1	4	10	44
TES12	4	17	38
TES11	4	17	38
TOTAL no. samples	**80**	**282**	**698**
% of total samples	**8%**	**27%**	**66%**
% of all days 2012-2016	**6%**	**20%**	**74%**

2.5 Tidal Influence

Tidal influence and its constant changes affect water temperature, salinity, turbidity and to some extent, nutrients. The timing of sampling relative to the tidal cycle can dramatically affect results of a fixed site sampling program. ABER (2012) noted that the Cobaki-Terranora Broadwater system is tidal and the results of that study were subject to considerable error since the sampling time did not consider the state of tide. The current study which does not account for tidal state is subject to the same level of error. As time of sample collection was not recorded, it is not possible to correct for this error.

3. WATER QUALITY COMPLIANCE

Compliance was measured against water quality objectives for the Tweed River (Estuaries) (OEH, 2016). Compliance was assessed for a key range of indicators against the objectives for aquatic ecosystem health (pH, dissolved oxygen, total suspended solids, total nitrogen, total phosphorus and chlorophyll *a*) and human health (enterococci).

Percentage compliance is defined as the percentage of samples that achieved the guideline value over the measurement period (2012-2016). The term 'percentage compliance' with water quality guidelines has been used to gain a relative and absolute indication of water quality at a site. Mapping of % compliance for sites within each functional zone was also undertaken to assess spatial trends and assist is identifying potential sources of water quality issues in the catchments by examining compliance in relation to adjacent and upstream catchment characteristics such as land use, vegetation coverage and potential point and non-point sources.

Figure 8 shows the overall compliance scores at each site (created by the average of compliance score across all parameters); Table 5 presents the percentage compliance for each site broken down by parameter; functional zone maps showing results at each site are included in Appendix 1. Further analysis of compliance with water quality guidelines is undertaken in Section 4 in relation to rainfall events, river flows and temporal trends. Compliance with water quality guidelines was greatest in the lower estuary and generally deteriorated with distance upstream.

Sites with an ‘A’ score achieved over 76% compliance across all parameters and were located in the lower estuary, Terranora Inlet, Terranora Creek and nexus functional zones, reflecting a generally well-flushed and healthy functioning estuarine system. Levels of TSS and enterococci occasionally exceeded guidelines (<75% compliance) in Jack Evans Boat Harbour (TES11), lower estuary (TES12), Tweed Heads Marina (TES8) and Terranora Creek sites TES6 and TES7 and this was associated with rainfall events indicating stormwater inputs. TSS also occasionally exceeded guidelines (<75% compliance) in Terranora Inlet sites TES9 and TES10 and this was also associated with rainfall events indicating stormwater inputs. TSS, TN and chlorophyll *a* were occasional issues for compliance in the nexus zone site TES2, reflecting increased pressure from catchment and upstream sources and reduced flushing capacity. TSS and enterococci were occasional issues at nexus site TES4 and this was also associated with stormwater runoff from nearby urban areas.

Both the Cobaki and Terranora Broadwater sites (TES1 and TES5) received a “B” grade (between 66-75% overall compliance) reflecting increasing influence of urban stormwater and upstream agricultural runoff and the shallow morphology of the lakes affecting water clarity. TSS was particularly elevated at both Broadwater sites (achieved guidelines only 29% of time in Cobaki Broadwater and only 11% of the time in the Terranora Broadwater). Nutrients, enterococci and chlorophyll *a* achieved aquatic ecosystem guidelines <75% of the time or less in both braodwaters. DO was also occasionally a problem in the Cobaki Broadwater.

The upper tributaries to both broadwaters (Cobaki, Bilambil and Duroby Creeks) displayed the poorest water quality, all receiving ‘D’ grades (<50% overall compliance). High nutrient, TSS and chlorophyll *a* concentrations were significant issues at these sites indicating frequent eutrophication. Low DO was also a frequent occurrence at all sites except TES14. High enterococci levels and low pH were also recurring issues, achieving guidelines less than 75% of the time. The results indicate poor ecosystem health and a high level of disturbance from natural state at these sites and also reflects catchment impacts and reduced tidal flushing.

Table 5: Water quality % compliance for each site broken down by parameter

Functional Zone	Site	DO	pH	TSS	TN	TP	Chla	Enterococci	Average score	Overall compliance rating
Lower Estuary	TES11	98	100	66	90	92	93	69	87	A
	TES12	97	100	68	90	92	92	66	86	A
	TWE1	97	98	76	91	91	95	92	91	A
Terranora Inlet	TES10	100	100	56	86	93	92	80	87	A
	TES9	98	100	66	92	95	89	77	88	A
	TES8	98	100	71	88	91	83	71	86	A
Terranora Creek	TES7	98	100	61	90	92	88	67	85	A
	TES6	99	100	66	90	93	88	76	87	A
Nexus	TES4	95	100	46	89	87	85	74	82	A
Terranora Broadwater	TES5	89	100	11	67	53	68	72	66	B
Duroby Creek	TES16	39	71	7	10	31	41	76	39	D
Bilambil Creek	TES15	31	61	56	0	19	49	73	41	D
Nexus	TES3	87	100	51	84	89	89	82	83	A
	TES2	85	97	48	75	82	69	78	76	A
Cobaki Broadwater	TES1	69	100	29	71	69	66	73	68	B
Cobaki Creek	TES14	76	73	34	19	17	34	66	46	D
	TES13	31	69	20	10	22	36	68	37	D

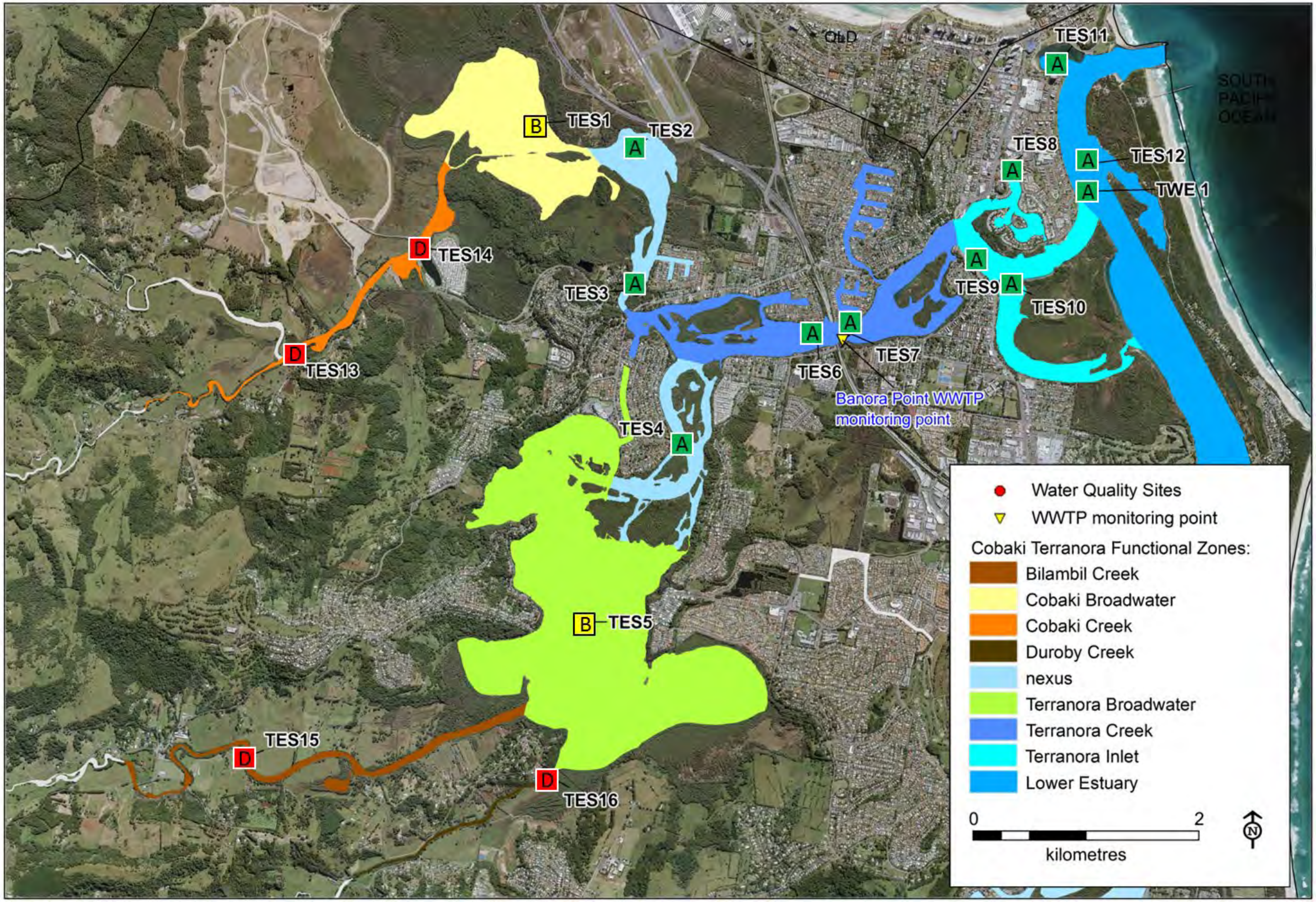


Figure 8: Overall water quality compliance scores at each site

4. WATER QUALITY RESULTS

4.1 Salinity

Salinity is a measure of dissolved salts in water. The salinity distribution within coastal waterways reflects the relative proportion of fresh water supplied by rivers, and marine water supplied by exchange with the ocean. Salinity of estuaries usually decreases away from the ocean (which is typically ~35ppk), although low flow periods combined with evaporation sometimes causes the salinity to rise in the upper sections of an estuary. Salinity is a dynamic indicator of the nature of the exchange system. Due to the density variation associated with salinity, it affects mixing and circulation patterns in an estuary and is important in some chemical processes (e.g. dissolved oxygen levels and nutrient cycling). Salinity is also an important ecological parameter in its own right with most aquatic organisms functioning optimally within a narrow range of salinity.

4.1.1 Spatial Trends

During low and moderate flow conditions salinity was highest at the lower tweed Estuary, Terranora Inlet, Terranora Creek and nexus sites indicating efficient tidal flushing of these reaches. Both Cobaki and Terranora Broadwaters showed slightly lower salinities, and salinity was significantly lower at the upstream tributary sites (Cobaki, Bilambil, and Duroby Creeks, Figure 9). The highest salinities were consistently recorded during low flow conditions when tidal influence was greatest and freshwater flows minimal. Salinity decreased with flow at all sites, and most markedly at the upstream tributary sites which tended to be completely fresh during high flow, but rapidly became brackish during moderate to low flow. These results are consistent with previous monitoring results (ABER, 2012).

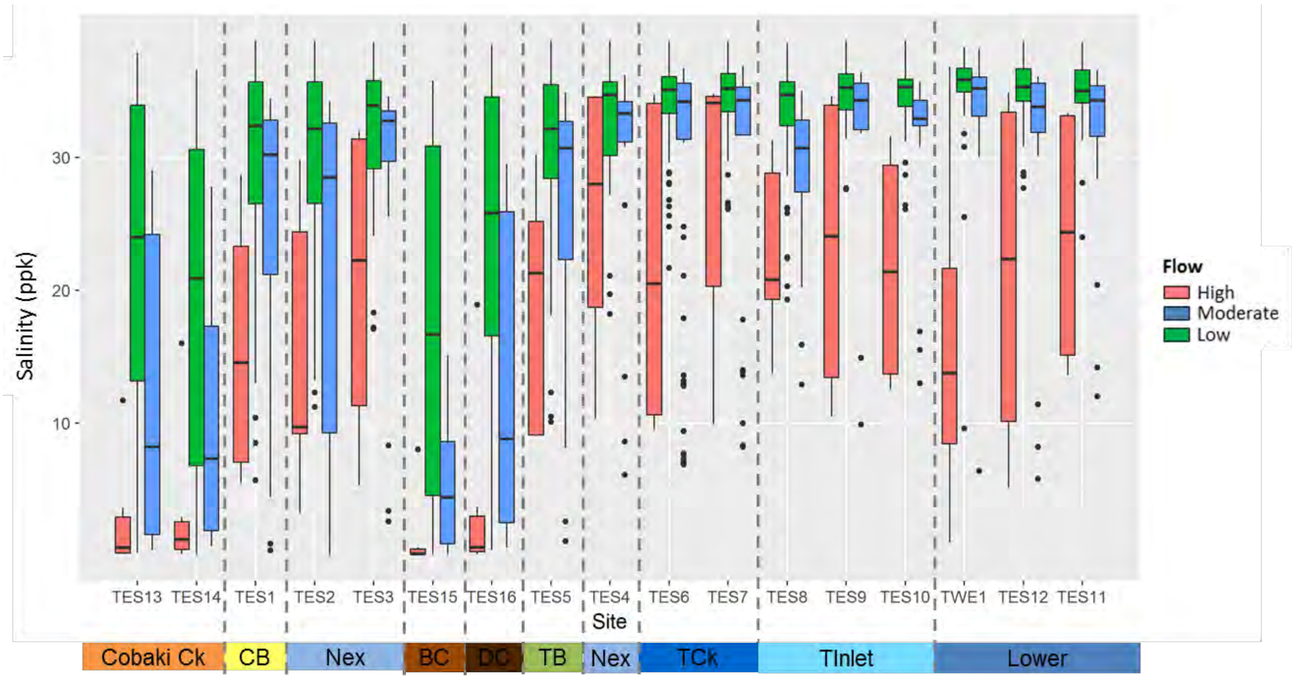


Figure 9: Spatial variation in salinity throughout the Cobaki Terranora Broadwater system during low, moderate and high rainfall conditions

4.1.2 Temporal Trends

Seasonal trends in salinity are less clear than other indicators, due to the variable nature in the timing, duration and magnitude of freshwater runoff events and tidal state (Figure 10). Freshwater influence increases greatly throughout the system during the summer-autumn wet season, which is particularly obvious in 2013, 2015 and 2016 shown by sharp decreases in salinity levels across most sites. Recovery of brackish estuarine conditions occurs rapidly throughout the system as the frequency and severity of runoff events diminishes into the winter-spring dry season. The upstream tributary sites tended to have longer periods of freshwater during the wet season. These trends were consistent with ABER (2012).

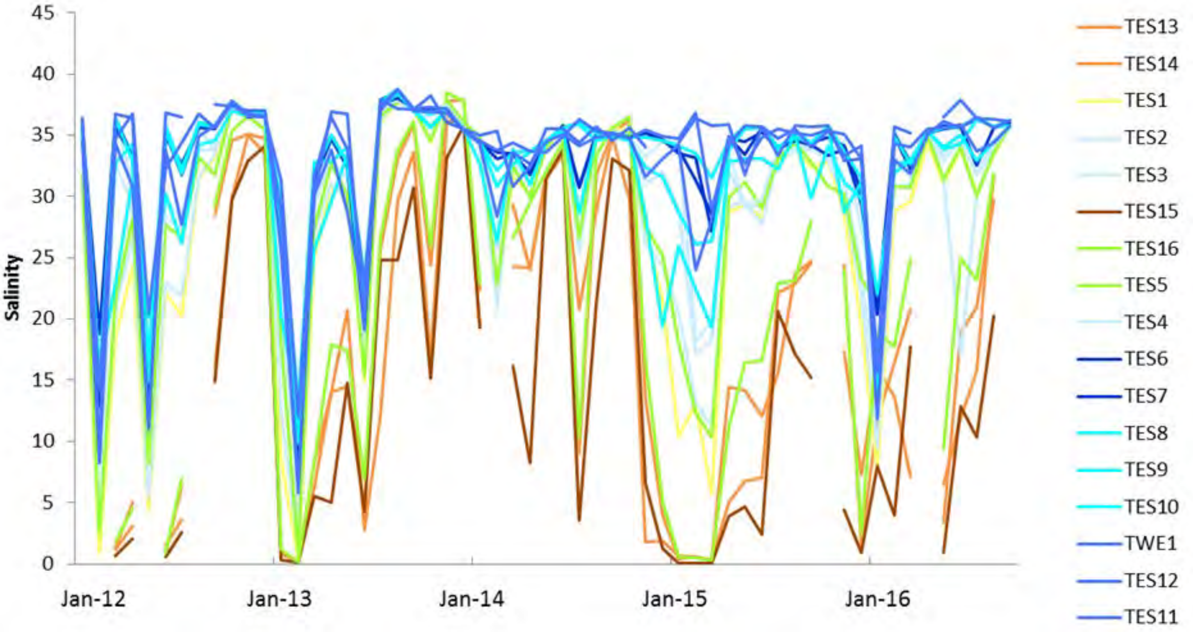


Figure 10: Temporal variation in salinity during the study period

4.1.3 Inter-annual variation

All years from 2012-2016 displayed the seasonal progression between lower salinities during the summer-autumn months and higher salinities during the late spring-early summer months (Figure 11). The greatest inter-annual variability occurred during summer and autumn, reflecting variation in rainfall and river flows associated with the wet season. High variability also occurs in the early winter months reflecting the occurrence of unusually high rainfall events in winter from time to time (e.g. July 2013). These trends were consistent with ABER (2012).

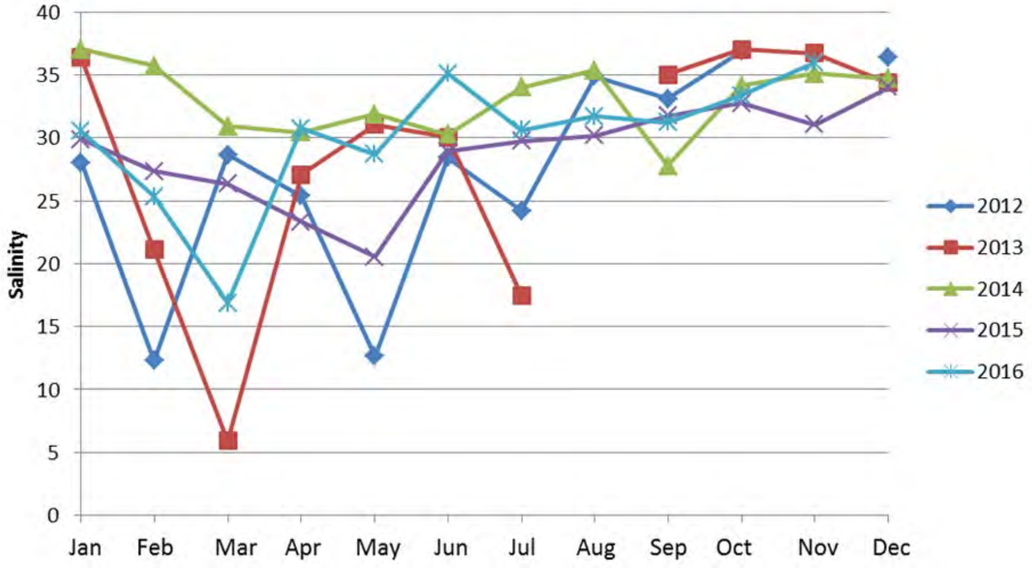


Figure 11: Inter-annual variation in mean estuary salinity over the study period

4.2 Temperature

Water temperature regulates ecosystem functioning both directly through physiological effects on organisms, and indirectly, as a consequence of habitat loss. Many ecosystem processes are affected by temperature including photosynthesis, aerobic respiration, nutrient cycling, and the growth, reproduction, metabolism and the mobility of organisms. Water is more likely to become anoxic or hypoxic under warmer conditions because of increased bacterial respiration and a decreased ability of water to hold dissolved oxygen. Stratification is also more likely with warmer temperatures and hence bottom layers are more at risk of low DO conditions.The major seasonal cause of water temperature change is due to the change in the amount of sunlight reaching the earth in addition to climate factors, currents and local hydrodynamics. Temperature in surface waters varies during the day and tends to be highest in the late afternoon as the sun sets, and coolest in the early hours of the morning.

4.2.1 Spatial Trends

Spatial trends in temperature were highly influenced by flow conditions at the time of sampling and there was a distinct difference between the upstream tributary sites and the lower estuary sites (Figure 12). At the upstream tributary sites (Cobaki, Bilambil, and Duroby Creeks) temperatures tended to be cooler during high flow periods reflecting reduced residence times and freshwater flow increases and greater influence of freshwater flows at these sites. During low and moderate flows at the upstream tributaries temperatures increased reflecting increasing residence times and solar heating of surface waters. The situation was reversed at all other sites where high flows resulted in the highest temperatures, and low flows resulted in lower temperatures which likely reflects the predominance of high flows during the summer-autumn period when ambient temperatures are highest and lower flows in winter-spring when ambient temperatures are lowest.

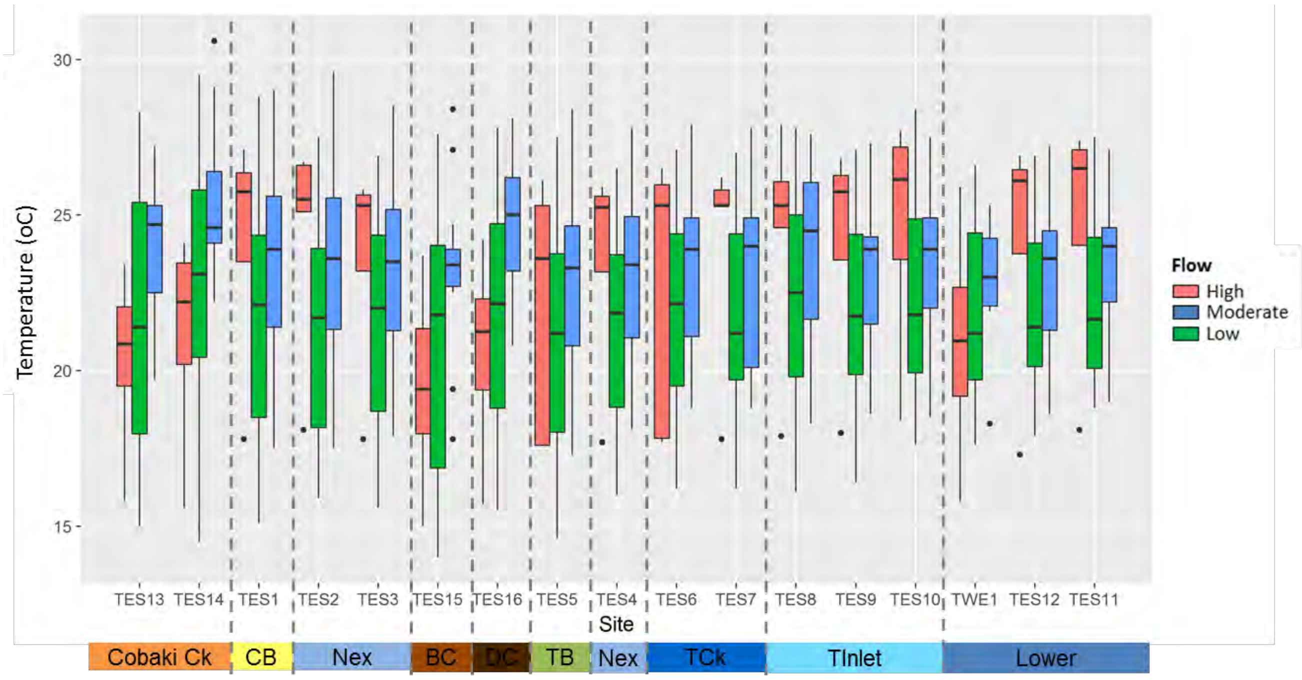


Figure 12: Spatial variation in temperature throughout the Cobaki Terranora Broadwater system during low, moderate and high rainfall conditions

4.2.2 Temporal Trends

There was a strong seasonal pattern to temperature with summer maximum water temperatures reaching 29.5ºC and winter minimum temperatures reaching 14ºC (Figure 13). The variation in temperature was greatest in the upstream tributary sites and the Broadwaters, with less variation at the lower estuary sites. This is due to both the greater influence of rainfall and flow conditions at the tributary sites and the shallow depth of the Broadwaters making them more susceptible to solar heating and also the overriding influence of ocean water in the lower estuary moderating temperature throughout the year. These trends were consistent with ABER (2012) however temperature extremes were reduced slightly and trends were more consistent during the current period without the same degree of noise in the data observed by ABER, attributed to more significant high rainfall events during 2007-2012 compared to 2012-2016. Also, ABER (2012) reported that the Tweed Heads Marina site (TES8) was out of phase with the remaining sites showing winter maximum temperatures and spring minimums, which was not recorded by the present study.

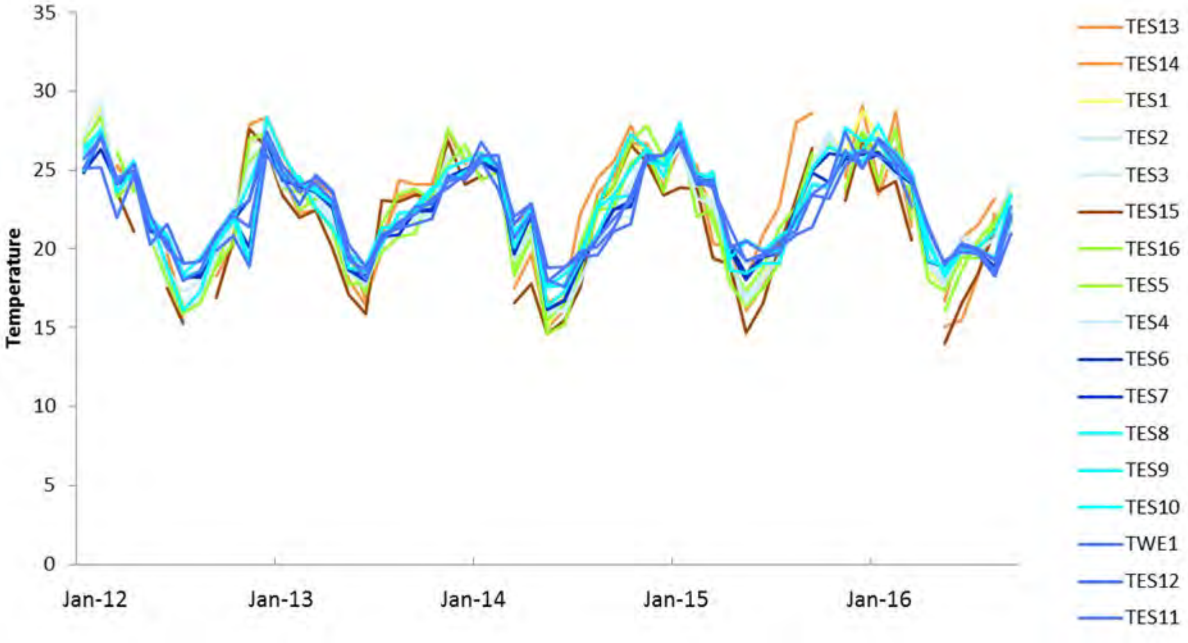


Figure 13: Temporal variation in temperature during the study period

4.2.3 Inter-annual variation

All years displayed the seasonal trend of highest water temperature during the mid- summer months to lowest temperatures during the late-winter months (Figure 14). Inter-annual variation was not significant with fairly consistent trends across all years. This was in contrast to a high level of inter-annual variability reported by ABER (2012), which was attributed to highly variable rainfall recorded during 2007-2012, particularly for 2008 when major flooding occurred.

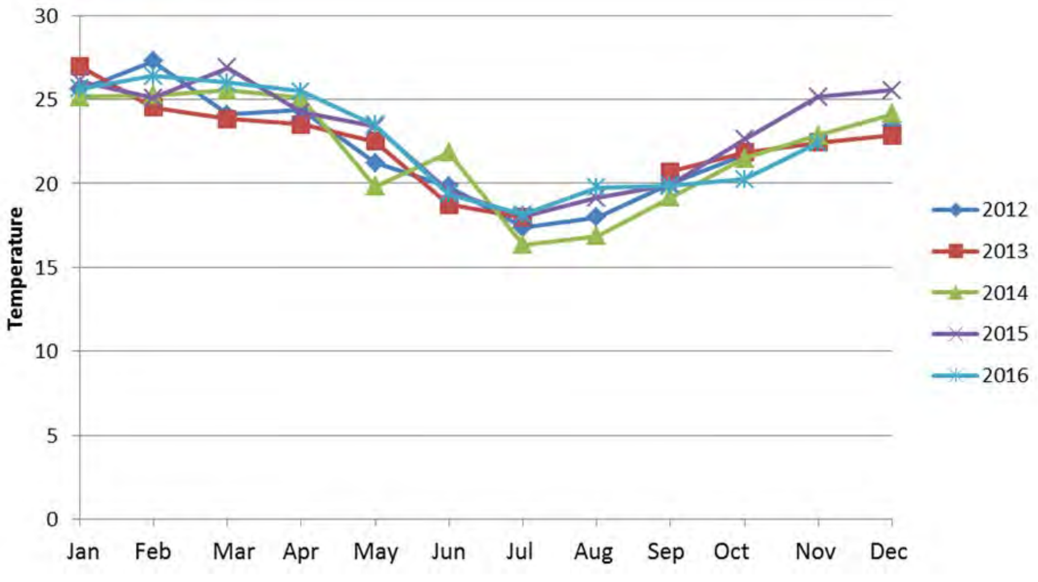


Figure 14: Inter-annual variation in mean estuary water temperature over the study period

4.3 pH

pH is a measure of how acid or alkaline a water body is on a log scale from 0 (extremely acidic) through 7 (neutral) to 14 (extremely alkaline). The pH of marine waters is close to 8.2, whereas most natural freshwaters have pH values in the range from 6.5 to 8.0. Sources of acid water in coastal systems include humic-rich groundwater (pH~ 4.5) and acid sulfate soil runoff (pH ~ 2 – 4). Most aquatic organisms and some bacterial processes require that pH be in a specified range. If pH changes above or below the preferred range of an organism (including microbes), physiological processes may be adversely affected. This is especially true for most organisms if the ambient pH drops to below ~7 or rises to above 9. Physical damage to the gills, skin and eyes can also occur when pH is sub-optimal for fish and skin damage increases susceptibility to fungal infections such as red spot disease.

4.3.1 Spatial Trends

pH generally increased moving downstream from the upper tributary sites to the river mouth reflecting the mixing of freshwater (median pH ~ 7 at TES13,14,15,16) with marine water (median pH ~8.2 at TES6,7,8,9,10,11,12) and along the estuarine gradient (Figure 15). There was a significant reduction in pH with increasing flow at all sites and this was most significant at the upper tributary sites (Cobaki, Bilambil and Duroby Creeks).

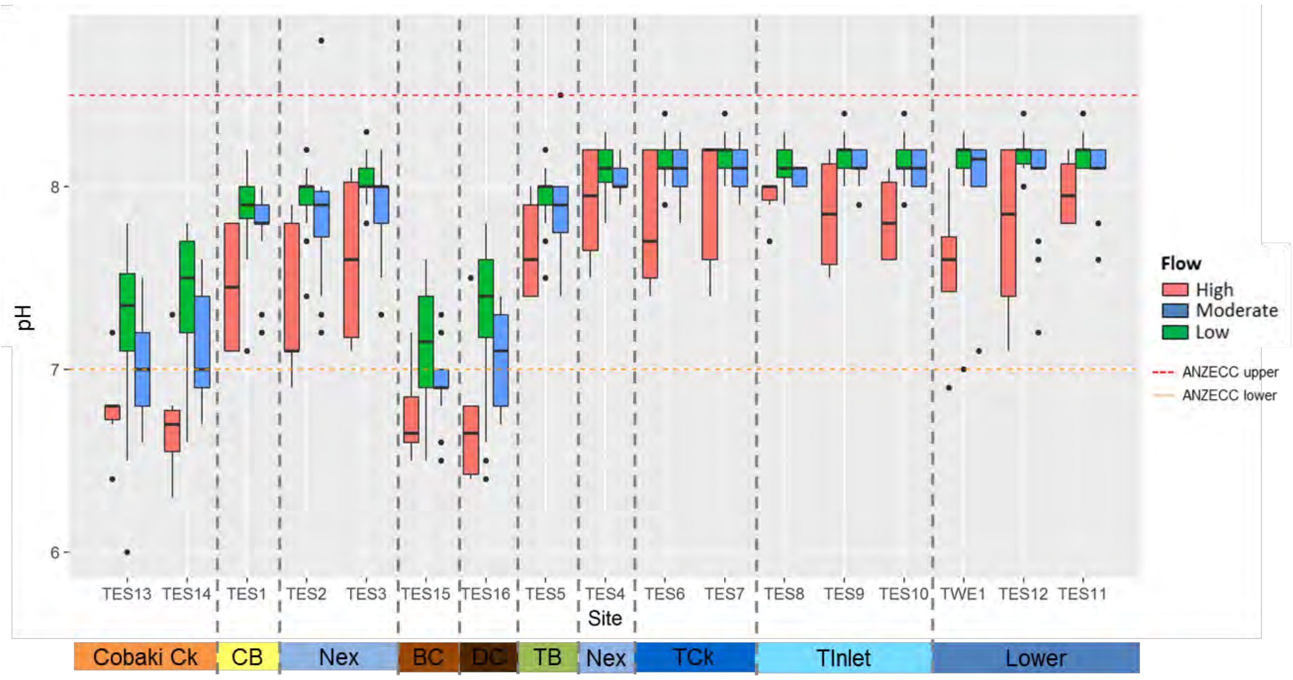


Figure 15: Spatial variation in pH throughout the Cobaki Terranora Broadwater system during low, moderate and high rainfall conditions

4.3.2 Temporal Trends

Temporal trends in pH were primarily driven by the relative importance of freshwater inflow, ocean water influence and possibly a minor influence of acid sulfate soil runoff. While there were no extreme low pH events recorded during the study period Figure 16 shows two events where pH dipped below pH 6.5 (the aquatic ecosystem threshold) at the upper tributary sites (TES13, TES15 and TES16) in June 2012 and Sep 2014. Significant rainfall preceded these events and acid sulfate soil runoff may have influenced pH levels at these sites.

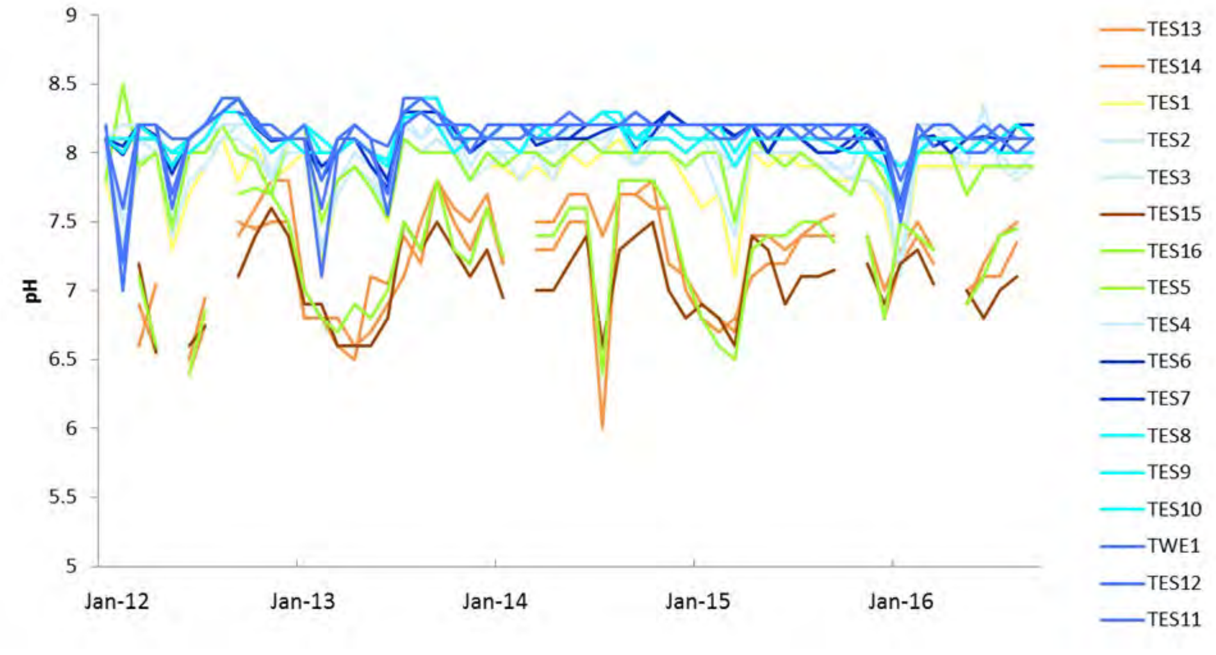


Figure 16: Temporal variation in pH during the study period

4.3.3 Inter-annual variation

Inter-annual variation in pH was minor for the study period. In contrast ABER (2012) reported significant inter-annual pH variation for the Cobaki-Terranora system and the difference is likely attributed to the greater variability in freshwater flows during the ABER reporting period.

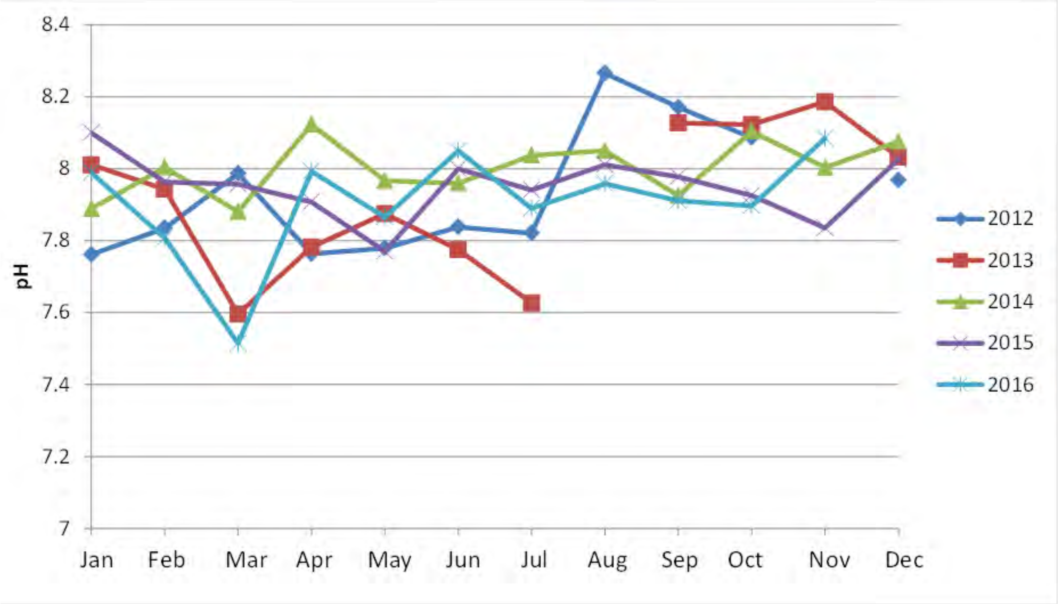


Figure 17: Inter-annual variation in mean estuary pH over the study period

4.3.4 Comparison with water quality objectives

pH levels were below the lower guideline threshold for greater than 75% of the time during high flow conditions at the upstream tributary sites (Cobaki, Bilambil and Duroby Creek sites). pH levels were also below the lower guideline threshold for greater than 50% of the time during moderate flow conditions at the Bilambil Creek. This may indicate acid sulfate soil runoff from rural lands is reducing pH below levels set to protect aquatic ecosystems during these flows. This is consistent with findings of ABER (2012) for the previous 5 years, where the Cobaki-Terranora system was indicated as a source of acid water during high flow. Compliance was achieved at all other sites during all other flow conditions.

4.3.5 Management Implications

While no severe low pH events were recorded by the present study, some minor acid runoff impacts were observed emanating from the upper tributaries (Cobaki, Bilambil and Duroby Creeks). The present monitoring program design does not target rainfall events and as discussed in Section 2.4, has not adequately captured these high risk times with particular implications for acid runoff events. It is therefore highly likely that low pH episodes in the Cobaki-Terranora Broadwater have been missed during 2012-2016. Targeted event sampling would assist in filling these gaps and better characterising these events. Nonetheless, acid sulfate soils remain a constant risk to water quality, particularly in the event of major rainfall events. Continued management effort should focus on working with floodplain landholders to reduce acid runoff wherever possible.

4.4 Dissolved Oxygen

Dissolved oxygen (DO) levels refer to the amount of oxygen contained in water, and define the living conditions for oxygen-requiring (aerobic) aquatic organisms. Any deviations from 100% saturation are largely due to biological or chemical processes in the water body which consume or produce oxygen. Oxygen consuming processes include aerobic respiration by phytoplankton, the oxidation of pyrite found in acid sulfate soils, and the biological breakdown of organic matter. Oxygen producing processes include photosynthesis by phytoplankton, seagrass and benthic algae. Most aquatic organisms require oxygen in specified concentration ranges, and DO concentration changes above or below this range can have adverse physiological effects. In extreme prolonged low DO events (e.g.DO <3mg/L or <~30% saturation), major kills of aquatic life can occur. Other effects of low DO include increased toxicity of many toxicants (e.g. lead, zinc, ammonia etc.), immune suppression in fish, and changes to nutrient cycling between sediment and water which can lead to algal blooms.

It should be noted that while DO is an important indicator for ecosystem health, when measured as part of routine sampling (i.e. 1 sample taken each month, not necessarily at the same time of day each time), interpretation of the data can be difficult due to the variability of DO throughout the day. Sampling in the early morning will typically produce lower DO concentrations when aquatic plants respire and lack of photosynthesis (in absence of sunlight) means there is a net consumption of oxygen from the water column. Conversely, sampling in the middle of the day will yield higher overall DO when plants are actively photosynthesising and producing oxygen. While an indication of overall health can be gleaned from routine samples over a long period, sampling DO over daily cycles is the only reliable method to get a handle on DO status at any particular site.

4.4.1 Spatial Trends

There was a clear spatial trend of higher dissolved oxygen saturation at the lower estuary, Terranora Inlet and Terranora Creek sites, gradually decreasing with distance upstream. DO tended to be slightly lower in the nexus zones and slightly lower again in the Broadwaters. The upper tributary sites displayed the lowest overall DO levels. There was a general decrease in DO saturation with increasing flow throughout most sites reflecting the influence of freshwater inflows. The reverse was observed at the upper tributary sites TES13, 14, 15 and 16 where high flows were associated with higher DO, possibly linked to increased water turbulence in confined streams. Moderate flows produced the lowest DO concentrations at these sites suggesting internal processes (i.e. oxygen production by plants and oxygen consumption by sediments) are more influential on DO where there is longer residence times (reduced flushing). Similar trends were reported by ABER (2012).

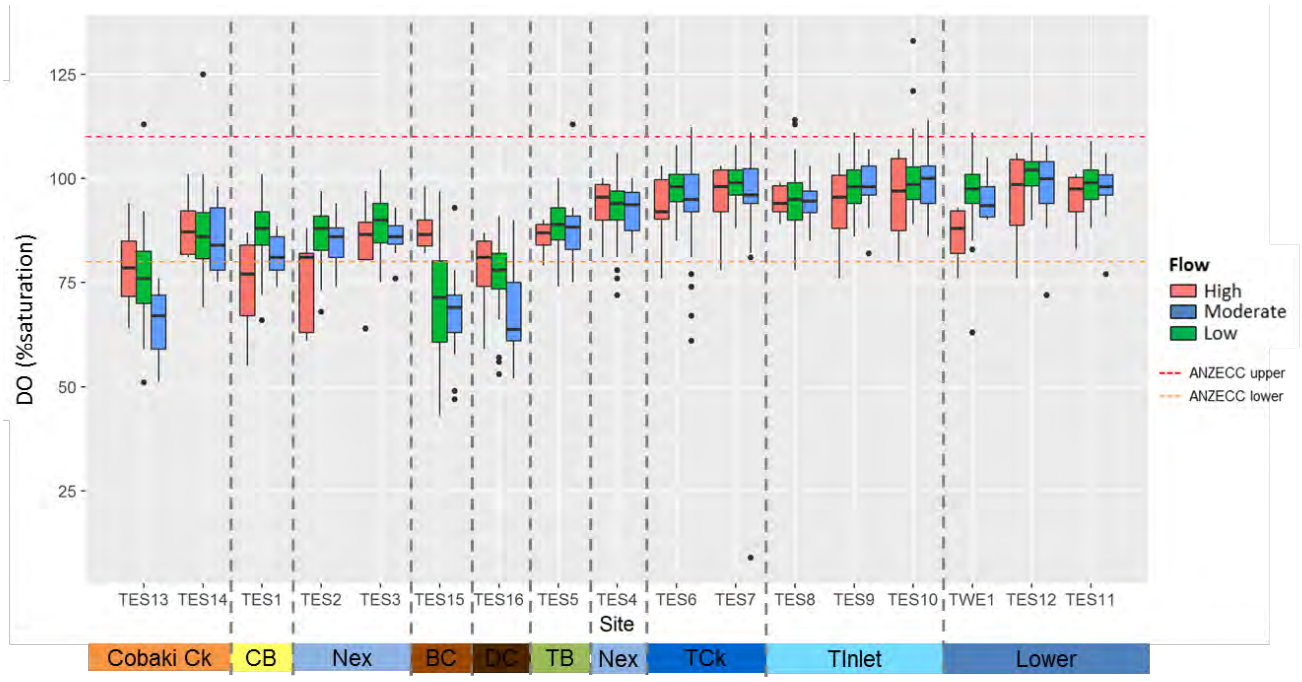


Figure 18: Spatial variation in dissolved oxygen throughout the Cobaki Terranora Broadwater system during low, moderate and high rainfall conditions

4.4.2 Temporal Trends

There were no clear seasonal trends in DO saturation observed for the study period. ABER (2012) detected a weak seasonal trend with higher DO in spring and lower DO during summer for 2017-2012.

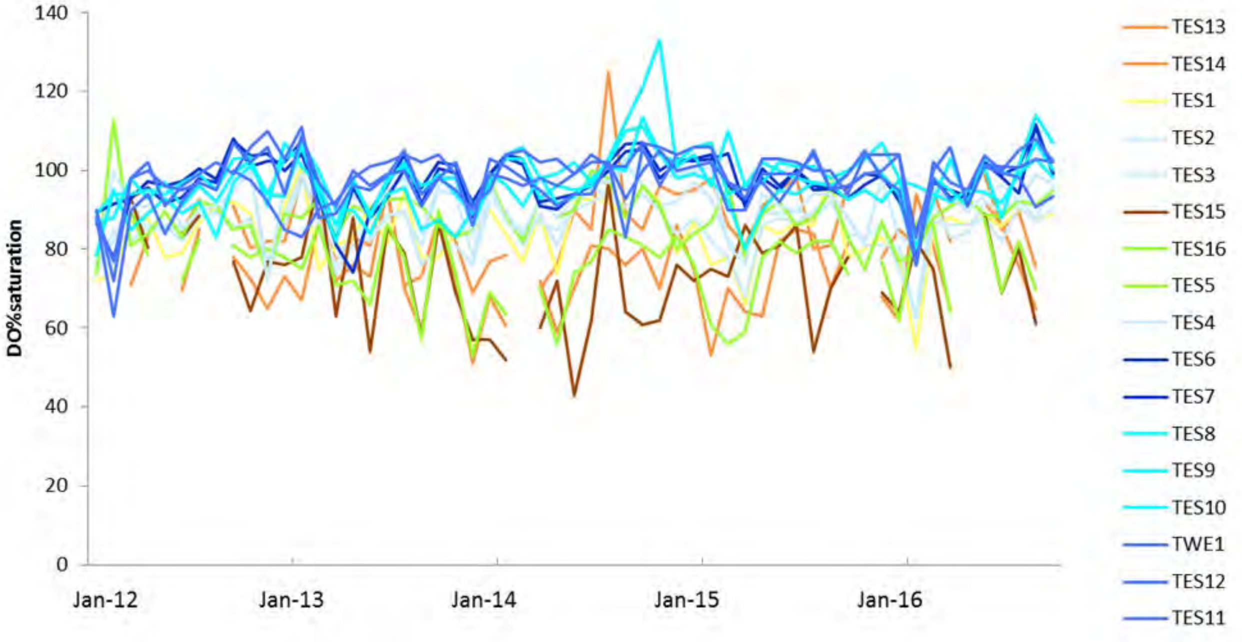


Figure 19: Temporal variation in dissolved oxygen during the study period

4.4.3 Inter-annual variation

There was some inter-annual variation in DO saturation during this study (Figure 20), particularly during the summer-autumn wet season. This is most likely due to the interaction of freshwater flows and temperature (i.e. the timing of wet season flows varied). These trends were consistent with ABER (2012), although variability was reduced during the current study period likely due to the reduced variation in rainfall.

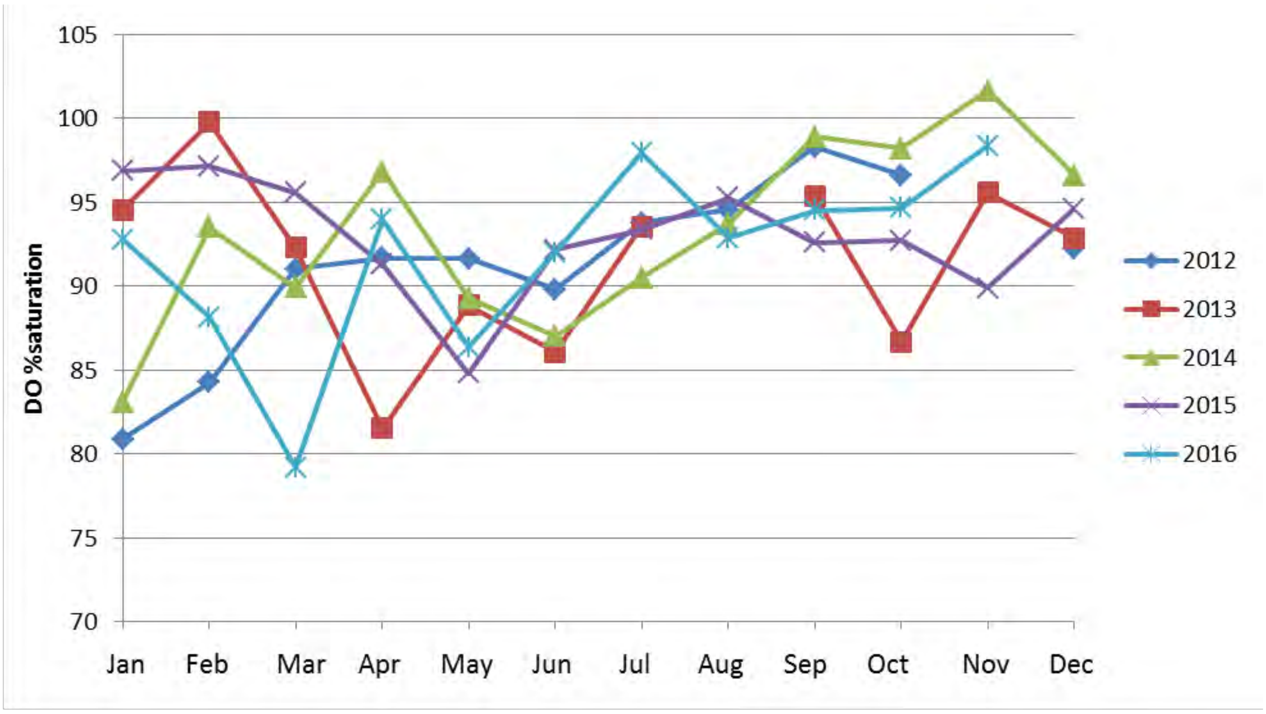


Figure 20: Inter-annual variation in mean estuary dissolved oxygen over the study period

4.4.4 Comparison with water quality objectives

DO levels were below the lower guideline threshold for greater than 75% of the time during moderate flow conditions throughout the upper tributary sites (Cobaki, Bilambil and Duroby Creeks). DO levels were also below the lower guideline threshold for greater than 50% of the time during low flow conditions at Bilambil Creek site TES15. DO levels were also below the lower guideline threshold for greater than 50% of the time during high flow conditions at Cobaki Creek site TES13 and Cobaki Broadwater site TES1indicating low DO waters being flushed from upstream tributaries to the Cobaki Broadwater during high flow. Compliance was achieved at all other sites during all other flow conditions.

4.4.5 Management Implications

Water quality results indicate that the upper tributary sites (Cobaki, Bilambil and Duroby Creeks) are susceptible to hypoxia and this is linked to high nutrient and chlorophyll *a* levels indicating eutrophic conditions and a poorly functioning aquatic ecosystem. Low DO runoff from Cobaki Creek also appears to be contributing to reduced DO in the Cobaki Broadwater. Management effort should focus on reducing nutrient inputs to the Cobaki-Terranora Broadwater system and management of agricultural land and drains to minimise low DO floodwaters developing and reaching the estuary.

4.5 Total Nitrogen

The nutrients nitrogen and phosphorus are elements, and are essential building blocks for plant and animal growth. Nitrogen exists in water both as inorganic and organic species, and in dissolved and particulate forms. Inorganic nitrogen is found both as oxidised species (e.g. nitrate (NO_3^-) and nitrite (NO_2^-)) and reduced species (e.g. ammonia NH_4^++NH_3; and dinitrogen gas N2). Total nitrogen represents the sum of all forms of nitrogen present in water. Nitrogen is commonly regarded as the limiting nutrient for primary production in estuarine ecosystems. Over enrichment with nitrogen in estuarine ecosystems can lead to excessive algae and plant growth, eutrophication and subsequent deterioration of water quality conditions affecting the balance of key ecosystem requirements such as DO, pH and water clarity.

4.5.1 Spatial Trends

Total nitrogen concentrations were greatest at the upper tributary sites and decreased through the broadwater and nexus sites, with lowest concentrations recorded throughout the Terranora Creek, Terranora Inlet and lower estuary sites (Figure 21). TN concentrations were significantly higher during high flow conditions throughout all sites. Results from the site downstream of the Banora Point WWTP discharge location (TES7) are in line with surrounding sites during all flows indicating minimal influence of this input over TN concentrations in Terranora Creek. These trends are consistent with ABER (2012), however levels of TN in the lower estuary, Terranora Creek and Terranora Inlet were generally higher during high flows than those reported for the previous 5 years.

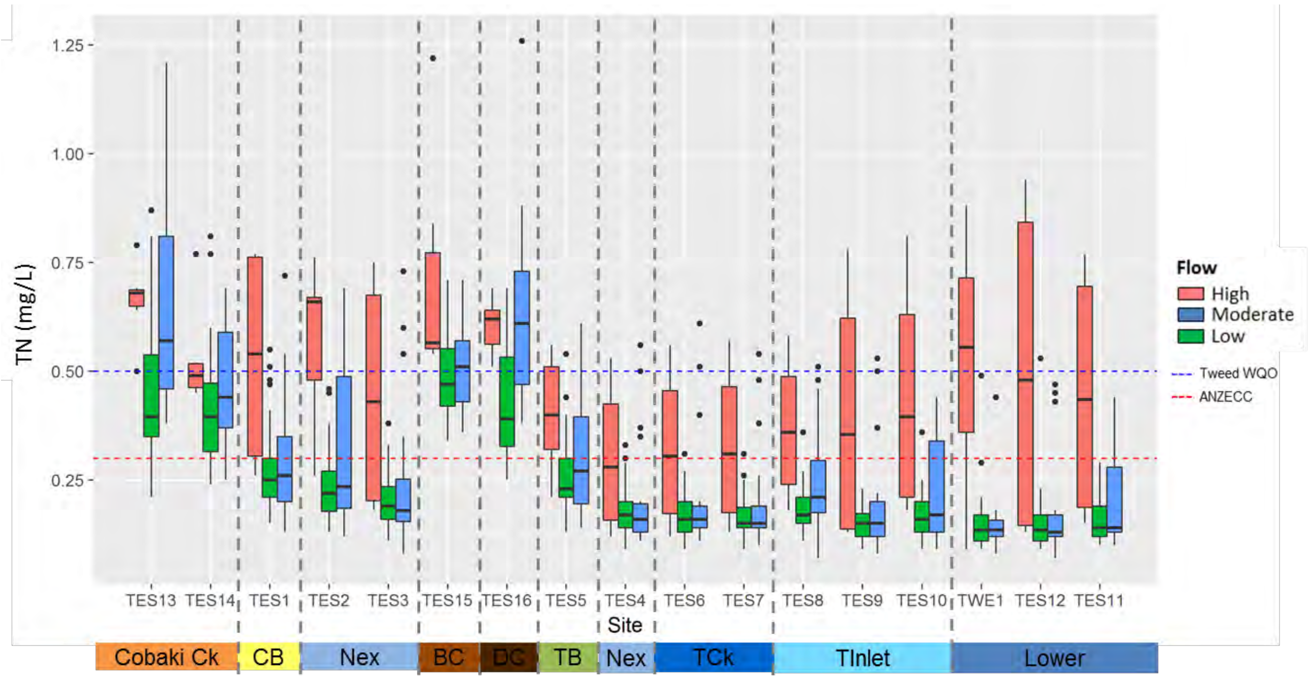


Figure 21: Spatial variation in total nitrogen throughout the Cobaki Terranora Broadwater system during low, moderate and high rainfall conditions

4.5.2 Temporal Trends

There were clear temporal trends in TN concentrations for some years during the study period (Figure 22). Higher concentrations during high flow times resulted during the summer – autumn wet season, particularly in the upper tributary sites in 2015 and 2016, but also during a wet period in mid-winter 2013. This seasonal effect was more pronounced than for the previous reporting period where ABER (2012) where weak seasonal trends in TN were detected.

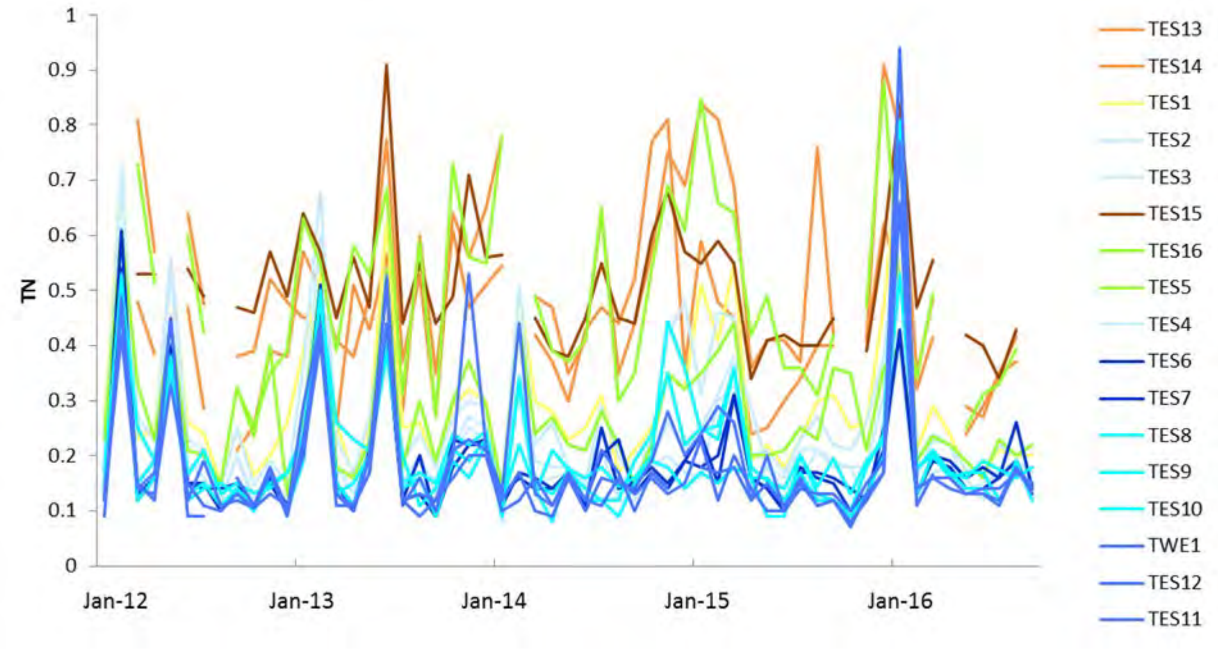


Figure 22: Temporal variation in TN during the study period

4.5.3 Inter-annual variation

There was inter-annual variability in TN concentrations during the study period caused by highly variable concentrations through the summer – autumn wet season (Figure 23). Variation was less pronounced during the late winter-spring dry season. This variation is primarily caused by interaction between the timing and magnitude of freshwater runoff events. ABER (2012) reported a much greater level of inter-annual variability for 2007-2012.

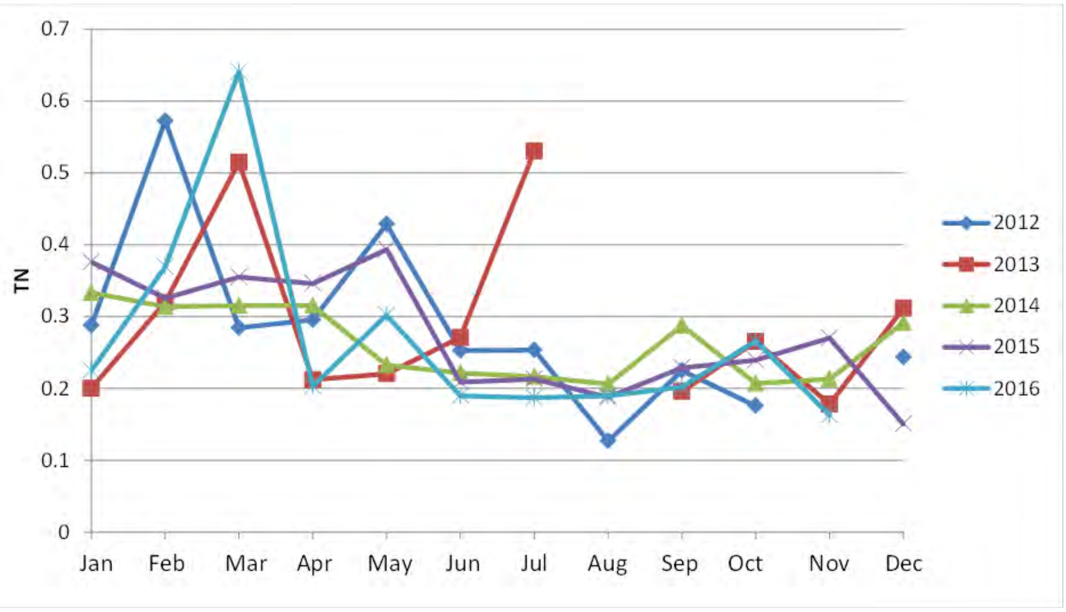


Figure 23: Inter-annual variation in mean estuary total nitrogen over the study period

4.5.4 Comparison with water quality objectives

Total nitrogen concentrations exceeded the ANZECC guideline thresholds for 100% of the time for all flow conditions throughout the upper tributaries. Thresholds were exceeded for 100% of the time during high flow conditions in both roadwaters, although all thresholds were achieved during moderate and low flows at these sites. These results suggest catchment import of TN from the upper tributaries during high flow. Compliance was better at nexus and lower estuary sites, but still exceeded guidelines for greater than 50% of the time during high flow. During low to moderate flow conditions, all remaining sites achieved ANZECC guidelines.

4.5.5 Management Implications

The data suggest that catchment import of TN to the Cobaki-Terranora Broadwater system is occurring during high flows. This is supported by previous analysis completed by ABER (2012) indicating a consistent trend through time of rural runoff impacting the aquatic ecosystem health of the estuary. Reducing nitrogen inputs to the system though catchment management will be an important ongoing management objective to improve estuary health.

4.6 Total Phosphorus

Total phosphorus represents the sum of dissolved inorganic, dissolved organic and particulate nutrients. While phosphorus is generally not regarded as limiting primary production in estuaries, it does limit production in freshwater and can control the occurrence of nitrogen-fixing organisms such as cyanobacteria which are commonly associated with toxic blooms.

4.6.1 Spatial Trends

There was a general trend of low concentrations in Terranora Creek, Terranora Inlet and lower estuary sites lower estuary increasing with distance upstream rising to a peak in the upper tributary sites (Figure 24). There was a trend of increasing TP concentrations with flow at most sites, particularly the upper tributary sites corresponding to peaks in TSS and indicating export of TP with eroded sediment from upper catchment areas. TP concentrations in Terranora Creek, nexus and Terranora Broadwater sites tended to be higher during moderate flows and could indicate wind/tidal resuspension of sediments as a source of TP in these areas. Results from the site downstream of the Banora Point WWTP discharge location (TES7) are in line with surrounding sites during all flows indicating minimal influence of this input over TP concentrations in Terranora Creek. These trends are consistent with ABER (2012), and TP levels were similar to the previous 5 years.

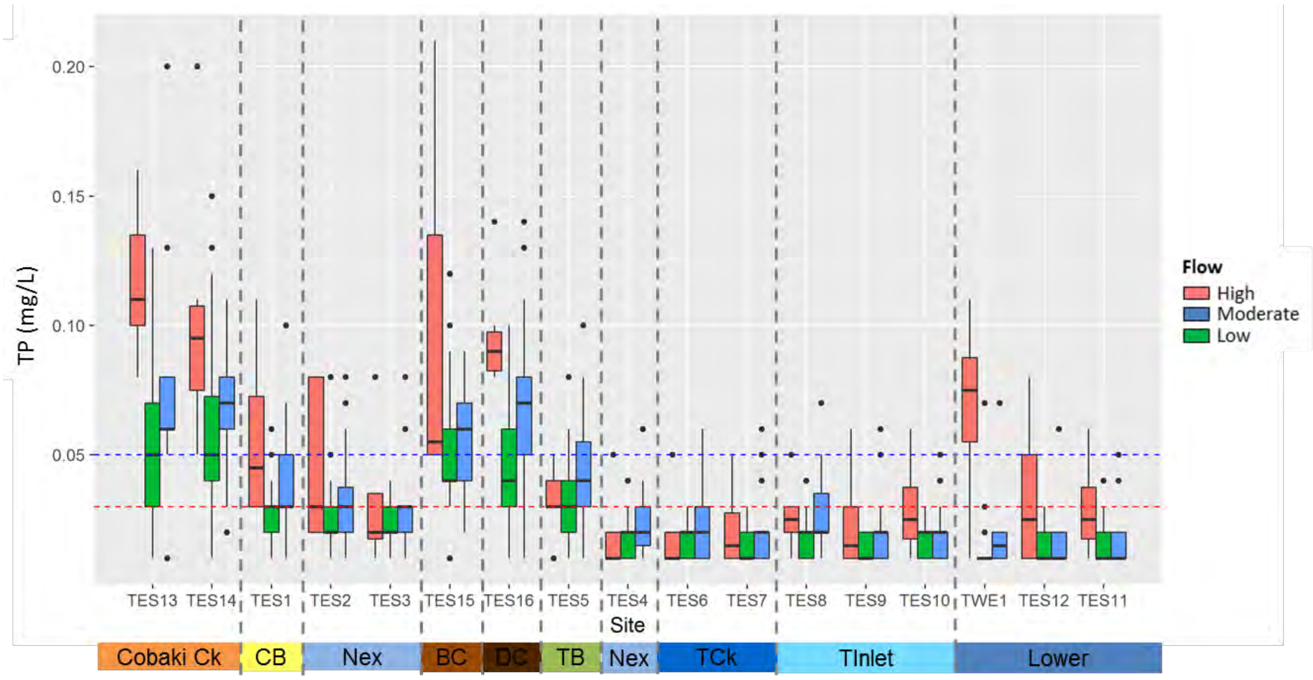


Figure 24: Spatial variation in total phosphorus throughout the Cobaki Terranora Broadwater system during low, moderate and high rainfall conditions

4.6.2 Temporal Trends

There was a reasonable seasonal trend of elevated TP concentrations during the summer – autumn wet season, followed by lower levels during late winter – spring (Figure 25). Variation in TP concentrations most likely arises from the timing of high flow events. ABER (2012) did not detect clear seasonal trends in TP for the previous 5 years, although this was attributed to poor data quality post Jan 2009.

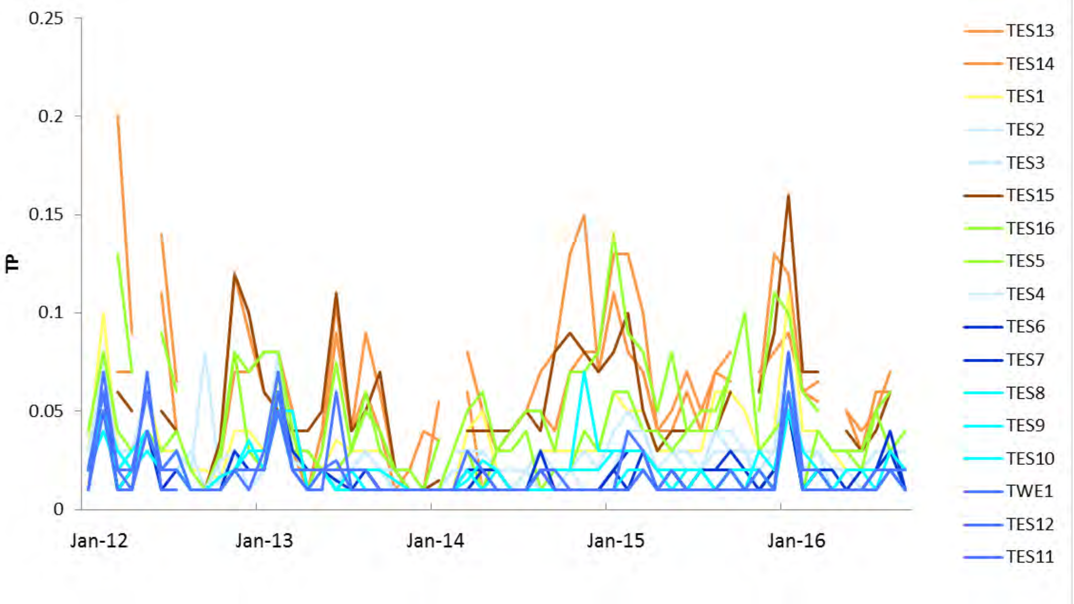


Figure 25: Temporal variation in total phosphorus during the study period

4.6.3 Inter-annual variation

There was significant inter-annual variability in TP concentrations, with different years experiencing highly variable concentrations during the summer – autumn wet season and to a lesser extent during the spring dry season (Figure 26). ABER (2012) also detected significant inter-annual variability in TP although variability was consistent throughout all months and again poor data quality was reported as a source of error in this analysis.

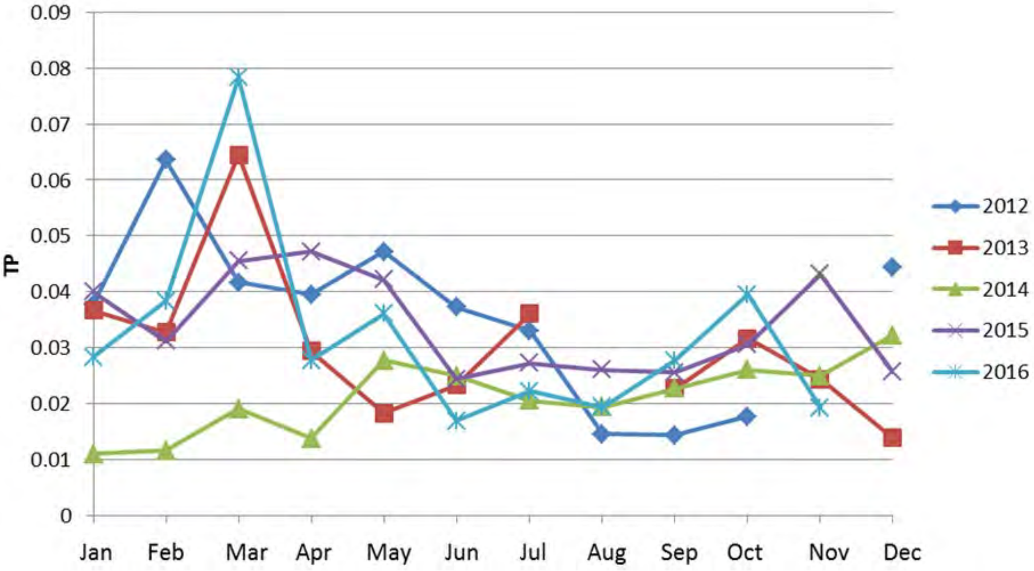


Figure 26: Inter-annual variation in mean estuary total phosphorus over the study period

4.6.4 Comparison with water quality objectives

As for TN, TP also exceeded the ANZECC guideline thresholds for 100% of the time for all flow conditions throughout the upper tributaries. Thresholds were exceeded for 100% of the time during high flow conditions in the Cobaki and Terranora Broadwaters, and >50% of the time during moderate flow. Again, these results suggest catchment import of TP from the upper tributaries during high flow. Compliance was much better at nexus, Terranora Creek, Terranora Inlet and lower estuary sites, with guidelines achieved during all flows, expect for the lower estuary sites during high flow.

4.6.5 Management Implications

Management strategies should focus on reducing catchment inputs of TP during rainfall events through catchment management (particularly soil conservation practices as phosphorus is strongly associated with sediment transport). It is recommended that any management actions aimed at the reduction of nutrients to the system consider both N and P.

4.7 Ammonium

Ammonium is the form of nitrogen taken up most readily by phytoplankton because nitrate must first be reduced to ammonia before it is assimilated into amino acids in organisms. When sediments are anoxic, nitrification is inhibited and ammonium levels in the water column may be elevated. The most common sources of ammonia entering surface waters and groundwaters are domestic sewage, industrial effluents and agricultural runoff (due to ammonia being a common constituent of fertilisers). When ammonia is present in water at high enough levels it can cause direct toxic effects on aquatic life.

4.7.1 Spatial Trends

Ammonium concentrations tended to be highest at the upper tributary sites during moderate flows (Figure 27) and to decrease to similar levels across the remaining sites. Relationships between ammonium concentrations and flow were spatially variable: there was an increase in concentrations with increasing flow in the lower estuary and Terranora Inlet; while concentrations tended to be highest during low and moderate flows at all other sites. Results from the site downstream of the Banora Point WWTP discharge location (TES7) are in line with surrounding sites during all flows indicating minimal influence of this input over ammonium concentrations in Terranora Creek.

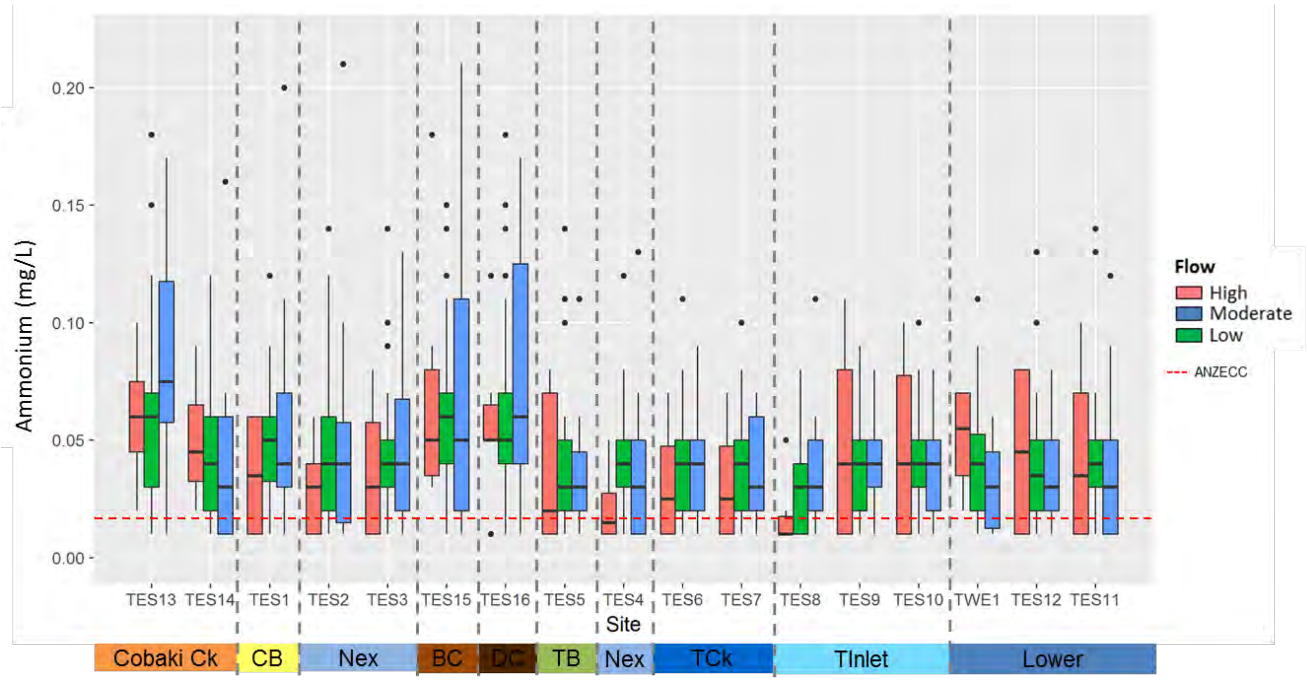


Figure 27: Spatial variation in ammonium throughout the Cobaki Terranora Broadwater system during low, moderate and high rainfall conditions

4.7.2 Temporal Trends

It appears that ammonium concentrations are highest during the summer wet season and diminish as flows decrease into winter and spring. This trend was most pronounced for upper tributary sites for the years 2014, 2015 and 2016.

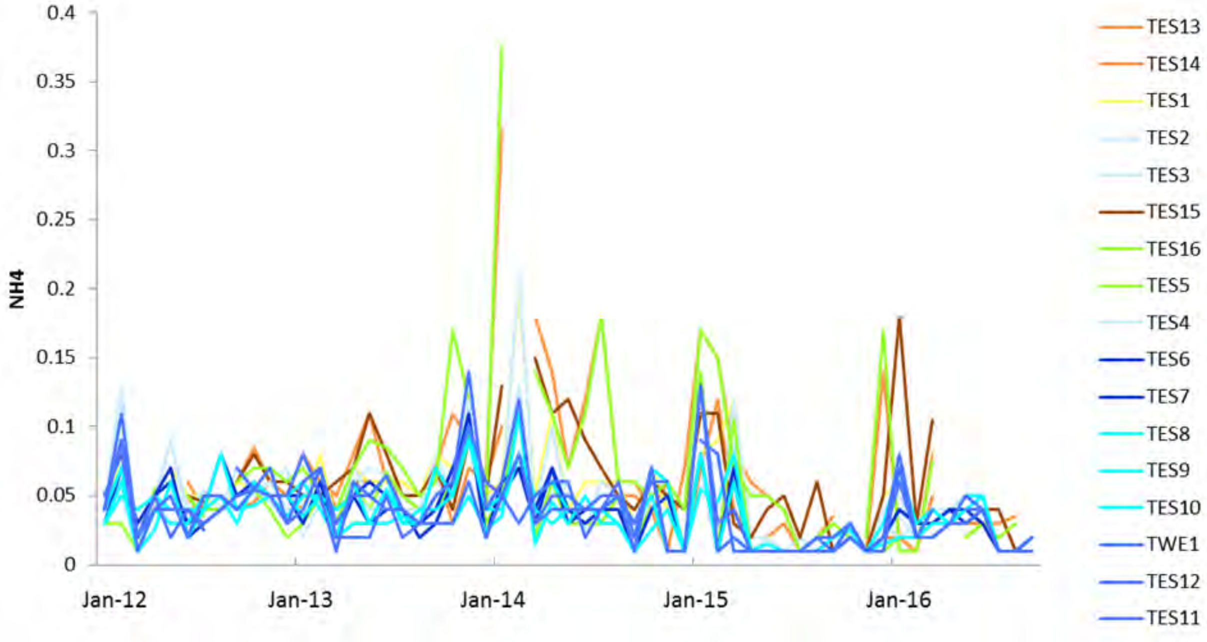


Figure 28: Temporal variation in ammonium during the study period

4.7.3 Inter-annual variation

There was significant inter-annual variability in ammonium concentrations, with different years experiencing highly variable concentrations during the summer – autumn wet season and to a lesser extent during the spring dry season (Figure 29).

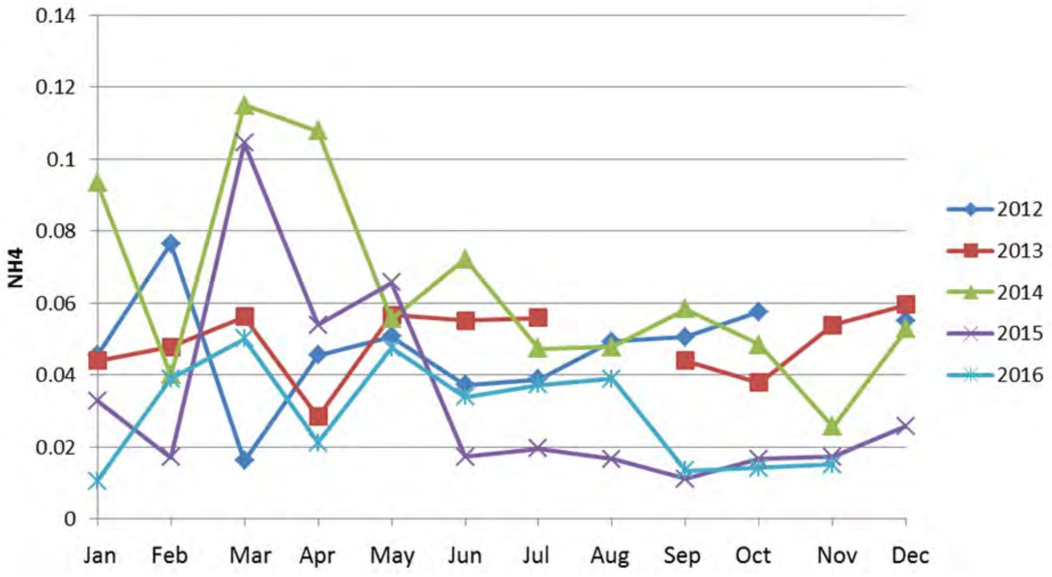


Figure 29: Inter-annual variation in mean estuary ammonium over the study period

4.7.4 Comparison with water quality objectives

Ammonium concentrations exceeded the guideline thresholds for greater than 50% of the time at all sites during all flows except for site TES8 during high flow in Terranora Inlet. Ammonium compliance was worse than reported for the previous five years.

4.7.5 Management Implications

Bioavailable nitrogen (i.e. ammonium and NOx) is the primary factor influencing phytoplankton blooms in the estuary and levels of ammonium observed during 2012-2016 were elevated throughout the Cobaki-Terranora Broadwater system throughout most flow conditions. Higher levels in the upper tributary sites indicate a potential source of ammonium to downstream waterways and catchment management addressing rural input of nitrogen should be targeted. The low DO levels observed at upper tributary sites are likely to be linked to corresponding elevated ammonium at these locations as ammonium is often prevalent under low DO conditions. The prevalence of high ammonium during low and moderate flow at many sites tends to suggest internal processes (e.g. sediment) as a source of ammonium to the system. Anoxic sediments can inhibit nitrification and lead to elevated ammonium in the water column.

4.8 Oxidised Nitrogen

4.8.1 Spatial Trends

Elevated NOx concentrations occurred in the lower estuary, Terranora Inlet and the upper tributary sites during high flows. NOx was also notably high at Bilambil Creek (site TES15) during all flows and levels increased with flow. There were no discernible spatial or flow related trends in NOx at any of the remaining sites. ABER (2012) did not detect clear spatial or flow related trends in NOx except for in Duroby Creek, which showed elevated NOx under all flows, with the highest levels during low flow. Results from the site downstream of the Banora Point WWTP discharge location (TES7) are in line with surrounding sites during all flows indicating minimal influence of this input over NOx concentrations in Terranora Creek. In general, levels of oxidised nitrogen levels were slightly higher than those reported for the previous 5 years across all sites, particularly in the lower estuary.

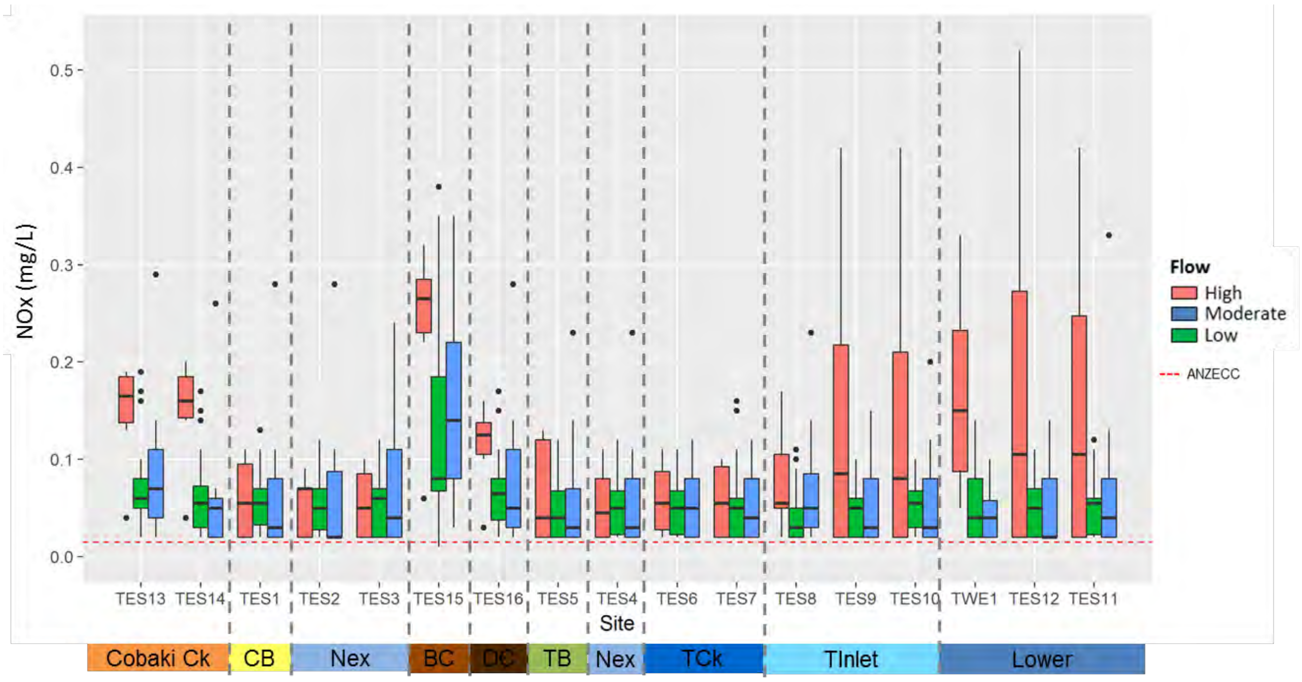


Figure 30: Spatial variation in Oxidised Nitrogen throughout the Cobaki Terranora Broadwater system during low, moderate and high rainfall conditions

4.8.2 Temporal Trends

Seasonal trends of elevated oxidised nitrogen concentrations during the summer – autumn wet season was observed for the study period, particularly in the lower estuary in 2014 and 2016 and at Bilambil Creek in 2013 and 2015 (Figure 31).

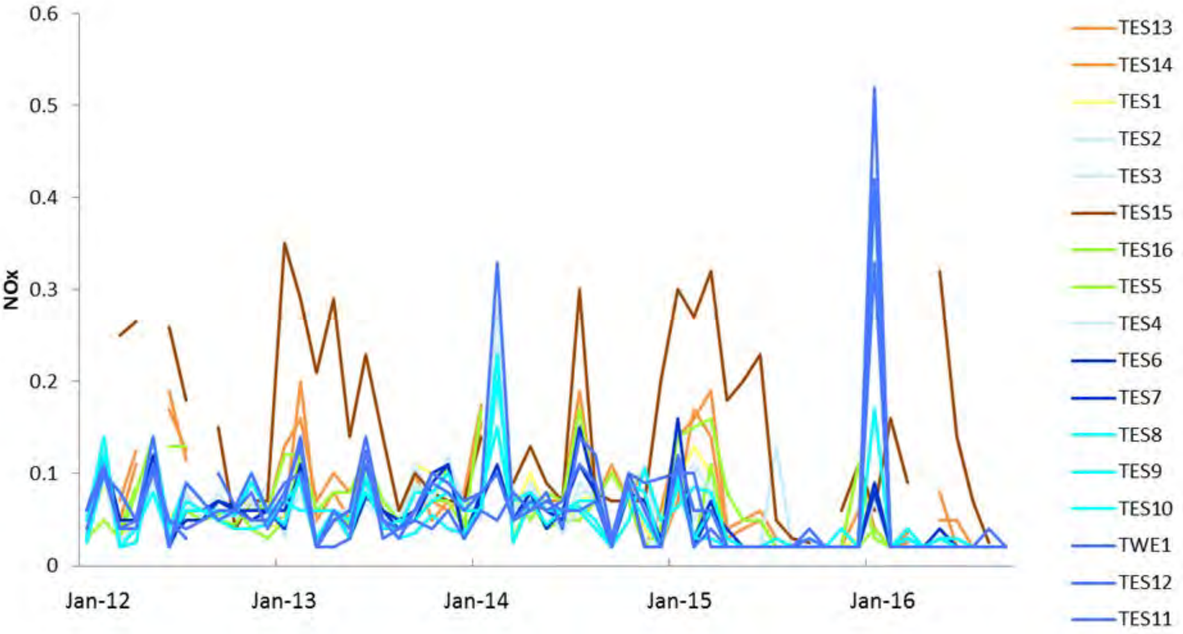


Figure 31: Temporal variation in oxidised nitrogen during the study period

4.8.3 Inter-annual variation

There was significant inter-annual variability in NOx concentrations, with different years experiencing highly variable concentrations during the summer – autumn wet season (Figure 32).

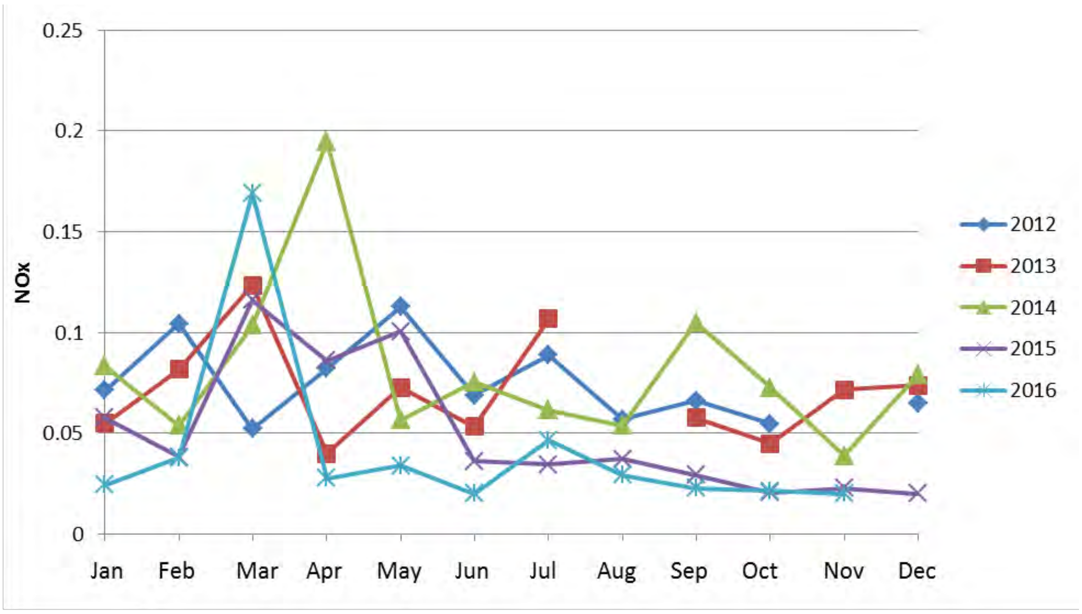


Figure 32: Inter-annual variation in mean estuary oxidised nitrogen over the study period

4.8.4 Comparison with water quality objectives

NOx concentrations exceeded the guideline thresholds for 100% of the time during all flow conditions at all sites.

4.8.5 Management Implications

Levels of NOx observed during 2012-2016 were elevated throughout the Cobaki –Terranora Broadwater system and particularly the upper tributary sites, Terranora Inlet and the lower estuary during high flows and Bilambil Creek during all flows. Management strategies should focus on reducing NOx inputs to the system. This can best be achieved through catchment management and stormwater treatment.

4.9 Dissolved Organic Nitrogen

Dissolved organic nitrogen (DON) is found in a wide range of complex chemical forms such as amino acids, proteins, urea and humic acids which are largely unavailable for biological uptake. DON commonly makes up the largest fraction of total nitrogen in Australian estuaries and rivers and therefore is a key consideration when interpreting TN data.

4.9.1 Spatial Trends

Spatial trends were generally characterised by concentrations increasing with distance upstream. There was a significant increase in DON during high flow conditions at most indicating DON inputs from the catchment including stormwater sources. The notable exception was at the upper tributary sites, where moderate and low flows resulted in the highest DON levels.

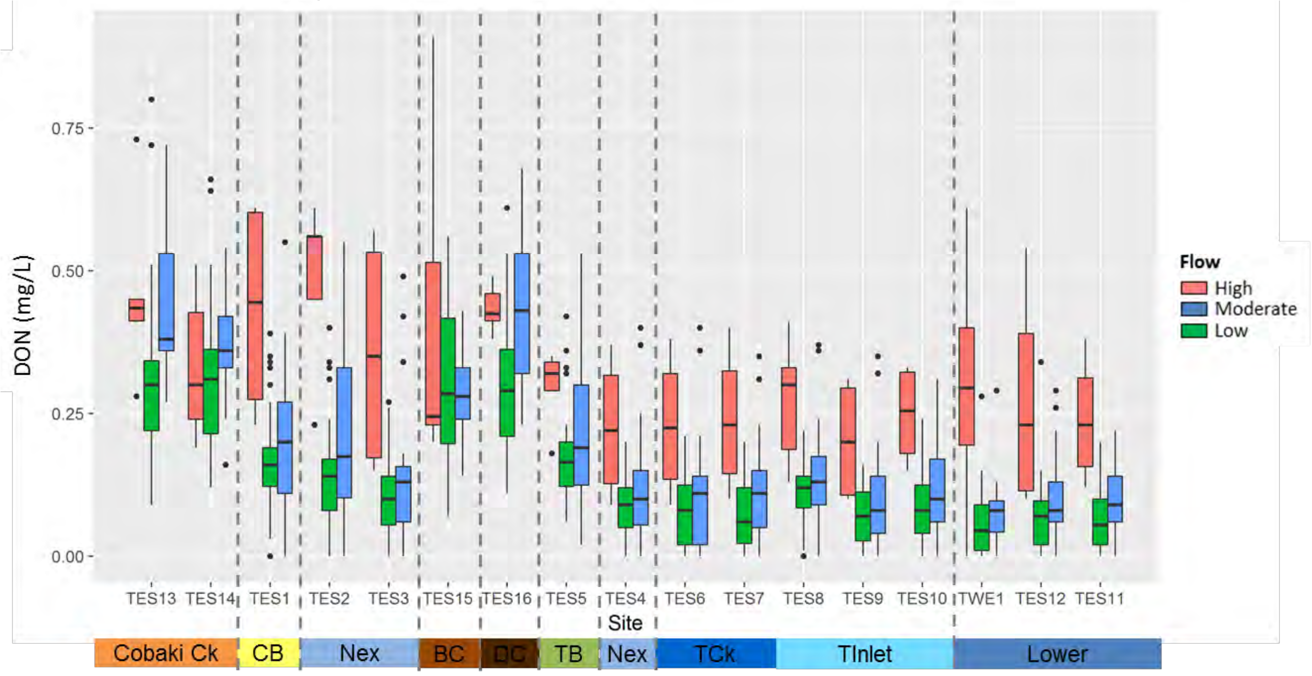


Figure 33: Spatial variation in Dissolved Organic Nitrogen throughout the Cobaki Terranora Broadwater system during low, moderate and high rainfall conditions

4.9.2 Temporal Trends

There were no clear temporal trends identified for DON concentrations during the study period (Figure 34). The variability observed is largely explained by slightly higher concentrations during high flow.

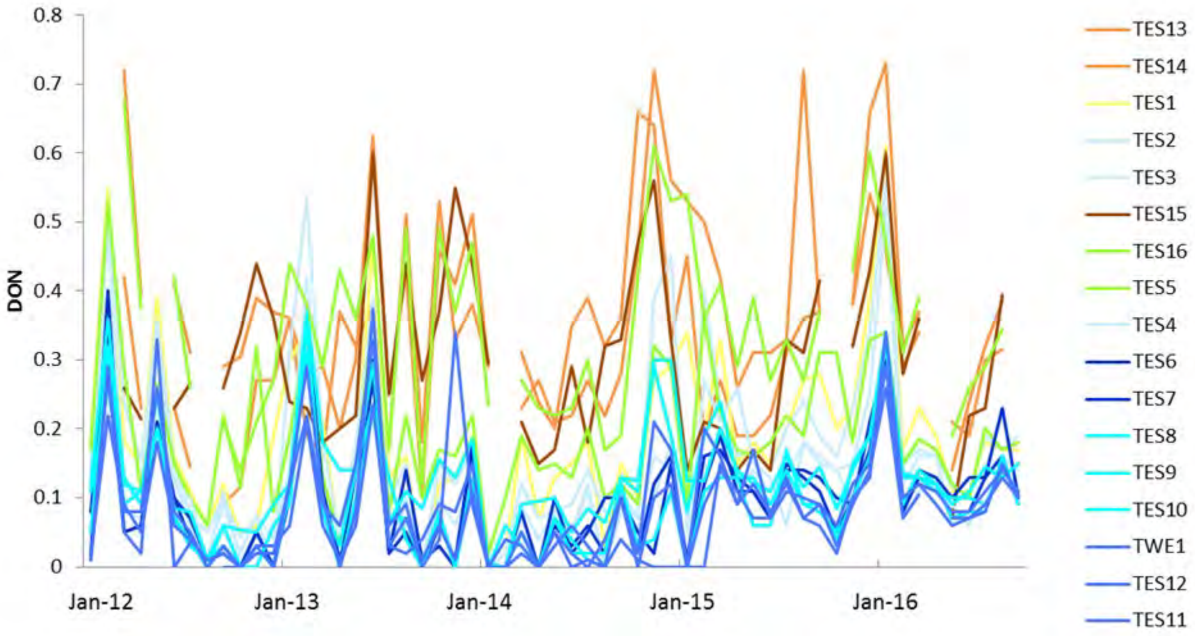


Figure 34: Temporal variation in dissolved organic nitrogen during the study period

4.9.3 Inter-annual variation

There was significant inter-annual variability in DON concentrations, with different years experiencing highly variable concentrations during the summer – autumn wet season, and to a lesser extent in winter-spring (Figure 35).

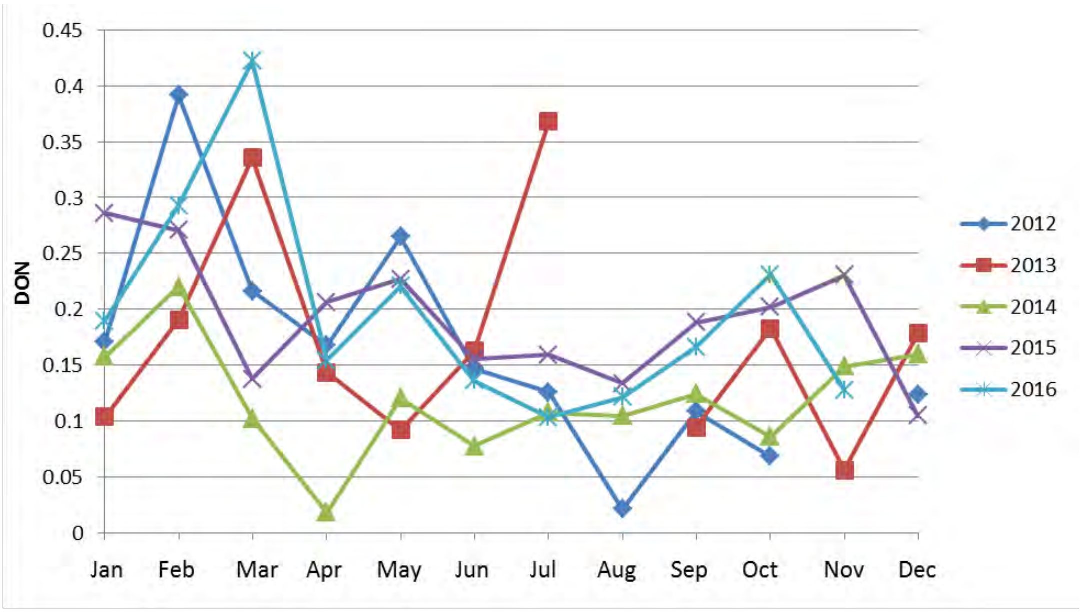


Figure 35: Inter-annual variation in mean estuary dissolved organic nitrogen over the study period

4.9.4 Management Implications

The results of this study indicate that sources of DON arise primarily from runoff from catchments including rural lands and stormwater from urban areas. Management strategies should focus on reducing catchment input of DON during rainfall events through catchment management including soil conservation practices and stormwater treatment.

4.10 TN:TP ratios

The ratio between TN and TP is commonly used to infer which nutrient is potentially limiting production within the system. The uptake ratio of TN to TP during growth is typically around 16 : 1 for most microalgae (e.g. phytoplankton) (Redfield, 1934). Where TN:TP falls below 16 it is generally held that the system is nitrogen limited. Under these conditions, addition of nitrogen to the system would stimulate algal growth, whereas extra phosphorus would not, as the system would remain nitrogen limited. However, in the case of blue green algae (which are able to fix nitrogen from the atmosphere) phosphorus remains the key controlling factor in bloom development.

4.10.1 Spatial Trends

The TN:TP ratio was predominantly well below 16 throughout the Cobaki-Terranora Broadwater system during most flow conditions suggesting that the system currently tends toward N limitation (Figure 36).

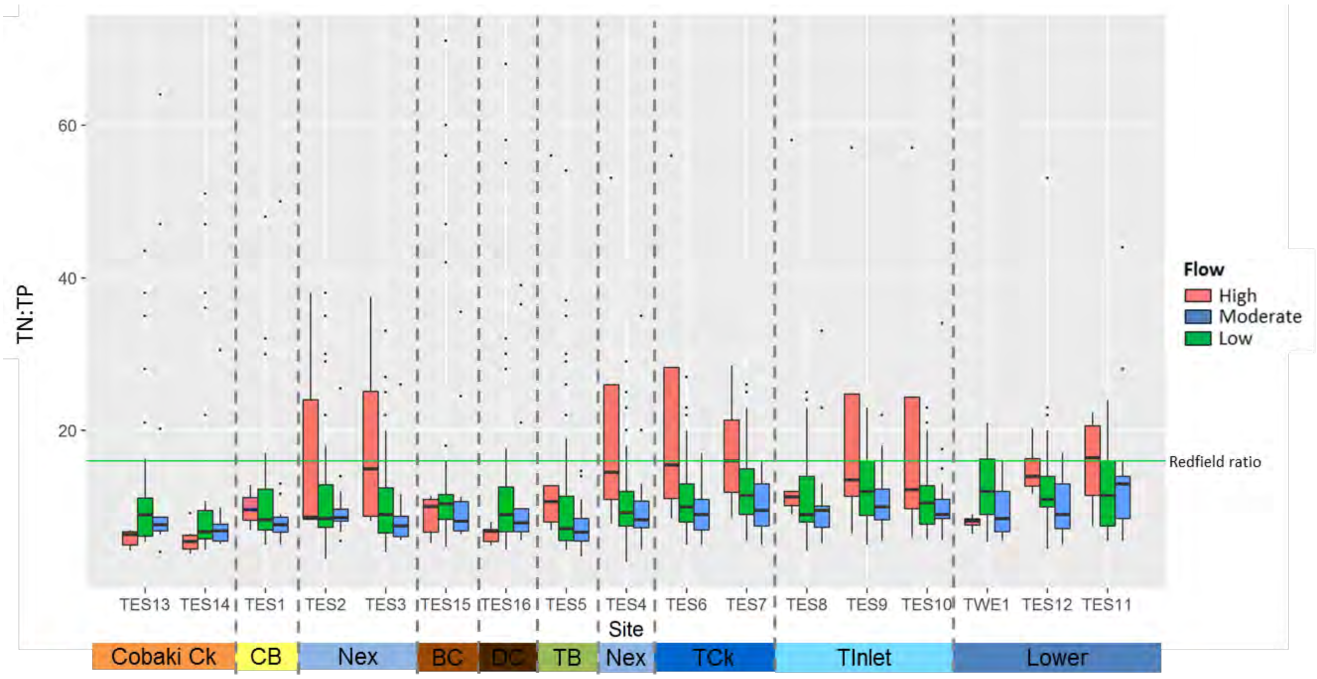


Figure 36: Spatial variation in TN:TP ratios throughout the Cobaki Terranora Broadwater system during low, moderate and high rainfall conditions

4.10.2 Management Implications

As nitrogen is the limiting nutrient, reducing nitrogen inputs to the estuary and particularly bioavailable forms (ammonium and NOx) is a key management action to reduce the risk of phytoplankton blooms and related impacts (e.g. increased turbidity, fluctuation in DO, disruption of chemical and biological processes etc.). However, reducing nitrogen only, may lead to a higher ratio of phosphorus and therefore a greater risk of blue green algae blooms. Therefore, it is important that management effort focuses on reducing inputs of both nitrogen and phosphorus to the estuary.

4.11 Chlorophyll *a*

Chlorophyll *a* is a green pigment found in plants. It absorbs sunlight and converts it to sugar during photosynthesis. Chlorophyll *a* concentrations are an indicator of phytoplankton abundance and biomass in coastal and estuarine waters. Chlorophyll *a* is probably a better 'instantaneous' indicator of trophic status than nutrient concentrations because nutrient concentrations are affected by a number of processes and may not reflect trophic status directly. Persistent high chlorophyll *a* levels indicate poor water quality and average low levels generally suggest good conditions. It should be noted that natural peaks in chlorophyll *a* concentrations do occur and include: higher levels after rainfall, particularly if the rain has flushed nutrients into the water; and higher levels are also common during the summer months when water temperatures and light levels are also higher. Chlorophyll *a* statistics therefore need to be evaluated with reference to nutrient trends, rainfall and other seasonal factors.

4.11.1 Spatial Trends

There was a consistent trend of low Chlorophyll *a* concentrations in the lower estuary, Terranora Inlet, Terranora Creek and nexus sites increasing slightly in the broadwaters and increasing significantly at the upper tributary sites (Figure 37). Higher levels were generally associated with low and moderate flows and lower concentrations during high flows when phytoplankton is more likely to be flushed from the estuary. Chlorophyll *a* was consistently highest in the upper tributary sites during low and moderate flows indicating greater phytoplankton biomass occurring when water residence times increase, where there is a ready supply of nutrient. These trends were consistent with findings of ABER (2012) and appear to be continuing trends.

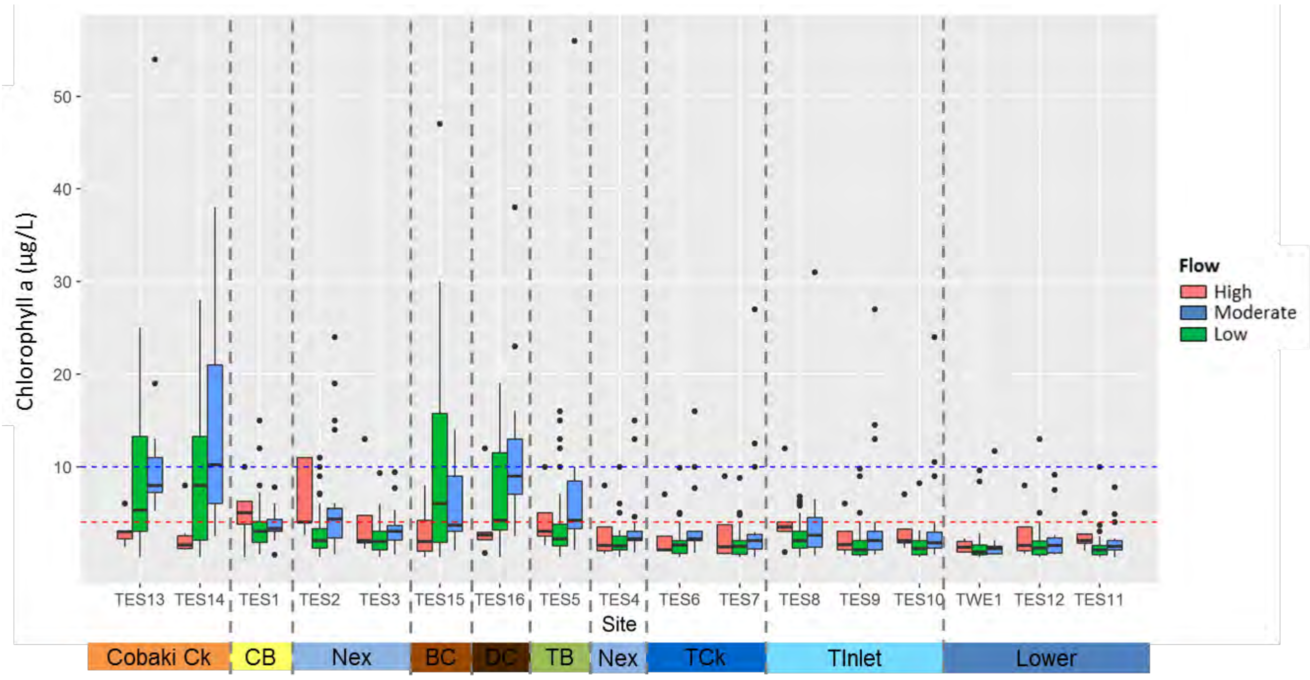


Figure 37: Spatial variation in Chlorophyll *a* throughout the Cobaki Terranora Broadwater system during low, moderate and high rainfall conditions

4.11.2 Temporal Trends

There was a clear increase in Chlorophyll *a* concentrations during summer, particularly at the upper tributary sites and the broadwaters. This reflects seasonal patterns of the primary drivers of phytoplankton growth (temperature, freshwater nutrient inputs, and light) (Figure 38).

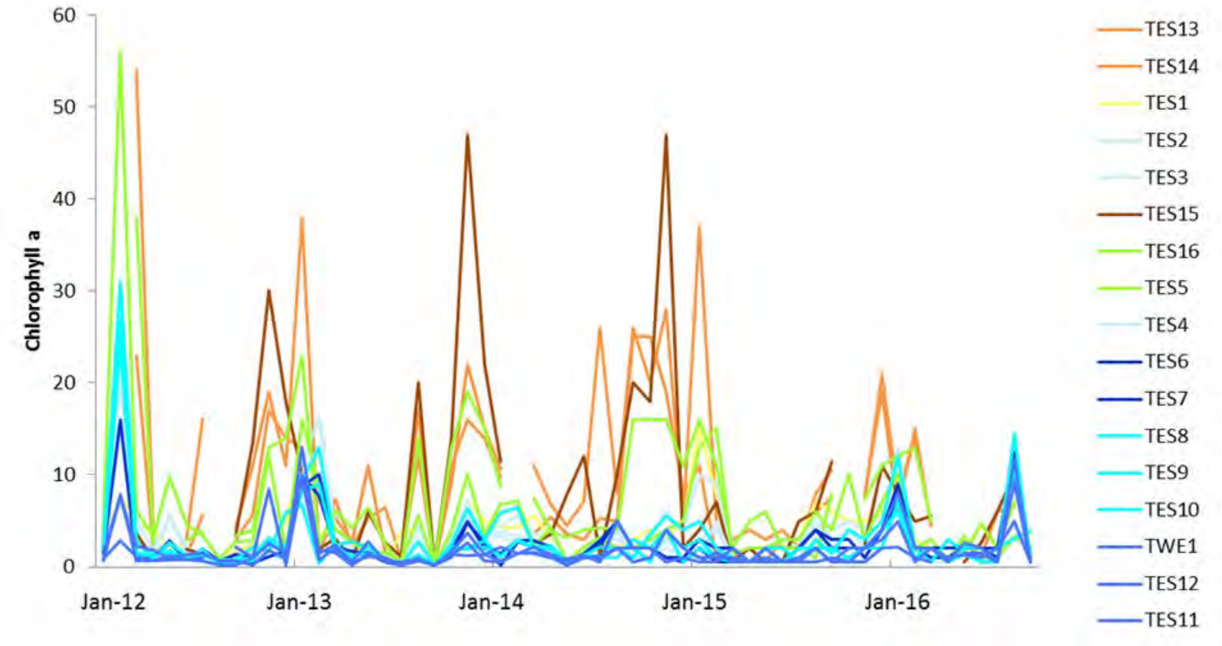


Figure 38: Temporal variation in Chlorophyll *a* during the study period

4.11.3 Inter-annual variation

There was significant inter-annual variability in Chlorophyll *a* concentrations during the study period (Figure 39). Higher chlorophyll *a* levels were consistently seen in summer-autumn months and to a lesser extent in spring throughout the study period where the timing and severity of phytoplankton blooms varied greatly according to primary forcing factors such as flow and residence times. Chlorophyll *a* levels were lower during the remainder of the year, and there was a lower degree of variability between years.

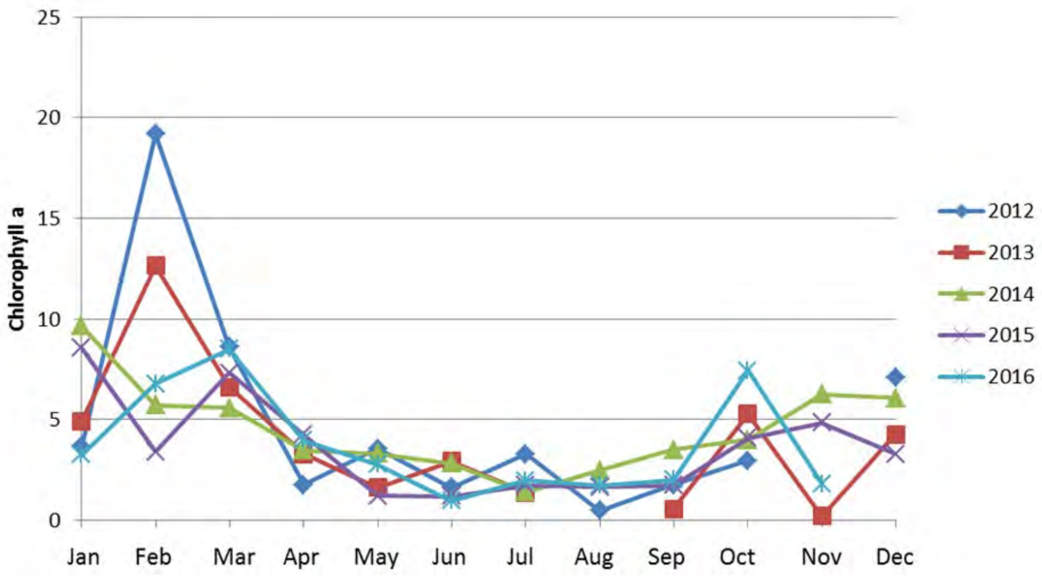


Figure 39: Inter-annual variation in mean estuary Chlorophyll *a* over the study period

4.11.4 Comparison with water quality objectives

Chlorophyll *a* concentrations achieved water quality guidelines at the lower estuary, Terranora Inlet, Terranora Creek and nexus site TES4 during all flow conditions. Compliance generally worsened with distance upstream and with diminishing flow. At all upper tributary sites (Cobaki, Bilambil and Duroby Creeks) guidelines were exceeded for greater than 50% of the time during moderate and low flows, while high flows resulted in 100% compliance. In contrast, chlorophyll a guidelines were exceeded 100% of the time during high flow in the Cobaki Broadwater (TES1) and nearby nexus sites (TES2). It is possible that this result reflects the flushing of phytoplankton from Cobaki Creek into these zones during flow events.

4.11.5 Management Implications

Results of the current study show that the upper tributaries of the Cobaki Terranora Broadwater system (Cobaki, Bilambil and Duroby Creeks) experience relatively severe phytoplankton blooms during dry and moderate flow periods suggesting moderate eutrophication. The Cobaki and Terranora Broadwaters both experience periodic phytoplankton blooms. These results are consistent with the previous 5 years monitoring and indicate ongoing trends. Modelling by ABER (2012) confirmed DIN loading as a primary factor influencing phytoplankton blooms in the estuary. Management efforts should focus on reducing DIN inputs and improving water clarity during moderate and high flow conditions. This can best be achieved by improving catchment management and stormwater treatment during high flow.

4.12 Total Suspended Solids

Total suspended solids (TSS) is a measure of the combined concentration of particulate matter (comprising inorganic sediments, organic matter and phytoplankton) in the water column. The relative contribution of these constituents varies widely according to position along the estuary, state of tide and state of flow. TSS is a major driver of water clarity, impacting on the light climate of the water column and sediments.

4.12.1 Spatial Trends

Total suspended solids (TSS) during the study period were consistently highest in Cobaki Creek, Duroby Creek and broadwater sites and decreased in the nexus, Terranora Creek, Terranora Inlet and lower estuary sites (Figure 40). There was a clear and consistent increase in TSS with flow category at all sites except for Terranora Broadwater site TES5 where moderate and low flows resulted in the highest TSS levels. This indicates the occurrence of wind/tide driven resuspension of sediment in the Terranora Broadwater and the overriding influence of sediment export from the catchment (as possibly some flow-generated resuspension of bottom sediments) creating turbid conditions at all other sites. As noted by ABER (2012) there was again no indication of elevated TSS concentrations at site TES14 relative to site TES13, indicating that the monitoring strategy did not detect significant impacts due to runoff from the Cobaki Lakes construction site. However, due to the routine sampling strategy (no targeting of rainfall events) several major rainfall events were missed by the current study which are key risk periods for runoff events.

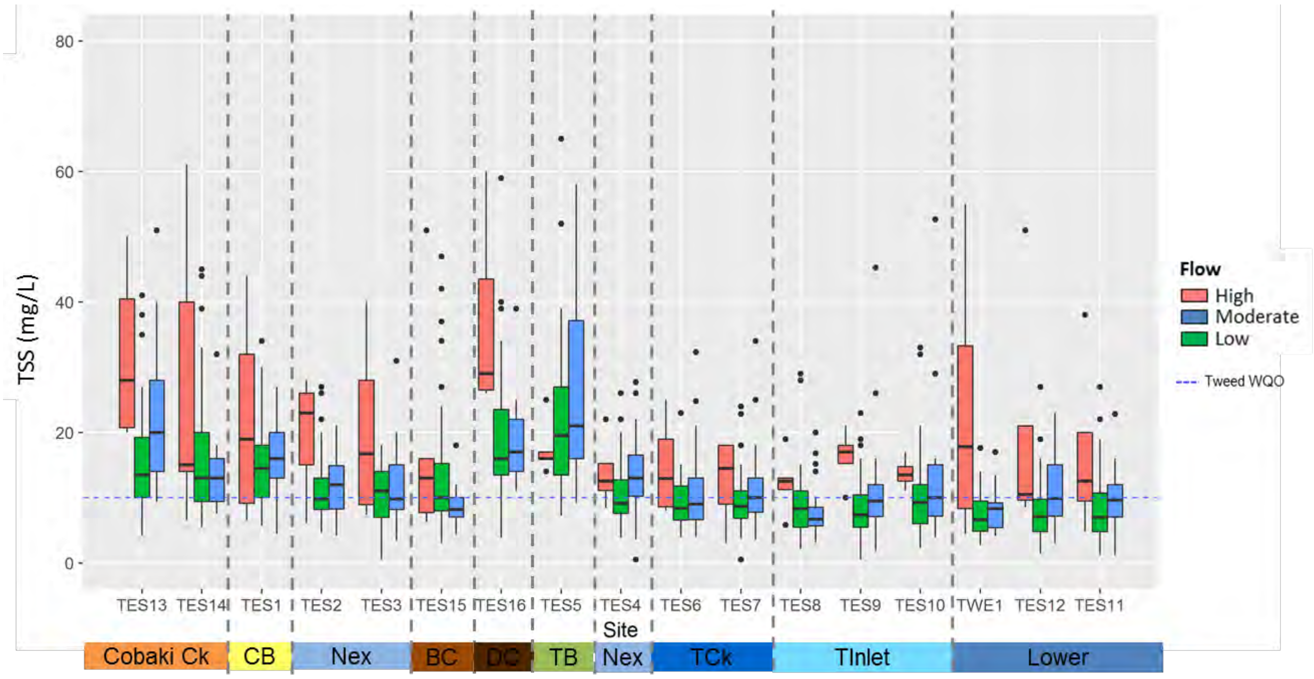


Figure 40: Spatial variation in total suspended solids throughout the Cobaki Terranora Broadwater system during low, moderate and high rainfall conditions

4.12.2 Temporal Trends

There were no clear temporal trends in TSS throughout the system (Figure 41). There was high variability in TSS concentrations over monthly to bimonthly timescales, reflecting variability in flow conditions and degree of wind and tide induced resuspension at the time of each sampling effort. This was consistent with ABER (2012) who also highlighted the failure of the routine monitoring strategy to capture significant runoff events to adequately assess the impact of TSS in the Cobaki Broadwater system.

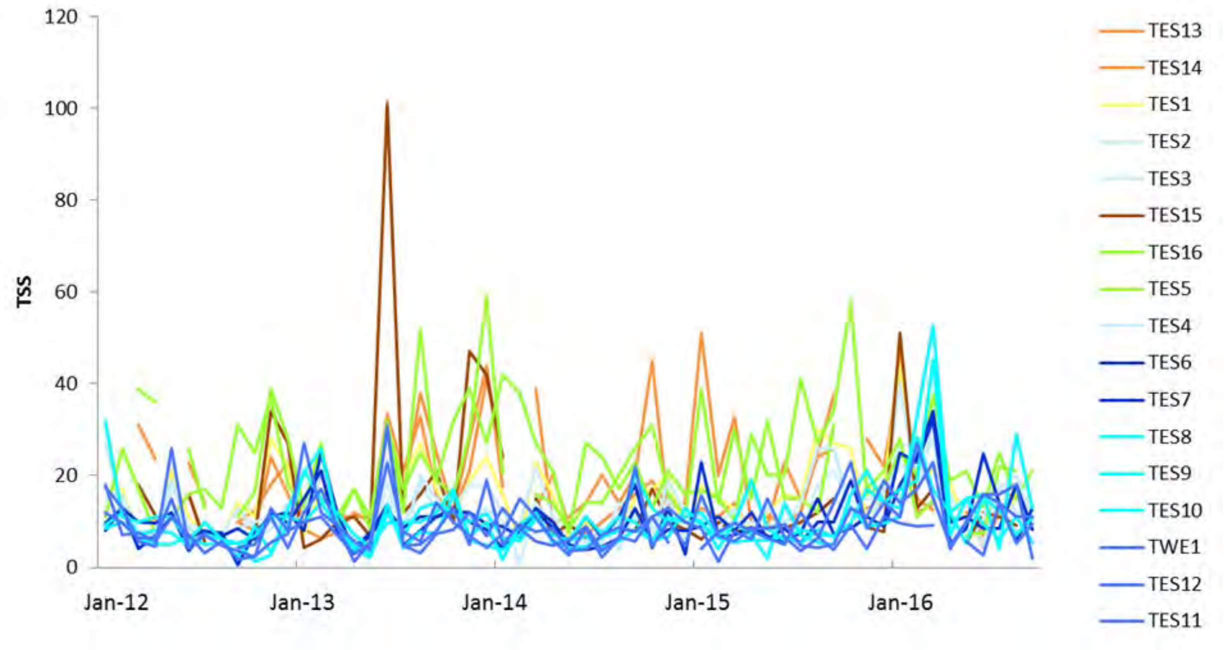


Figure 41: Temporal variation in TSS during the study period

4.12.3 Inter-annual variation

There was significant inter-annual variability in TSS concentrations, with different years experiencing highly variable concentrations during the summer – autumn wet season, and to a lesser extent in winter-spring, excluding the major rainfall event in July 2013 (Figure 42). Such inter-annual variability is affected by the same issue as discussed in section 4.12.2, where scheduled sampling events are likely to unreliably capture rainfall related TSS events.

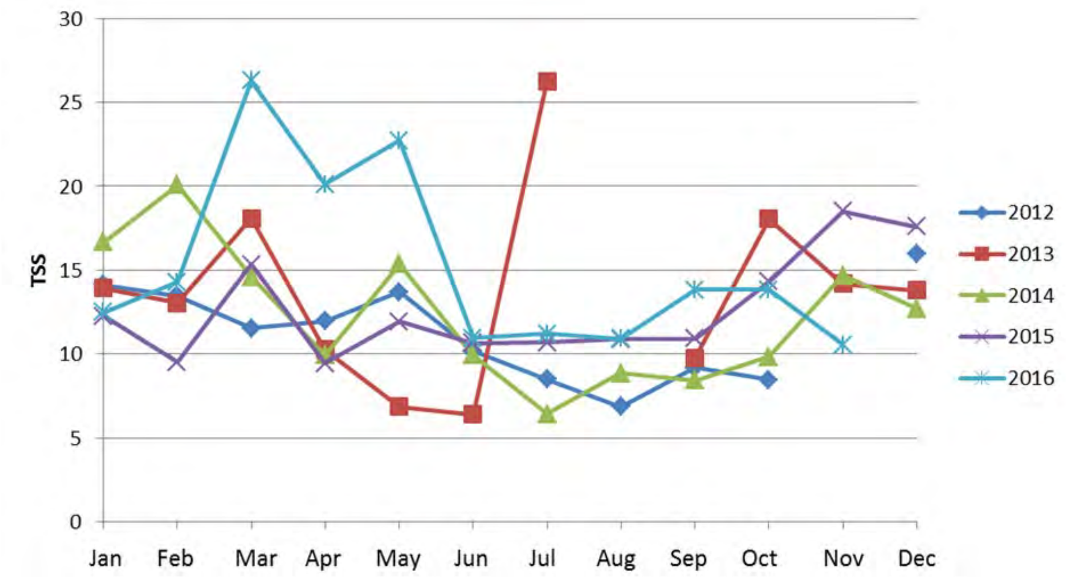


Figure 42: Inter-annual variation in mean estuary total suspended solids over the study period

4.12.4 Comparison with water quality objectives

TSS levels exceeded the guideline thresholds for 100% of the time during all flow conditions throughout Cobaki Creek, Duroby Creek and the broadwaters indicating these zones remains turbid for the majority of flow conditions. Compliance generally improved with distance downstream and with decreasing flow however during high flows however TSS levels still exceeded the guideline thresholds for greater than 75% of the time during high flow conditions throughout the remaining estuary sites. During low to moderate flow conditions Terranora Creek, Terranora Inlet and lower estuary sites achieved greater than 50% compliance.

4.12.5 Management Implications

Management strategies should focus on reducing TSS in catchment and stormwater runoff during high and moderate flows. There are a number of soil conservation strategies that could be employed depending on site conditions, landuse, slope etc. but in general involve maintenance of vegetative cover on land surfaces, vegetated riparian zones, employing erosion and sediment controls where vegetative cover cannot be maintained, or end of pipe solutions to filter runoff including sedimentation basins, infiltration or bioretention beds etc. Reduction of TSS in runoff will reduce the episodic turbid conditions in the estuary following rainfall and also reduce further accumulation of fine sediment on the estuary bed that are susceptible to resuspension. Strategies to reduce phytoplankton blooms will also significantly reduce TSS concentrations.

4.13 Water Clarity (Secchi Depth)

4.13.1 Spatial Trends

Secchi depths ranged from less than detection (0.1m) to 6m (Figure 43). There were a number of quality issues associated with the secchi data during this monitoring period including:

- Inaccurate measurements due to tidal state: due to significant depth changes according to tide, particularly in the lower estuary secchi depth does not always reflect water clarity accurately (i.e. the disc could be seen all the way to the bottom, but as depth was shallow due to low tide water clarity is underestimated). This was frequently observed in secchi depth measurements for the current period and recorded as a “greater than” value. There was no way to determine an accurate secchi depth for the bulk of samples at the clearer lower estuary, Terranora Inlet and Terranora Creek sites and values were removed from the dataset. Figure 43 is therefore skewed towards poorer water quality times and does not provide any indication of true spatial trends; and

- Secchi depth was not recorded for the upper tributary sites.

Nevertheless, the remaining data generally show poorer water quality in both broadwaters compared to sites further downstream. There was a reduction in water clarity with increased flow at all sites, indicating water clarity is reduced by rainfall/runoff events. These trends are consistent with results for TSS during high flow, but not consistent with Chlorophyll *a* levels which were lower during high flows indicating suspended sediment is a primary cause of decreased water clarity during rainfall/runoff events.

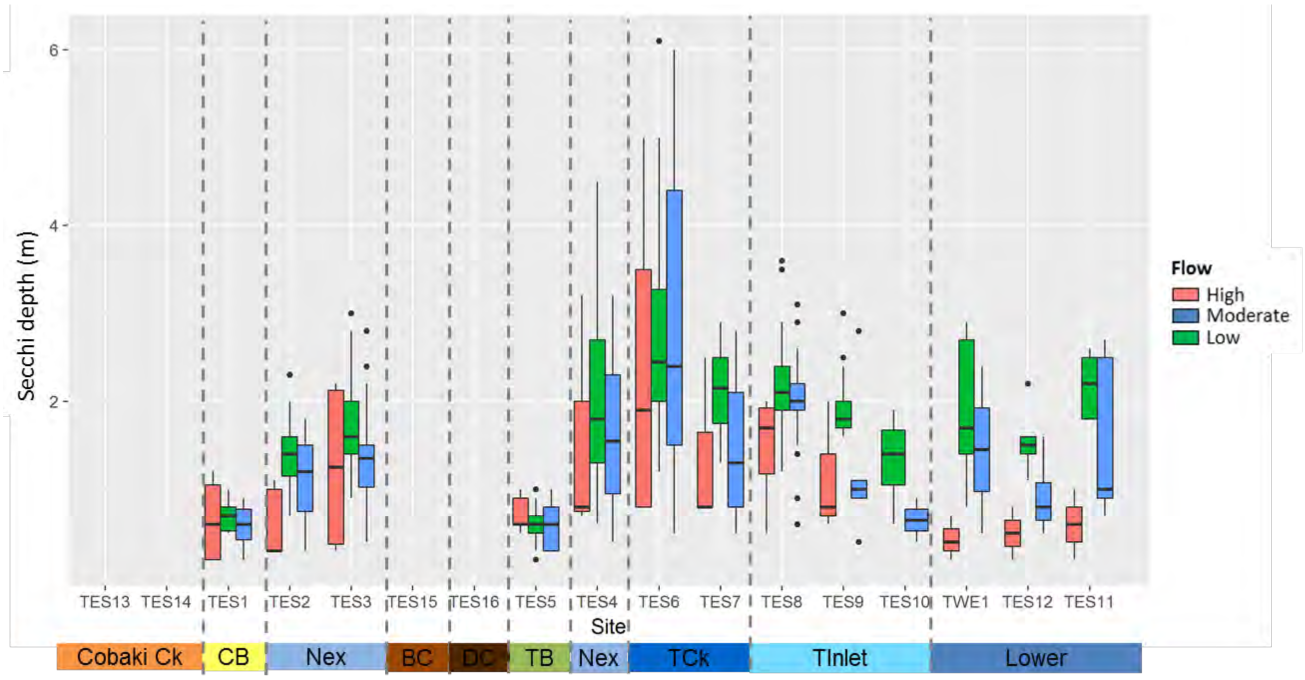


Figure 43: Spatial variation in Secchi disk depth throughout the Cobaki Terranora Broadwater system during low, moderate and high rainfall conditions

4.13.2 Temporal Trends

There were no clear temporal trends in secchi disc depth during study period and this is also likely to be affected by poor data quality discussed above (Figure 44).

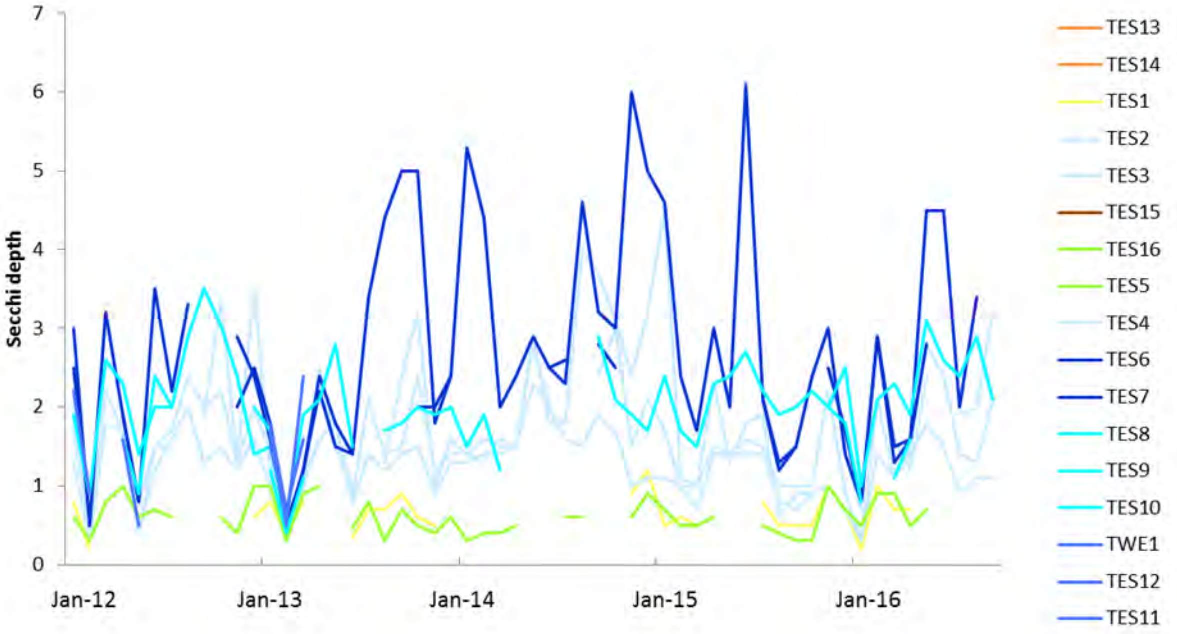


Figure 44: Temporal variation in secchi depth during the study period

4.13.3 Inter-annual variation

There was significant inter-annual variability in secchi depth data, although given the data limitations discussed above it is difficult to determine if variability reflects true trends or simply noise (Figure 45).

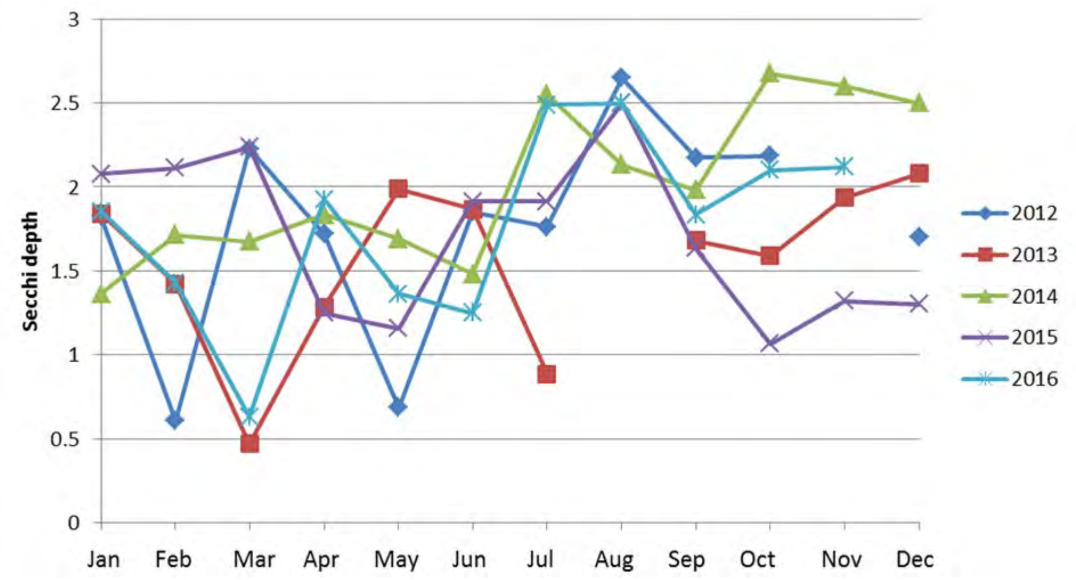


Figure 45: Inter-annual variation in mean estuary secchi depth over the study period

4.14 Faecal Indicator Bacteria (enterococci)

Enterococci are a group of bacteria commonly found in the stomach of warm blooded animals and humans. High levels of these bacteria can help indicate a decrease in water quality for swimmers. Although enterococci are not harmful themselves, they can indicate the possible presence of harmful microorganisms such as bacteria, viruses and protozoa.

4.14.1 Spatial Trends

Enterococci concentrations ranged between 0.5 and 4,650 cfu/100mL during the study period (Figure 46) (note the highest outliers were omitted from the graph in order to display the majority of values more clearly). The highest enterococci concentrations were detected at site TWE1 in the lower estuary during high flows and could indicate a stormwater source in this vicinity. High and moderate flows were correlated with higher enterococci levels at most sites suggesting catchment or stormwater runoff as sources during rainfall events.

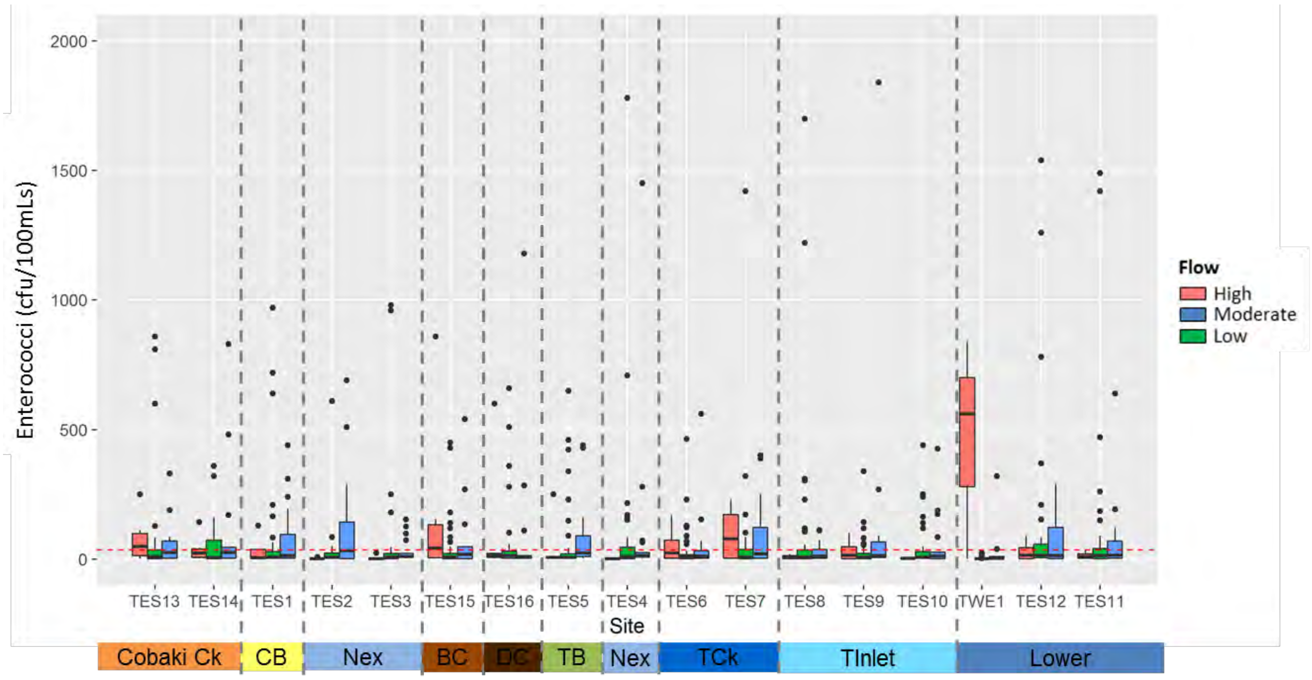


Figure 46: Spatial variation in enterococci throughout the Cobaki Terranora Broadwater system during low, moderate and high rainfall conditions.

4.14.2 Temporal Trends

There were no clear temporal trends evident in enterococci although results show strong association with some rainfall events (e.g. Jan 2012 and 2016).

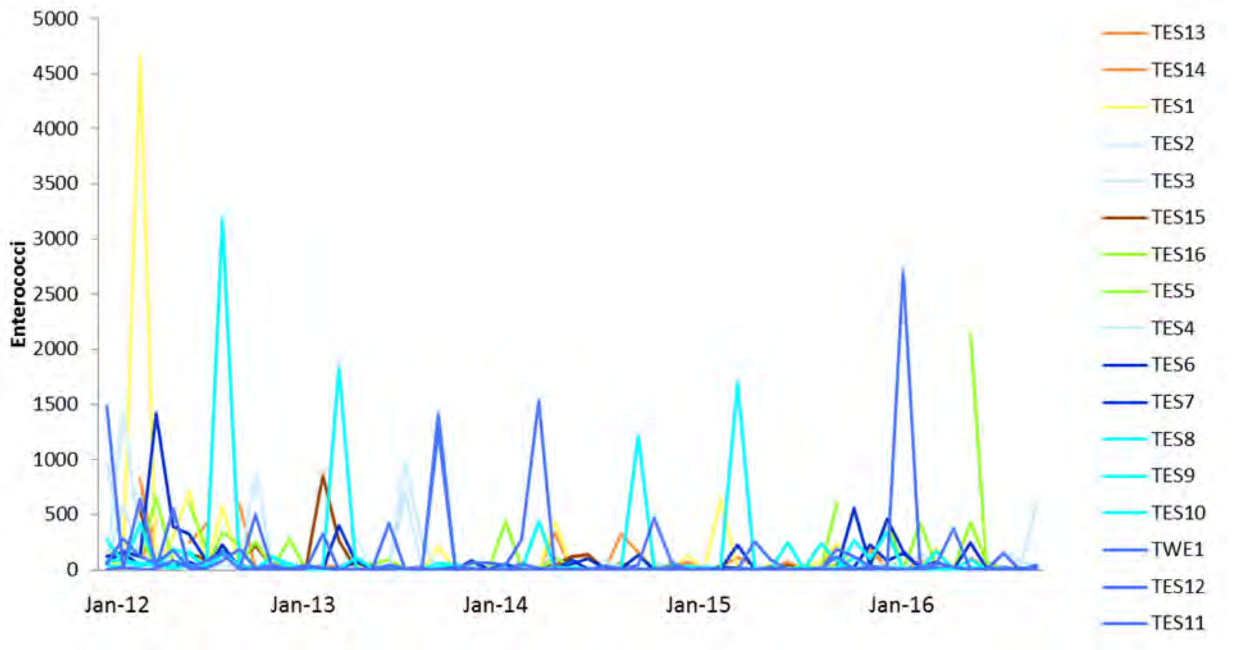


Figure 47: Temporal variation in enterococci during the study period

4.14.3 Inter-annual variation

Some inter-annual variation in enterococci was detected throughout the study period, and 2012 experienced much higher levels than subsequent years although it is not clear why this is the case (rainfall was above long-term average but similar to 2013 and 2015).

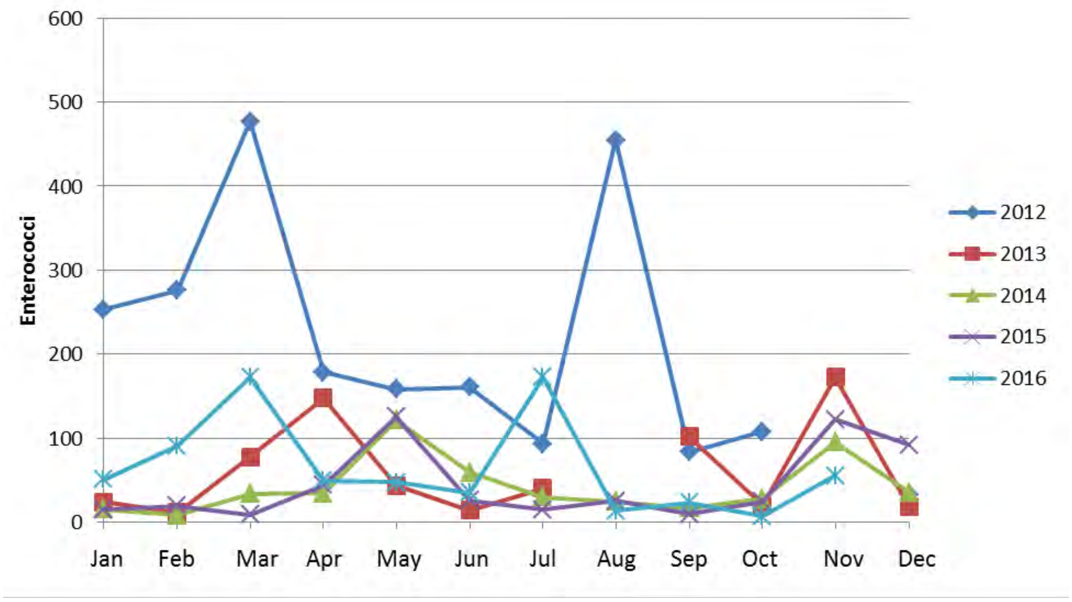


Figure 48: Inter-annual variation in mean estuary enterococci over the study period

4.14.4 Comparison with water quality objectives

Enterococci concentrations exceeded the ANZECC guideline thresholds for 100% of the time during high flow conditions at the lower estuary site TWE1, and greater than 50% of the time during high flows at Terranora Creek, Cobaki Creek and Bilambil Creek. Moderate flow conditions in both broadwaters, TES2 in nexus zone and TES7 in Terranora Creek also resulted in guideline thresholds being exceeded for greater than 50% of the time. Compliance was generally achieved at all sites during low flow conditions.

4.14.5 Management Implications

Potential sources of faecal contamination to the estuary include wastewater; domestic animals including livestock and pets; and wildlife. The ability to discriminate human and animal faecal contamination is important since it is widely accepted that faecal pollution from a human source (such as sewage) is likely to present a greater human health risk than faecal pollution from animal sources.

Currently enterococci levels in the estuary are in excess of human health guidelines at some sites during high and moderate flows. Approaches to management include:

- Advising the community that primary contact recreation (e.g. swimming) is not advisable for a certain period following significant rainfall throughout the estuary.
- Investigate sources of pathogen inputs (i.e. human or animal sources and key locations) to better assess the risk to human health and to direct management effort to specific areas of the estuary. A short-term, a targeted study of the sources of pathogens could be undertaken to fill this gap. Methods to trace high risk sources of pathogens could be employed at key sites. Human faecal source tracking using mitochondrial DNA is one technique currently available for this purpose. This type of project lends itself to a short-term study such as post-graduate research.
- Stormwater controls in urban areas and education regarding pet droppings, illegal sewer connections etc.
- Restricting direct stock access to waterways in rural areas.

4.15 Stratification

Physico-chemical data collected as depth profiles at sites TES6 and TES7 are summarised as box plots in Figure 49 for the period of record (2012-2016). Daily profiles taken on 6th June 2012 are shown in Figure 50, illustrating typical conditions during low flows. Both TES6 and TES7 in Terranora Creek showed signs of some vertical stratification in DO, salinity and temperature with levels tending to increase with depth. As this zone is tidal, this pattern could be explained by warm, oxygenated oceanic waters propagating up the estuary as a saltier and therefore more dense layer on the bottom of the water column. pH was generally consistent throughout the water column (pH8 at all depths at TES7 and pH8.1-8.2 at TES6). During high flow samples, vertical stratification tended to be minimal due to better mixing and shorter residence times.

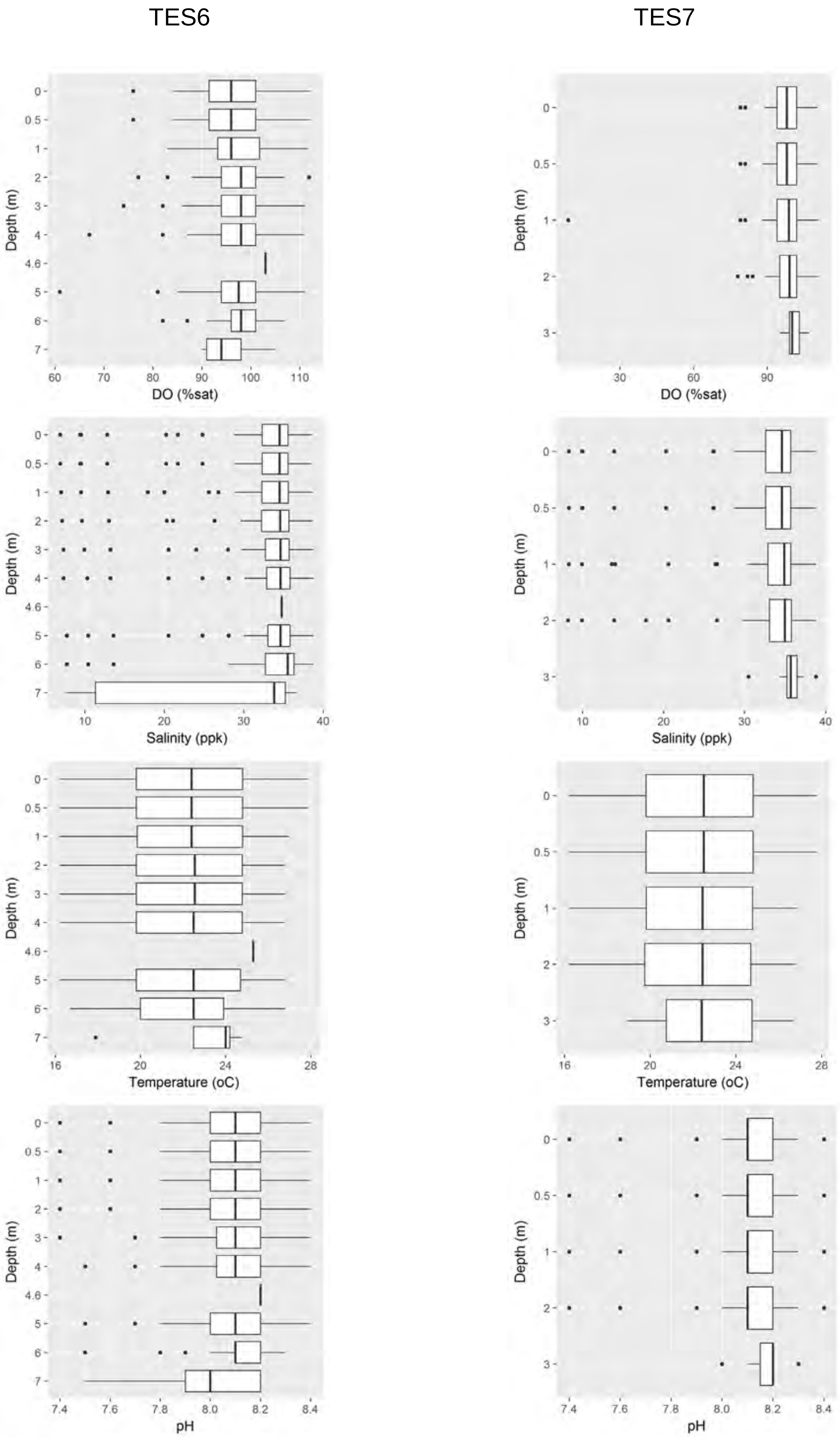
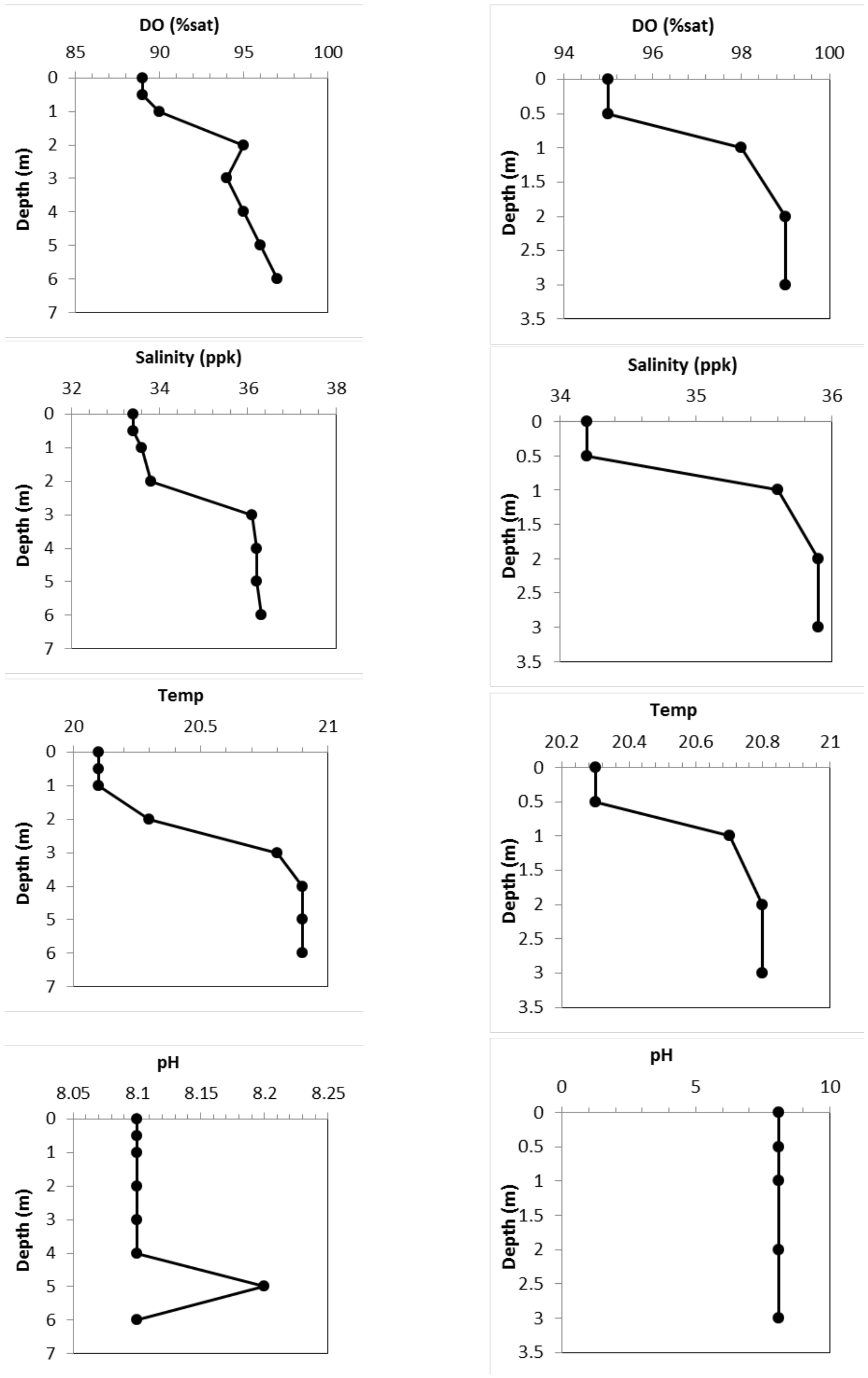


Figure 49: Boxplot summaries of physico-chemical profiles at sites TES6 and TES7 (all data from 2012-2016).



TES6

TES7

Figure 50: Depth profiles of DO, salinity and temperature at sites TES6 and TES7 under low flow conditions on 6/6/2012.

4.16 Wastewater Treatment Plants

The Banora Point WWTP currently discharges tertiary treated wastewater to Terranora Creek adjacent to the Pacific Highway bridge. Details of the WWTP are provided in Table 6. Recent upgrades to the plant included processes to significantly reduce nutrient levels in the final effluent discharged from the plant.

Table 6: Details of Banora Point WWTP (Source: TSC, 2016 & Hydrosphere Consulting, 2014)

Name	Monitoring site (refer Figure 4 for locations)	Capacity (people served)	Capacity (ML/d)	Treatment Process	Effluent Management
Banora Point WWTP	Point 1 – Terranora Inlet (outside study area) approx. 3km u/s of TES9	75,000	18	5-stage Bardenpho process with tertiary filtration. Upgrade completed in December 2012.	Irrigation of golf course and planned for sports fields. Tertiary treated wastewater discharged to Terranora Creek.

4.17 TSC WWTP Effluent Monitoring 2012-2016

Each WWTP must comply with conditions of their respective licenses issued and administered by the NSW EPA. Effluent monitoring license limits include a maximum value (100% limit) that should not be exceeded at any time and a 90% limit where at least 90% of readings in the twelve month license period should be below this value, i.e. up to 10% of readings can exceed this value and the licence may still be complied with (provided the maximum limit has not also been exceeded). The sections below present an assessment of each WWTP monitoring against license limits from 2012-2016.

4.17.1 Banora Point WWTP

Table 7 and Figure 51 show the results of TSC monitoring of effluent quality at the Banora Point WWTP. EPA licences discharge point to the Tweed River Estuary from 2012-2016. In general, compliance with licenced conditions was high with the majority of samples achieving 100% compliance. Nutrient compliance was particularly good with Non-compliances were recorded on a small number of occasions for BOD5 (2014); oil and grease (2015); pH >8.5 (2012-2015); total suspended solids (2013); thermotolerant coliforms (2012, 2013, 2015 and 2016); and total nitrogen (2012). TSC reporting of limit exceedances (TSC, 2016) explains that exceedances were a result of either: algal growth in the effluent lagoon pushing pH >8.5; equipment failure that was identified and corrected; or issues that were unclear but when investigated and retested returned normal results.

The current study compared water quality from the site downstream of the Banora Point WWTP discharge location (TES7) to upstream (TES6) and surrounding sites and determined that there was minimal influence of this input over nutrient concentrations in Terranora Creek. These trends are consistent with ABER (2012) for the previous 5 years.

Table 7: Banora Point WWTP Point 1 - % compliance with EPA licence limits (red cells show non-compliances with the licence)

		NH4	BOD5	O&G	pH	pH	TSS	T.Coli	TN	TP
Year	EPA limits*	<2/5	<10/20	<5/10	>8.5	<6.5	<15/30	<200/600	<10/20	<0.5/1
2012	100th%ile		100	100	95	100	100	100	100	100
	90th%ile		100	100	95	100	92	59	90	100
2013	100th%ile		100	100	83	100	100	100	100	100
	90th%ile		100	100	83	100	89	45	100	100
2014	100th%ile	100	98	100	81	100	100	100	100	100
	90th%ile	100	98	98	81	100	98	92	100	100
2015	100th%ile	100	100	98	94	100	100	100	100	100
	90th%ile	98	100	94	94	100	100	75	100	100
2016	100th%ile	100	100	100	100	100	100	100	100	100
	90th%ile	98	100	100	100	100	100	81	100	100

* Two numbers separated by a slash " / " denote a 90% limit and a maximum limit.

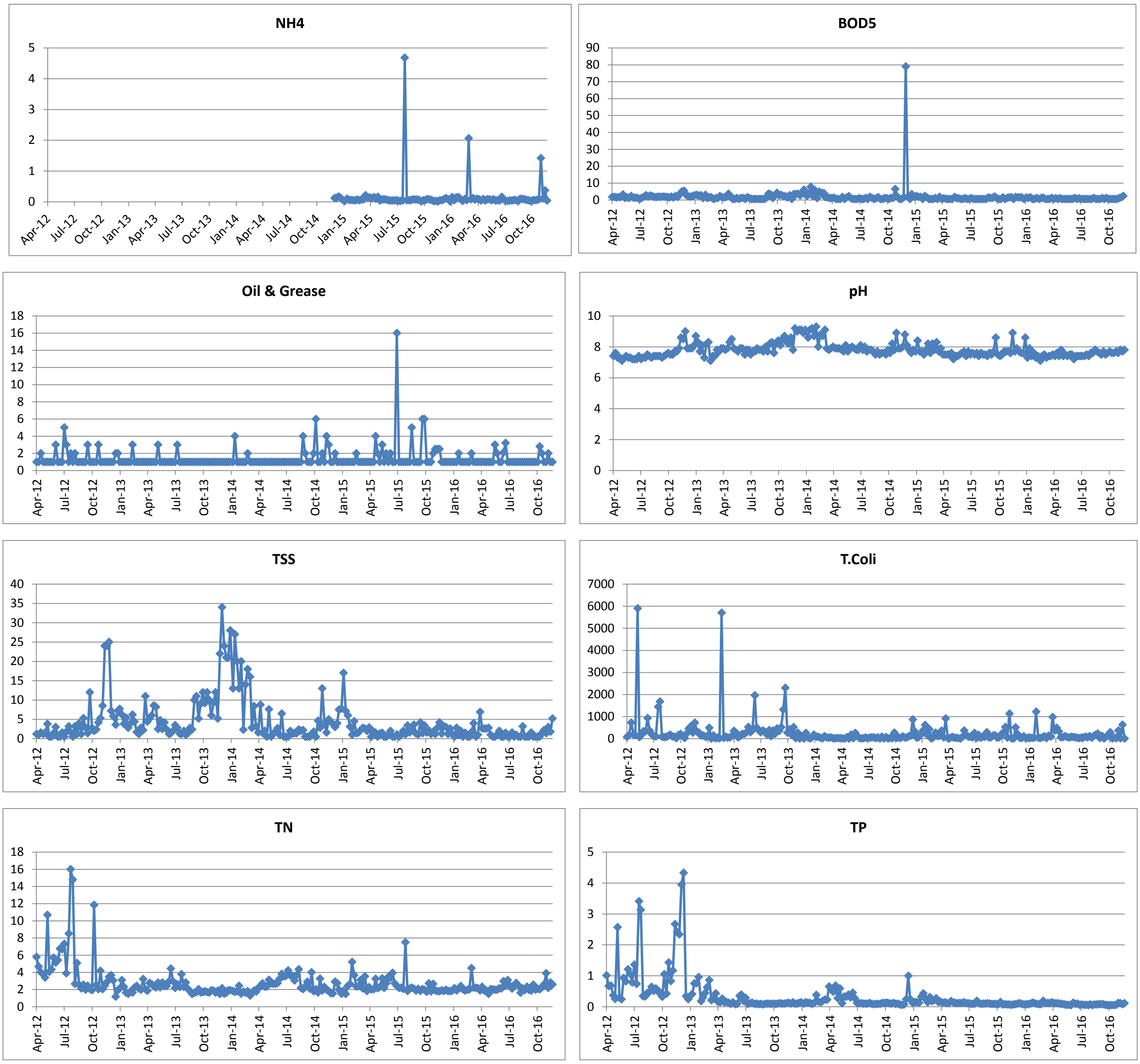


Figure 51: Banora Point WWTP Point 1 monitoring results from 2012-2016

5. RECOMMENDATIONS FOR ONGOING MONITORING

From this review of water quality data, elements of the existing monitoring program have been examined and key areas for improvement identified below:

5.1 Targeted event sampling

Section 2.4 identified that routine monthly sampling was not sufficient to sample a representative number of rainfall events at these sites. As rainfall is a key determinant of hydrologic conditions and has been shown to significantly influence water quality parameters assessed as part of this study, event sampling is considered a key component of sampling. This will be particularly important in capturing potential catchment runoff events (e.g. high TSS, low pH etc.) and to help better characterise the conditions that lead to runoff events. It is recommended that a minimum of four ‘events’ should be captured by the program annually. Event sampling is triggered by >50mL of rain over 3 days preceding sampling, based on BOM rainfall station at Tweed Heads. Routine monthly sampling should continue to allow for the continued assessment of ongoing trends, compliance with water quality guidelines and key risk factors to estuary health.

5.2 Sample sites

The majority of sample sites are located at representative locations spanning the functional zones of the estuary and providing good spatial resolution. During review of water quality site locations and cross-checking with Tweed Labs field staff, it was found that two sites in the lower estuary (TES12) and Terranora Inlet (TES10) had been moved from their original locations due to safety considerations and boating rules. Figure 52 shows the original location of TES12 at the Tweed River mouth between training walls and the current location near Kerosene Inlet approximately 240m north of TWE1; and the original location of TES10 in Ukerebagh Passage now moved to Terranora Inlet approx. 350m southeast from TES9. In both cases the new locations of sampling sites are not considered to provide any additional insight into estuary function or specific contamination sources etc. They are also likely to be too close to adjacent water quality sites to provide independent data and this is supported by water quality results similar to nearby sites assessed by this study. For these reasons it is recommended that both TES12 and TES10 be discontinued.

Figure 52: Changes to location of TES12 and TES10

5.3 Consideration of tidal state

The timing of sampling relative to the tidal cycle can dramatically affect results of a fixed site sampling program (refer Section 2.5). As noted by ABER in 2012 the results of that study were subject to considerable error since the sampling time did not consider the state of tide. As noted in Section 2.5, the current study which also does not account for tidal state is subject to the same level of error. As time of sample collection was not recorded, it is not possible to correct for this error.

However, there are significant advantages of the current fixed site sampling program compared to an alternate sampling strategy based on salinity gradient (e.g. sampling every 2 PSU): being quicker and easier to sample; same locations are sampled each time allowing for spatial trends to be easily assessed and mapped; and the entire estuary is sampled every time; there is a significant historical dataset established for the current sites. For these reasons it is considered appropriate to continue the fixed site sampling program, however recording the time of sampling each sample site is a simple and effective addition which allow tidal state to be retrospectively considered when analysing data.

5.4 Parameters

A key gap in the current program was the absence of ortho-phosphate data (dissolved inorganic form of phosphorus). As bioavailable phosphorus is a primary nutrient in biological processes and particularly important in assessing the risk of blue-green algae development, it is recommended that analysis of ortho-phosphate is undertaken in future sampling.

Secchi disk depth is currently recorded at each site and provides an indication of water clarity. However, there are a number of factors that can limit the usefulness of secchi disk depths including:

- depth of visibility for the secchi disk is dependent on external factors such as sun light intensity and waves. Hence, measurements should be taken at the same general time between 10am and 4pm, in the shade, and in calm waters. In a dynamic and tidal estuary it is unlikely that these conditions can be met every sample event; and
- due to significant depth changes according to tide, particularly in the lower estuary secchi depth does not always reflect water clarity accurately (i.e. the disc could be seen all the way to the bottom, but as depth was shallow due to low tide water clarity is underestimated). This was frequently observed in secchi depth measurements for the current period which had to be omitted from the dataset.

Due to the above reasons, it is recommended that secchi disk depth be discontinued from the monitoring program and turbidity used as a more reliable measure of water clarity throughout the estuary. Typically, turbidity is included in a multiple parameter water quality sonde used to take in-situ physico-chemical measurements and should therefore be a low cost option to include in the program.

5.5 Depth profiles

The current program includes depth profiles (DO, temp, salinity and pH) at two locations in Terranora Creek (TES6 and TES7). Depth profiles were useful in determining levels of stratification occurring at these sites and establishing estuary characteristics and key processes used in modelling described by ABER (2012). The ongoing measurement of physico-chemical properties at depth is considered of limited value for the ongoing program without any specific monitoring objectives to utilise this information. It is therefore recommended that depth profiles are discontinued.

5.6 Reporting of water quality results

Through the 2016 community consultation phase of the CMP, a desire for regular reporting of estuary water quality to the community was identified. A simplified annual report card approach is an effective way to communicate water quality results to the community in plain language. The water quality compliance assessment and mapping completed as part of this study (Section 3, and Appendix 1) provides an example of the type of analysis and visual presentation of results that could be undertaken on an annual basis and published on TSC website, distributed to the Tweed Coast and Waterways Committee and interested community members. Full analysis of spatial and temporal trends, key risk factors and changes through time should be completed at appropriate intervals (e.g. every 5 years).

6. REFERENCES

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7. GLOSSARY AND ABBREVIATIONS

Acid sulfate soils (ASS)	Acid sulfate soils are the common name given to soils containing iron sulfides. In Australia, the acid sulfate soils of most concern are those which formed within the past 10,000 years, after the last major sea level rise. When the iron sulfides are exposed to air and produce sulfuric acid, they are known as actual acid sulfate soils. The soil itself can neutralise some of the sulfuric acid. The remaining acid moves through the soil, acidifying soil water, groundwater and, eventually, surface waters.
Algal bloom	The rapid growth of phytoplankton resulting in a high biomass in the water column.
Ammonia (NH_3 & NH_4^+)	A measure of the most reduced inorganic form of nitrogen in water and includes dissolved ammonia (NH_3) and the ammonium ion (NH_4^+). Nitrogen is an essential plant nutrient and although ammonia is only a small component of the nitrogen cycle, it contributes to the trophic status of a body of water. Natural waters typically have ammonia concentrations less than 0.1 mg/L. Excess ammonia contributes to eutrophication of water bodies and at high concentrations is toxic to aquatic life.
Anoxic	A total depletion in the level of oxygen in water.
Anthropogenic	Any phenomenon caused by human activities.
Aerobic respiration	The process of producing cellular energy involving oxygen.
Aquatic	Living or growing in water, not on land.
Bio-available	Nutrient forms (usually inorganic) available for plant growth.
Brackish	Slightly salty water
Chlorophyll *a*	The green pigment in plants used to capture and use energy from sunlight to form organic matter (see photosynthesis). Concentrations of Chlorophyll *a* are used as an indicator for phytoplankton and benthic algae biomass.
Diffuse Source Pollution	Non-point source pollution such as sediment or nutrients from catchment runoff or groundwater inputs.
Dissolved Inorganic Nitrogen (DIN)	The sum of nitrate, nitrite and ammonium. It comprises the forms of nitrogen available for plant growth.
Dissolved Inorganic Phosphorus (DIP)	Ortho-Phosphate. See Ortho-P below.
Dissolved Oxygen. (DO)	A measure of the amount of oxygen dissolved in water. Typically the concentration of dissolved oxygen in surface water is less than 10 mg/L. Although tolerance varies between species, the level considered suitable for most forms of aquatic life is above 6mg/L or above 80%saturation. The DO concentration is subject to diurnal and seasonal fluctuations that are due, in part, to variations in temperature, photosynthetic activity and river discharge. The maximum solubility of oxygen (fully saturated) ranges from approximately 15 mg/L at 0°C to 8 mg/L at 25°C (at sea level). Natural sources of dissolved oxygen are derived from the atmosphere or through photosynthetic production by aquatic plants. Natural re-aeration of waterways can take place in areas of waterfalls, riffles and rapids. Dissolved oxygen is essential to the respiratory metabolism of most aquatic organisms. It affects the solubility and availability of nutrients, and therefore the productivity of aquatic ecosystems. Low levels of dissolved oxygen facilitate the release of nutrients from the sediments.
Ecosystem	Refers to all the biological and physical parts of a biological unit (e.g. an estuary, forest, or planet) and their interconnections.
Eutrophication	The process of nutrient enrichment of a water body resulting in the increase in plant biomass (algal blooms) and bacterial decay (heterotrophic activity). Often results in a reduction in species diversity, visual amenity, and the prevalence of toxic algal species.
Hydrodynamics	The motion of a fluid and interactions with its boundaries
Hypoxic	Refers to low or depleted oxygen in a water body
Inter-annual variation	Variation observed between years.

Nitrite (NO_2^-)	A measure of a form of nitrogen that occurs as an intermediate in the nitrogen cycle. It is an unstable form that is either rapidly oxidized to nitrate (nitrification) or reduced to nitrogen gas (de-nitrification). This form of nitrogen can also be used as a source of nutrients for plants. It is normally present in only minute quantities in surface waters (<0.001 mg/L). Nitrite is toxic to aquatic life at relatively low concentrations.
Nitrate (NO_3^-)	The measurement of the most oxidized and stable form of nitrogen in a water body. Nitrate is the principle form of combined nitrogen found in natural waters. It results from the complete oxidation of nitrogen compounds. Nitrate is the primary form of nitrogen used by plants as a nutrient to stimulate growth. Excessive amounts of nitrogen may result in phytoplankton or macrophyte proliferations. At high levels it is toxic to infants. Without anthropogenic inputs, most surface waters have less than 0.3 mg/L of nitrate.
Organic Nitrogen	A measure of that portion of nitrogen that is organically bound. Organic nitrogen includes all organic compounds such as proteins, polypeptides, amino acids, and urea. Organic nitrogen is not immediately available for biological activity. Therefore, it does not contribute to furthering plant proliferation until decomposition to the inorganic forms of nitrogen occurs.
Ortho-P	Ortho-Phosphorus (dissolved inorganic phosphate) is the form of phosphorus required by plants for growth and is the form readily available in aquatic environments for algal uptake. In freshwater, Ortho-P is often the limiting factor for algal growth, where light is not limiting.
Oxidised Nitrogen (NOx)	The sum of nitrite and nitrate. Oxidised nitrogen is immediately available to plants.
pH	The measurement of the hydrogen-ion concentration in the water.
Photosynthesis	the process by which plants, some bacteria and some protistans use the energy from sunlight to produce glucose from carbon dioxide and water. Oxygen is also produced.
Physico-chemical	Basic water quality parameters e.g. temperature, pH, conductivity, turbidity.
Physiological	relating to the way in which a living organism functions
Phytoplankton	Microscopic single-cell plants growing in the water column.
Point Source Pollution	A single point of pollutant discharge. For example, effluent from a sewage treatment plant.
Total Nitrogen (TN)	A measure of all forms of nitrogen (organic and inorganic). Nitrogen is an essential plant element and is often the limiting nutrient in marine waters. The importance of nitrogen in the aquatic environment varies according to the relative amounts of the forms of nitrogen present, be it ammonia, nitrite, nitrate, or organic nitrogen.
Total Phosphorus (TP)	A measure of both inorganic and organic forms of phosphorus. Phosphorus can be present as dissolved or particulate matter. It is an essential plant nutrient and is often the most limiting nutrient to plant growth in fresh water. It is rarely found in significant concentrations in surface waters.
Tributary	A waterway flowing into a larger river
Salinity	Salinity is a measure of dissolved salts in water.
Turbid	Cloudy or dirty (not clear)

APPENDIX 1: WATER QUALITY COMPLIANCE MAPS

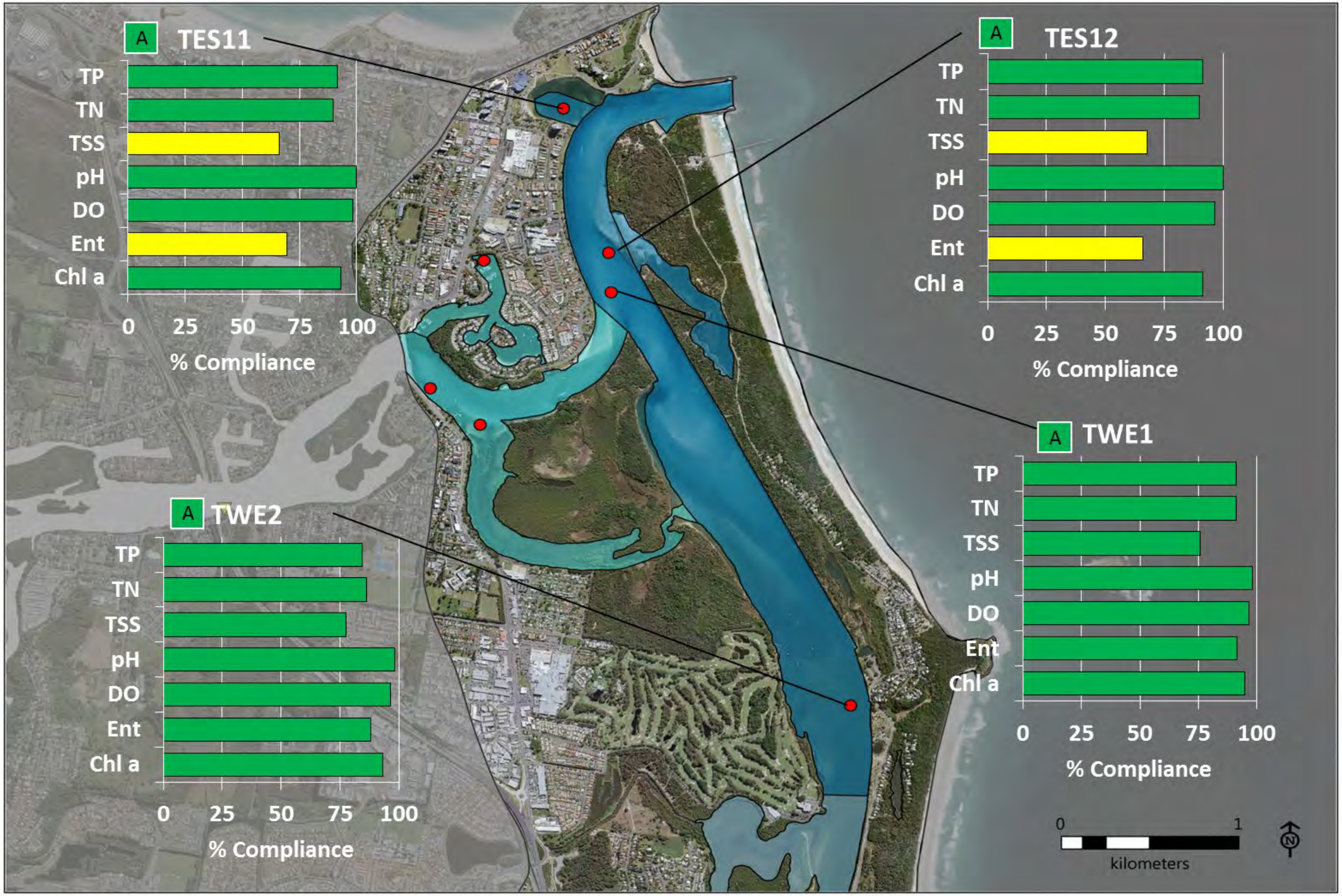

Figure 53: Lower estuary functional zone water quality compliance scores

Figure 54: Terranora Inlet functional zone water quality compliance scores

Figure 55: Terranora Creek functional zone water quality compliance scores

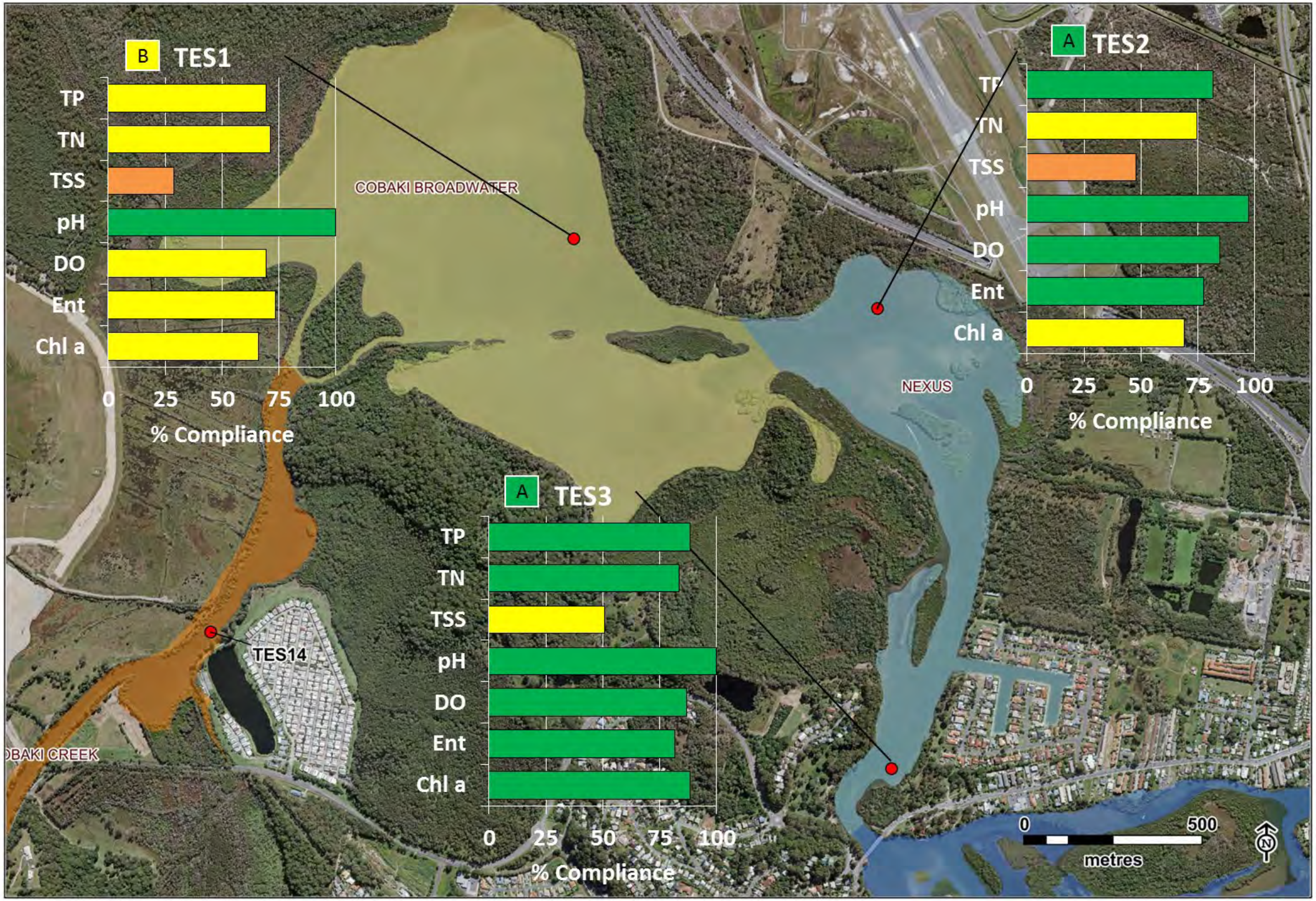

Figure 56:Nexus and Cobaki Broadwater functional zone water quality compliance scores

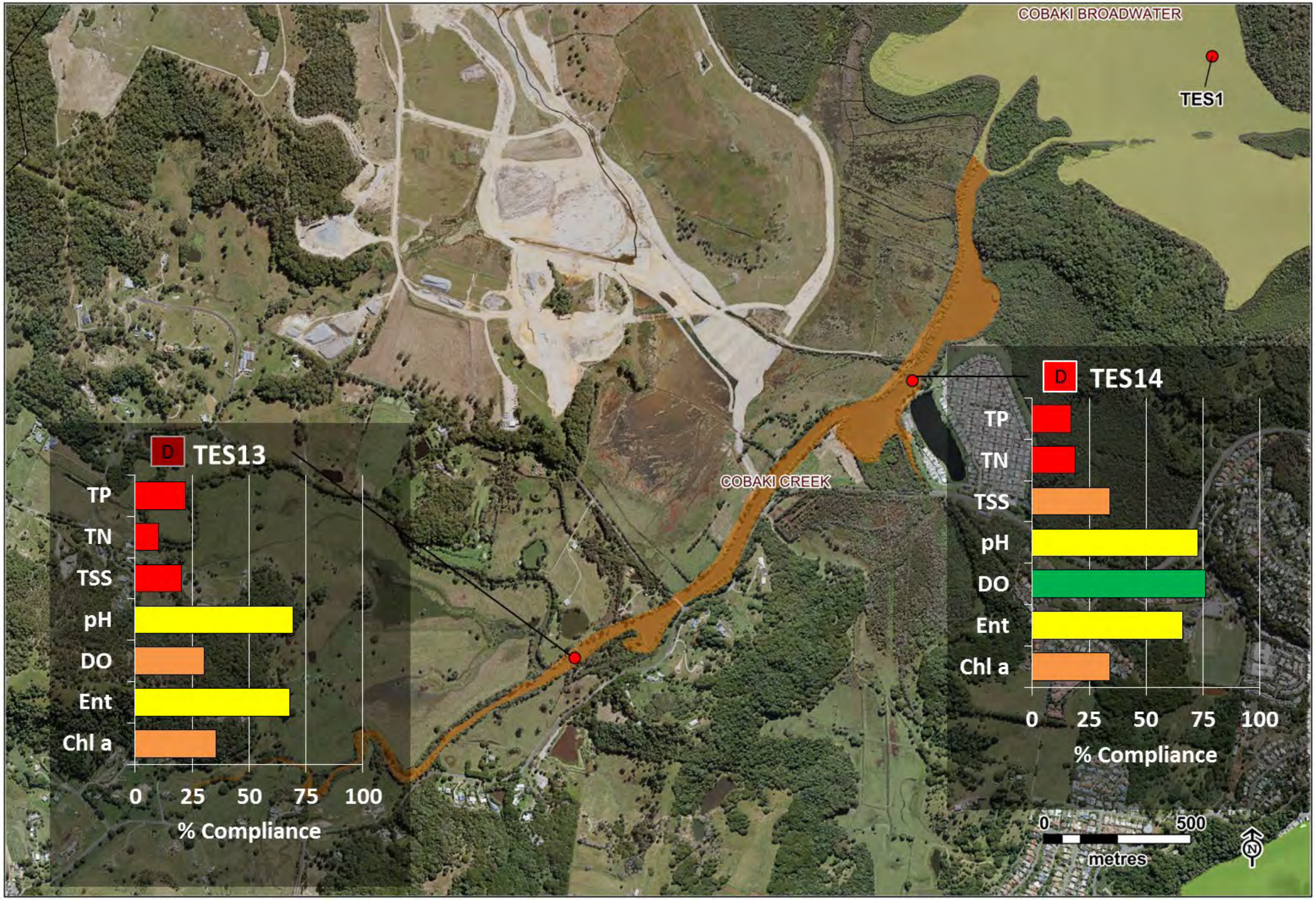

Figure 57: Cobaki Creek functional zone water quality compliance scores

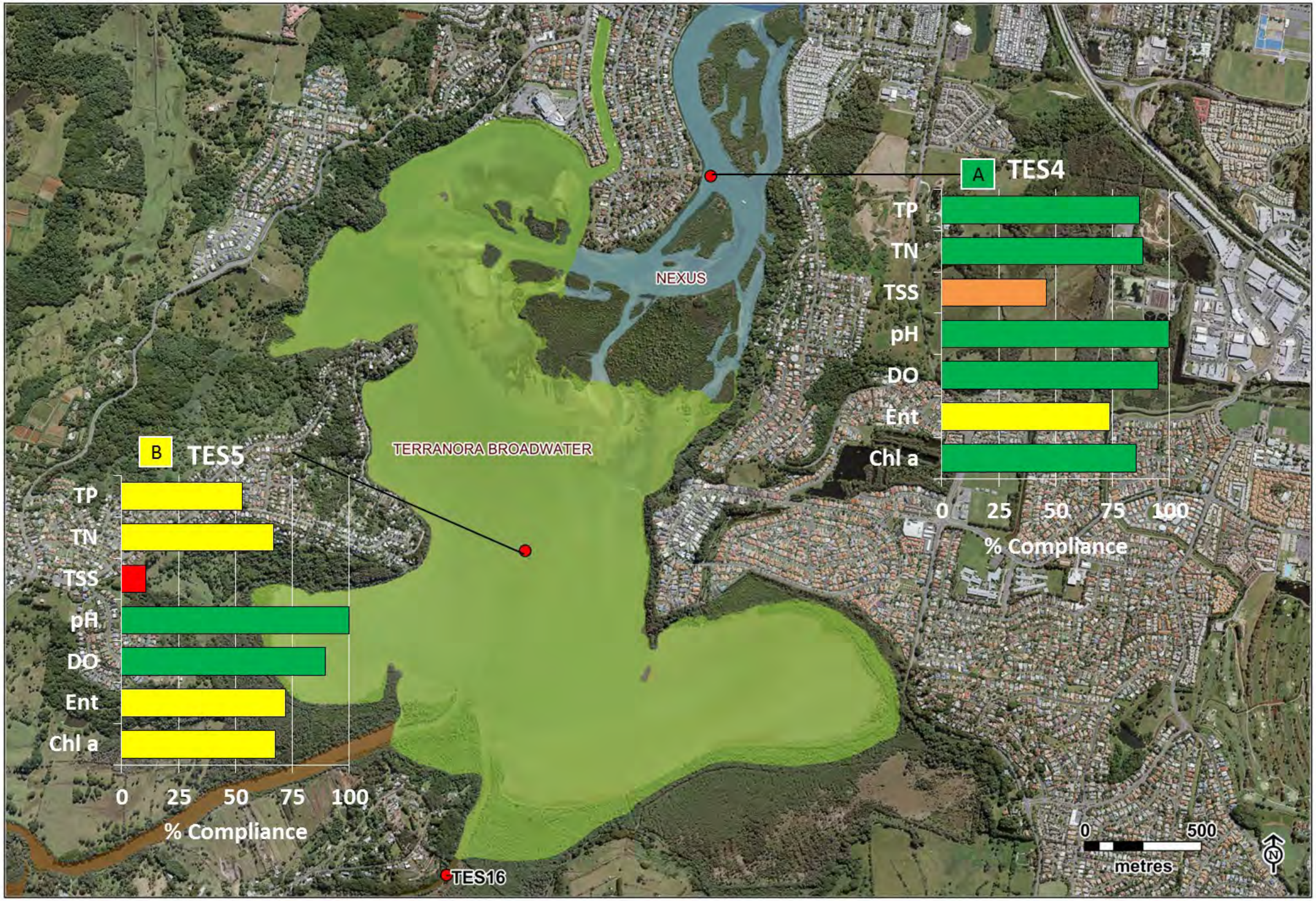

Figure 58: Nexus and Terranora Broadwater functional zone water quality compliance scores

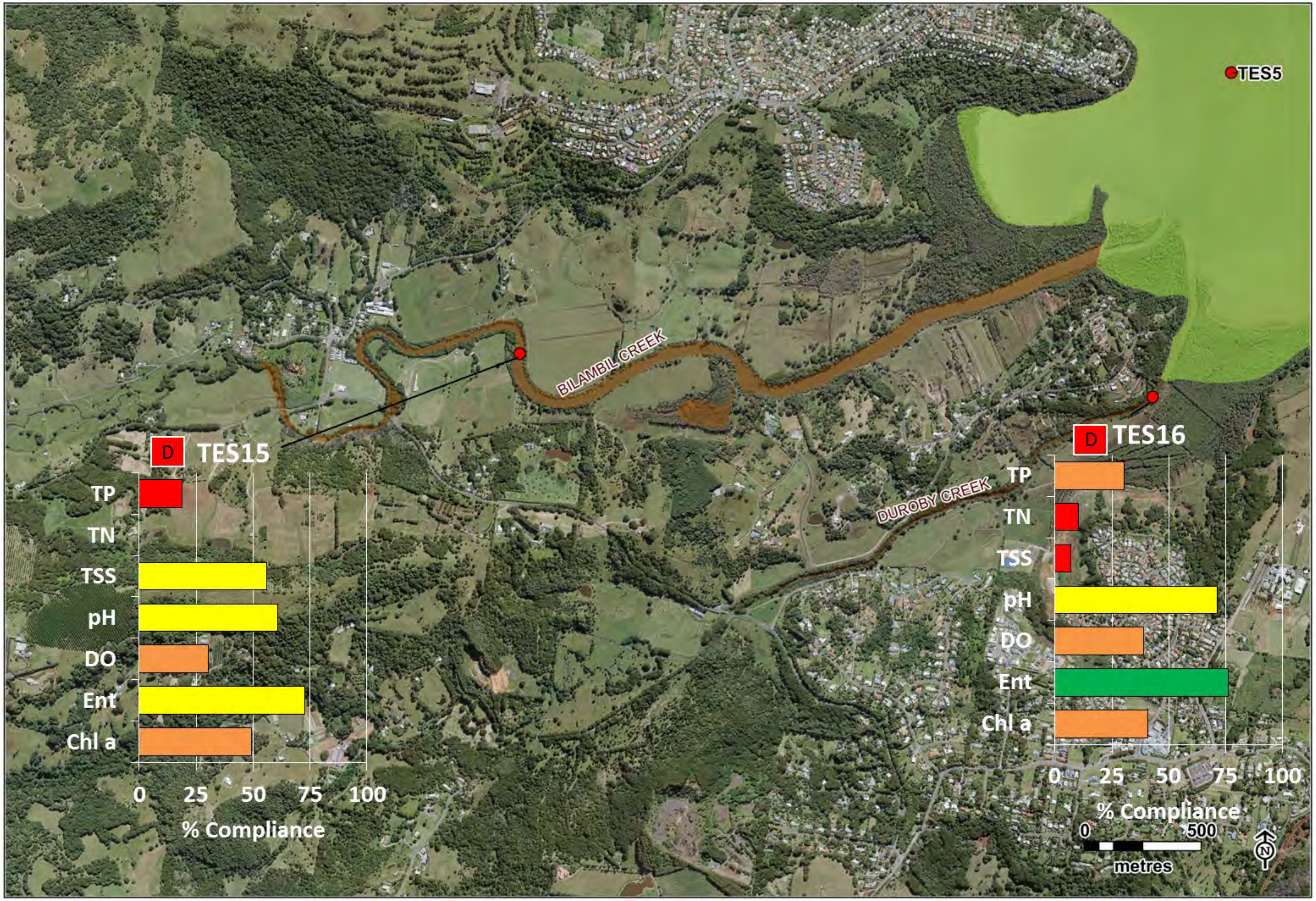

Figure 59: Bilambil Creek and Duroby Creek functional zone water quality compliance scores