Coastal Management Program for the Tweed River Estuary

Water Quality Assessment




Final Report

May 2017

Prepared on behalf of Tweed Shire Council by Hydrosphere Consulting.

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Cover photos: Clockwise from top left: lower estuary near the Tweed River mouth (Hydrosphere Consulting, 2015); Terranora Inlet and Ukerebagh Passage (TSC, 2016); the middle estuary atTumbulgum (Hydrosphere Consulting, 2015); and the upper estuary at Condong (TSC, 2016).

PROJECT 16-051 – TWEED RIVER ESTUARY CMP – WATER QUALITY ASSESSMENT

REV	DESCRIPTION	AUTHOR	REVIEW	APPROVAL	DATE
0	Draft for TSC review	K. Pratt	M. Howland	M. Howland	9 Feb 2017
1	Final Report	K. Pratt	M. Howland	M. Howland	24 Apr 2017
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EXECUTIVE SUMMARY

Tweed Shire Council (TSC) monitors water quality at a number of sites in the Tweed River Estuary to assess estuary health. The objective of this study was the review water quality data collected by the program over 5 years from 2012 to 2016 to better understand the Tweed River Estuary including: 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. Based on the findings of water quality analysis, a Water Quality Improvement Strategy was developed outlining management actions to address identified water quality issues and which will inform the Tweed River Estuary Coastal Management Program (CMP). A summary of key findings are 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 4, page 16). 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 and transitional functional zones, reflecting a generally well-flushed and healthy functioning estuarine system. All sites in the middle and upper estuary, except for TWE8, received a “B” grade (between 66-75% overall compliance) reflecting increasing influence of agricultural runoff and point sources such as wastewater discharge combined with reduced tidal flushing in these zones. Site TWE8 in the upper estuary and site TWE11 in the lower Rous River received “C” grades (between 51-66% overall compliance), with evidence of eutrophication, reduced water clarity and bacterial contamination at these sites. The uppermost sites in the Rous River (TWE12 and TWE13) displayed the poorest water quality receiving ‘D’ grades (<50% overall compliance). 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:

- Acid sulfate soil runoff impacts were observed in the middle and upper estuary and particularly in the Rous River during moderate and high flow. Although effects were reduced in 2012-2016 compared to the previous 5 year monitoring period, acid sulfate soils remain as a continuing risk factor to water quality, particularly following major rainfall events.
- The Rous River, and to a lesser extent the middle estuary, are susceptible to episodes of low DO, although levels were improved compared to the previous 5 years. Low DO is linked to high nutrient and Chlorophyll *a* levels indicating eutrophic conditions and a poorly functioning aquatic ecosystem. Excess nutrient input to the estuary and direct runoff of low DO waters from rural lands are the primary factors likely to be contributing to reduced DO in these zones.
- Total nitrogen (TN) concentrations were elevated in the middle and upper estuary and the Rous River. TN levels were strongly associated with river flow with significantly higher levels during high flow conditions. The exception was the Rous River where high levels were more persistent throughout all flow conditions. This suggests catchment inputs of nitrogen during rainfall events are a significant source of TN to the middle and upper estuary and more consistent inputs from point sources such as WWTP discharge are dominant in the Rous River.
- 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 estuary and particularly the middle and transitional estuary zones during high flows. In the Rous River, high bioavailable nitrogen levels were consistent throughout all flows.

- There was a general trend of low total phosphorus (TP) concentrations in the lower estuary rising to a peak in the middle estuary and diminishing towards the top of the estuary. TP concentrations in the Rous River were consistently high throughout all flows. Apart from the Rous River, at all other sites there was a trend of increasing TP concentrations with flow indicating significant sources of TP in catchment runoff.
- Results indicate the Tweed River Estuary currently tends toward nitrogen limitation meaning that nitrogen (particularly bioavailable forms) are 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.).
- Phytoplankton blooms were indicated in the middle and upper estuary and the Rous River and higher levels were associated with low and moderate flows when residence times are long enough for blooms to develop.
- The Tweed River Estuary experiences poor water clarity (i.e. high total suspended solids) during high flow conditions, particularly in the middle estuary, reflecting the erosion of sediments from the catchment, bank erosion, resuspension of bottom sediments and in some locations algal blooms also contribute to reduced clarity. Water clarity was consistently poor in the Rous River indicating this zone remains turbid for the majority of flow conditions.
- Currently, enterococci levels in the estuary are in excess of human health guidelines at most sites during high flow (i.e. freshwater dominated) conditions and throughout most flow conditions in the Rous River.
- Releases of freshwater from Clarrie Hall Dam in times of low natural river flow, combined with flow through the Bray Park Weir Fish Ladder, has an impact on salinity in the upper estuary. Management of environmental and extractive water releases from the dam, and future management of the fish ladder and a larger dam and will have ecological implications for salinity and for connectivity between the estuary and freshwater reaches of the river.

Recommended Management Actions for consideration in Tweed Estuary CMP

- 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).
- Reduce nutrient inputs to the system by:
    - Reducing point source inputs (e.g. WWTP loading) in the middle, upper and Rous River zones. Actions should focus on reducing nutrient loads during low-moderate flows with the Rous River as a priority area;
    - Reducing diffuse inputs through catchment management throughout rural areas in the middle, upper and Rous River zones. The focus of management is to reduce export of sediment and nutrients during rainfall/runoff events; and
    - Stormwater control and treatment in urban areas.
- 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;

    - Addressing bank erosion;
    - Reduce 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.
- It will be important for any future development in the catchment likely to impact freshwater flows to consider the existing effect of Bray Park Weir.
- The potential raising of Clarrie Hall Dam and potential changes in upstream hydrology impacting the estuary will need to be assessed as part of the environmental impact assessment of the proposal.

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;
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).

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1. INTRODUCTION

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

The current study analysed and assessed water quality data collected since the ABER (2012) report spanning 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 considered water quality results in terms of the overall data set as well as separately as 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. Based on the findings of this study a Water Quality Improvement Strategy (section 5) was developed outlining management actions to address identified water quality issues and which will inform the Tweed River Estuary Coastal Management Program (CMP).

1.1 Study Area

The Tweed River Estuary is located between Tweed Heads and Murwillumbah on the NSW north coast within the Tweed Shire Council (TSC) local government area (LGA). It is the northern-most river in NSW. The Tweed River Estuary runs approximately 35 km from the Bray Park Weir to its confluence with the ocean at Tweed Heads. The boundary of the Tweed River Estuary CMP study area follows the topographical catchment for the Tweed River Estuary as shown in Figure 1, bounded by Bray Park Weir at the upstream extent.

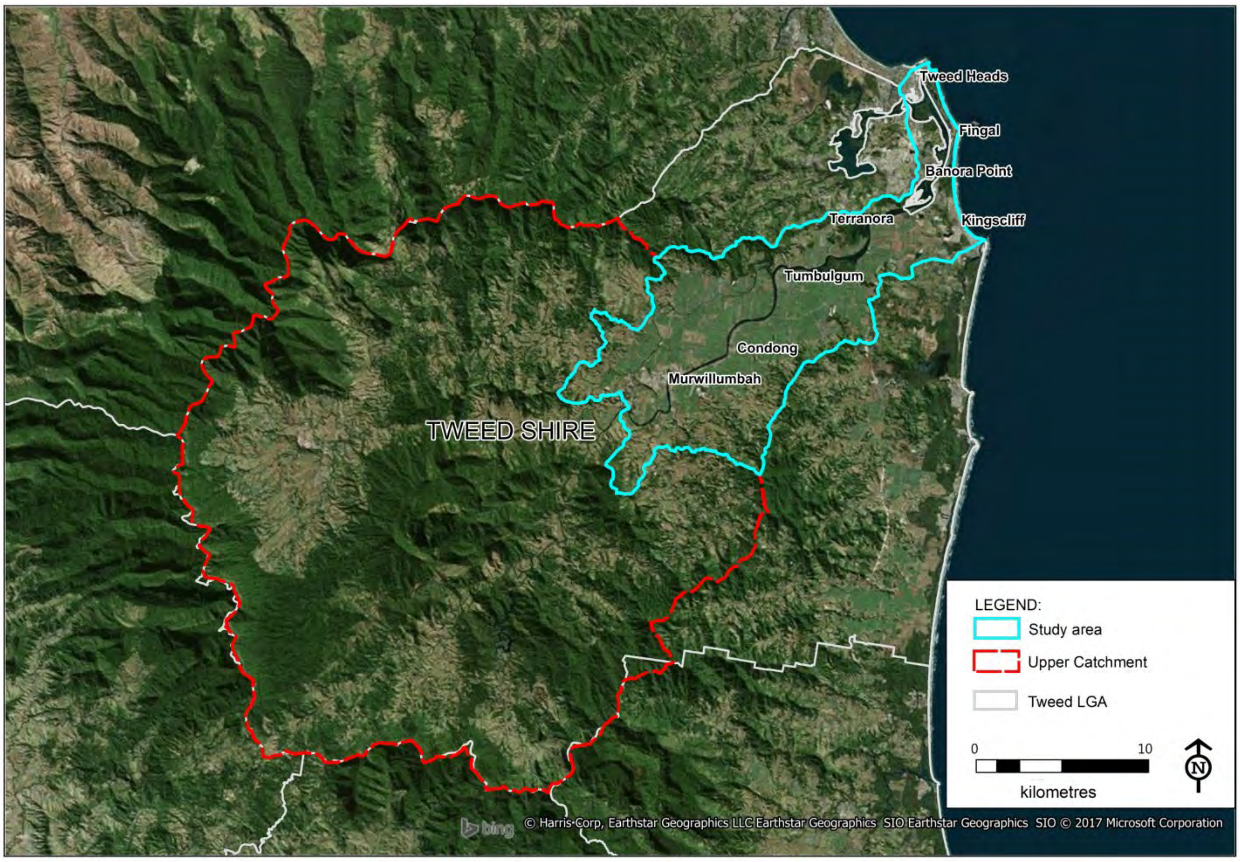

Figure 1: Tweed River Estuary study area and upper catchment upstream of Bray Park Weir

In the upper catchment upstream of Murwillumbah, the Tweed and Oxley Rivers drain the steep ranges encircling Mount Wollumbin, and meet at Byangum, just above the Bray Park Weir. The Bray Park Weir forms the upward limit of tidal influence and the extraction point for the Tweed Shire potable water supply. Below Murwillumbah the estuary meanders across an extensive floodplain that is dominated by sugar cane, and is joined by its northern tributary, the Rous River, at Tumbulgum.

Other major tributaries of the Tweed River system are the Cobaki and Terranora systems, which join the estuary in Tweed Heads. The Cobaki and Terranora systems do not form part of the study area for this assessment. A separate assessment of water quality in the Cobaki and Terranora systems has been completed in parallel to this report.

1.1.1 Functional Zones

Previous study of water quality in the Tweed River Estuary (ABER, 2012) divided the waterway into five 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 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;
- transition – from Shallow Bay up to and including the Tweed Broadwater;
- middle estuary – from the Tweed Broadwater to the village of Condong;
- upper estuary – from Condong to Bray Park Weir; and
- Rous River – the tidal extent of the Rous River from the confluence with the Tweed River at Tumbulgum to Numinbah Road bridge at Boat Harbour.
- 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.

ABER (2012) note that the functional boundaries of each zone are nominal and can vary considerably with seasonal changes in freshwater inflows, with the greatest variability experienced in the ‘transitional zone’.

1.2 Background

Water quality in the Tweed River Estuary and upper catchment 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 Tweed Estuary 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 estuary 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 Tweed Estuary 2007 – 2011 (ABER, 2012)

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

- Water quality objectives for nutrients, dissolved oxygen (DO), Chlorophyll *a* and turbidity are regularly exceeded in the Tweed River Estuary.

- Seasonal processes are a primary influence on water quality. The Tweed River Estuary ecosystem has evolved with episodic pulses of high nutrients and organic matter to the system during floods, followed by opportunistic increases in primary (phytoplankton) and secondary (benthic invertebrates, detritivores, fish, birds) productivity during the months following the flood event.
- During flood flows, low-lying catchments on the floodplain discharge water with low pH (acid) and low oxygen.
- During the dry season inputs of nitrate from STP effluent and the ocean are the primary drivers of new productivity in the estuary at this time.
- The Tweed River Estuary has elevated concentrations of Total Nitrogen (TN) especially in the middle estuary which receives inputs of nutrient-rich wastewater. Concentrations are highest during high flows when diffuse catchment sources dominate. Nitrogen input is stimulating algae growth in estuary reaches, the decomposition of which is leading to depressed levels of dissolved oxygen.
- The Tweed River Estuary experiences moderately severe phytoplankton blooms in the middle and upper estuary and lower Rous River. Modelling shows that blooms are controlled by wastewater inputs of bio-available nitrogen and water residence times.
- The Tweed River Estuary is prone to moderate hypoxia along the middle to upper estuary reaches during low to median flow conditions. Hypoxia is due to high sediment oxygen demand caused by organic matter enrichment from phytoplankton blooms.
- During high flow, oxygen-poor flood waters draining from low lying swamps and cane land cause hypoxia to extend to the lower estuary transition zone.
- The Tweed River Estuary experiences greatly elevated Total Suspended Solids (TSS) concentrations (poor water clarity) during floods and high flow conditions reflecting the erosion of sediments from the catchment. Much of this material is deposited in the estuary as flows subside.
- Catchment runoff and discharge of treated sewage effluent are identified as the primary causes of poor water quality in the estuary. River bank erosion is also an issue of concern. In the upper catchment, issues of concern include high levels of nutrients in runoff, (particularly nitrogen) as well as sediment, algae and bacterial contamination.
- Recommended management actions included: reducing nutrient export through STP management; reduce acid and low-oxygen water by reducing ponding on cane land, introducing wet pasture management and reinstating back swamp flood reserves.

Conceptual Model of the Tweed Estuary

ABER (2012) developed a conceptual model of estuarine function for the Tweed River Estuary 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. Hence during high flow times, water quality along the estuary reflects catchment inputs, while during the dry season biological uptake of inorganic nutrients dominates. Improvement of water clarity during the dry season increases the relative importance of benthic productivity as a nutrient sink. Inputs of nutrients from STPs and recycling from the sediments dominate during median to low flow conditions (ABER, 2012).

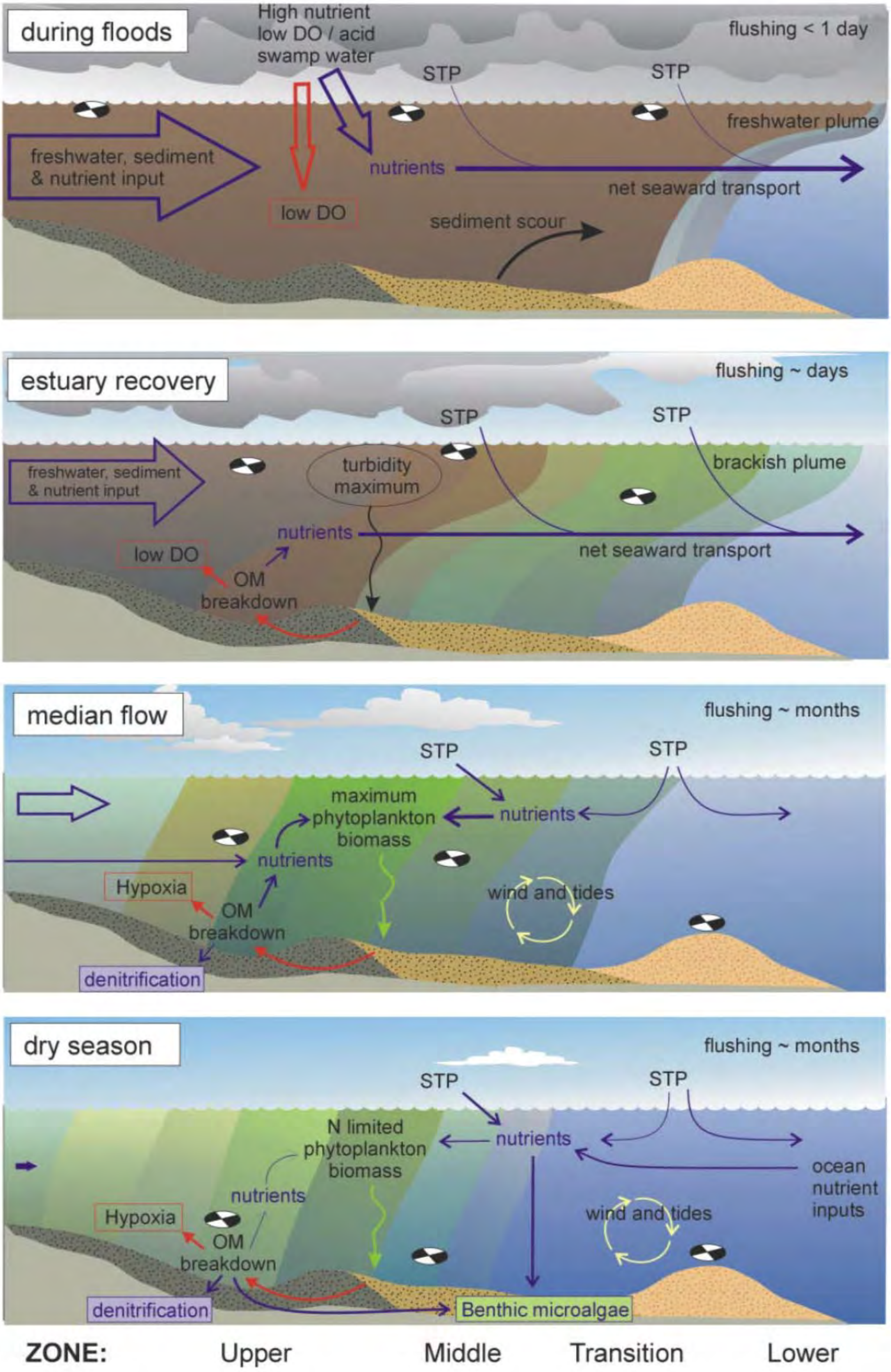

Figure 2: Conceptual model of the Tweed River Estuary (Source: ABER, 2012)

1.2.2 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 Tweed Estuary with the following summary points of ecosystem health status:

- Some healthy seagrass;
- Cleared streambank habitat;
- Localised wastewater impacts;
- Agricultural runoff impacts;
- Consistently high phytoplankton; and
- Well flushed river mouth.

The Rous River received a D-; upper estuary received a C; The mid estuary received a D; and the lower estuary performed the best scoring an A-.

Figure 3: Conceptual model of Tweed River Estuary catchment (University of Queensland, 2003)

1.2.3 Tweed River and Catchment Interim Water Quality Management Plan (WBM Oceanics, 2000)

WBM Oceanics (2000) collated and reviewed existing data and proposed management and further investigations. Key water quality problems for the Tweed River Estuary were reported as:

- Lower estuary – High bacterial levels; acid sulfate soils;
- Mid estuary - Elevated nutrient and algal levels; potential for Cyanobacterial (Blue green algae) blooms; acid sulfate soils; and
- Upper estuary - Elevated nutrient and algal levels.

1.2.4 Improving the quality of drainage water from NSW canelands (Beatie *et al*., 2004)

This was a NSW Sugar industry funded study where continuous water quality data were collected via automated water quality stations installed in six cane drains across the Tweed, Richmond and Clarence catchments and discrete monthly samples taken between 1999-2002. The study examined pesticides, nutrients and physico-chemical properties of water. In the Tweed study area, an automated station was set up in Bartlett's Creek (Condong). Beattie *et al*. (2004) provided a general overview of all sites spread over the Tweed, Richmond and Clarence catchments with little detail specifically reported for the Tweed sites. While it was difficult to draw conclusions about the Tweed sites based on the data reported, the following conclusions were given in the report:

- While pesticide residue was detected, levels did not exceed Australian Drinking Water Guidelines (1996) or recreational use guidelines (ANZECC, 2000) at any sites.
- Barletts drain showed low overall acidity with pH>6.0 for 97% of the time. This indicates there were periods of acidic conditions in the drain (3% of the time).
- DO ranged from 0-13.2 mg/L across all sites, with Barletts drain having a median value of 7.7 mg/L (within ANZECC guidelines). This indicates that there were periods of anoxic and low DO conditions at some sites.
- Total Nitrogen and Total Phosphorus concentrations were in excess of ANZECC guidelines (2000) for lowland coastal rivers in NSW at all sites.
- Ammonium-N consistently contributed more to DIN across all drains than oxidised-N and this was attributed to suppression of nitrification from strong acidity in soils and some drain waters.
- Dissolved Inorganic Phosphorus (DIP) levels were below ANZECC guidelines at Bartlett's Creek.

1.2.5 Assessing the Seasonal Influence of Sewage and Agricultural Nutrient Inputs in a Subtropical River Estuary (Costanzo et al., 2003)

The study examined a combination of physical and chemical measurements and biological indicators over wet and dry seasons to identify nutrient impacts throughout the Tweed River Estuary. Key conclusions were:

- Primary nutrient impacts were identified as sewage inputs in the lower river and agricultural inputs in the mid-upper river. Impacts were greater in the wet season due to greater agricultural surface runoff.
- Strong spatial (within river) and temporal (seasonal) variability was observed in all parameters.
- Poorest water quality was detected in the middle (agricultural) region of the river in the wet season, attributable to large diffuse inputs in this region.
- Water quality towards the river mouth remained constant irrespective of season due to strong oceanic flushing.

- Phytoplankton bioassays found the system to be primarily responsive to nutrient additions in the warmer wet season, with negligible responses observed in the cooler dry season.
- These results indicate that the Tweed River is sensitive to the different anthropogenic activities in its catchment and that each activity has a unique influence on receiving water quality.

1.2.6 Water Quality in the Lower Tweed Estuary System (KEC Science, 1998)

KEC Science (1998) provided a detailed analysis of water quality data collected over a 12-month period from 1997-98. Key conclusions from the study were:

- Primary contact guidelines were met.
- Nutrient levels approached or exceeded guidelines but algal growth was not excessive.
- Suspended solids exceeded guidelines and catchment erosion was identified as the primary source.
- Stormwater had a significant impact accounting for 70-90% of the variation in water quality.

1.2.7 A Spatially Intensive Approach to Water Quality Monitoring in the Rous River Catchment (Eyre and Pepperell, 1997)

A spatially intense water quality monitoring project was undertaken in the Rous River in 1997 (Eyre and Pepperell, 1997).

- Three point sources being the Murwillumbah STP, a dairy shed and horse stables had the largest impact on water quality in the Rous River catchment. Most water quality parameters assessed greatly exceeded ANZECC guidelines immediately downstream of these point sources. The impact of the dairy shed and horse stables was localised with an improvement in most water quality parameters further downstream due to dilution and assimilation. However nutrient loads from the STP were more persistent and Eyre and Pepperell (1997) attributed these loads to the stimulation of algal growth throughout most of the Rous River estuary.
- The poorest water quality due to non-point source inputs was associated with cane land, which had elevated nutrient concentrations and elevated temperatures, stimulating algal growth, resulting in high turbidity.
- High instream oxidised nitrogen concentrations were attributed to the use of nitrate based fertilisers leaching from upstream banana plantations.
- Catchment-wide water quality (excluding cane and horticultural areas and downstream of point sources) was generally good for aquatic ecosystem health, but poor for human health.
- Elevated faecal coliforms concentrations across the catchment were attributed to direct cattle access to waterways.

2. SAMPLING PROGRAM

2.1 Monitoring sites

The Tweed River Estuary water quality monitoring program involves *in situ* monitoring and collection of samples for laboratory analysis. There are a total of 19 water quality sampling sites within the Tweed River CMP study area. Figure 4 shows the location of sites within the catchment. Table 1 provides details of sampling sites.

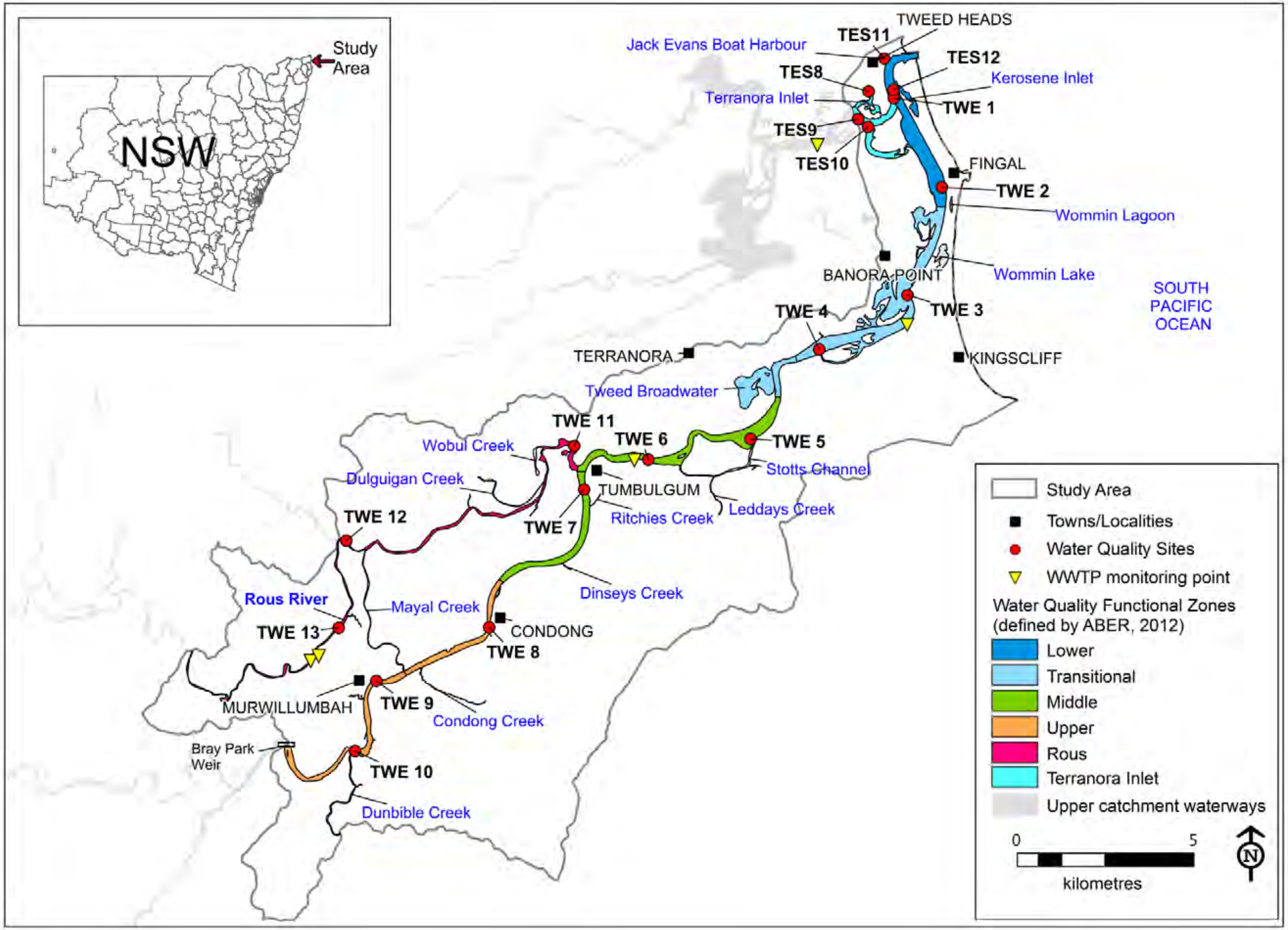

Figure 4: Water Quality sampling sites within the Tweed CMP study area

Table 1: Details of water quality sampling sites

Site Code	Waterway	Functional Zone	Surrounding landuse	Sample day	Site Description
TWE13	Rous River	Rous	Sugarcane, rural residential	Day 1	Approx. 1.3km downstream of Murwillumbah WWTP effluent discharge point. Just downstream of Queensland Road bridge. Depth profiles are taken at this location.
TWE12	Rous River	Rous	Sugarcane, grazing, horse stables, rural residential, bushland.	Day 1	Approx. 250m downstream of confluence with Dungay Creek. Adjacent to the Tweed Valley Equine Centre on Dulguigan Road.
TWE11	Rous River	Rous	Sugarcane, grazing, bushland	Day 1	Approx. 750m upstream of confluence with Tweed River and Tumbulgum Village. Just downstream of confluence with Wobul Creek and Thomson Gully.
TWE10	Tweed River	Upper	Grazing, sugarcane, bushland	Day 2	Upstream extent of sample sites in Tweed River Estuary. At confluence with Dunbible Creek.
TWE9	Tweed River	Upper	Urban residential, urban recreational, transport and communication, commercial, industrial, pasture	Day 2	Adjacent to Murwillumbah CBD, approx.100m downstream of Wollumbin St. bridge. Several stormwater drain outlets in the vicinity.
TWE8	Tweed River	Upper	Sugarcane, urban residential, pasture	Day 2	Adjacent to village of Condong and the Condong Sugar Mill and effluent discharge. Approx. 100m downstream of Cane Rd bridge and cane drain outlet. Two stormwater outlets in vicinity.
TWE7	Tweed River	Middle	Sugarcane, urban residential, pasture	Day 2	Approx. 200m upstream of village of Tumbulgum and 650m upstream of confluence with Rous River. Several cane drain outlets and stormwater outlets in the vicinity.
TWE6	Tweed River	Middle	Sugarcane, grazing, rural residential	Day 2	Approx. 1km downstream of village of Tumbulgum and 400m downstream of Tumbulgum WWTP effluent discharge point. Depth profiles are taken at this location. Several cane drain outlets in the vicinity.
TWE5	Tweed River	Middle	Sugarcane, bushland, pasture	Day 2	Just downstream of Stotts Island and adjacent to confluence with Stotts Channel. Several cane drain outlets in the vicinity.
TWE4	Tweed River	Transitional	Sugarcane, grazing, bushland	Day 2	Adjacent to Dodds Island and confluence of Dodds Island channel with Tweed River. Close to Actions Sands dredging operations on sand bar/mud flat in river. Several cane drain outlets in the vicinity.

Site Code	Waterway	Functional Zone	Surrounding landuse	Sample day	Site Description
TWE3	Tweed River	Transitional	Urban residential, urban recreational, pasture, bushland	Day 2	Approx. 600m upstream of Barneys Point Bridge, adjacent to Chinderah Bay and Banora Point urban areas. Approx. 1km downstream of Kingscliff WWTP effluent discharge point. Several stormwater outlets in the vicinity. Depth profiles are taken at this location.
TWE2	Tweed River	Lower	Urban residential, urban recreational, pasture, bushland	Day 2	Adjacent to urban areas of Fingal and Tweed Golf Course. Several stormwater outlets in the vicinity.
TWE1	Tweed River	Lower	Urban residential, commercial and industrial, pasture, bushland	Day 2	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	Day 3	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	Day 3	Jack Evans Boat Harbour, surrounded by parklands, urban areas and shops. Several stormwater outlets in the vicinity.
TES10	Terranora Creek	Terranora Inlet	Urban residential, commercial and industrial, bushland	Day 3	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.
TES9	Terranora Creek	Terranora Inlet	Urban residential, urban recreational, bushland	Day 3	Located in Terranora Creek approx. 200m downstream of Boyds Bay Bridge. Boat mooring location.
TES8	Tweed Heads Marina	Terranora Inlet	Urban residential, commercial and industrial, transport and communication	Day 3	Located at northern end of Tweed Heads Marina. Several stormwater outlets in the vicinity.

2.2 Sample Collection

Routine sampling of the Tweed River Estuary 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.

Sampling is carried out over three days with the upper estuary sites (TWE11-13) sampled on day one, mid and lower estuary sites (TWE1-TWE10) sampling on day 2, and lower estuary and Terranora Inlet sites (TES8-12) sampled on day 3.

No allowance is made for tidal state except at shallow sites, when timing of sampling must be according to tide to allow boat access (generally Day 3 sites only). 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 1 site in the lower (TWE3), middle (TWE6) and upper estuary (TWE13). Samples for nutrients, total suspended solids, colour, and Chlorophyll *a* were collected from a depth of 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. We note that 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 2: 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 two locations in the study are: Murwillumbah (Bray Park station), and 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 and Murwillumbah from 2012-2016 as compared to long term averages. Tweed Heads (1,695mm/yr) generally experiences slightly higher and more frequent rainfall than Murwillumbah (1,602mm/yr) likely due to the influence of the storms along the coastal fringe. 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 (particularly at Tweed Heads) 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 250mm 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).

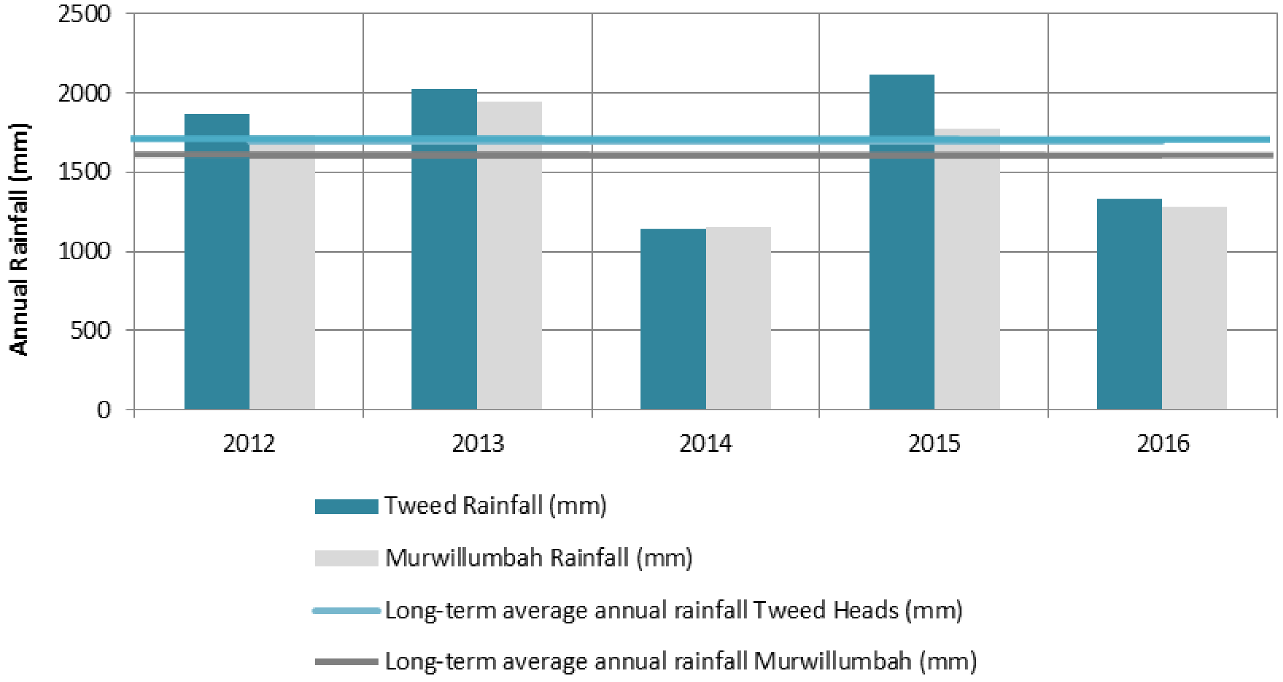

Figure 5: Annual rainfall for each year of the study period (2012-2016) at Tweed Heads and Murwillumbah showing the long-term average annual rainfall (Source: BOM, 2016 and Silo Data Drill, 2016)

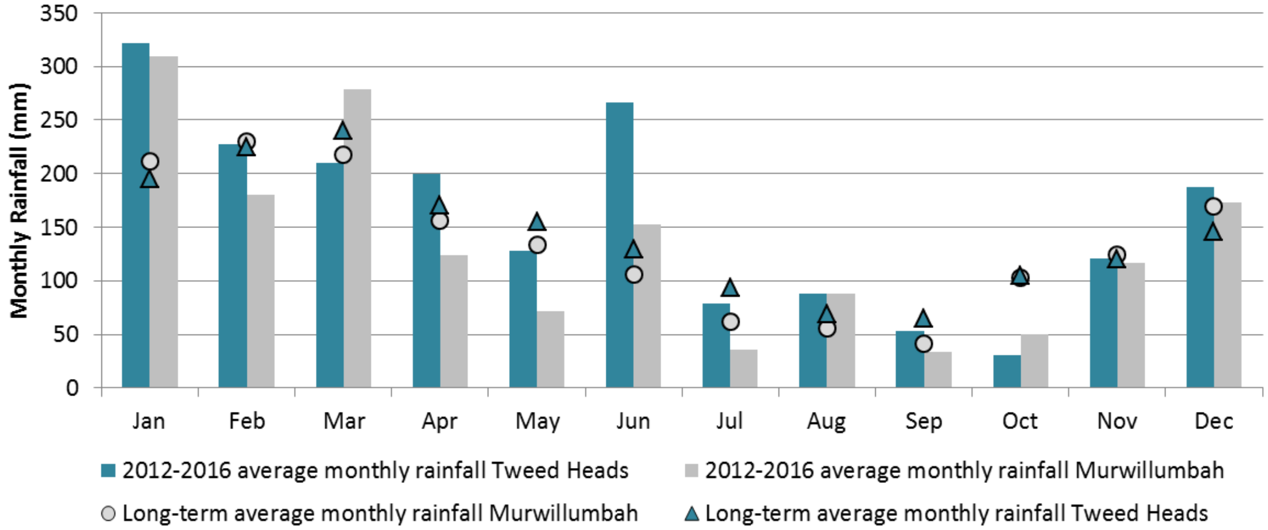

Figure 6: Average monthly rainfall Tweeds Heads and Murwillumbah from 2012-2016 showing the long-term averages

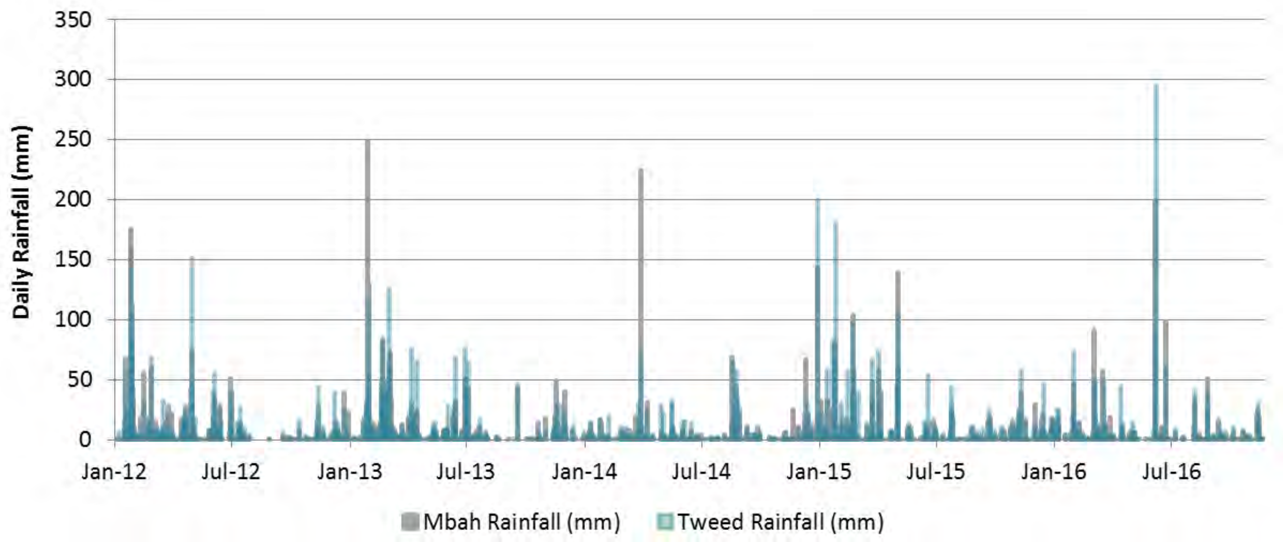

Figure 7: Daily rainfall at Tweeds Heads and Murwillumbah 2012-2016

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 Tweed River Estuary 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.

During analysis of local rainfall, some minor variation in both rain days and rainfall totals was identified between Tweeds Heads and Murwillumbah (see above). To account for the variation in rainfall across the estuary, Tweed Heads rainfall station data was assigned to lower estuary sites (TWE1-4 and TES8-12) and Murwillumbah rainfall data was assigned to mid and upper estuary sites (TWE5-13).

Table 3 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 (73%) have been collected during low rainfall conditions, with 20% collected during moderate rainfall conditions. High rainfall or 'event' samples comprise approximately 7% 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 3). This highlights a need to target wet events in future sampling to adequately represent water quality under a range of hydrologic conditions.

Table 3: Sample counts at each site classified by rainfall condition compared to all days from 2012-2016

Site	High	Moderate	Low
TES10	4	17	38
TES11	4	17	38
TES12	4	17	38
TES8	6	23	63
TES9	4	17	40
TWE1	4	10	44
TWE10	6	8	50
TWE11	6	19	84
TWE12	5	16	43
TWE13	4	12	43
TWE2	4	10	44
TWE3	4	10	44
TWE4	6	12	56
TWE5	4	10	45
TWE6	4	9	45
TWE7	4	12	58
TWE8	5	10	60
TWE9	4	8	46
TOTAL no. samples	**82**	**237**	**879**
% of total samples	**7%**	**20%**	**73%**
% 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) took salinity measurements continuously over three days at three fixed sites in the Tweed River Estuary (lower, upper and middle sites). Figure 8 shows that salinity at a fixed site within the estuary can vary by more than 10 PSU over a single tidal cycle and this influence extends to the middle estuary near Stotts Island some 15kms upstream of the ocean entrance. 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. 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.

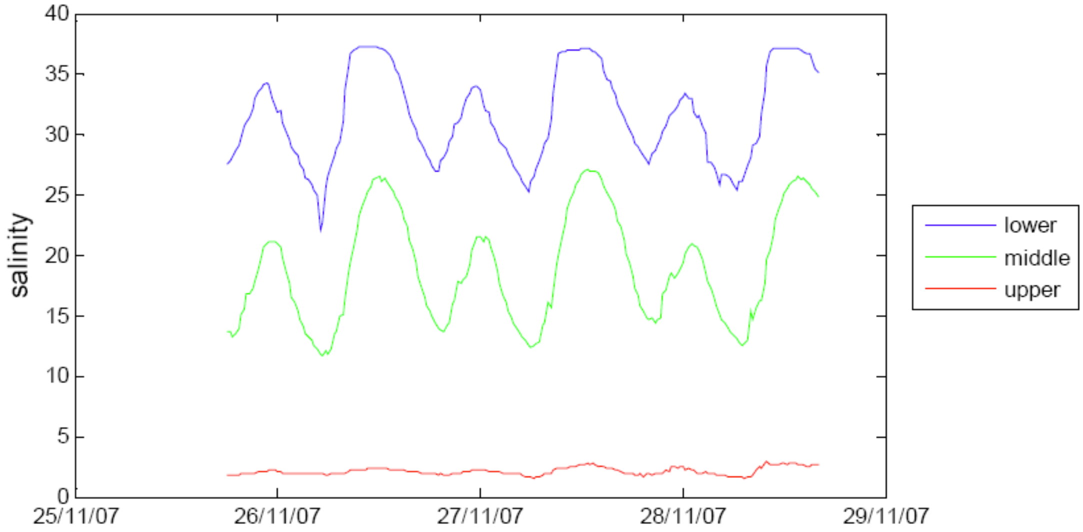

Figure 8: Salinity variation over three days at three locations in the Tweed estuary (lower = downstream of Pacific Highway bridge; middle = downstream of Stotts Island; upper = upstream of Murwillumbah). Source: ABER (2012)

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 9 shows the overall compliance scores at each site (created by the average of compliance score across all parameters); Table 4 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 and transitional 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) and Tweed Heads Marina (TES8) and this was associated with rainfall events indicating stormwater inputs (refer section 4.12.1 and 4.14.1). TSS, nutrients and Chlorophyll *a* were occasional issues for compliance in the transitional zone, reflecting increased pressure from catchment and upstream sources and reduced flushing capacity.

All sites in the middle and upper estuary, excerpt for TWE8, received a “B” grade (between 66-75% overall compliance) reflecting increasing influence of agricultural runoff and wastewater discharges in this zone. Nutrients, TSS, DO and enterococci occasionally exceeded guidelines and Chlorophyll *a* only achieved aquatic ecosystem guidelines 50% of the time or less indicating elevated algae is often a problem in this zone.

Site TWE8 in the upper estuary and site TWE11 in the lower Rous River received “C” grades (between 51-66% overall compliance). Nutrients, Chlorophyll *a*, DO and enterococci were all issues at these sites and TSS was also an issue at TWE11 in the Rous River. TWE8 was the only site to show a worse compliance result than the sites immediately upstream, possibly indicating a point source affecting this location. This site is located adjacent to the village of Condong and the Condong Sugar Mill effluent discharge location which may be impacting results for this site. There are also cane drain and stormwater outlets within this vicinity which could be adding to water quality degradation.

The uppermost sites in the Rous River TWE12 and TWE13 displayed the poorest water quality receiving ‘D’ grades (<50% overall compliance). High nutrient and Chlorophyll *a* concentrations were significant issues in the Rous River indicating frequent eutrophication. High enterococci levels was also a significant issue and dissolved oxygen, pH and total suspended solid levels were achieving guidelines less than 75% of the time, indicating poor ecosystem health and a high level of disturbance from natural state.

Table 4: 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
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
Lower	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
	TWE2	97	98	78	86	84	93	88	89	A
Transitional	TWE3	89	94	83	72	74	84	80	82	A
	TWE4	88	93	72	70	68	73	83	78	A
Middle	TWE5	73	86	68	64	66	63	78	71	B
	TWE6	69	84	74	55	62	50	76	67	B
	TWE7	72	85	81	57	64	50	71	68	B
Upper	TWE8	73	85	80	48	52	47	69	65	C
	TWE9	88	91	86	52	48	40	61	67	B
	TWE10	92	98	91	48	41	48	75	71	B
Rous River	TWE11	56	80	61	50	52	36	60	56	C
	TWE12	66	66	45	33	19	39	23	42	D
	TWE13	68	64	71	32	8	36	20	43	D

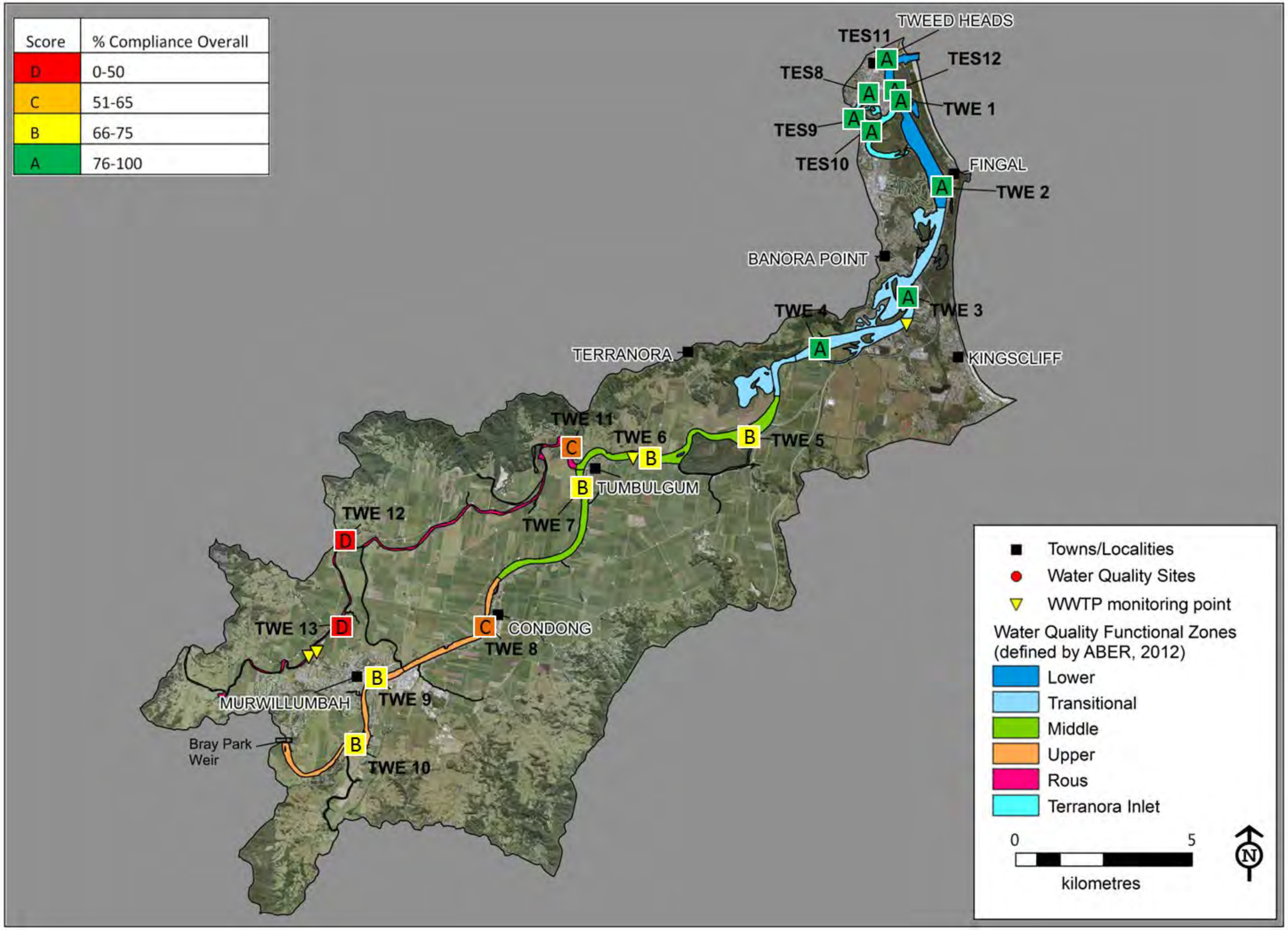

Figure 9: Overall water quality compliance scores at each site

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, 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

As expected, salinity decreased from the estuary mouth to the upper estuary during all flow conditions. The highest salinities were consistently recorded during low flow conditions when tidal influence was greatest and freshwater flows minimal. There was considerable overlap in salinities under low and moderate flow conditions, while high flow salinities were significantly lower. The variation in salinity was greatest during high flow conditions in the lower estuary (e.g. TES12) when the full exchange of seawater with freshwater flows is experienced with the tides. Results show that brackish conditions extend to the upper estuary sites during low flow. These results are consistent with previous monitoring results (ABER, 2012).

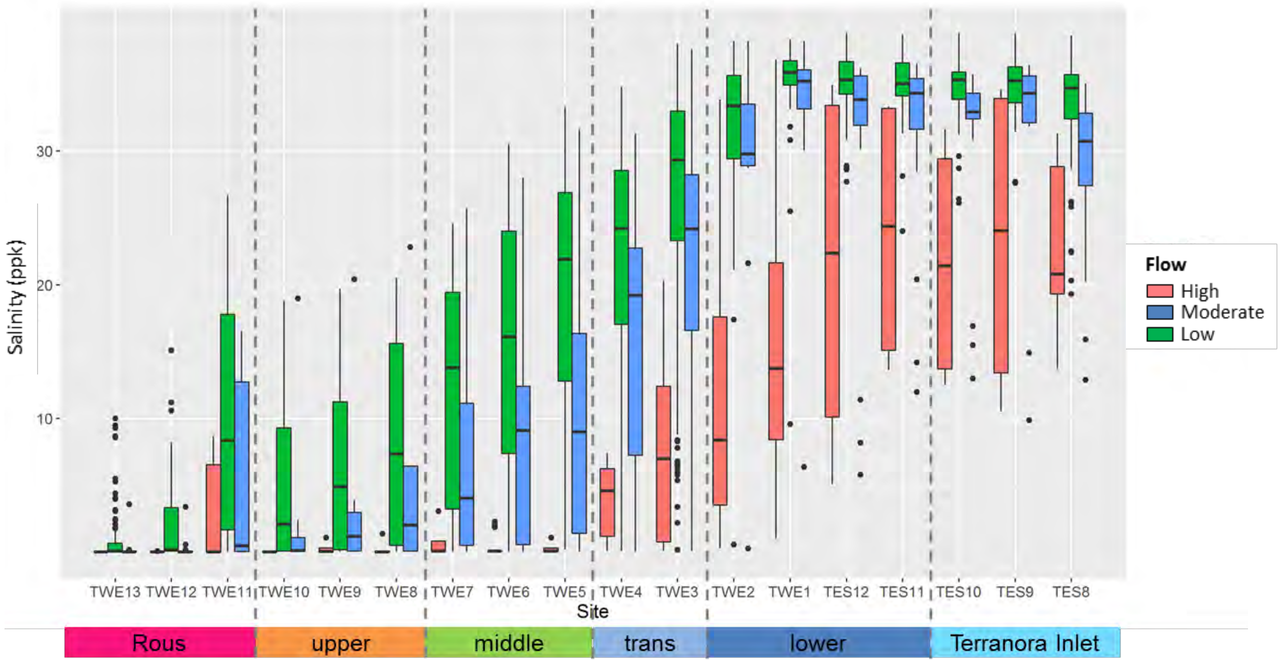

Figure 10: Spatial variation in salinity throughout the Tweed River Estuary during low, moderate and high rainfall conditions

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 11). Freshwater influence increases greatly throughout the estuary during the summer-autumn wet season, which is particularly obvious at lower estuary sites in 2012, 2013 and 2016 shown by sharp decreases in salinity levels. Recovery of brackish estuarine conditions occurs as the frequency and severity of runoff events diminishes into the winter-spring dry season. These trends were consistent with ABER (2012).

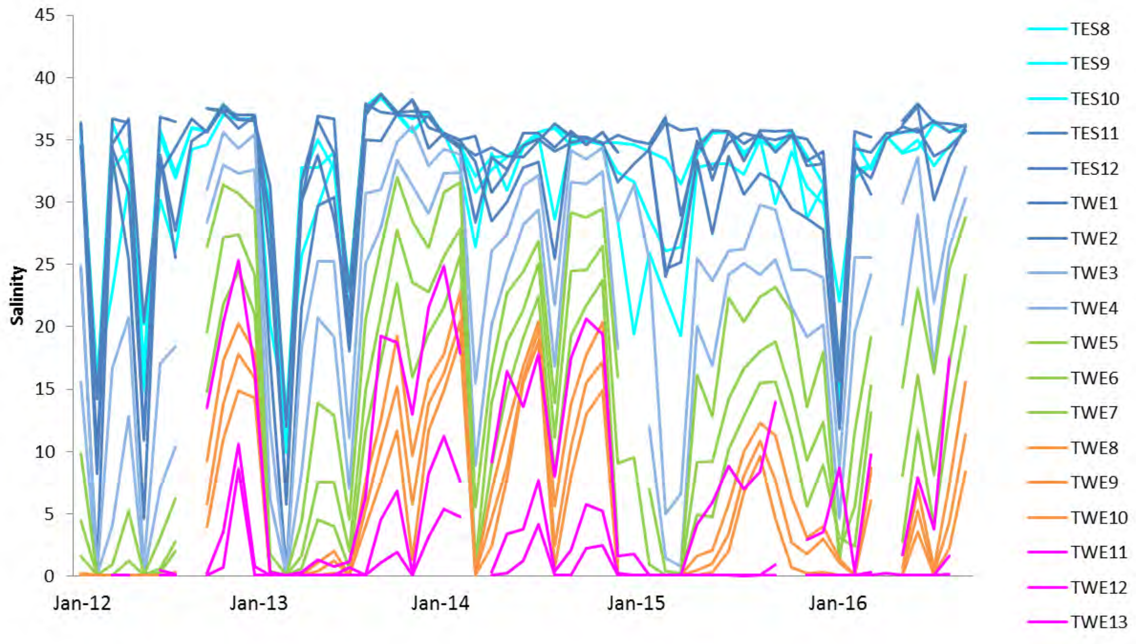

Figure 11: Temporal variation in salinity during the study period

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 12). 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 form time to time (e.g. June 2016). These trends were consistent with ABER (2012).

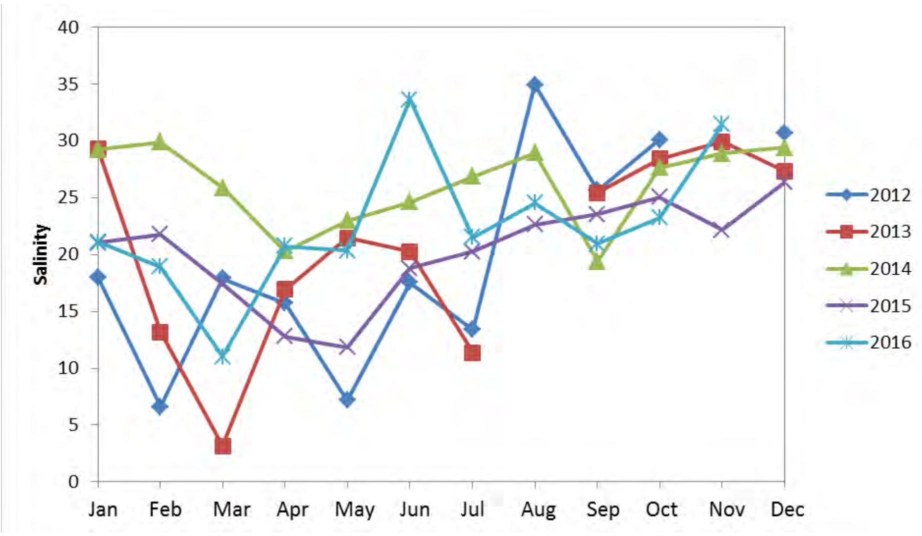

Figure 12: Inter-annual variation in mean estuary salinity over the study period

4.1.4 Management Implications

The Bray Park Weir above Murwillumbah is a major anthropogenic influence on salinity in the upper estuary. The weir forms a barrier to tidal flow, and prevents saline influence upstream. Freshwater releases from the Clarrie Hall Dam flow down the Tweed River and through the fish ladder in the Bray Park Weir. The presence of the weir and fish ladder along with release of water for environmental flow and extraction have implications for water quality and fish passage.

It will be important for any future development in the catchment likely to impact freshwater flows to consider the existing effect of Bray Park Weir. The potential raising of Clarrie Hall Dam and potential changes in upstream hydrology impacting the estuary will need to be assessed as part of the environmental impact assessment of the proposal.

Modelling conducted by ABER (2012) indicate that releases of freshwater effluent from STPs have very minor impacts on salinity in the Tweed estuary.

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. 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 (Figure 13). During high flow periods temperatures tended to be cooler reflecting reduced residence times and freshwater flow increases. During low and moderate flows temperatures increased reflecting increasing residence times and solar heating of surface waters. This trend was reversed in the lower estuary where water temperatures tended to be warmer during high flows. This was likely due to the overriding influence of warm ocean water on the lower estuary during summer and autumn months coinciding with the wet season.

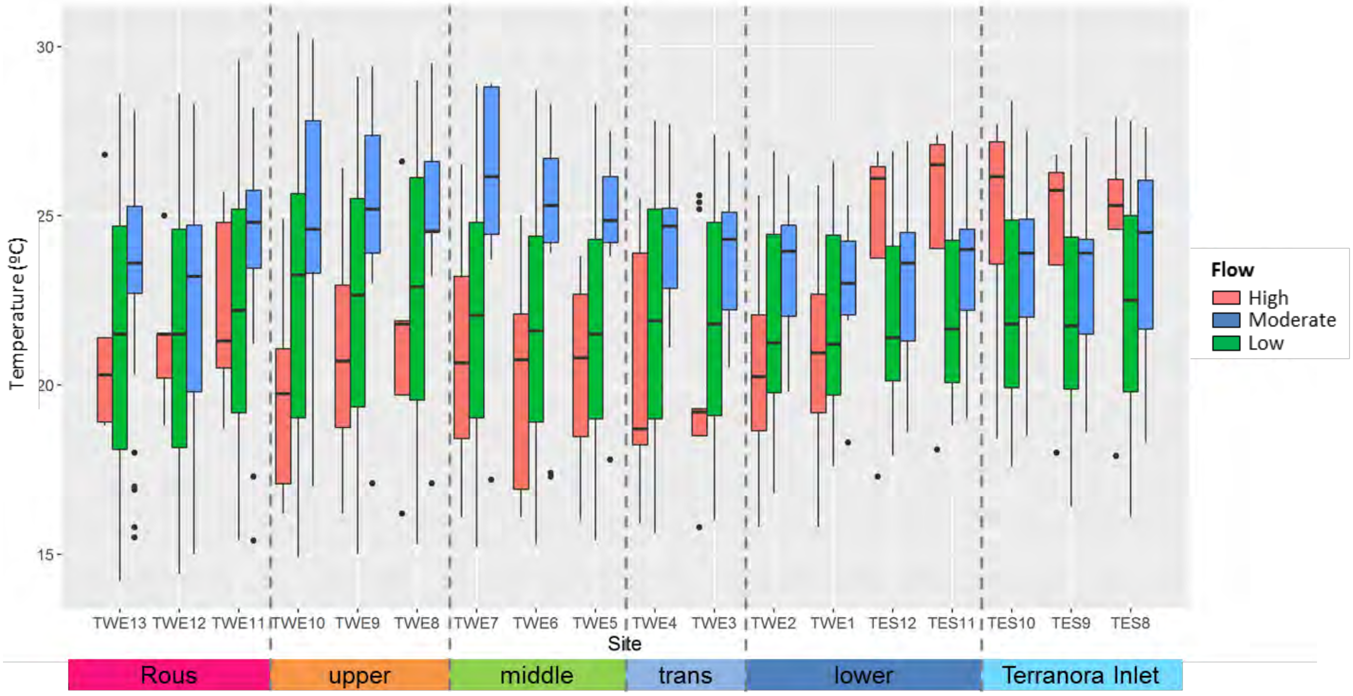

Figure 13: Spatial variation in temperature throughout the Tweed River Estuary during low, moderate and high rainfall conditions

4.2.2 Temporal Trends

There was a strong seasonal pattern to temperature with summer maximum water temperatures reaching 30.4ºC and winter minimum temperatures reaching 14.2ºC (Figure 14). The variation in temperature was greatest in the middle, upper and Rous River sites, with considerably less variation at the lower estuary sites. This is due to both the greater influence of rainfall and flow conditions in the upper estuary and the overriding influence of ocean water in the lower estuary moderating temperature throughout the year. These trends were consistent with ABER (2012) however both maximum and minimum temperature extremes were higher during 2012-2016 compared to the previous 5 years (i.e. maximum temperatures up by 1.4ºC and minimum temperature up by 0.2ºC). Due to the observed trend of lower temperatures with rainfall, slightly higher temperatures may be due to lower rainfall falling in the 2012-2016 (annual average of 1,515mm) compared to 2007-2011 (annual average of 1,703mm).

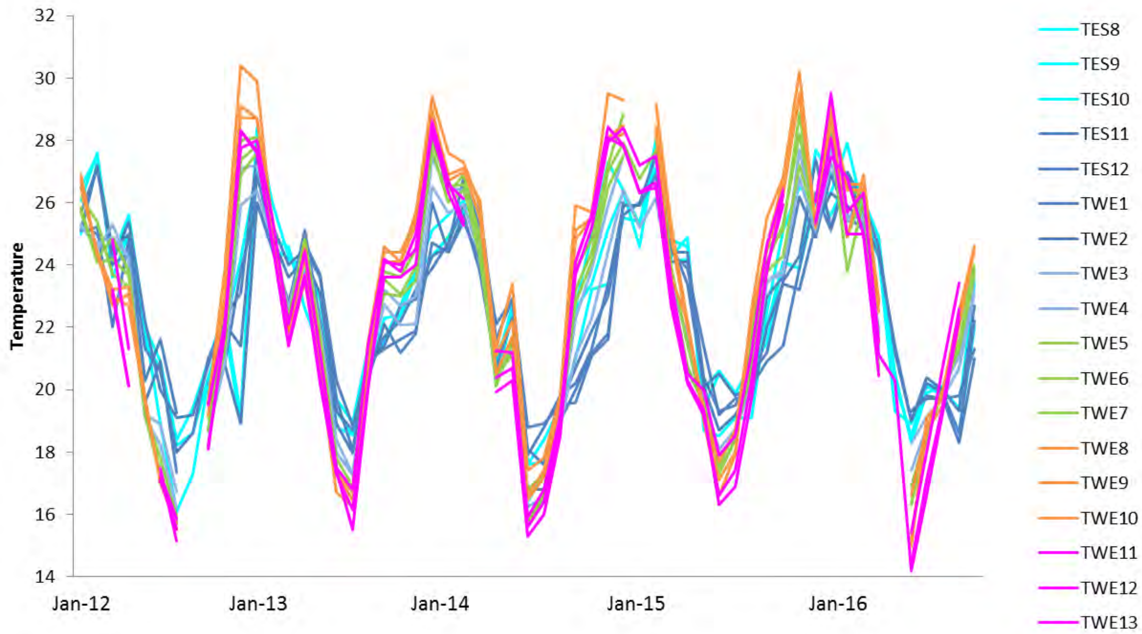

Figure 14: Temporal variation in temperature during the study period

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 15). The greatest inter-annual variation in temperature was seen during early summer and early autumn, most likely reflecting the influence of the timing of wet season onset and duration. Inter-annual variation was lowest during the spring months of September and October due to lesser influence from freshwater inflow during the dry season. These trends were consistent with ABER (2012) however there was greater variability in winter temperatures during the current study period likely reflecting the greater extremes in rainfall experienced during the last 5 years compared to the long-term averages (refer Figure 6).

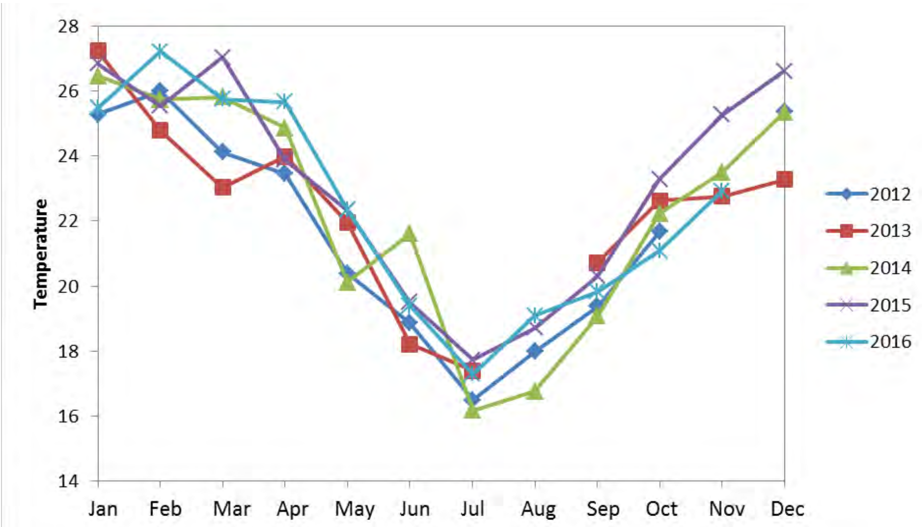

Figure 15: Inter-annual variation in mean estuary water temperature over the study period

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 estuary to the mouth reflecting the mixing of freshwater (median pH ~ 7.2 at TWE12 and TWE13) with marine water (median pH ~8.2 at TES11 and TES12) and along the estuarine gradient (Figure 16). It is noted that pH levels observed during this monitoring period (generally ranging from pH 6 to pH 8.5 in 2012-2016) were improved compared to the previous period (generally ranging from pH 3.5 to pH 8.5 in 2007-2011) reported by ABER (2012). This is likely due to lower rainfall falling in the 2012-2016 compared to the previous 5 years, and the absence of significant flooding events such as the January 2008 flood captured by previous monitoring where extremely low pH levels were recorded (e.g. down to pH <2) across a number of sites in the upper and middle estuary and Rous River. It is also possible that during 2012-2016 the routine monthly sampling program missed significant rainfall events which are a known risk factor in development of acid runoff and therefore reduce pH in the estuary. Targeted event monitoring would increase the chances of capturing potential acid runoff events and to help better characterise the conditions that lead to acid runoff.

Many of the common patterns observed by ABER (2012) were also observed during the present monitoring period. These included:

- reduced pH associated with moderate and high flow conditions across most sites with the lowest pH observed consistently in the Rous, upper and middle estuary zones. This likely indicates influence of acid sulfate soil runoff from floodplain areas, albeit having less impact than observed previously; and
- slightly increased pH was observed during low flow which most likely reflects the decreased influence of freshwater runoff and increased influence of marine water mixing. During low flow conditions when freshwater inputs to the estuary are minimal and residence times are long, it is likely that internal biological processes (i.e. the production and consumption of organic matter) form the primary control over spatial trends in pH.

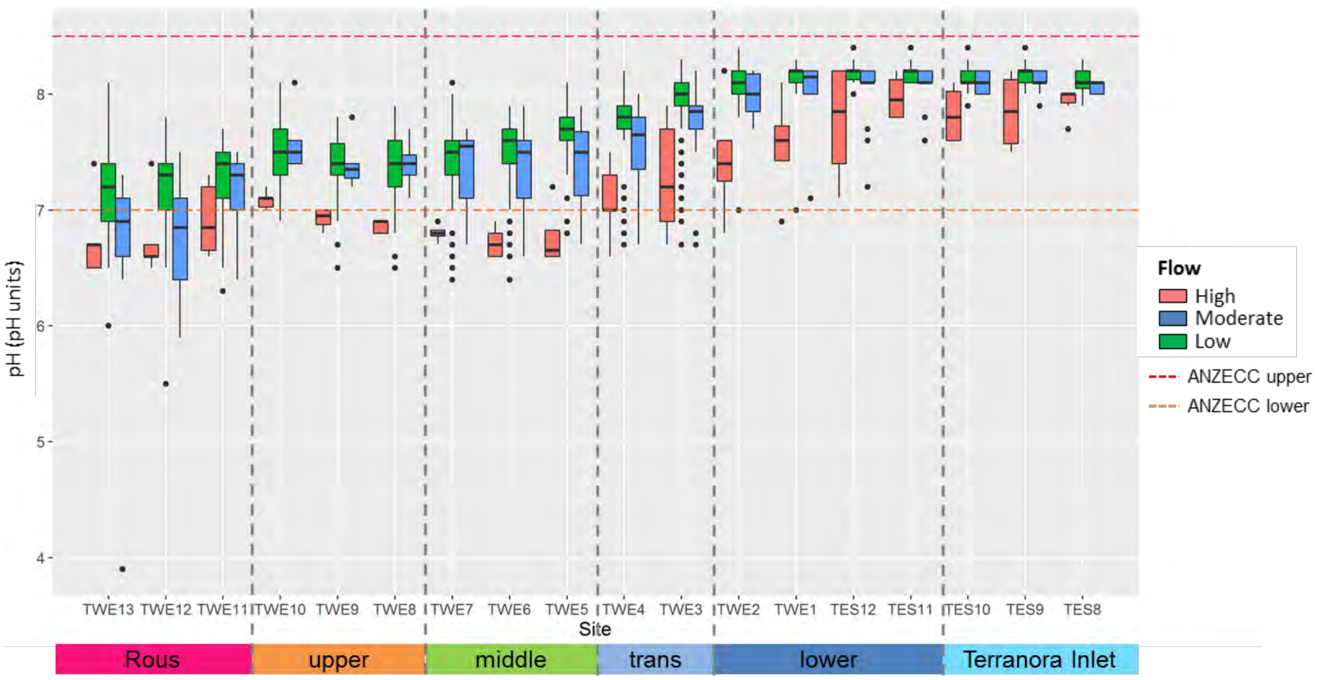

Figure 16: Spatial variation in pH throughout the Tweed estuary during low, moderate and high rainfall conditions

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. Low pH events tended to coincide with the summer and autumn wet season, with higher pH during winter and autumn when oceanic influence is greater. Figure 17 shows three events where pH dipped below pH 6.5 (the aquatic ecosystem threshold) in the Rous and upper estuary (i.e. July 2013, March 2014 and April 2015). Significant rainfall preceded these events and acid sulfate soil runoff is likely to have influenced pH levels at these sites, particularly TWE12 and TWE13 in the Rous River. Consistently lower pH measurements in the Rous River indicate a relatively greater influence of acid sulfate soil runoff in this zone.

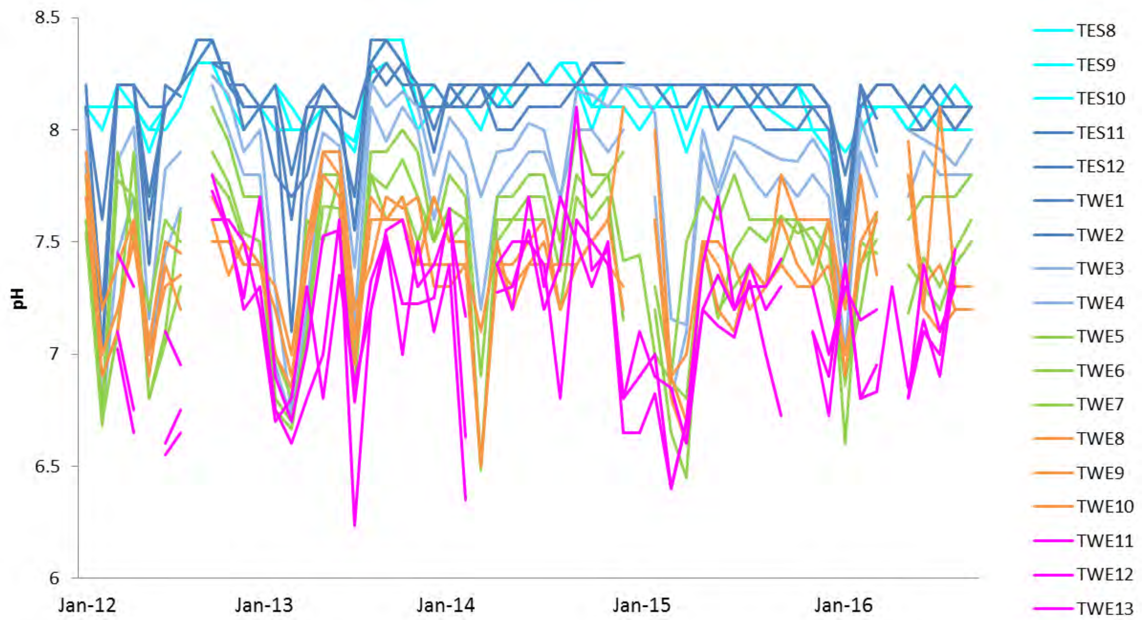

Figure 17: Temporal variation in pH during the study period

4.3.3 Inter-annual variation

Inter-annual variation in pH appears to be minor. Generally, 2014 and 2016 showed higher pH levels compared to other years and these were also the only below average rainfall years in the study period. ABER (2012) also reported inter-annual pH variation as insignificant.

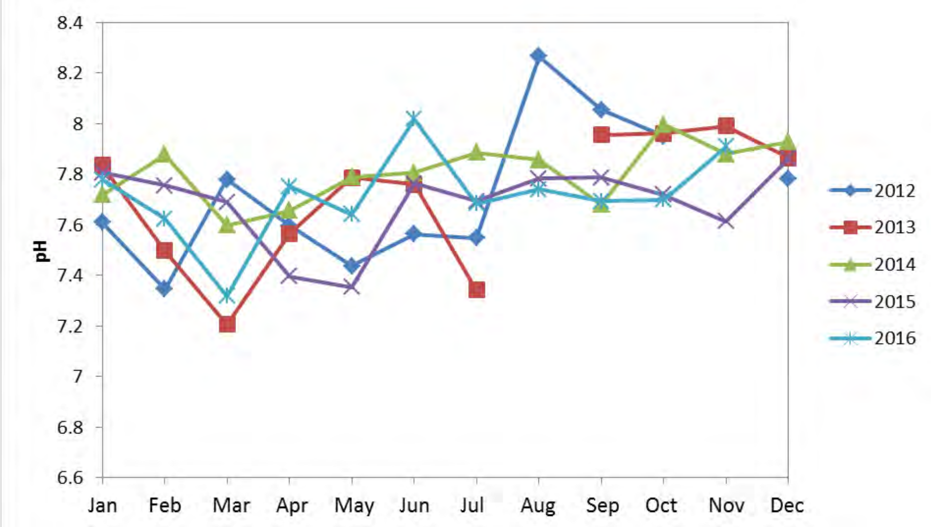

Figure 18: Inter-annual variation in mean estuary pH over the study period

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 throughout the Rous, middle and upper estuary sites, except for TWE10 which was within guideline thresholds for all flows. pH levels were also below the lower guideline threshold for greater than 50% of the time during moderate flow conditions at the upper Rous River sites TWE12 and TWE13. This again indicates that 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, although pH compliance was improved compared to the previous 5 years. Compliance was achieved at all other sites during all other flow conditions.

4.3.5 Management Implications

While pH levels were improved during this monitoring period compared to the previous 5 years, this has been attributed largely to lower rainfall and the absence of major flooding events triggering substantial acid sulfate runoff. The present study did identify some acid runoff impacts in the middle and upper estuary and particularly in the Rous River. 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 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

Dissolved oxygen saturation was consistently higher in the lower estuary and Terranora Inlet (sites TWE 1 and 2 and TES 8-12) compared to other sites. DO tended to be at lower levels in the transitional and middle estuary and slightly improved in the upper Tweed River Estuary sites. The Rous River sites displayed the lowest overall DO levels. Similar trends were reported by ABER (2012) however, the present study period generally showed improved DO levels across all sites compared to the previous five years. There was also less variation in DO levels with different flow conditions. Notably, the moderately severe sags in DO along the middle and upper estuary during low to moderate flows observed by ABER (2012) were not detected in the present study. Moderate and high flows were associated with lower DO levels at most sites. At the upper Rous River sites (TWE12 and 13), moderate flows produced the lowest DO concentrations suggesting WWTP nutrient loading with longer residence times (reduced flushing) is having a detrimental effect on water quality. This was consistent with findings of ABER (2012) and it appears to be a continuing phenomenon although DO levels have improved somewhat. The input of low DO water from low lying catchments adjacent to the middle estuary and along the Rous River most likely accounts for reduced overall DO saturation during high flow and this was also reported by ABER (2012).

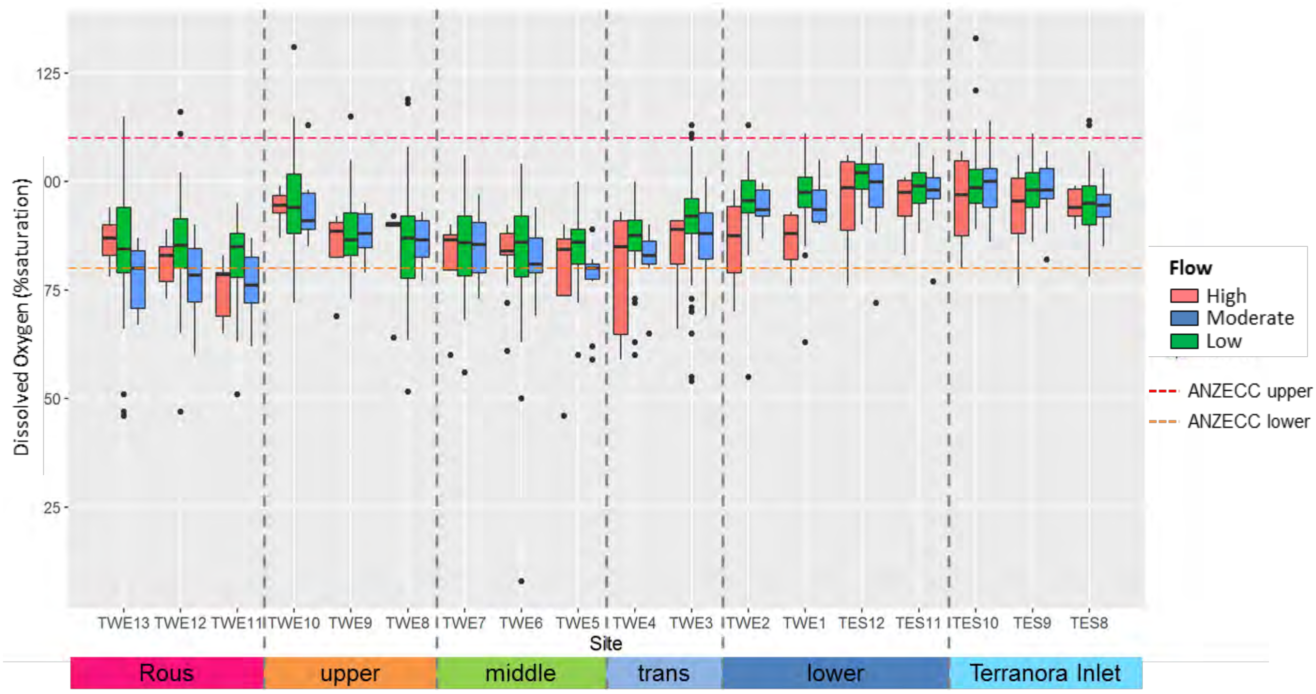

Figure 19: Spatial variation in dissolved oxygen throughout the Tweed River Estuary during low, moderate and high rainfall conditions

4.4.2 Temporal Trends

Seasonal trends in DO saturation were apparent, with the summer-autumn wet season consistently producing low DO levels in the middle and upper estuary, and to a lesser extent at transitional and lower estuary sites. This seasonal effect was more pronounced than for the previous reporting period where ABER (2012) did not detect clear trends.

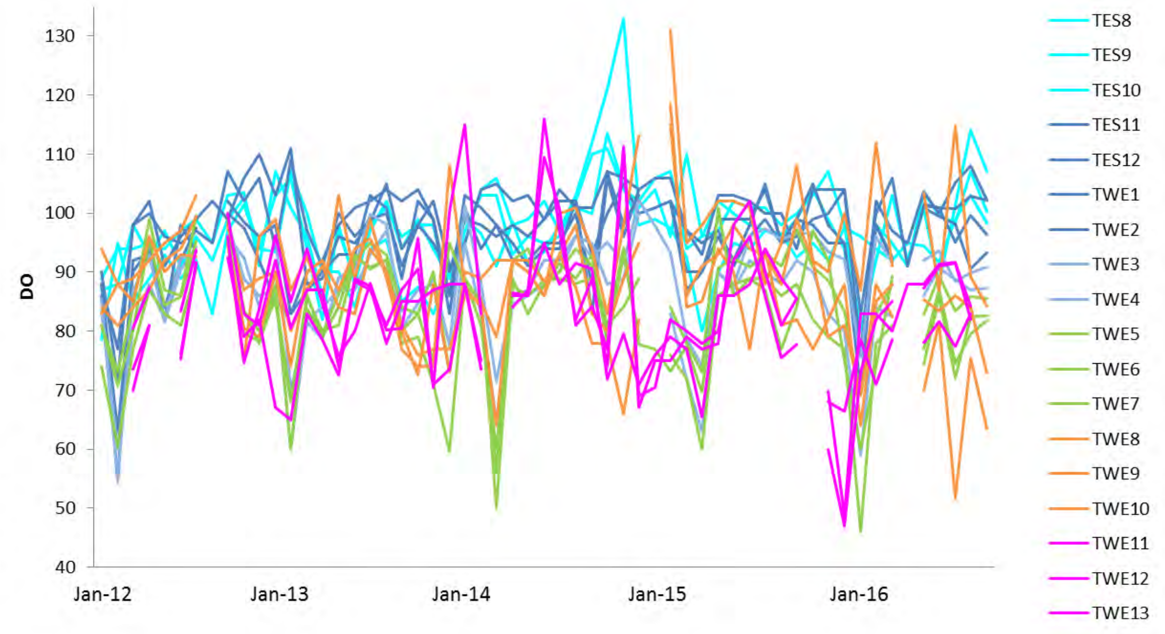

Figure 20: Temporal variation in dissolved oxygen during the study period

4.4.3 Inter-annual variation

There was some inter-annual variation in DO saturation during this study (Figure 21), 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).

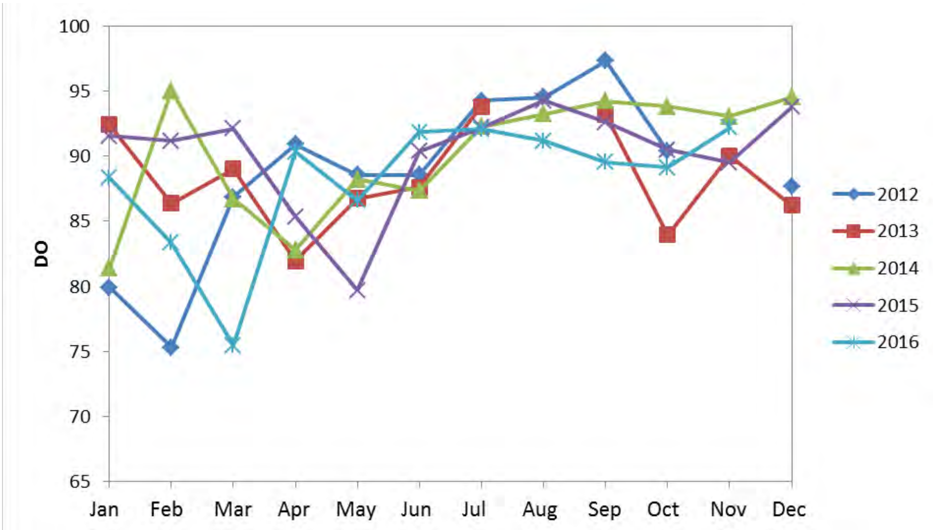

Figure 21: Inter-annual variation in mean estuary dissolved oxygen over the study period

4.4.4 Comparison with water quality objectives

DO levels were below the lower guideline threshold for greater than 50% of the time during moderate and/or high flow conditions throughout the Rous River sites. DO levels were also below the lower guideline threshold for greater than 25% of the time during high flow conditions at sites TWE4 and TWE5 in the middle estuary. Compliance was achieved at all other sites during all other flow conditions.

4.4.5 Management Implications

Water quality results indicate that the Rous River is 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 rural lands is also contributing to reduced DO in this zone. Management effort should focus on reducing nutrient inputs to the Rous River (WWTP management during low-moderate flow and catchment management during high flow) 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 (TN) concentrations ranged between 0.06 and 2.4mg/L during the study period. During low and moderate flow conditions there was a consistent trend of low TN concentrations in the lower estuary gradually increasing with distance upstream (Figure 22). TN concentrations were significantly higher during high flow conditions with peak TN concentrations in the transitional and middle estuary. The Rous River was the exception where high levels were more persistent throughout all flow conditions. These trends are consistent with ABER (2012), however levels of TN were generally higher than those reported for the previous 5 years, particularly in the lower and middle estuary during high flows.

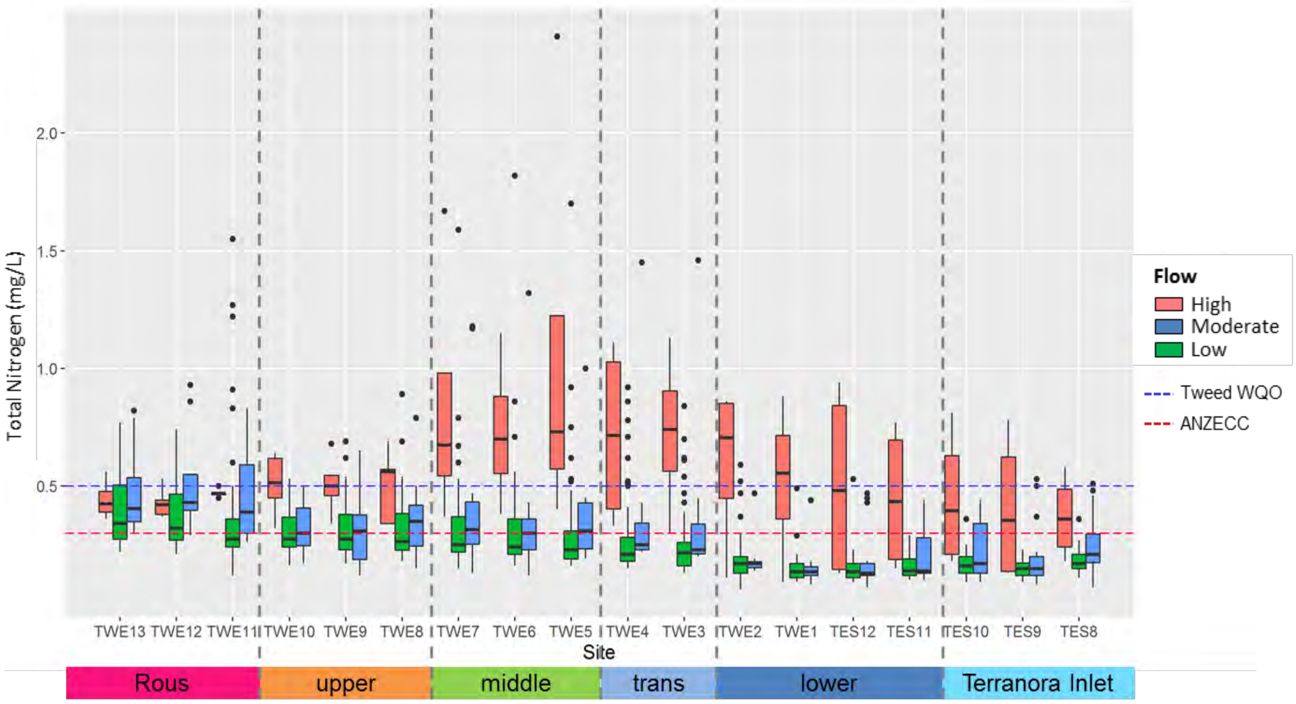

Figure 22: Spatial variation in total nitrogen throughout the Tweed River Estuary during low, moderate and high rainfall conditions

4.5.2 Temporal Trends

There were clear temporal trends in TN concentrations for some years during the study period (Figure 23). Higher concentrations during high flow times resulted during the summer – autumn wet season, particularly in the middle estuary in 2014 and 2016. Both these years had below average rainfall and high TN following rainfall events could indicate the effect of ‘first flush’ from a catchment that had been accumulating nutrients over extended dry periods. This seasonal effect was more pronounced than for the previous reporting period where ABER (2012) did not detect clear trends and may be attributed to more variable rainfall in 2012-2016.

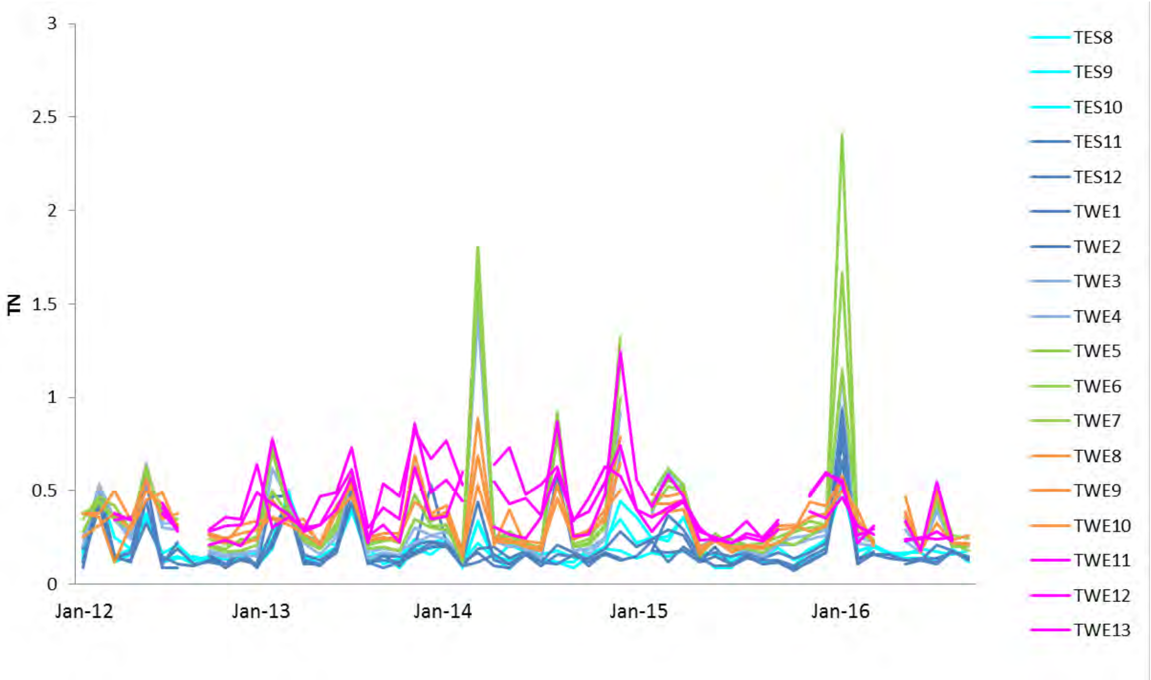

Figure 23: Temporal variation in TN during the study period

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 24). 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. These trends were consistent with ABER (2012).

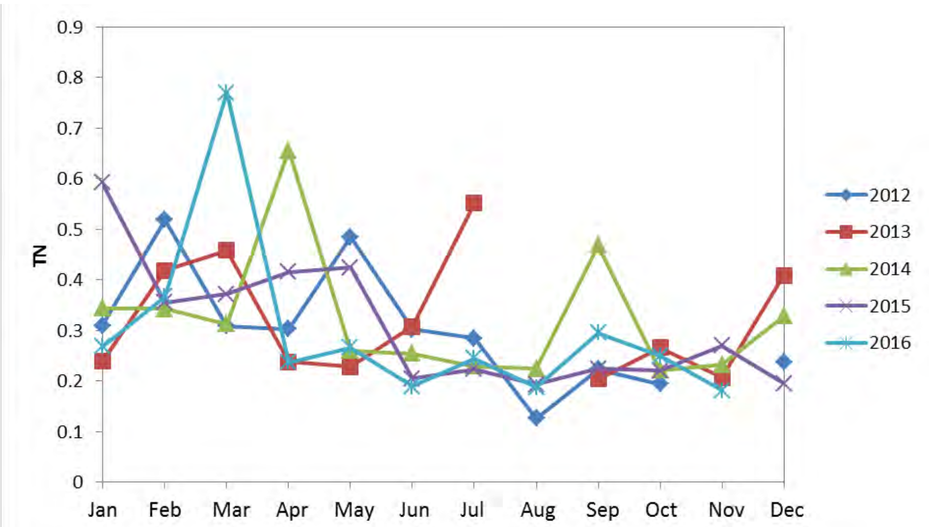

Figure 24: Inter-annual variation in mean estuary total nitrogen over the study period

4.5.4 Comparison with water quality objectives

Total nitrogen concentrations exceeded the ANZECC guideline thresholds for 100% of the time during high flow conditions throughout the transitional, middle, and upper estuary sites, with the highest results observed at the transition and middle zone sites. Moderate flow conditions in the Rous River also resulted in guideline thresholds being exceeded for 100% of the time. Compliance was better during low to moderate flow conditions throughout the Tweed River Estuary sites, although the middle, upper and Rous River sites still exceeded thresholds for greater than 50% of the time during these flow conditions.

4.5.5 Management Implications

It is likely that TN concentrations are in part controlled by point source inputs (i.e. WWTP discharges) during low to median flow conditions when catchment inputs are minimal, and the data suggests this is particularly so in the Rous River. This is supported by previous modelling completed by ABER (2012). Therefore, reducing nitrogen inputs to the system can best be achieved by reducing point source loading (particularly the Rous River) during low and moderate flows and catchment management during high flows.

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

Total phosphorus (TP) ranged between below detection (<0.02mg/L) to 0.21mg/L during the study period. There was a general trend of low concentrations in the lower estuary rising to a peak in the middle estuary and diminishing towards the top of the estuary (Figure 25). TP concentrations in the Rous River were consistently high throughout the study period. There was a trend of increasing TP concentrations with flow, with high flow conditions having significantly higher concentrations than both moderate and low flow conditions. These trends are consistent with ABER (2012), and TP levels were similar to the previous 5 years, however there was a greater increase in TP levels with high flow in the middle estuary compared to 2007-2011.

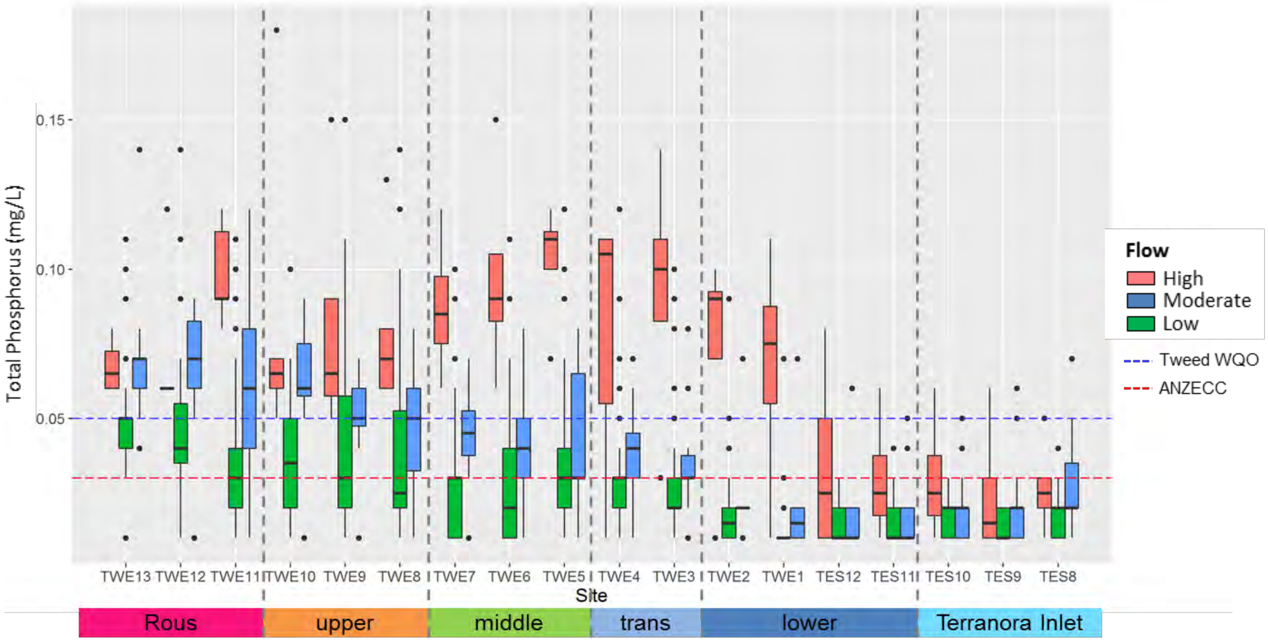

Figure 25: Spatial variation in total phosphorus throughout the Tweed River Estuary during low, moderate and high rainfall conditions

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 26). Variation in TP concentrations most likely arises from the timing of high flow events. These trends were consistent with ABER (2012).

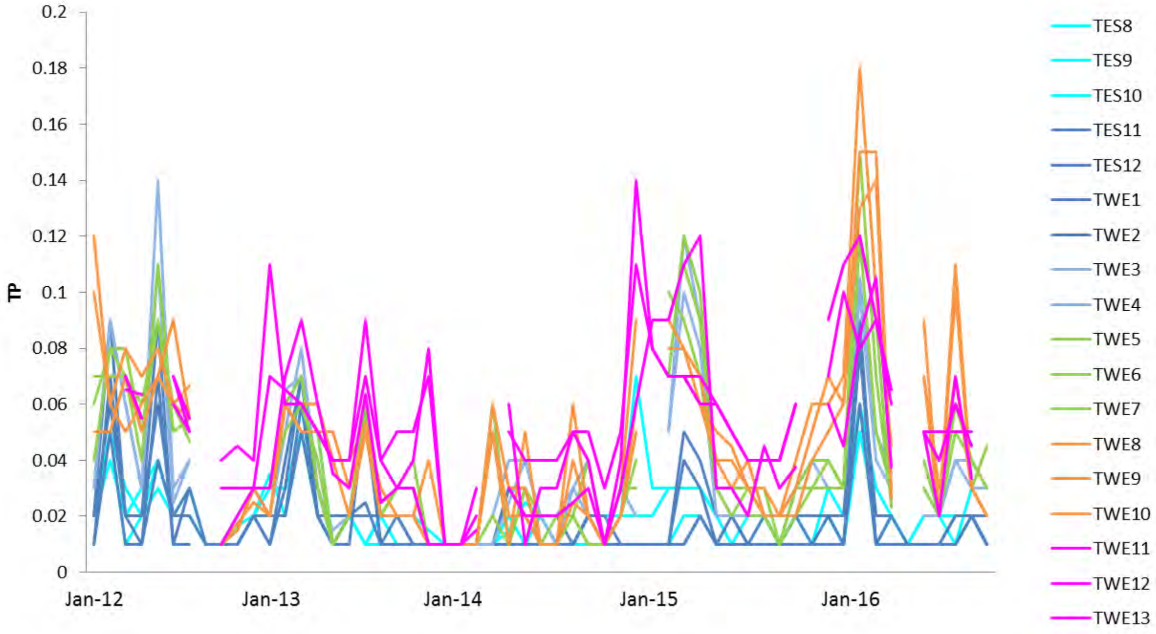

Figure 26: Temporal variation in total phosphorus during the study period

4.6.3 Inter-annual variation

There was significant inter-annual variability in total phosphorus 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 27). These trends were consistent with ABER (2012).

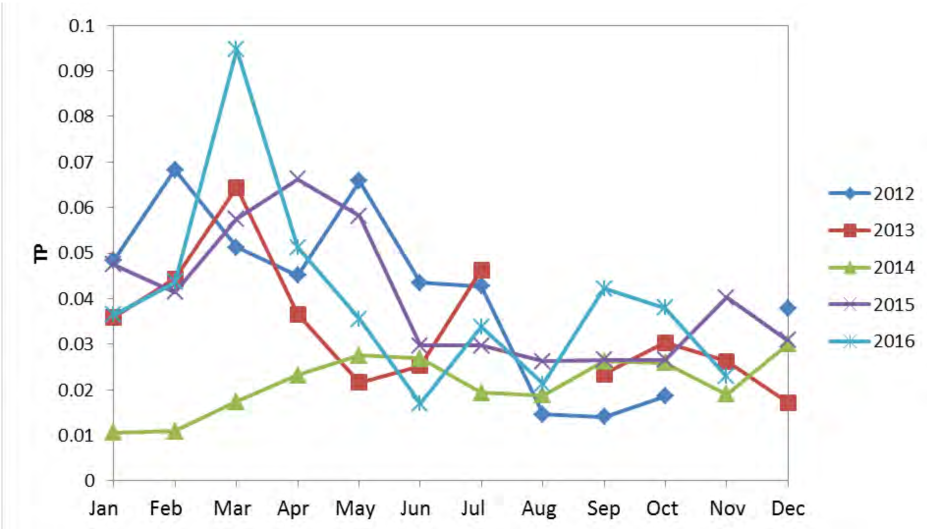

Figure 27: Inter-annual variation in mean estuary total phosphorus over the study period

4.6.4 Comparison with water quality objectives

Total phosphorus concentrations exceeded the ANZECC guideline thresholds for 100% of the time during high flow conditions throughout the transition, middle and upper estuary and Rous River sites. The transition, middle and upper estuary and Rous River sites exceeded thresholds for greater than 75% of the time during moderate flow conditions. Compliance was better during low flow conditions, however the upper estuary and

Rous River sites still exceeded thresholds for greater than 50% of the time. Rous River sites generally exceeded thresholds for the majority of the time during all flow conditions.

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); and reducing WWTP loading (particularly important during low and moderate flows), with the Rous River as a priority area.

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 ($NH4^+$) concentrations varied between below detection (<0.02mg/L) and 0.24mg/L during the study period (Figure 28). There was a trend of lower concentrations in the lower and upper estuary with higher concentrations in the middle and transitional estuary, particularly during high flow at sites TWE3, 4 and 5. There was a trend for increasing concentrations with flow across most sites except for in the Rous River where moderate flows were associated with the highest ammonium levels. These trends are consistent with ABER (2012), however levels of ammonium were generally higher than those reported for the previous 5 years across all sites, with less differentiation seen across different flows.

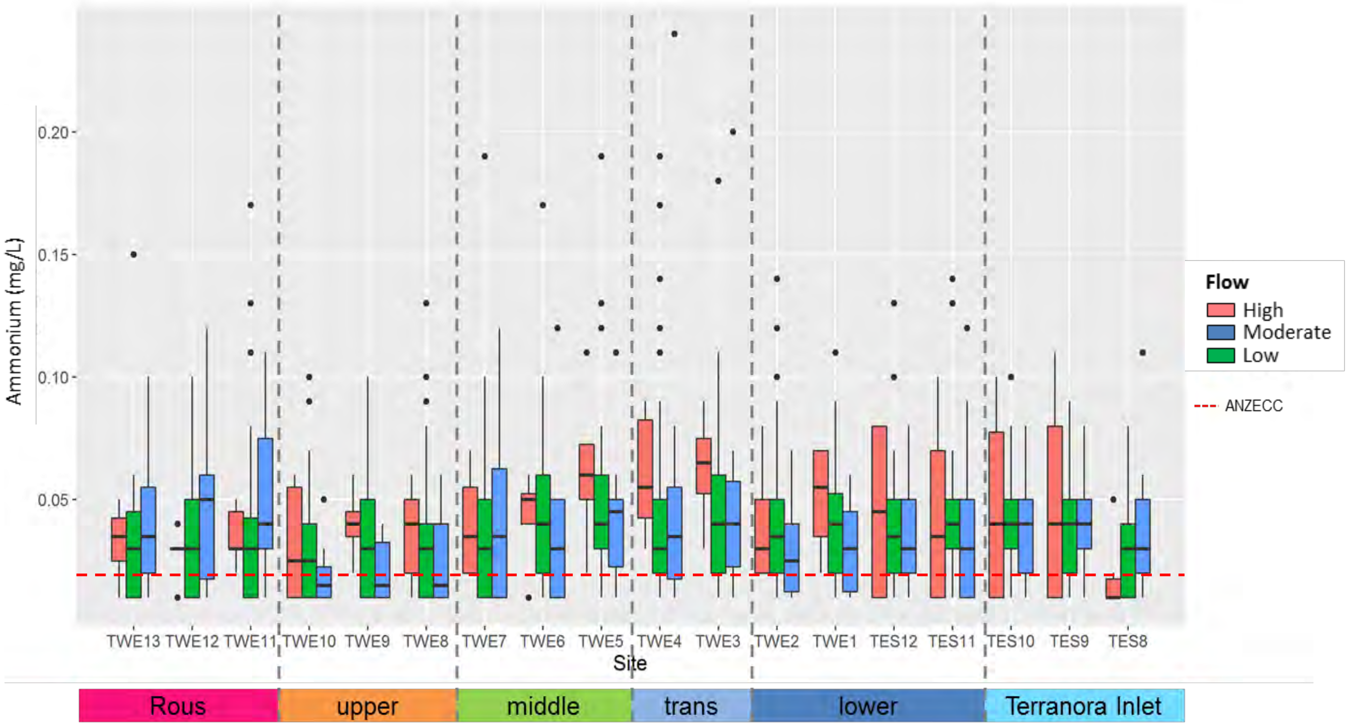

Figure 28: Spatial variation in ammonium throughout the Tweed River Estuary during low, moderate and high rainfall conditions

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 is consistent with ABER (2012). Ammonium levels appear to have decreased somewhat since mid-2015.

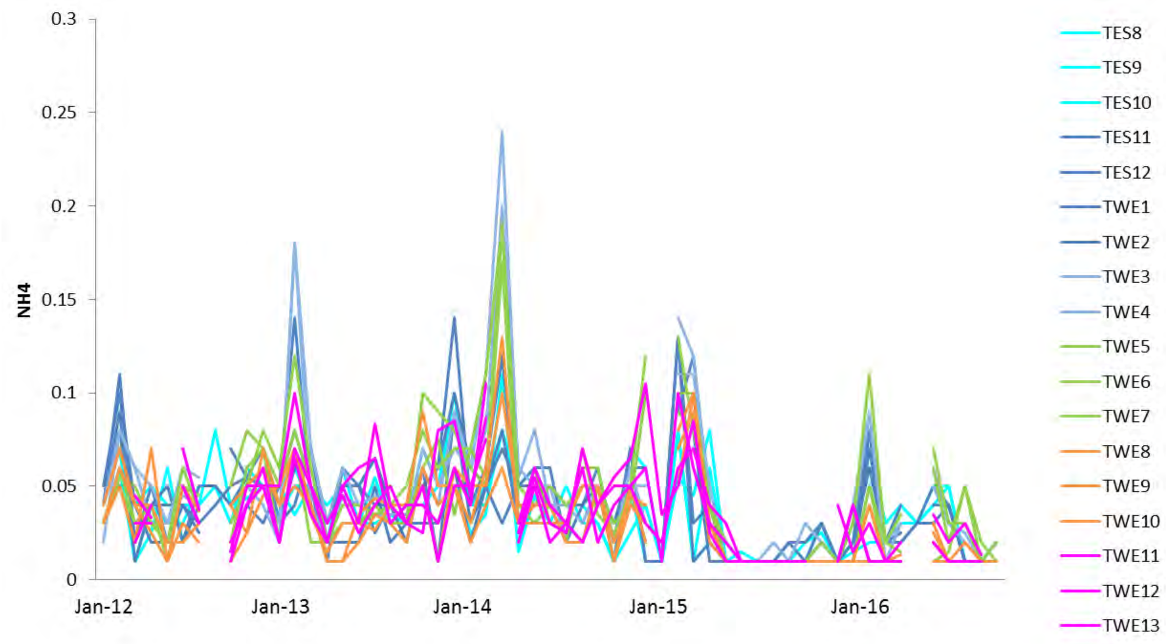

Figure 29: Temporal variation in ammonium during the study period

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 30).

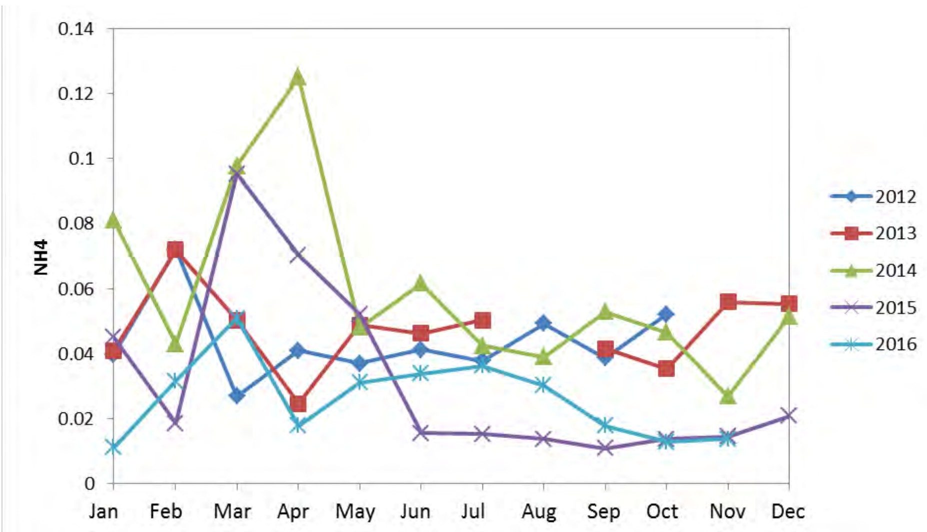

Figure 30: Inter-annual variation in mean estuary ammonium over the study period

4.7.4 Comparison with water quality objectives

Ammonium concentrations exceeded the guideline thresholds for greater than 75% of the time during high flow conditions at the middle and transitional estuary sites and at TWE1 in the lower estuary, TWE9 in the upper estuary and TWE11 and 12 in the Rous River. Levels were generally lower during low to moderate flow conditions, however the majority of sites (except for the upper estuary) still exceeded thresholds for greater than 50% of the time during these flows. 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 estuary and particularly the middle and transitional estuary zones during high flows. In a water quality study conducted in Bartlett's Drain in the middle estuary, Beatie *et al.* (2004) reported that ammonium consistently contributed more dissolved inorganic nitrogen than NOx. Therefore management of ammonium input from cane drains should also be targeted, noting that ammonium can form under low DO conditions and is a common constituent in fertiliser. In the Rous River, high ammonium levels were consistent throughout all flows. Management strategies should focus on reducing bioavailable nitrogen inputs to the system. This can best be achieved by reducing WWTP loading during low and moderate flows and catchment management during high flows.

4.8 Oxidised Nitrogen

4.8.1 Spatial Trends

Oxidised nitrogen (nitrate + nitrite) ranged between detection limits and 1.69mg/L during the study period. As observed for ammonium (although much more pronounced) there was a middle estuary peak in oxidised nitrogen compared to upper and lower sites (Figure 31). The highest concentrations were consistently recorded during high flow conditions, except for in the Rous River when equally high levels were produced with moderate flows. Moderate and low flow conditions were associated with greatly reduced concentrations These trends are consistent with ABER (2012), however levels of oxidised nitrogen levels were generally lower than those reported for the previous 5 years across all sites.

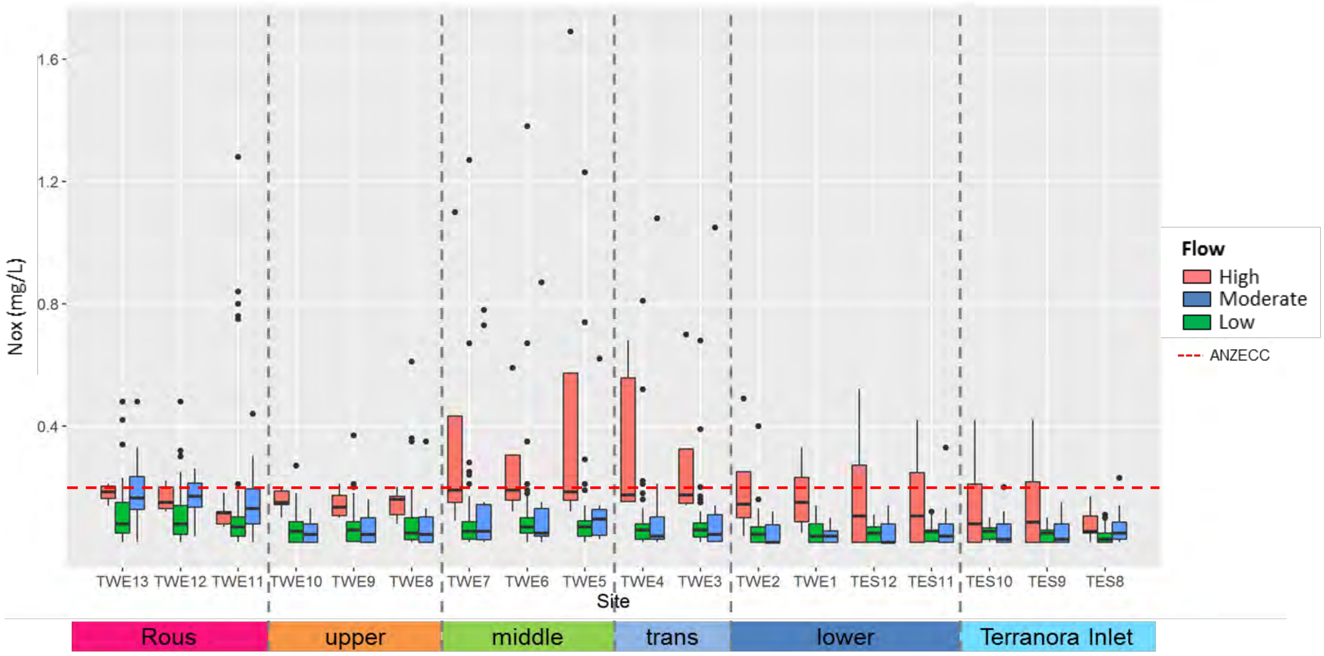

Figure 31: Spatial variation in Oxidised Nitrogen throughout the Tweed River Estuary during low, moderate and high rainfall conditions

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 middle estuary in 2014 and 2016 (Figure 32). As noted for TN, both these years had below average rainfall and high NOx following rainfall events indicates the effect of 'first flush' from a catchment that may have been accumulating nutrients over extended dry periods. This trend is consistent with ABER (2012).

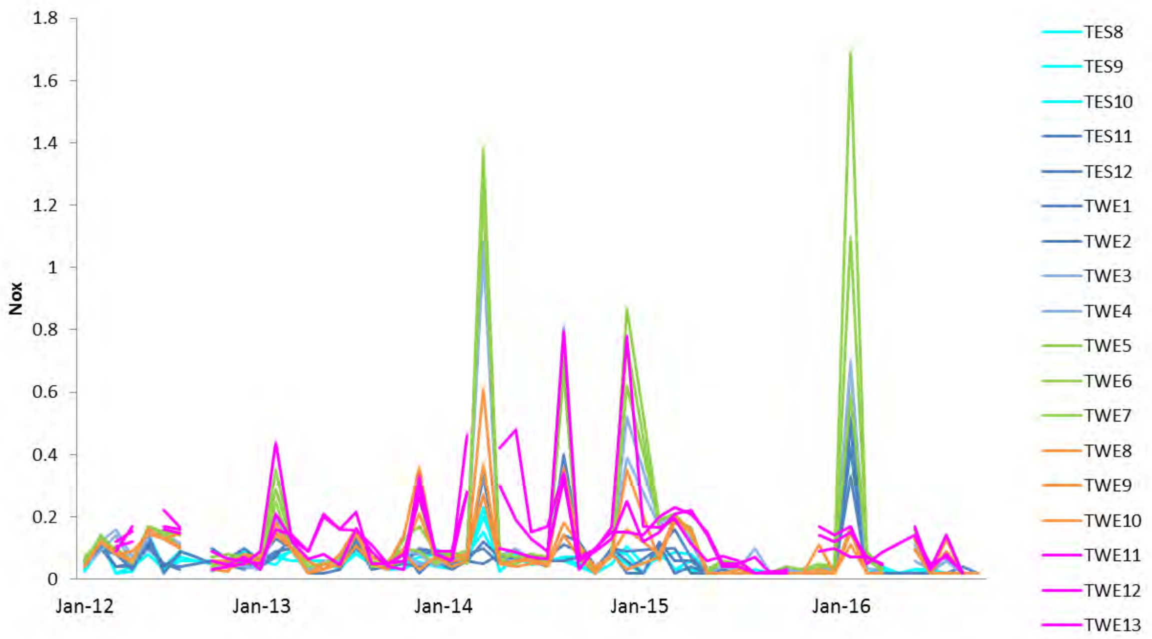

Figure 32: Temporal variation in oxidised nitrogen during the study period

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 33).

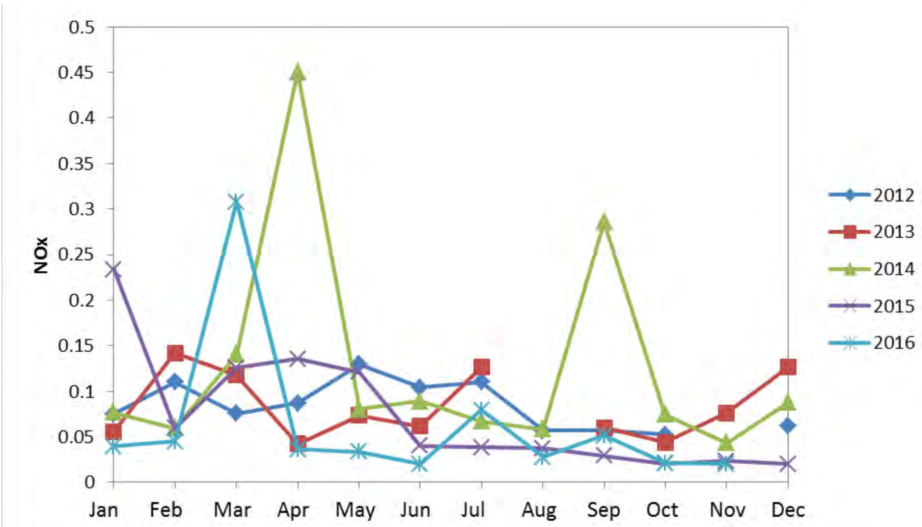

Figure 33: Inter-annual variation in mean estuary oxidised nitrogen over the study period

4.8.4 Comparison with water quality objectives

NOx concentrations exceeded the guideline thresholds for greater than 75% of the time during high flow conditions in the middle and transition estuary and site TWE13 in the Rous River. In the lower and upper estuary sites, thresholds were exceeded from between 25 - 50% of the time during high flow conditions.

Compliance was better during moderate and low flow conditions, with all sites achieving compliance with guidelines except for the Rous River during moderate flows where thresholds were exceeded for greater than 50% of the time. NOx compliance was better than reported for the previous five years (ABER, 2012).

4.8.5 Management Implications

Levels of NOx observed during 2012-2016 were elevated throughout the estuary and particularly the middle and transitional estuary zones during high flows. In the Rous River, high NOx levels were associated with low and moderate flows. Management strategies should focus on reducing NOx inputs to the system. This can best be achieved by reducing WWTP loading during low and moderate flows and catchment management during high flows.

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.

4.9.1 Spatial Trends

DON concentrations ranged from detection limits to 0.67mg/L during the study period. Spatial trends were generally characterised by concentrations increasing towards the middle estuary. There was a significant increase in DON during high flow conditions, which is consistent with ABER (2012) and indicates DON inputs from low lying floodplain catchment along the middle estuary. For the upper Rous River sites, DON levels were similar across all flow conditions.

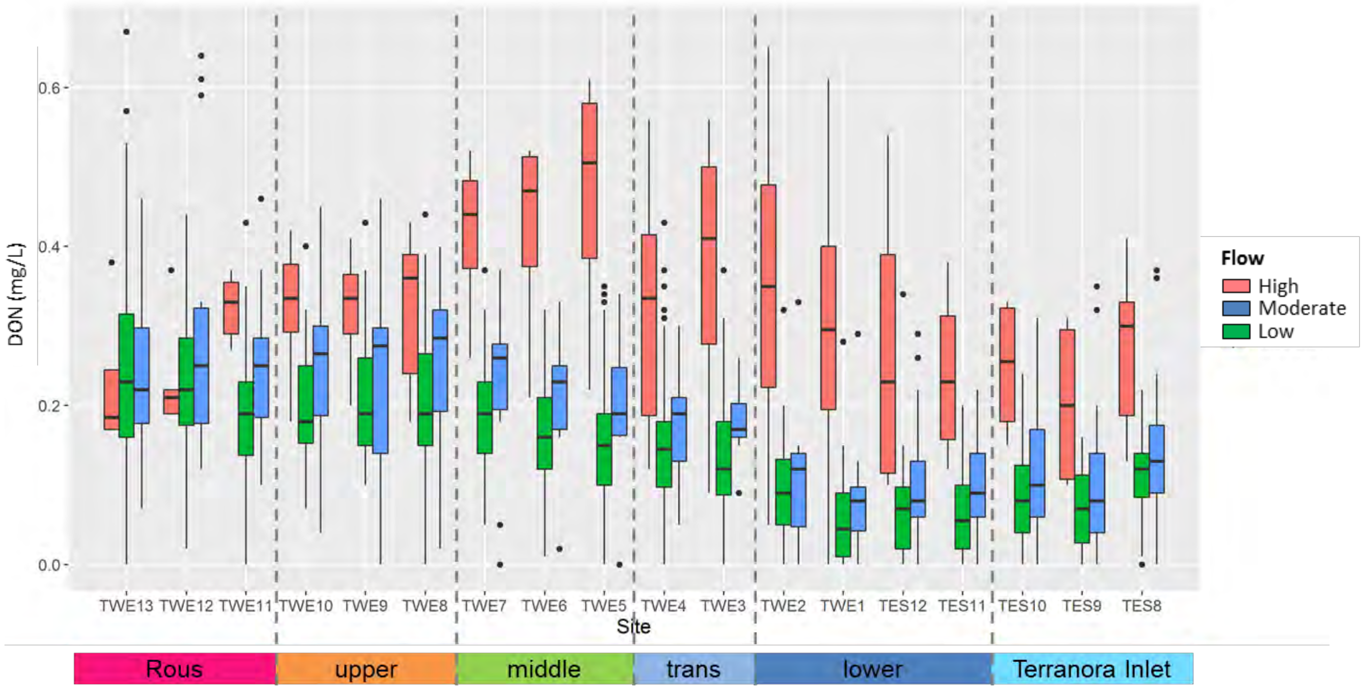

Figure 34: Spatial variation in Dissolved Organic Nitrogen throughout the Tweed River Estuary during low, moderate and high rainfall conditions

4.9.2 Temporal Trends

There was a weak seasonal trend of elevated DON concentrations during the summer – autumn wet season most likely reflecting the higher concentrations prevalent during high flow, however this trend was not as pronounced as for oxidised nitrogen. DON consistently accounted for between 40% and 70% of the total nitrogen pool. These trends are consistent with ABER (2012).

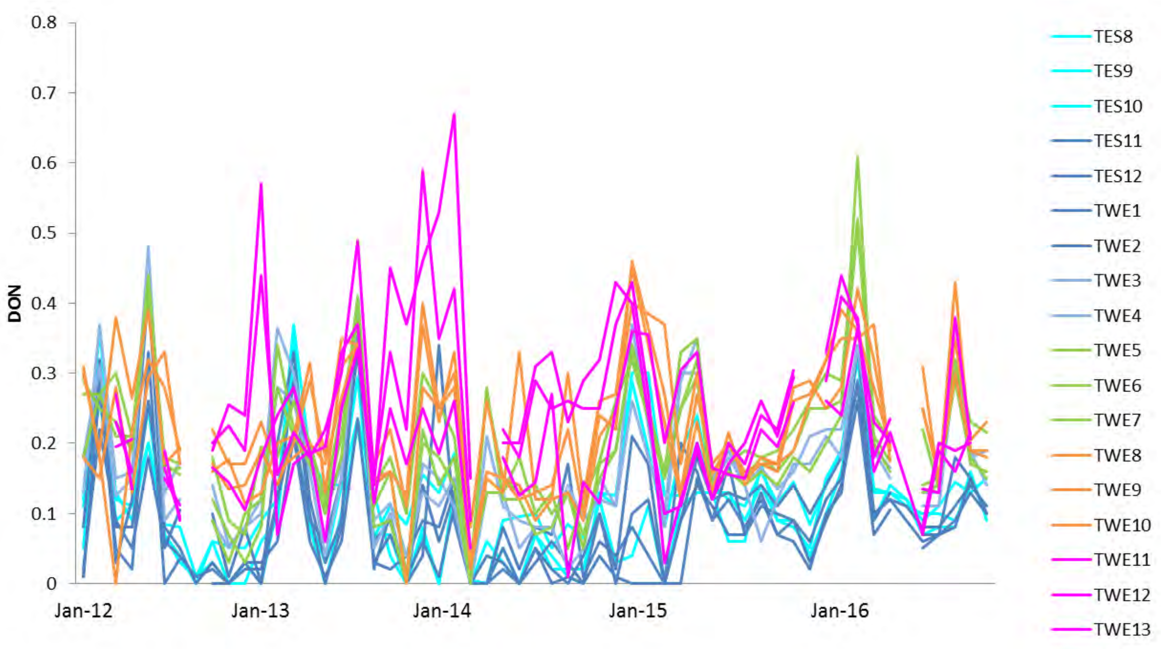

Figure 35: Temporal variation in dissolved organic nitrogen during the study period

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 36).

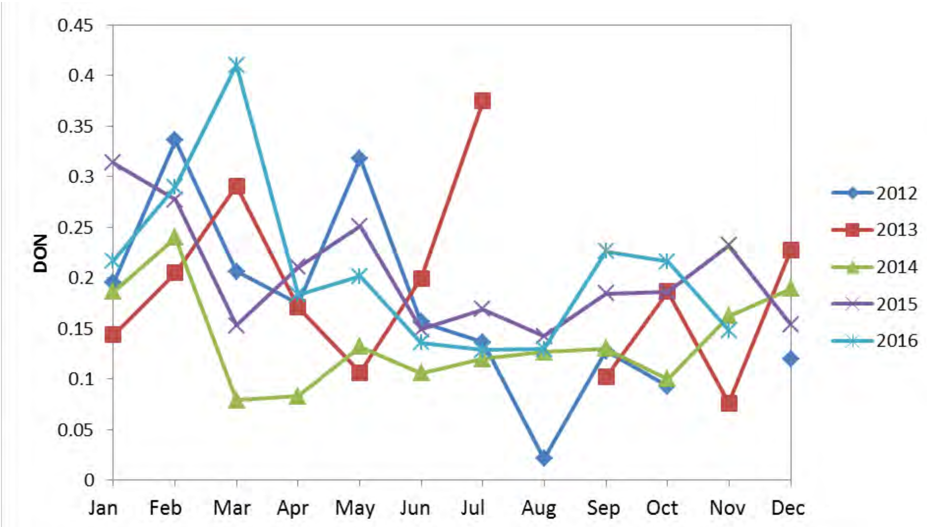

Figure 36: Inter-annual variation in mean estuary dissolved organic nitrogen over the study period

4.9.4 Management Implications

The results of this study indicate that sources of DON arise primarily from runoff from low lying floodplain catchment along the middle estuary during rain events, and more constant inputs (probably from WWTP) in the Rous River. Management strategies should focus on reducing catchment input of DON during rainfall events through catchment management including soil conservation practices.

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.

4.10.1 Spatial Trends

The TN:TP ratio was predominantly well below 16 throughout the Tweed River Estuary during most flow conditions suggesting that the system currently tends toward N limitation (Figure 37).

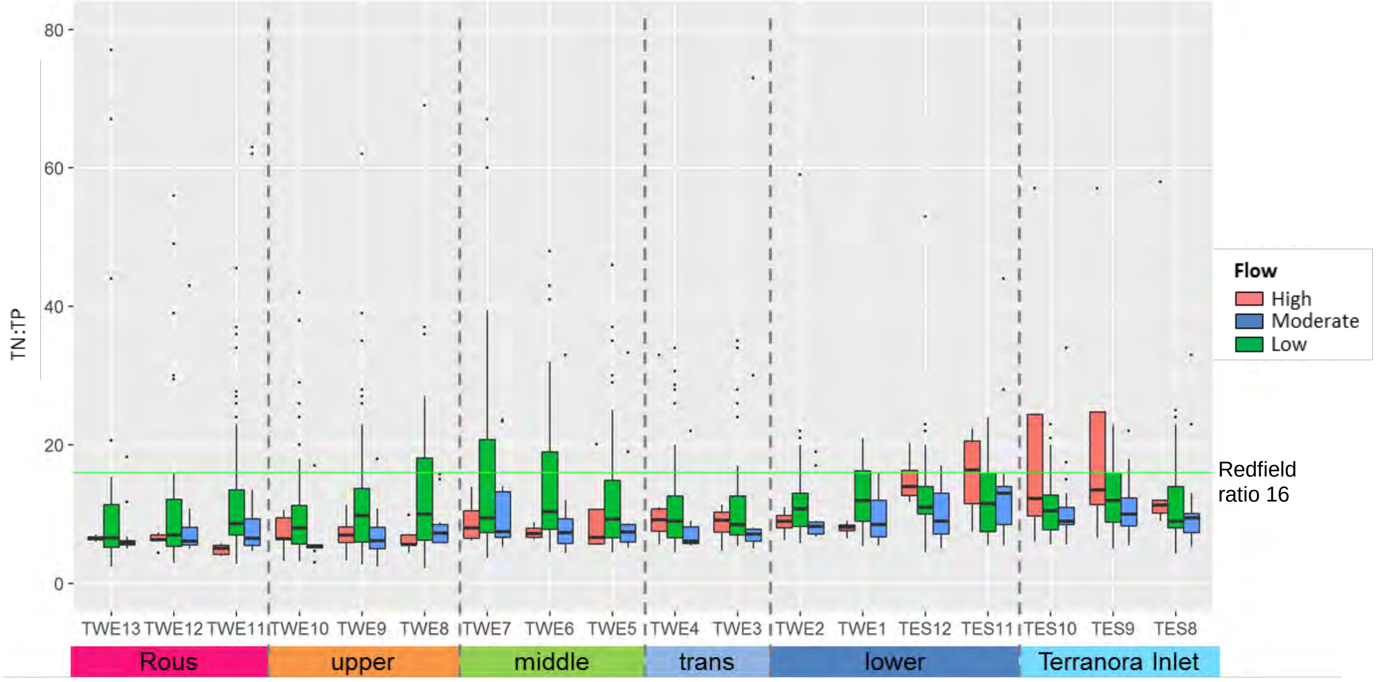

Figure 37: Spatial variation in TN:TP ratios throughout the Tweed River Estuary during low, moderate and high rainfall conditions

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 (which are able to fix nitrogen from the atmosphere). 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

Chlorophyll *a* concentrations ranged from below detection (0.4 µg/L) to 77 µg/L during the study period (Figure 38). There was a consistent trend of low Chlorophyll *a* concentrations in the lower estuary increasing to a peak in either the middle or upper estuary. Higher levels were 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 Rous River during low flows. These trends were consistent with findings of ABER (2012) and appear to be continuing trends.

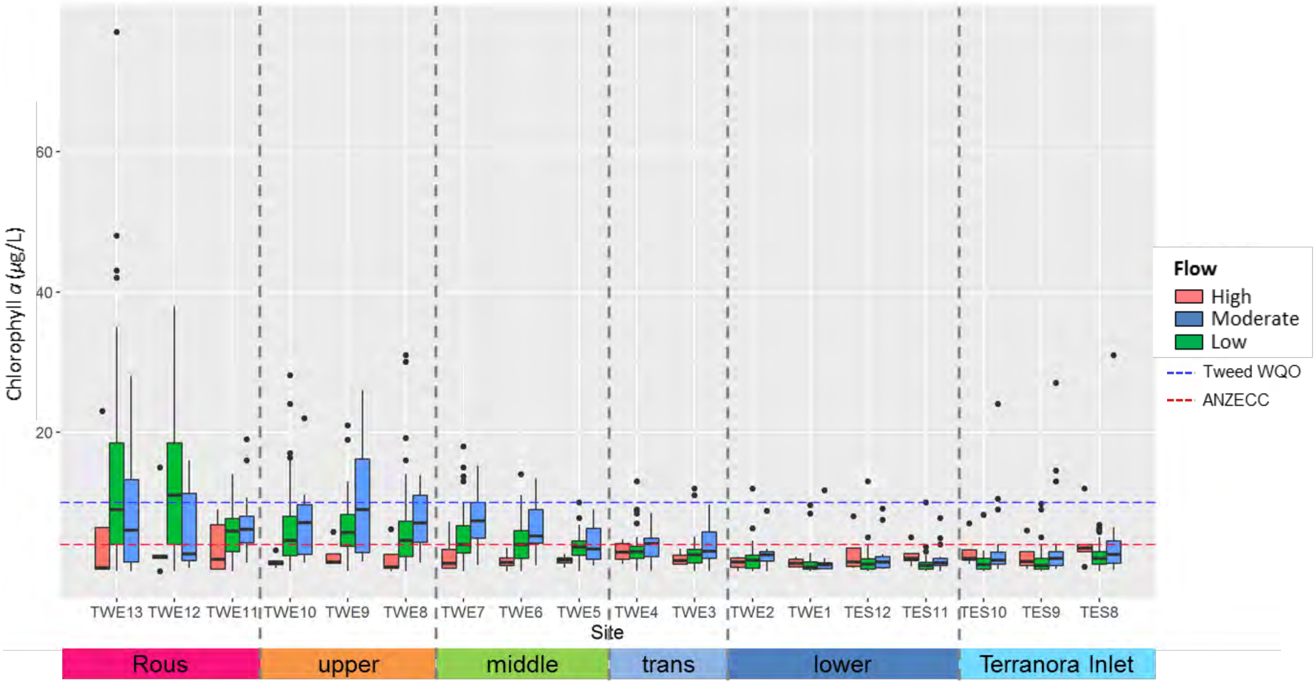

Figure 38: Spatial variation in Chlorophyll *a* throughout the Tweed River Estuary during low, moderate and high rainfall conditions

4.11.2 Temporal Trends

There was a high level of variation in Chlorophyll *a* concentrations on monthly to bimonthly timescales, most likely reflecting the boom-bust nature of phytoplankton blooms in estuarine systems. Underlying this variation was a seasonal trend of higher concentrations during the summer – autumn period when both solar radiation (light) and nutrient supply (freshwater inflow) are greatest (Figure 39). Overall, mid-summer had the highest concentrations during the study period. Concentrations in the Rous River were considerably higher than at other sites, particularly at the upper-most sites TWE12 and TWE13 during mid-summer of 2013, 2014 and 2015, indicating persistent algal blooms in the upper Rous River. These trends were consistent with ABER (2012) and indicate continuing issues with eutrophication in the Rous River.

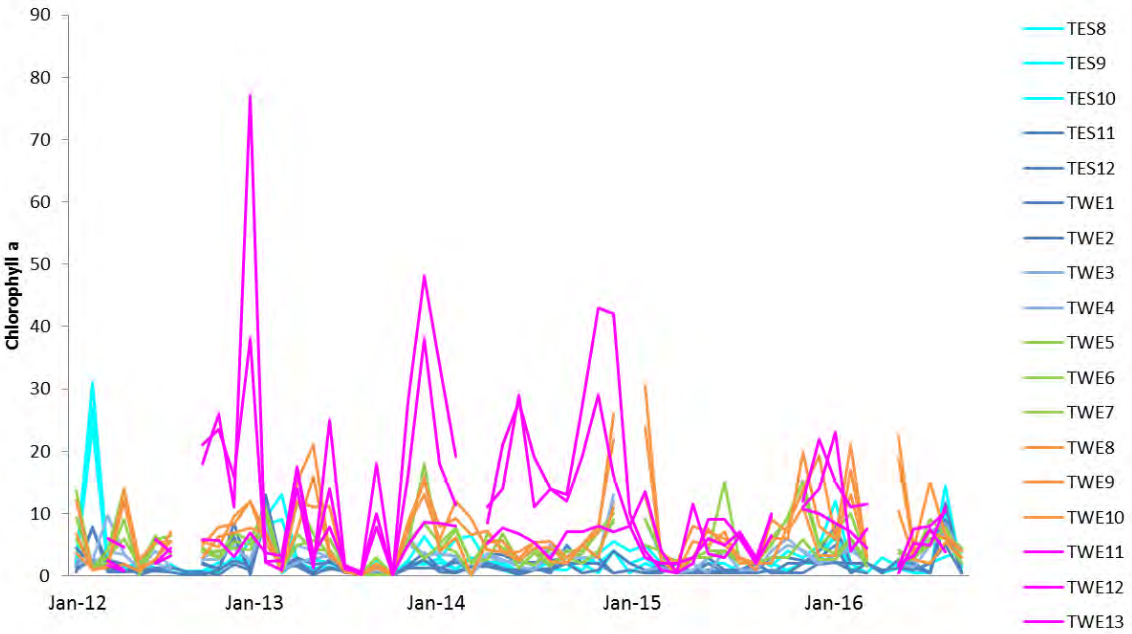

Figure 39: Temporal variation in Chlorophyll *a* during the study period

4.11.3 Inter-annual variation

There was significant inter-annual variability in Chlorophyll *a* concentrations during the study period (Figure 40). Higher Chlorophyll *a* levels were consistently seen in summer-autumn months 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. While Chlorophyll *a* levels were lower during the remainder of the year, a high degree of variability between years continued throughout all months.

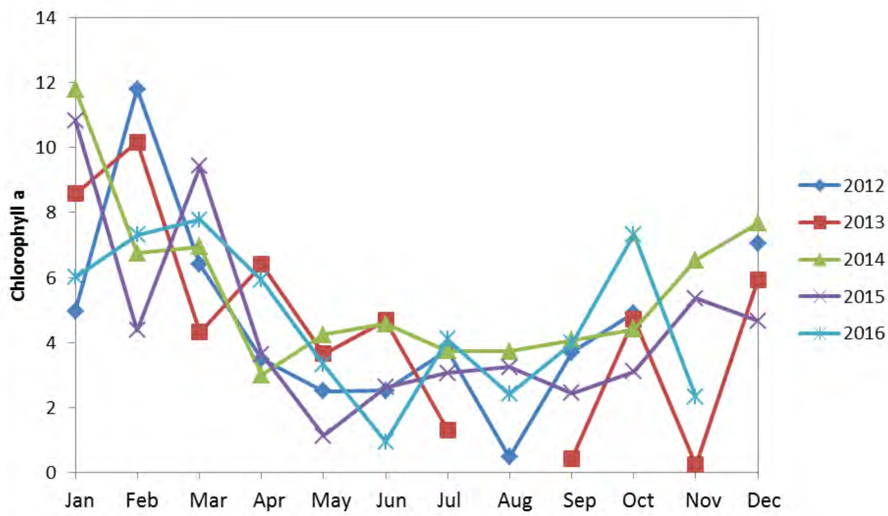

Figure 40: Inter-annual variation in mean estuary Chlorophyll *a* over the study period

4.11.4 Comparison with water quality objectives

Chlorophyll *a* concentrations achieved water quality guidelines at the lower estuary sites during all flow conditions. Compliance generally worsened with distance upstream with guidelines exceeded greater than 50% of the time during moderate and low flows in the transitional and middle estuary and greater than 75% of the time in the upper estuary and Rous River. Chlorophyll *a* compliance was similar to that reported for the previous five years (ABER, 2012).

4.11.5 Management Implications

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 median and high flow conditions. This can best be achieved by WWTP management during median flow and catchment management 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) concentrations ranged between 0.5 and 90 mg/L during the study period (Figure 41). TSS concentrations were generally lowest at the estuary mouth, increased towards the middle estuary, and diminished towards the upper estuary. TSS in the Rous River were generally higher than the upper Tweed River Estuary sites. There was a clear and consistent increase in TSS with flow category, with the highest TSS concentrations recorded during high flow conditions, particularly in the middle estuary. These trends are consistent with ABER (2012) and could indicate sediment inputs from low lying floodplain catchment along the middle estuary and also fine sediment from eroding river banks during high flow events. However, results of *in situ* data loggers reported by ABER (2012) suggest that resuspension of bottom sediments may also play a significant role in elevating TSS in the middle estuary.

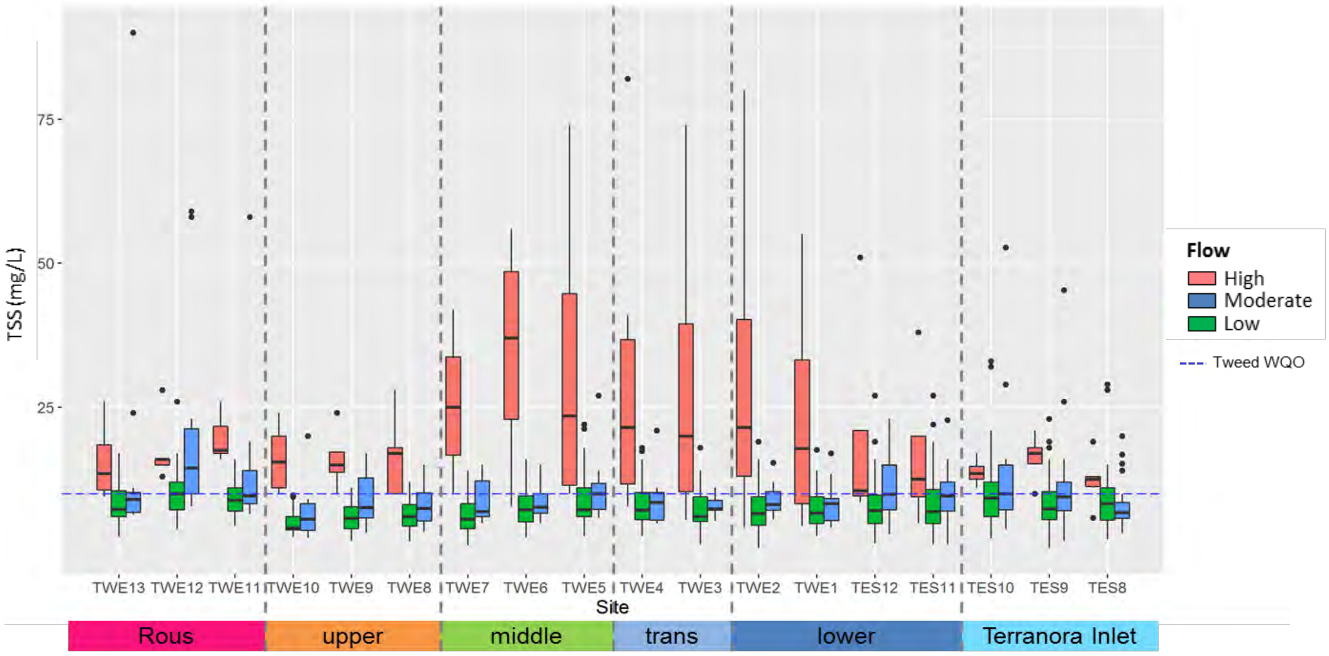

Figure 41: Spatial variation in total suspended solids throughout the Tweed River Estuary during low, moderate and high rainfall conditions

4.12.2 Temporal Trends

The results for TSS show strong association with rainfall events, with TSS spikes in summer-autumn wet season months (e.g. Jan 2016), but also associated with unseasonal high rainfall in winter (e.g. July 2013) (Figure 42). This is supported by the strong trend of increasing TSS concentrations with flow (Figure 41). Due to the relatively rapid decline in high TSS concentrations following rainfall events, it is likely that the routine sampling strategy would have missed some TSS peaks during the study period, despite rainfall and high TSS events that may have occurred during those months. There was also high variability in TSS concentrations over monthly to bimonthly timescales, reflecting variability in flow conditions at the time of each sampling effort. As discussed above, ABER (2012) reported that the state of tide at the time of sample collection also significantly affected the results due to resuspension which would account for the monthly variability throughout the year.

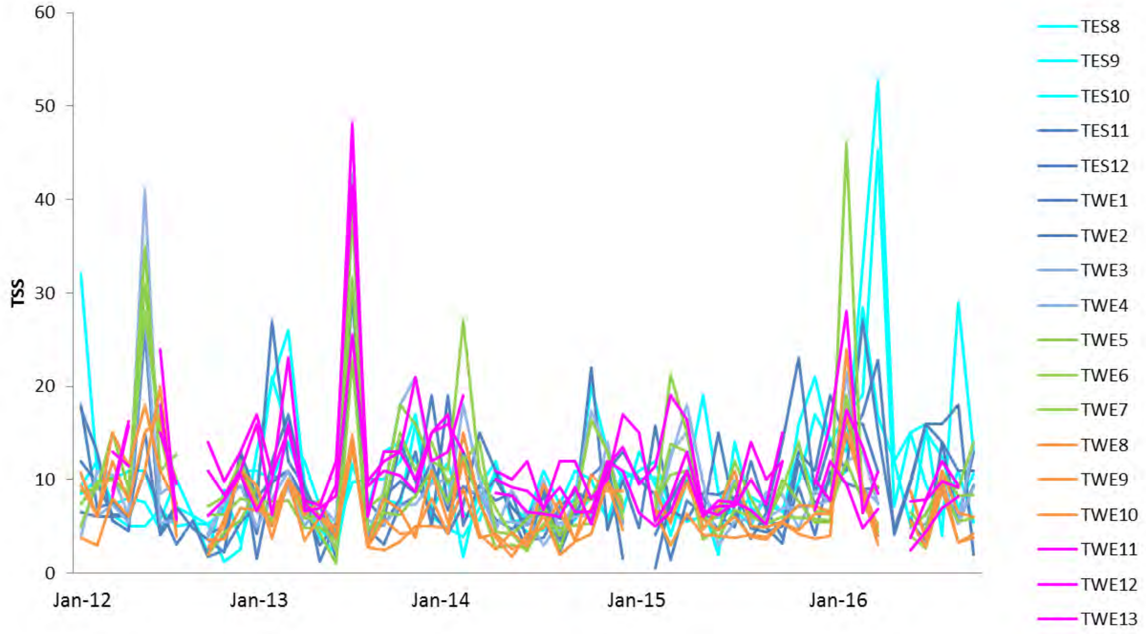

Figure 42: Temporal variation in TSS during the study period

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 43). 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.

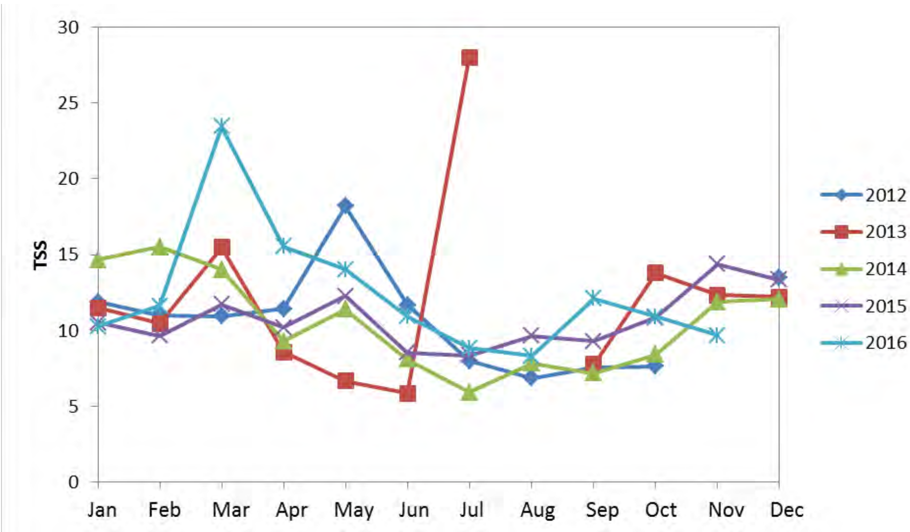

Figure 43: Inter-annual variation in mean estuary total suspended solids over the study period

4.12.4 Comparison with water quality objectives

TSS levels exceeded the guideline thresholds for greater than 75% of the time during high flow conditions throughout the estuary. Compliance was generally better during low to moderate flow conditions, with most sites achieving greater than 50% compliance during these flows. The lowest TSS compliance during low and moderate flows was seen in the Rous River (particularly site TWE12) indicating this zone remains turbid for the majority of flow conditions. Compliance rates were similar to those reported for the previous 5 years (ABER, 2012).

4.12.5 Management Implications

Management strategies should focus on reducing TSS in catchment 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 significantly reduce TSS concentrations in the middle and upper reaches of the estuary.

4.13 Water Clarity (Secchi Depth)

4.13.1 Spatial Trends

Secchi depths ranged from less than detection (0.1m) to 3.6m (Figure 49). There was a consistent spatial trend of greatest secchi depths in the lower estuary becoming progressively shallower towards the upper estuary. This reflects better water clarity and deeper overall water depths in the lower estuary and gradually decreasing water clarity and shallower water depth with distance upstream. The Rous River consistently had shallower secchi depths than the main Tweed River Estuary during all flows, indicating this zone is turbid for the majority of the time. There was a significant reduction in secchi depths 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.

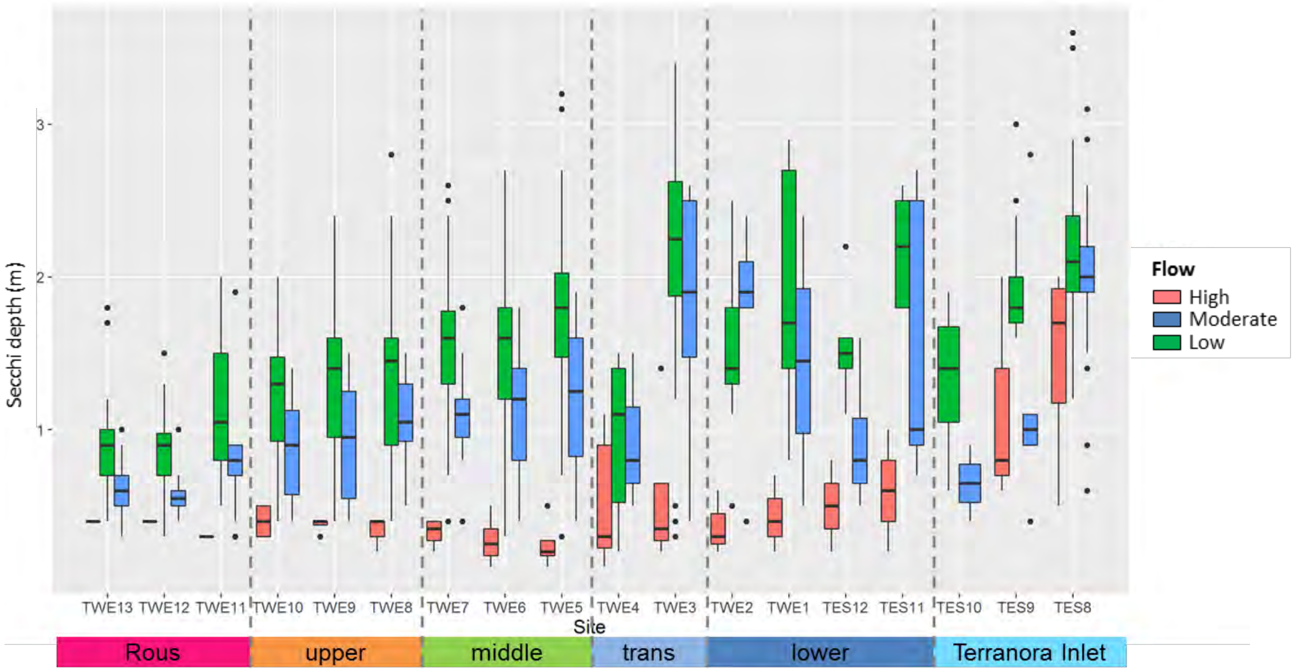

Figure 44: Spatial variation in Secchi disk depth throughout the Tweed River Estuary during low, moderate and high rainfall conditions

4.13.2 Temporal Trends

There were no clear temporal trends in secchi disc depth during study period (Figure 45). Decreased secchi disk depth during high flow times resulted in a weak seasonal trend of reduced water clarity during the summer – autumn wet season. The Rous River generally experienced poor water clarity throughout the study period.

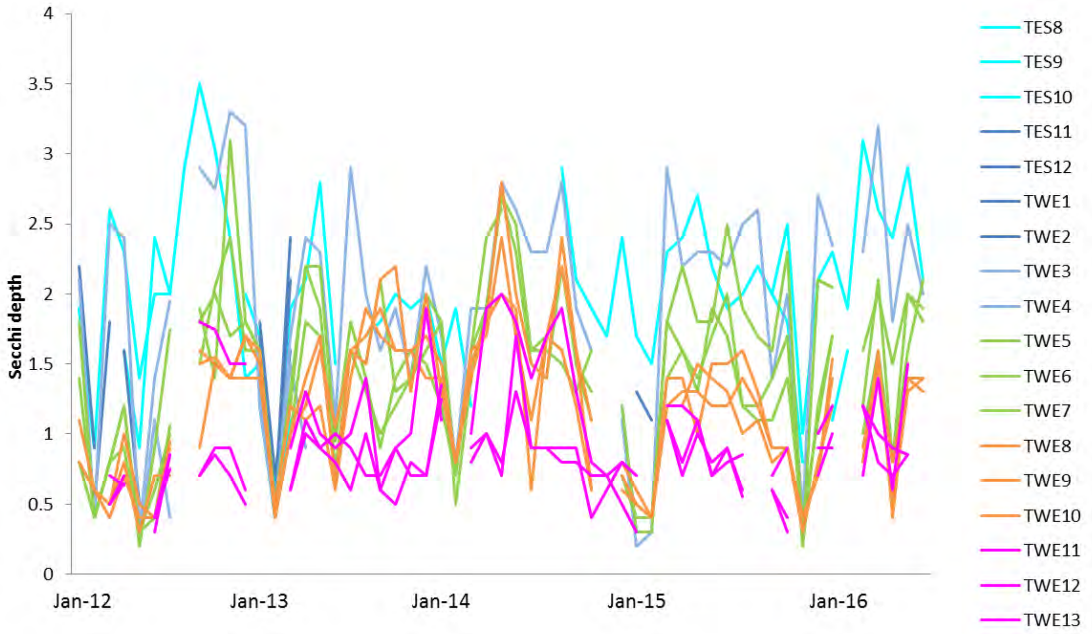

Figure 45: Temporal variation in secchi depth during the study period

4.13.3 Inter-annual variation

There was significant inter-annual variability in secchi depths (Figure 46), due to the high temporal variability in freshwater inflow and residence times controlling factors affecting water clarity (e.g. TSS, Chlorophyll *a*).

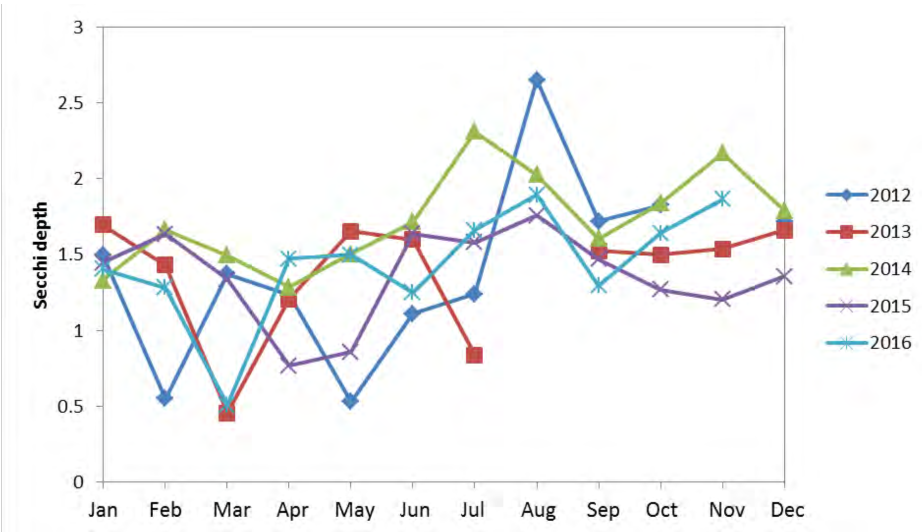

Figure 46: Inter-annual variation in mean estuary secchi depth over the study period

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 6,400 cfu/100mL during the study period (Figure 47). enterococci concentrations were generally lowest in the lower estuary, increased towards the middle estuary, and diminished towards the upper estuary. The highest levels were measured at the Rous River sites during all flows. There was a clear and consistent increase in enterococci with flow category, with the highest concentrations recorded during high flow conditions, particularly in the middle estuary and Rous River.

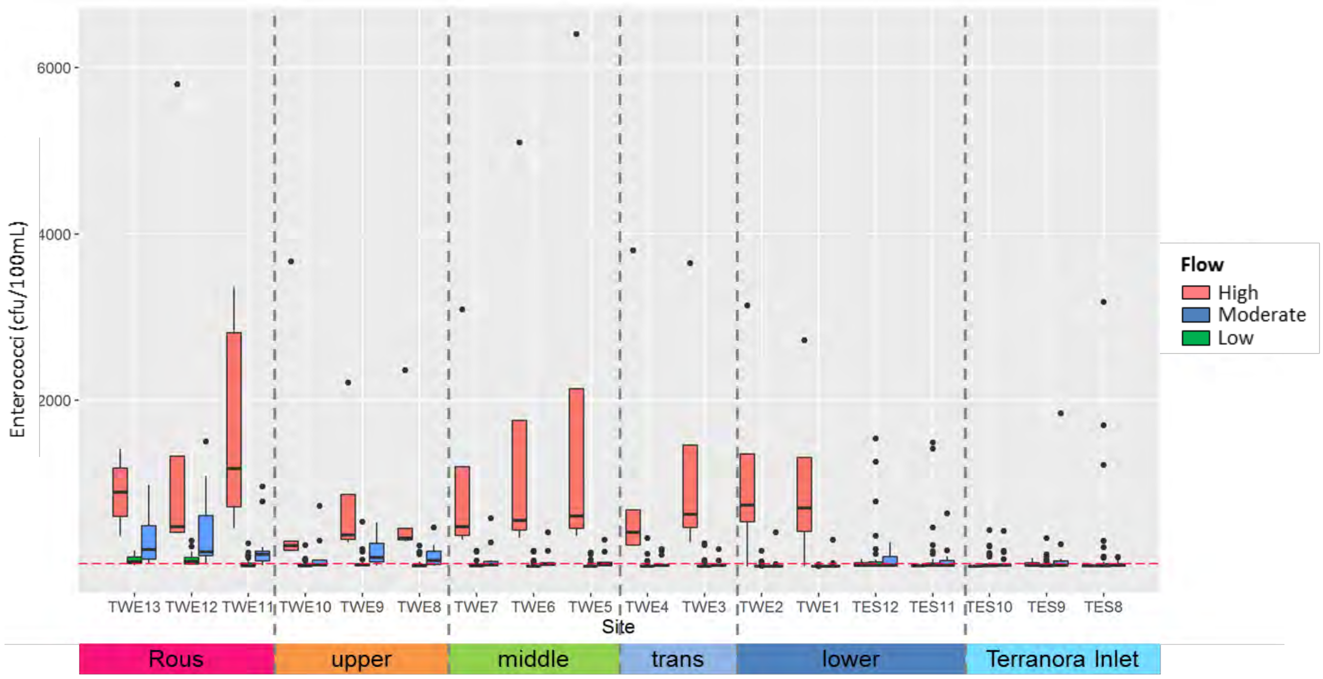

Figure 47: Spatial variation in enterococci throughout the Tweed River Estuary during low, moderate and high rainfall conditions.

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 2016).

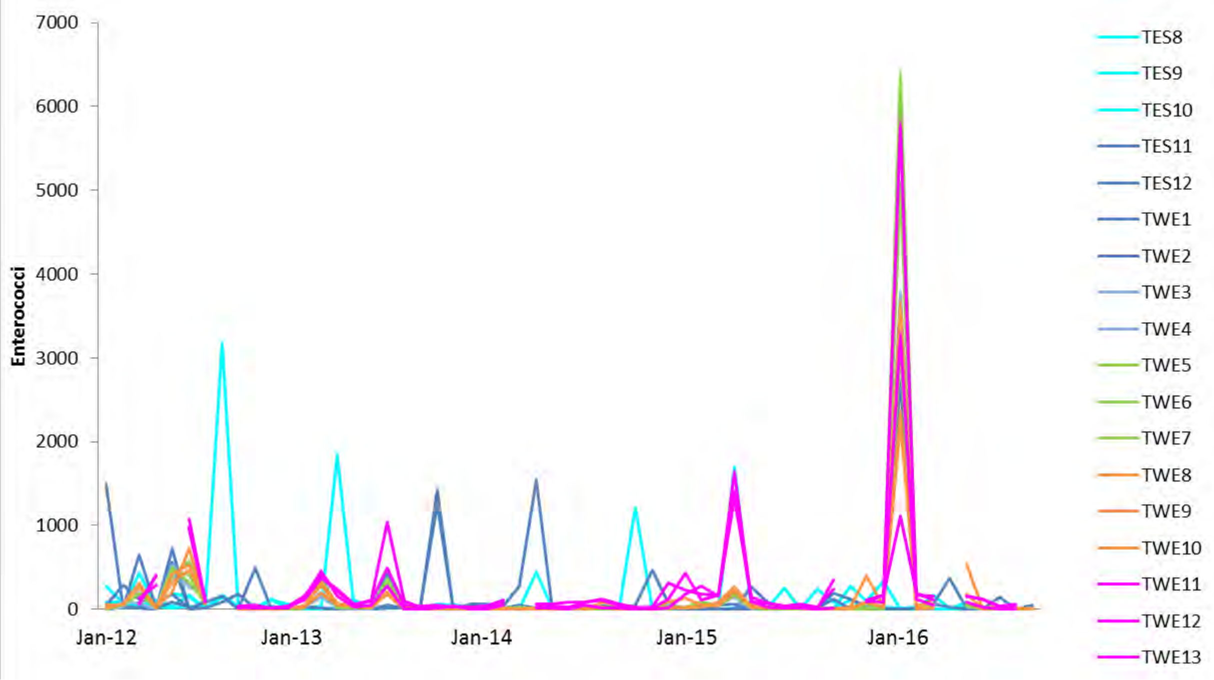

Figure 48: Temporal variation in enterococci during the study period

4.14.3 Inter-annual variation

Inter-annual variation in enterococci was minimal throughout the study period, although there appears to be slightly less variability in the dry season compared to the rest of the year again indicating a likely relationship with rainfall events.

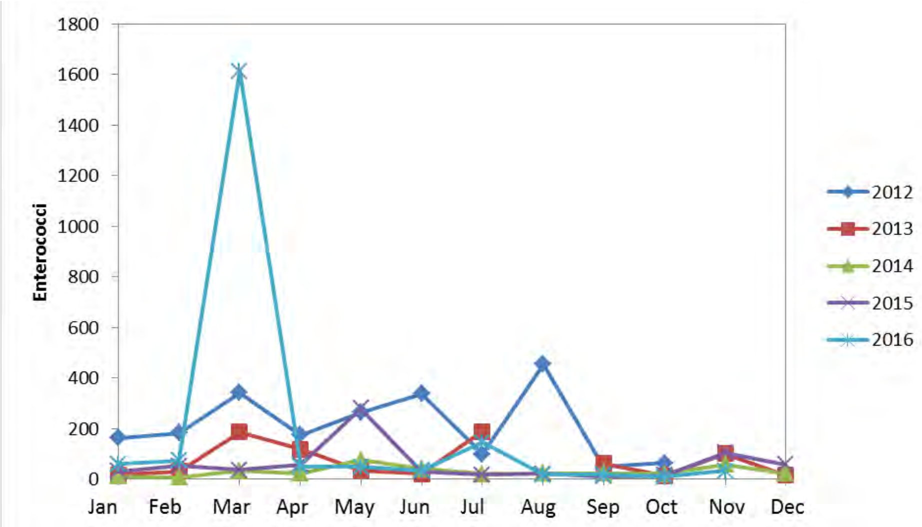

Figure 49: Inter-annual variation in mean estuary enterococci over the study period

4.14.4 Comparison with water quality objectives

enterococci concentrations exceeded the ANZECC guideline thresholds for 100% of the time during high flow conditions throughout the lower estuary sites TWE1 and TWE2, and all sites within the transitional, middle, upper estuary and the Rous River. Moderate flow conditions in the Rous River and upper estuary also resulted in guideline thresholds being exceeded for 100% of the time. Compliance was generally achieved at all sites during low flow conditions except for the Rous River sites where guidelines were still exceeded for greater than 50% of the time during low flow.

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. Eyre and Pepperell (1997) attributed high levels of faecal bacteria in the Rous River to unrestricted stock access.

Currently enterococci levels in the estuary are in excess of human health guidelines at most sites during high flow and for the majority of time in the Rous River. 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 and not advisable in the Rous River at all.
- 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.

4.15 Stratification

Physico-chemical data collected as depth profiles at sites TWE3, TWE 6 and TWE13 are summarised as box plots in Figure 50 for the period of record (2012-2016). Daily profiles taken on 7th October 2015 are shown in Figure 51, illustrating typical conditions during low flows. Both TWE3 and TWE6 in the transitional and middle estuary zones respectively showed signs of some vertical stratification in DO, salinity and temperature with levels tending to increase with depth. As tidal influence is known to extend at least as far as Stotts Island in the middle estuary (refer Section 2.5), 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. A reverse situation was observed in the upper estuary site TWE13 (Rous River) where DO and temperature both decreased with depth. Salinity was low (freshwater) and was consistent throughout the water column. During high flow samples, vertical stratification tended to be minimal due to better mixing and shorter residence times.

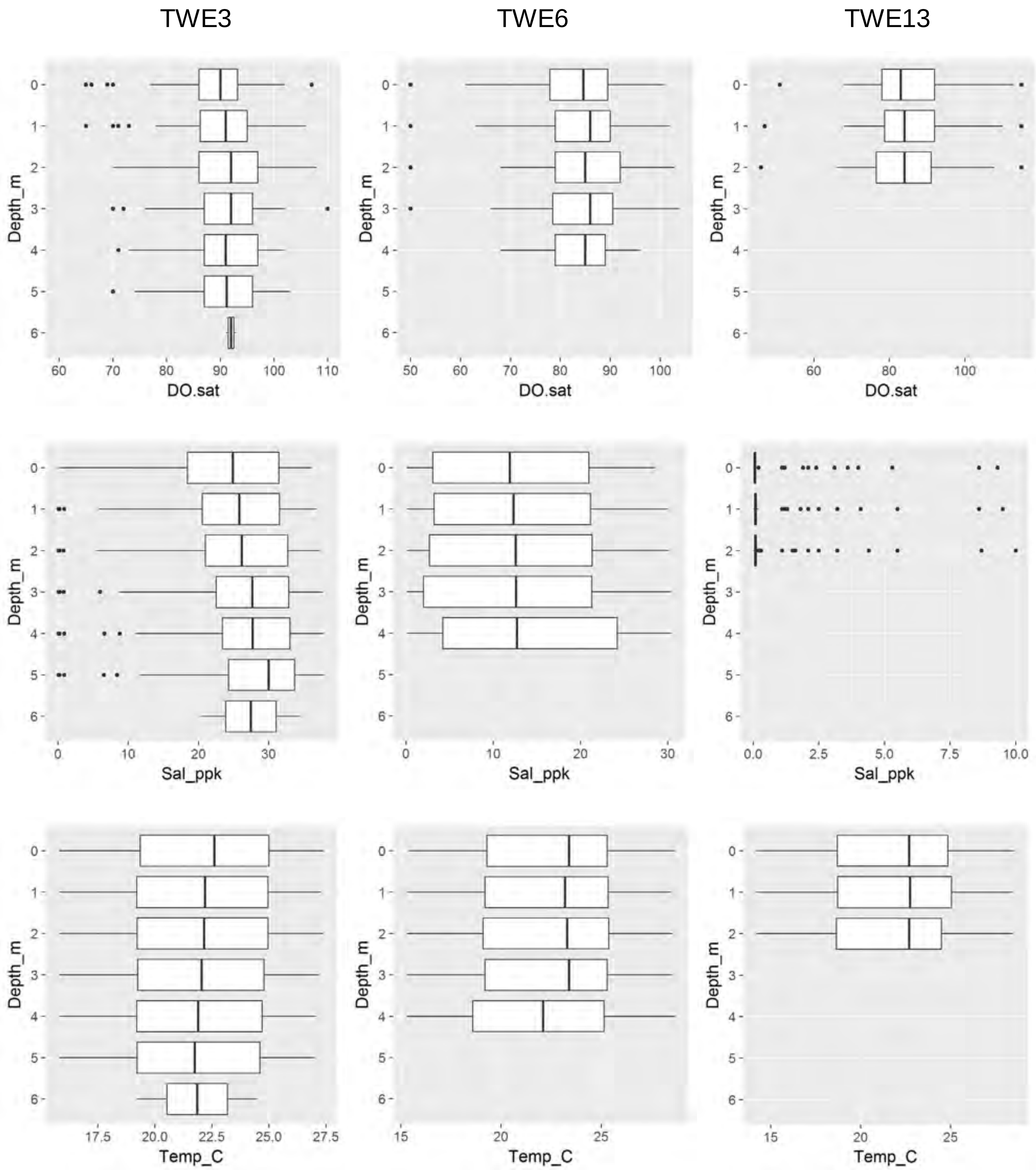

Figure 50: Boxplot summaries of physico-chemical profiles at sites TWE3, TWE6 and TWE13 (all data from 2012-2016).

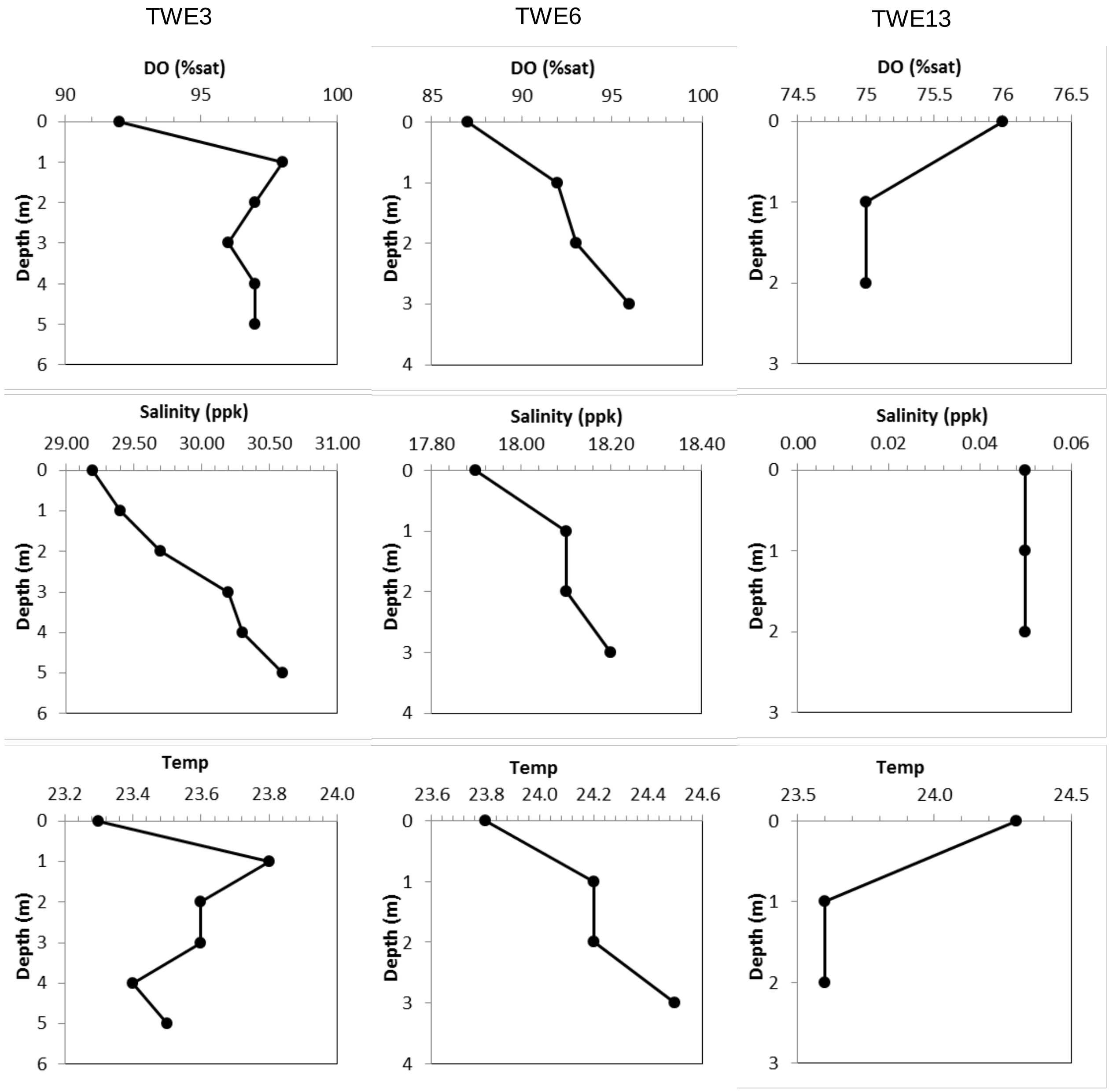

Figure 51: Depth profiles of DO, salinity and temperature at sites TWE3, TWE6 and TWE13 under low flow conditions on 7/10/2015.

4.16 Wastewater Treatment Plants

There are three wastewater treatment plants that currently discharge tertiary treated wastewater to the Tweed River Estuary study area: Murwillumbah WWTP, Tumbulgum WWTP and Kingscliff WWTP. Banora Point WWTP discharges to Terranora Inlet approximately 2kms upstream of the study area boundary. Details of each WWTP are provided in Table 5. Murwillumbah and Kingscliff WTTPs are the largest in the study area with a capacity of 3.84 and 6 ML/day respectively. Tumbulgum is a much smaller plant licenced for 0.168ML/day.

Table 5: Details of TSC WWTPs in the Study Area (Source: TSC, 2016 & Hydrosphere Consulting, 2014)

Name	Monitoring site (refer Figure 4 for locations)	Capacity (people served)	Capacity (ML/d)	Treatment Process	Effluent Management
Murwillumbah WWTP	Point 1 - Rous River approx. 1.3km u/s TWE13	16,000	3.84	IDEAT, phosphorus removal, pH correction, UV disinfection, deodorisation, tertiary filtration. Construction completed 2000. Tertiary treated effluent system for reuse at Condong Sugar Mill built 2007.	Reuse at Condong Sugar Mill in cooling towers (approx. 30% of effluent). Tertiary treated wastewater discharged into Rous River.
Tumbulgum WWTP	Point 1 – middle zone approx. 400m u/s TWE6	700	0.168	Activated sludge process with phosphorus removal, UV disinfection. Construction completed 1998.	Tertiary treated wastewater discharged into Tweed River.
Kingscliff WWTP	Point 1 – transitional zone approx. 1km u/s TWE3	25,000	6	Chemically enhanced biological nutrient removal (CEBNR) process. Construction completed 2008.	Irrigation of Chinderah Golf course and used on site. Tertiary treated wastewater discharged into the Tweed River.
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 Inlet.

4.16.1 Modelling of WWTP flows

ABER (2012) used a 1D salt balance model to predict the concentration of dissolved pollutants emanating from the effluent discharge as they are diluted along the Tweed River Estuary. The impacts of WWTP effluent discharge increased with diminishing flow. WWTP effluent accounted for up to 60%, 10% and 0.1% of total freshwater inputs during low, median, and high flows respectively. Effluent quality varied widely (primarily according to season) giving rise to a large range in potential impacts. The impact of WWTP effluent was imperceptible during high flow due to the massive dilution by catchment runoff. Results highlighted the importance of DIN loading from the WWTPs (particularly during low flows when water residence times were longer) in controlling phytoplankton biomass in the Tweed River Estuary.

Discharge of treated wastewater was identified by ABER (2012) as one of the primary causes of poor water quality in the estuary, along with catchment runoff. Accordingly, reducing nutrient input through WWTP management was a key recommended management action.

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 Murwillumbah WWTP

Table 6 and Figure 52 show the results of TSC monitoring of effluent quality at the Murwillumbah 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. Non-compliances were recorded on a small number of occasions for ammonium (2014 and 2015); total suspended solids (2012, 2014, 2015); thermotolerant coliforms (2015 and 2016); and total nitrogen (2014). TSC reporting of limit exceedances (TSC, 2016) explains that exceedances were a result of either short term maintenance activities at the WWTP, equipment failure that was identified and corrected or extreme rainfall/whether events.

Table 6: Murwillumbah WWTP Point 1 - % compliance with EPA licence limits (red cells show non-compliances with the licence)

		NH4	BOD5	O&G	pH<8.5	pH >6.5	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	100	100	100	100	100	100	100
	90th%ile	100	95	100	100	100	80	95	100	100
2013	100th%ile	100	100	100	100	100	100	100	100	100
	90th%ile	100	100	100	100	100	100	92	100	100
2014	100th%ile	96	100	100	100	100	96	100	100	100
	90th%ile	96	100	100	100	100	92	96	88	100
2015	100th%ile	98	100	100	100	100	98	98	100	100
	90th%ile	98	100	100	100	100	89	95	93	100
2016	100th%ile	100	100	100	100	100	100	94	100	100
	90th%ile	100	100	100	100	100	90	90	100	100

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

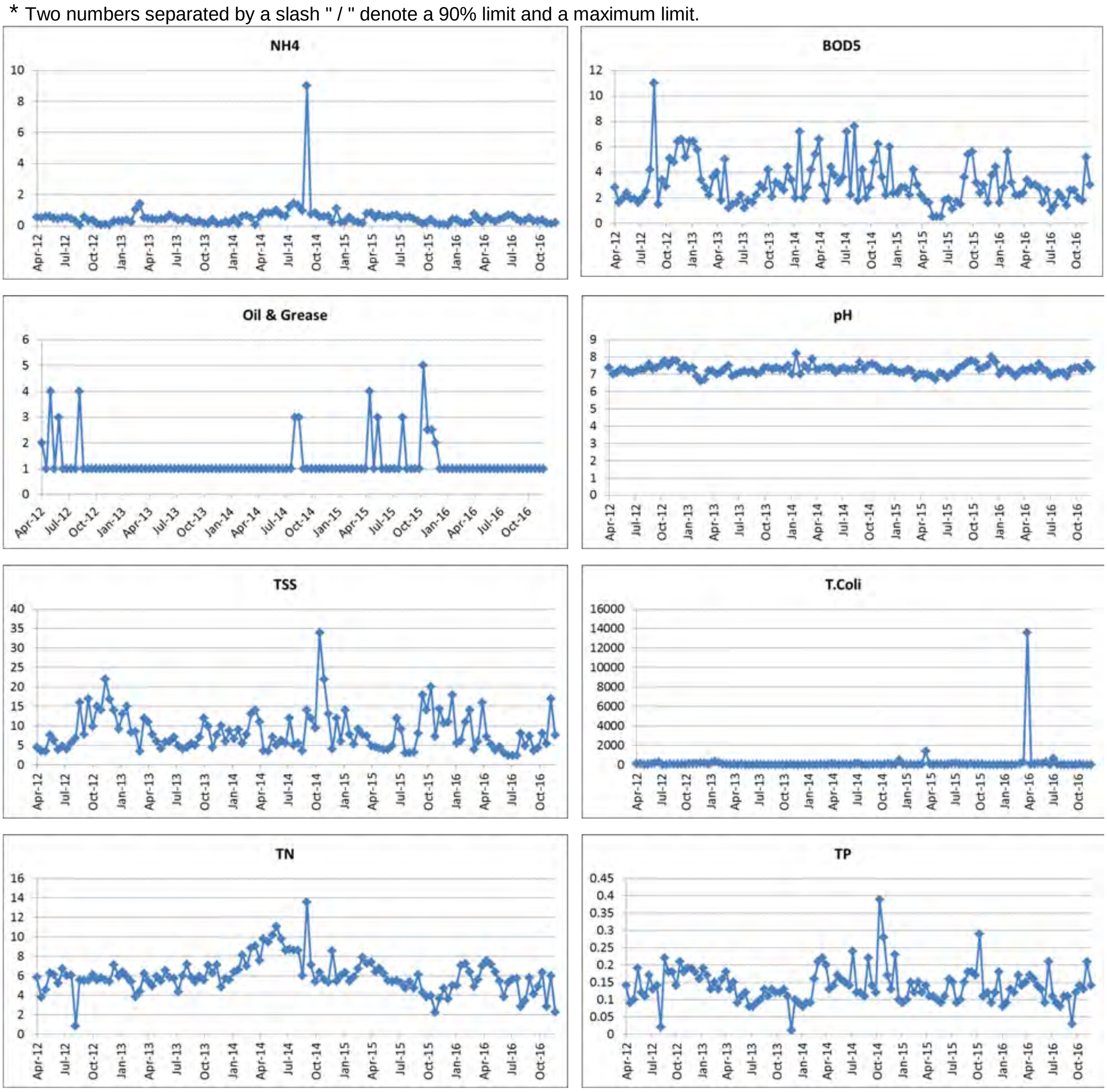

Figure 52: Murwillumbah WWTP Point 1 monitoring results from 2012-2016

4.17.2 Tumbulgum WWTP

Table 7 and Figure 53 show the results of TSC monitoring of effluent quality at the Tumbulgum 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. Non-compliances were recorded on a small number of occasions for ammonium (2015 and 2016); pH (below lower level 2012, 2014); total suspended solids (2016); thermotolerant coliforms (2012 and 2015); and total nitrogen (2016). TSC reporting of limit exceedances (TSC, 2016) explains that exceedances were a result of either equipment failure or dosing error that was identified and corrected, power supply interruption, or extreme rainfall/whether events.

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

		NH4	BOD5	O&G	pH<8.5	pH >6.5	TSS	T.Coli	TN	TP
Year	**EPA limits***	**<5/10**	**<15/35**		**<8.5**	**>6.5**	**<20/40**	**<200/600**	**<15/25**	**<1/3**
2012	100th%ile	100	100	100	100	95	100	95	100	100
	90th%ile	90	100	100	100	95	100	95	100	100
2013	100th%ile	100	100	100	100	100	100	100	100	100
	90th%ile	100	100	100	100	100	100	100	100	96
2014	100th%ile	100	100	100	100	85	100	100	100	100
	90th%ile	100	100	100	100	85	100	100	100	96
2015	100th%ile	96	100	100	100	100	100	96	100	100
	90th%ile	96	100	100	100	100	100	96	96	96
2016	100th%ile	96	100	100	100	100	96	100	96	100
	90th%ile	96	96	100	100	100	96	100	92	96

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

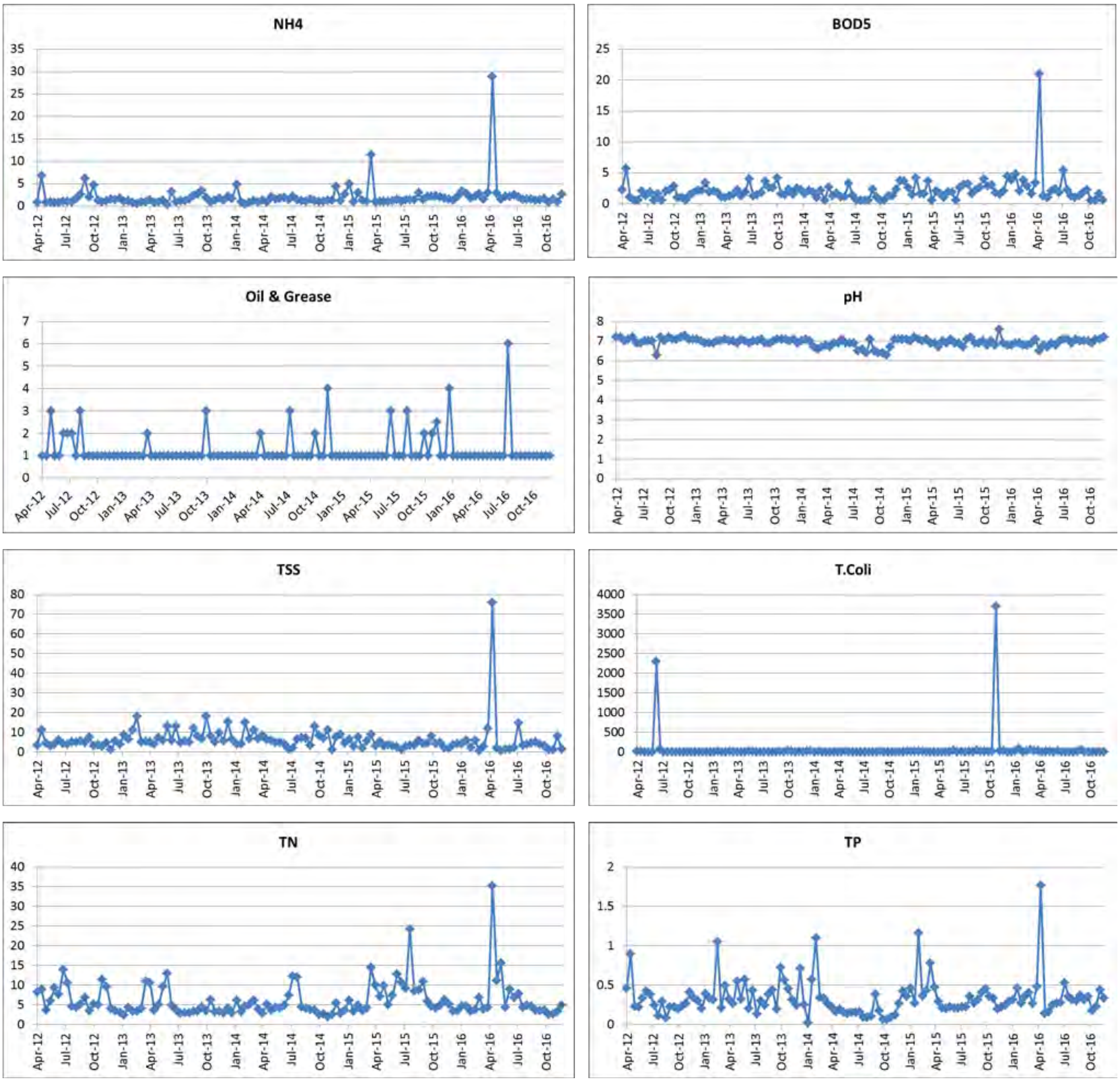

Figure 53: Tumbulgum WWTP Point 1 monitoring results from 2012-2016

4.17.3 Kingscliff WWTP

Table 8 and Figure 54 show the results of TSC monitoring of effluent quality at the Kingscliff WWTP EPA licences discharge point to the Tweed River Estuary from 2012-2016. Compliance with licenced conditions was very high with just one non-compliance recorded for thermotolerant coliforms in 2015. TSC reporting of limit exceedances (TSC, 2016) explains that the exceedance was a result of equipment failure that was identified and corrected.

Table 8: Kingscliff WWTP Point 1 - % compliance with EPA licence limits (red cells show non-compliances with the licence)

		NH4	BOD5	O&G	pH>8.5	pH <6.5	TSS	T.Coli	TN	TP
Year	**EPA limits***	**<2/4**	**<15/35**	**<5/10**	**<8.5**	**>6.5**	**<15/30**	**<100/600**	**<5/10**	**<0.5/1**
2012	100th%ile	100	100	100	100	100	100	100	100	100
	90th%ile	95	100	100	100	100	100	95	95	100
2013	100th%ile	100	100	100	100	100	100	100	100	100
	90th%ile	100	100	100	100	100	96	100	100	100
2014	100th%ile	100	100	100	100	100	100	100	100	100
	90th%ile	100	100	100	100	100	100	96	100	100
2015	100th%ile	100	100	100	100	100	100	96	100	100
	90th%ile	100	100	100	100	100	100	92	100	100
2016	100th%ile	100	100	100	100	100	100	100	100	100
	90th%ile	100	100	100	100	100	100	96	100	100

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

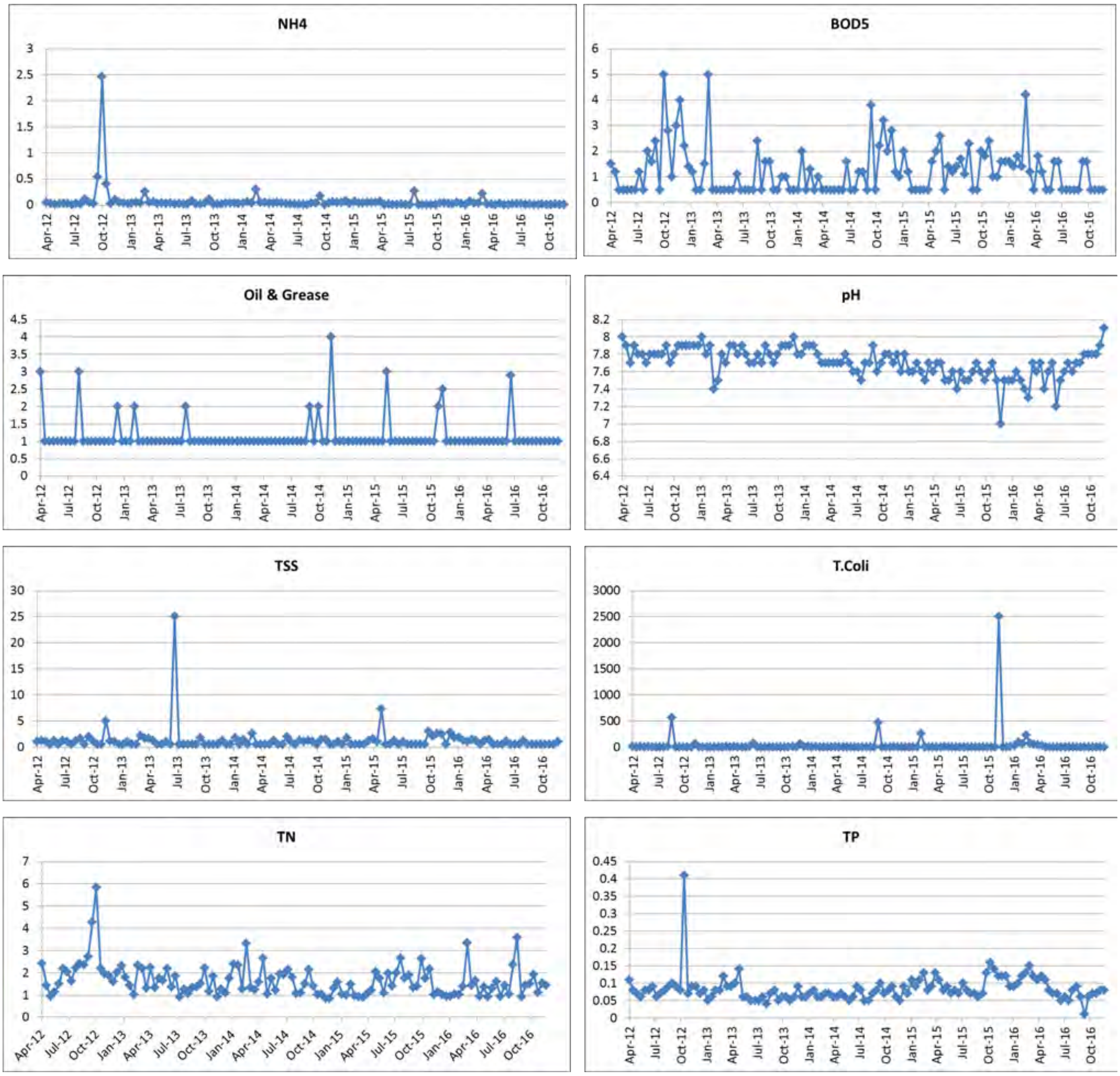

Figure 54: Kingscliff WWTP Point 1 monitoring results from 2012-2016

5. WATER QUALITY IMPROVEMENT STRATEGY

Based on the results of TSC water quality monitoring, key processes, problems and threats to water quality have been identified. Table 9 presents the resulting water quality improvement strategy for the Tweed River Estuary itemising priority issues and recommended management that can be actioned through CMP implementation.

Table 9: Water Quality Improvement Strategy

Identified management issue	Functional Zone	Recommended Actions to be considered in CMP development
Acid sulfate soil runoff impacts were observed in the middle and upper estuary and particularly in the Rous River during moderate and high flow. Although effects were reduced in 2012-2016 compared to the previous 5 year monitoring period, acid sulfate soils remain as a continuing risk factor to water quality, particularly following major rainfall events.	Upper estuary Middle estuary Rous River	Continued management effort should focus on working with floodplain landholders to reduce acid runoff wherever possible. Management strategies include: planning controls, drain shallowing, laser levelling, liming, tidal flushing etc.
The Rous River and to a lesser extent the middle estuary, are susceptible to episodes of low dissolved oxygen although levels were improved compared to the previous 5 years. This is linked to high nutrient and Chlorophyll *a* levels indicating eutrophic conditions and a poorly functioning aquatic ecosystem. Direct runoff of low DO waters from rural lands is also likely to be contributing to reduced DO in these zones.	Middle estuary Rous River	Reducing nutrient inputs to the middle estuary and Rous River through: • WWTP management during low-moderate flow; and • Catchment management during high flow. Management of agricultural land and drains to minimise low DO floodwaters developing and reaching the estuary.
TN concentrations were elevated in the middle and upper estuary and the Rous River. TN levels were strongly associated with flow with significantly higher levels during high flow conditions, followed by and moderate and low flow conditions, except for in the Rous River where high levels were more persistent throughout all flow conditions. This suggests catchment inputs during rainfall events are a significant source of TN to the middle and upper estuary and more consistent inputs from point sources such as WWTP discharge are dominant in the Rous River.	Upper estuary Middle estuary Rous River	Reducing nitrogen inputs to the system can best be achieved by reducing WWTP loading (particularly the Rous River) and catchment management throughout rural areas in the middle, upper and Rous River zones. Management strategies include: soil conservation practices; addressing erosion; maintaining vegetative cover; minimising excess fertilizer use; and establishing and maintaining vegetated riparian zones.
There was a general trend of low TP concentrations in the lower estuary rising to a peak in the middle estuary and diminishing towards the top of the estuary. With TP concentrations in the Rous River were consistently high throughout the study period. There was a trend of increasing TP concentrations with flow indicating significant sources of TP in catchment runoff.	Middle estuary Rous River	Reduce catchment input of TP during rainfall events through catchment management (particularly soil conservation practices as phosphorus is strongly associated with sediment transport). Reduce WWTP loading (particularly important during low and moderate flows), with the Rous River as a priority area.

Identified management issue	Functional Zone	Recommended Actions to be considered in CMP development
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 estuary and particularly the middle and transitional estuary zones during high flows. In the Rous River, high bioavailable nitrogen levels were consistent throughout all flows.	All zones with particular focus on: Transitional zone Middle estuary Rous River	Management strategies should focus on reducing bioavailable nitrogen inputs to the system. This can best be achieved by reducing point source loading (e.g. WWTP discharge) during low and moderate flows and catchment management during high flows.
DON concentrations increased towards the middle estuary. There was a significant increase in DON during high flow conditions, which indicates DON inputs from low lying floodplain catchment along the middle estuary.	Middle estuary	Reduce catchment input of DON during rainfall events through catchment management including soil conservation practices.
Results indicate the Tweed River Estuary currently tends toward N limitation.	All zones	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 (which are able to fix nitrogen from the atmosphere). Therefore, it is important that management effort focuses on reducing inputs of both nitrogen and phosphorus to the estuary.
Phytoplankton blooms (indicated by elevated Chlorophyll *a*) were indicated in the middle and upper estuary and the Rous River and higher levels were associated with low and moderate flows when residence times are long enough for blooms to develop. Chlorophyll *a* was consistently highest in the Rous River during low flows.	Upper estuary Middle estuary Rous River	As discussed above, phytoplankton blooms are primarily controlled by bioavailable nitrogen and management efforts should focus on reducing DIN inputs and improving water clarity during moderate and high flow conditions. This can best be achieved by WWTP management during low and moderate flow and catchment management during high flow.

Identified management issue	Functional Zone	Recommended Actions to be considered in CMP development
TSS increased with flow category, with the highest TSS concentrations recorded during high flow conditions, particularly in the middle estuary. This indicates the primary sources of sediment inputs are from the erosion of catchment soils and river banks along the middle estuary during high flow events. However, previous monitoring indicates that resuspension of bottom sediments may also play a significant role in elevating TSS in the middle estuary. TSS levels in the Rous River were consistently high during low and moderate flows indicating this zone remains turbid for the majority of flow conditions. There was evidence of occasional high TSS following rainfall events in Jack Evans Boat Harbour (TES11), lower estuary (TES12), Terranora Inlet (TES10, TES9) and Tweed Heads Marina (TES8) indicating stormwater inputs.	Middle estuary Rous River	Management strategies should focus on reducing TSS in catchment 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, and stormwater treatment. Addressing bank erosion will also assist in reducing TSS loads. Strategies to reduce phytoplankton blooms will also significantly reduce TSS concentrations in the middle and upper reaches of the estuary. Stormwater controls in urban areas.
Currently, enterococci levels in the estuary are in excess of human health guidelines at most sites during high flow and throughout most flow conditions in the Rous River. There was evidence of occasional high enterococci levels following rainfall events in Jack Evans Boat Harbour (TES11), lower estuary (TES12) and Tweed Heads Marina (TES8) indicating stormwater inputs.	All zones during high flow Rous River during all flows	Community education advising that primary contact recreation (e.g. swimming) is not advisable for a certain period following significant rainfall (to be defined) throughout the estuary and not advisable in the Rous River most of the time. 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. Restricting direct stock access to waterways.
The Bray Park Weir above Murwillumbah is a major anthropogenic influence on salinity in the upper estuary. The weir forms a barrier to tidal flow, and prevents saline influence upstream. Freshwater releases from the Clarrie Hall Dam flow down the Tweed River and through the fish ladder in the Bray Park Weir. The presence of the weir and fish ladder along with release of water for environmental flow and extraction have implications for water quality and fish passage.	Upper estuary	It will be important for any future development in the catchment likely to impact freshwater flows to consider the existing effect of Bray Park Weir. The potential raising of Clarrie Hall Dam and potential changes in upstream hydrology impacting the estuary will need to be assessed as part of the environmental impact assessment of the proposal. Appropriate measures such as environmental flow requirements will need to be adopted where necessary to mitigate potential adverse impacts on the estuary.

6. RECOMMENDATIONS FOR ONGOING MONITORING

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

6.1 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 acid runoff events and to help better characterise the conditions that lead to acid runoff. 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 Murwillumbah. 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.

6.2 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 55 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 55: Changes to location of TES12 and TES10

6.3 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 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.

6.4 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.

6.5 Depth profiles

The current program includes depth profiles (DO, temp, and salinity) at three locations in the transitional zone (TWE3), middle estuary zone (TWE6) and Rous River (TWE13). Depth profiles were useful in determining levels of stratification occurring at different locations along the estuary 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.

6.6 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).

7. REFERENCES

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8. 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

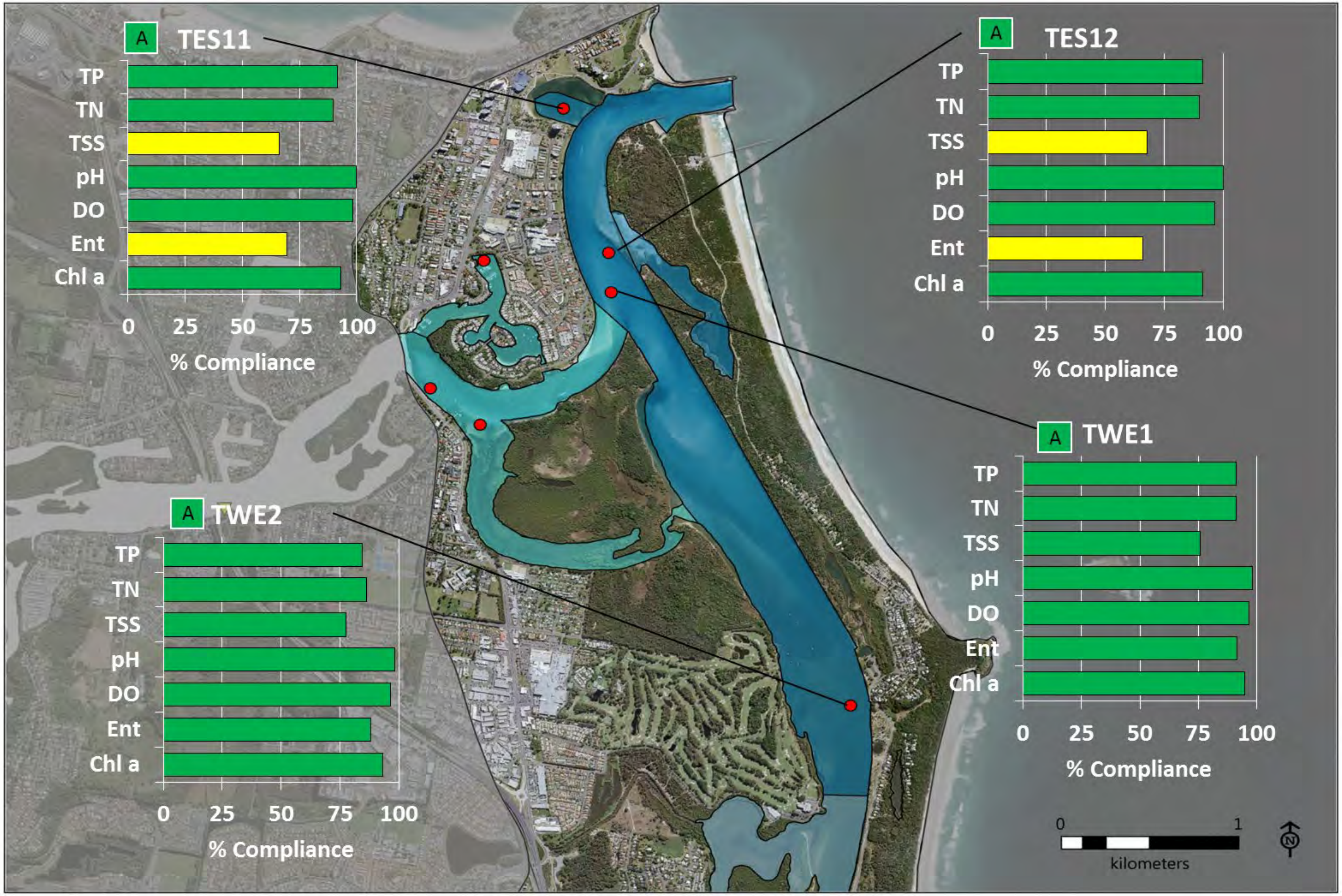

Figure 56: Lower estuary functional zone water quality compliance scores

Figure 57: Terranora Inlet functional zone water quality compliance scores

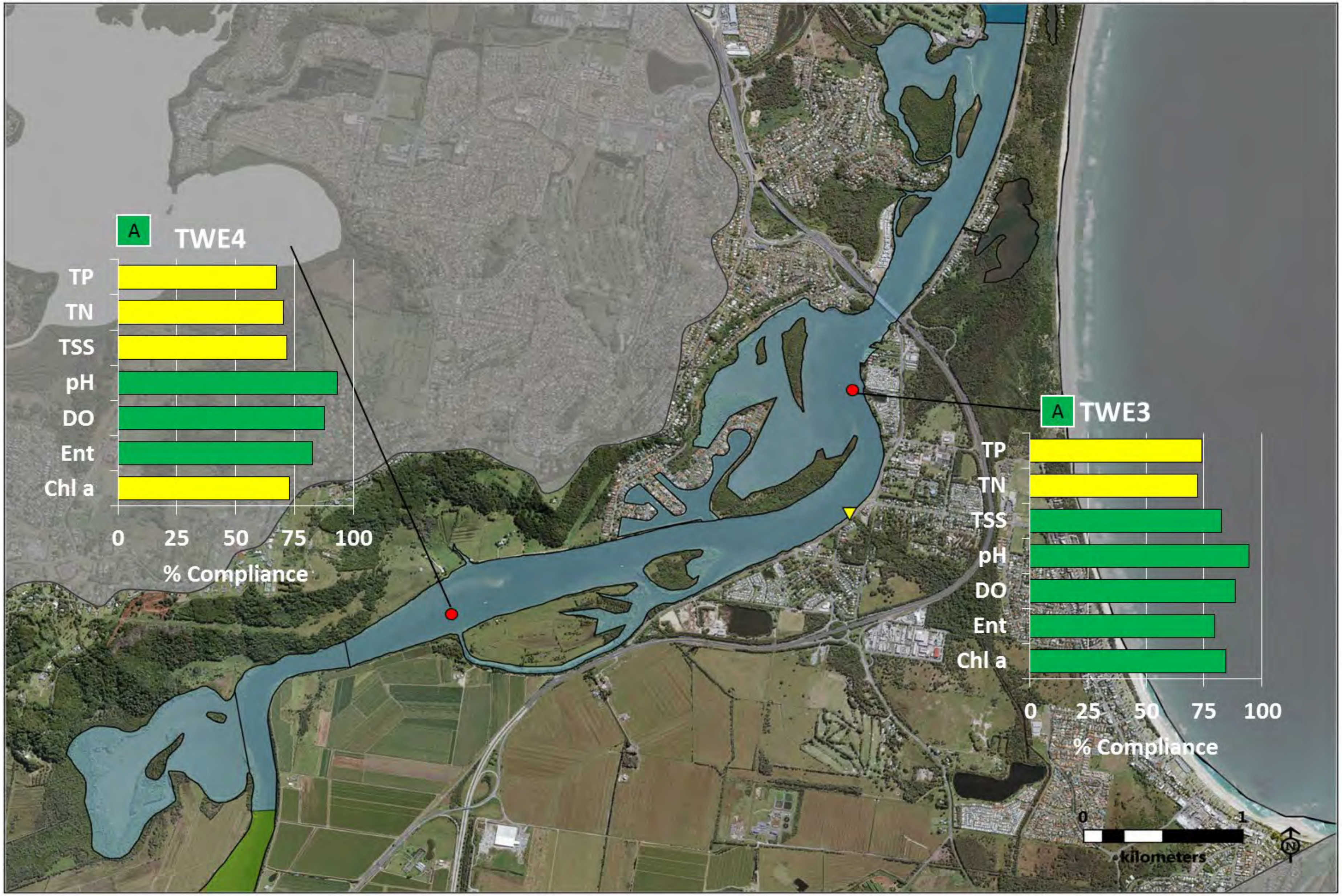

Figure 58: transitional functional zone water quality compliance scores

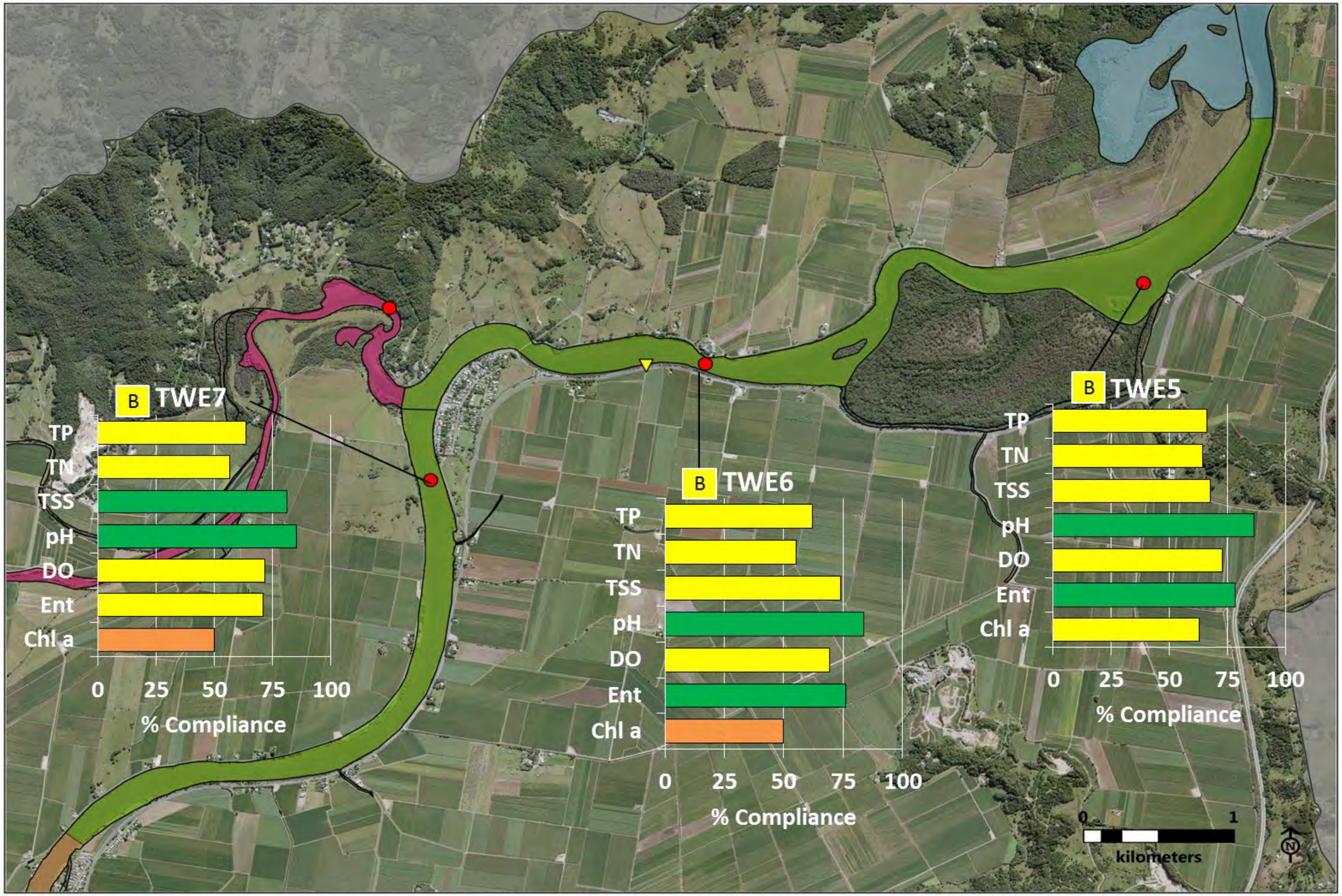

Figure 59: Middle estuary functional zone water quality compliance scores

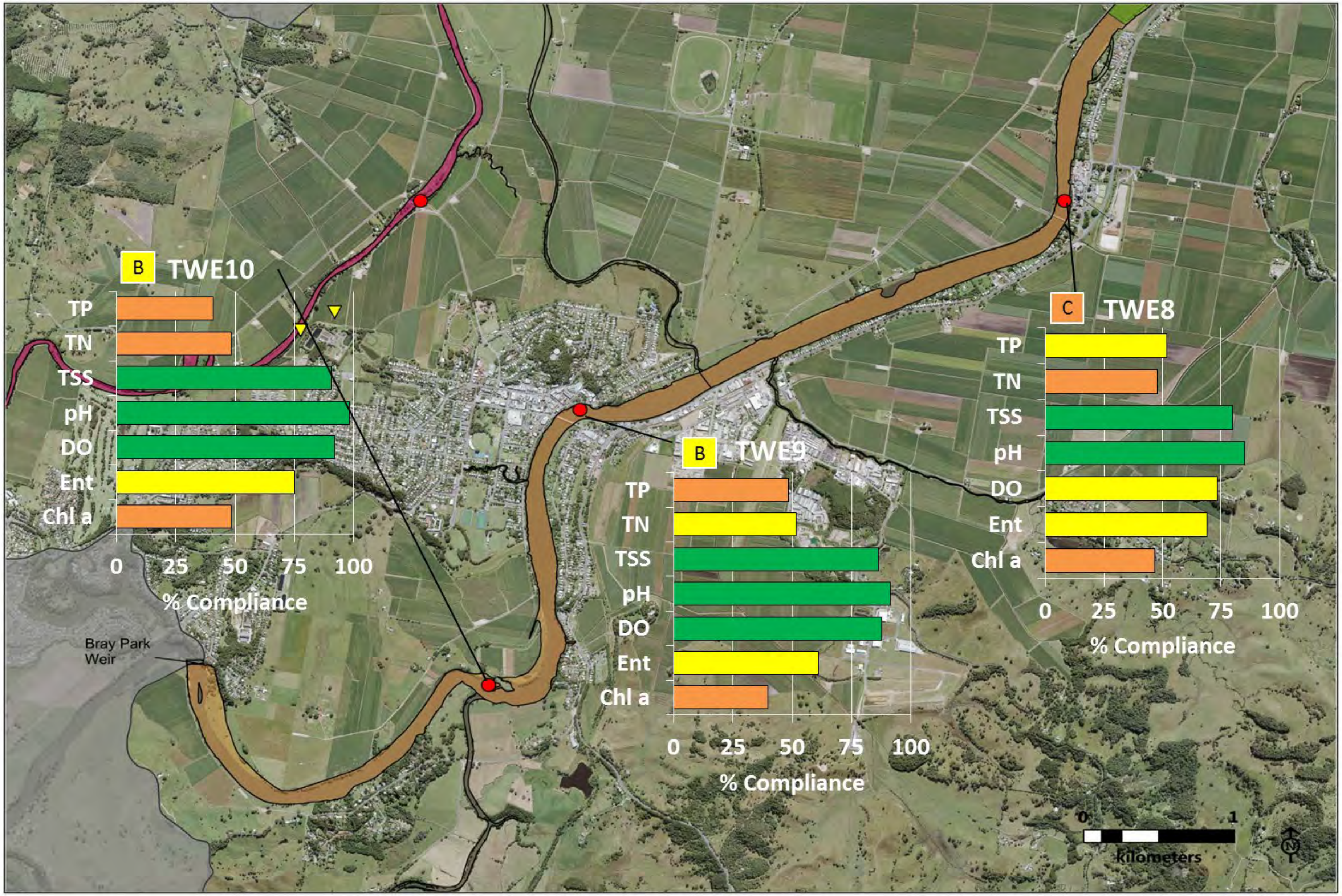

Figure 60: Upper estuary functional zone water quality compliance scores

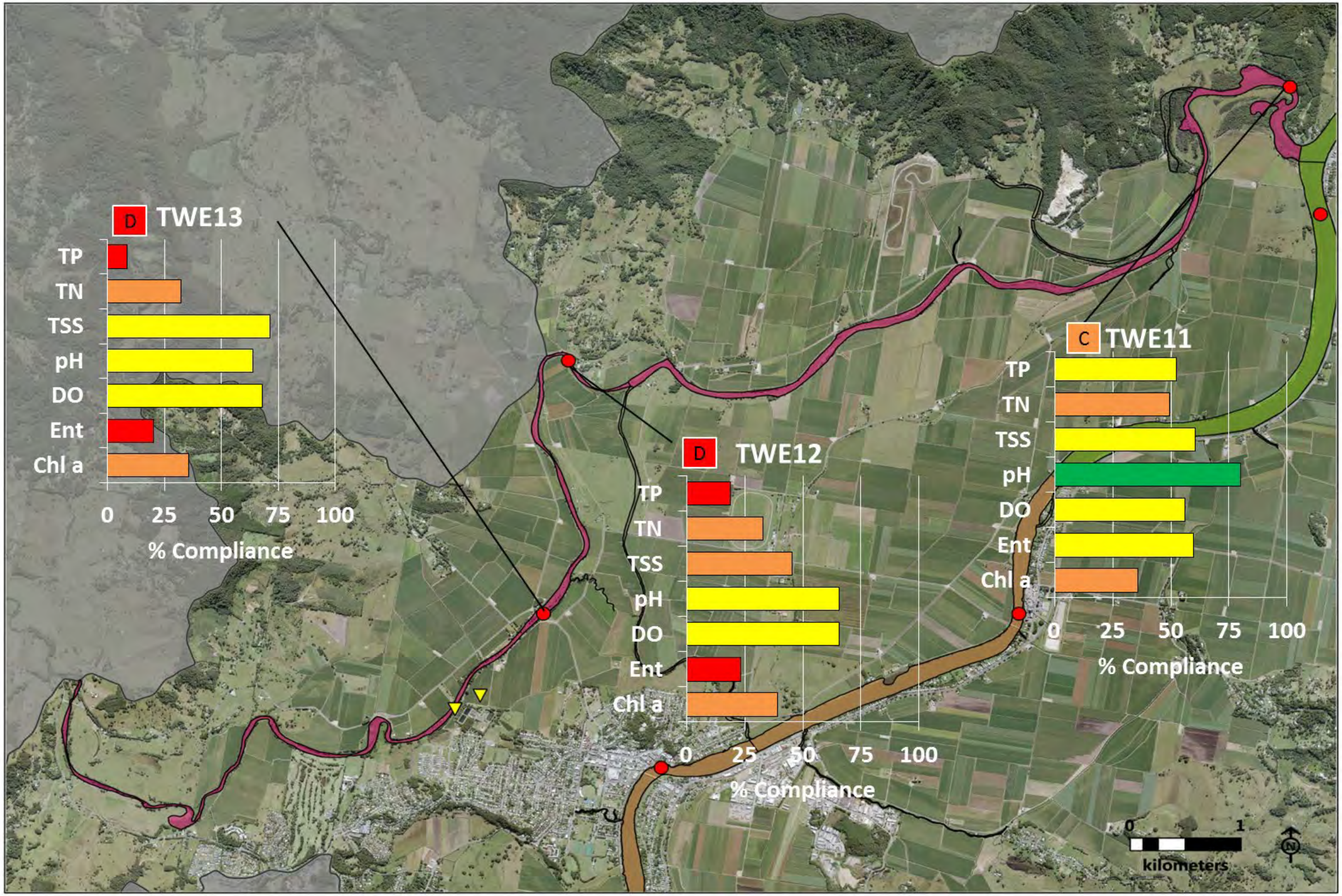

Figure 61: Rous River functional zone water quality compliance scores