Sewage Treatment System Impact Monitoring Program

Hawkesbury-Nepean River Interpretive Report 2020 (Volume 1: Main report)

Trends in WWTP nutrient loads and water quality of the Hawkesbury-Nepean River

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Commercial-in-Confidence

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Executive summary

Context

A requirement of Sydney Water's Environment Protection Licences (EPLs) is to undertake an ongoing Sewage Treatment System Impact Monitoring Program (STSIMP) to identify and quantify environmental impacts associated with Sydney Water's wastewater services across our area of operations. The program aims to monitor the environment to determine the general trends in water quality over time and investigate where Sydney Water's contribution to water quality may pose a risk to environmental ecosystems and human health.

The sampling program is designed to provide a longitudinal and spatial dataset that allows the identification of statistically significant changes in water quality or ecosystem health parameters that may be related to discharges or network overflows from wastewater systems.

As part of our EPL conditions (M5.1), Sydney Water is required to produce two types of reports:

1. Annual data report: presents the latest data and data summaries from the monitoring program on a yearly basis; data trends and exceptions are also explored with limited interpretation
2. Interpretive report: compiled every four years to identify and assess the impact on water quality and ecosystem health that may be related to Sydney Water's wastewater systems.

The focus of this year's (2020) interpretive report is comprehensive statistical analysis and interpretation of long-term datasets for all inland wastewater treatment plants (WWTPs) and receiving water quality data for the Hawkesbury-Nepean River and tributaries. This will improve Sydney Water's understanding of the current receiving water quality conditions and identify the impact of wastewater discharge on downstream water quality. The findings from this report will also inform an overarching review of the monitoring program and other catchment management projects.

Objectives

The overall aim of the Hawkesbury-Nepean River Interpretive Report is to understand the long-term trends in WWTP nutrient loads and the water quality of the river. The impact of short-listed or prioritised WWTPs and their influence on nutrients and chlorophyll-*a* concentrations in the Hawkesbury-Nepean River was further explored with in-depth analysis and interpretation.

More specifically the objectives of this report were to:

1. understand the long-term temporal trends in key nutrient concentrations and loads from each inland WWTP and recent performance against their respective EPL
2. understand the long-term temporal trends in receiving water quality (for all analytes tested and all routine monitored sites) and compare these trends against the respective Australian

and New Zealand Water Quality Guidelines for Fresh and Marine Waters (ANZG 2018) guideline values

3. select WWTPs and water quality sites for comprehensive analysis, assessment and interpretation
4. develop a suitable statistical model or data analysis method based on one WWTP to determine the impact of discharges on downstream receiving water quality (Stage 1)
5. refine and apply the statistical model developed for one location to four short-listed zones of the river with site-specific data and information (Stage 2)
6. interpret the data analysis outcomes together to understand the overall condition of the river and impact of wastewater discharges
7. use the findings of this report to inform future planning to reduce the impact of WWTP discharges.

Approach

The long-term data analysis outcomes presented in this report covers the last 25 years, from 1995 to 2020. Currently, 15 WWTPs and one Advanced Water Treatment Plant (St Marys AWTP) operate in the Hawkesbury-Nepean River catchment (Figure ES-1). Previously, an additional six poorer performing WWTPs operated in the catchment, but were progressively decommissioned between 1995 and 2008. Receiving water quality is monitored at 16 locations along the mainstream river from Maldon Weir on the Nepean River to Leets Vale on the Hawkesbury River. Monitoring is also undertaken at five other sites; four in major tributaries (South, Cattai and Berowra creeks and the Colo River) and at one lagoon (Winmalee) (Figure ES-1).

The generalised long-term trends and current performance of discharge from all inland WWTPs and receiving water quality conditions of all monitoring sites of the Hawkesbury-Nepean River and tributaries were first determined by:

- fitting Generalised Additive Models (GAM) with smoothing functions and plotting results to identify long-term trends and any step changes
- comparing EPL limits and performance at each WWTP
- assessing the receiving water quality with respect to ANZG default levels

WWTPs and water quality sites were then prioritised and key analytes selected for comprehensive analysis and assessment based on one or more of the following key conditions:

- consistent data collection
- increasing or deteriorating trends observed in long-term temporal GAM plots
- statistically significant increasing/deteriorating trend in the latest year. 2019-2020 data was compared statistically with the previous nine year's data
- WWTP discharge EPL exceedances for nutrient concentrations or loads, in recent years or the latest year (2019-2020)

- consistent high concentrations of nutrients in WWTP discharges (even if below the EPL licence limits)
- water quality concentrations consistently exceeding the ANZG default level or 2019-2020 median value exceeding the guideline
- represents a zone of the river subject to future change or other special significance (eg impact by growth areas)
- priority analytes associated with nutrient enrichment ie eutrophication, algal bloom or macrophyte infestation.

Based on the above conditions, long-term data for eight WWTPs and nine water quality sites from the following four representative zones of the Hawkesbury-Nepean River (Figure ES-1) were chosen for comprehensive data analysis and assessment:

Nepean River at Sharpes Weir – West Camden WWTP (Stage 1 pilot study zone)

- West Camden WWTP
- Water quality sites:
  - N75 – Sharpes Weir (downstream of West Camden WWTP)
  - N78 – Nepean River at Macquarie Grove Road (upstream of West Camden WWTP)

Nepean River at Yarramundi – Winmalee WWTP

- Winmalee WWTP (includes data for Blackheath, North Katoomba and Wentworth Falls WWTPs, decommissioned and transferred to Winmalee)
- Water quality sites:
  - N44 – Nepean River at Yarramundi (downstream of Winmalee WWTP)
  - N48A – Nepean River at Smith Road (upstream of Winmalee WWTP)

Hawkesbury River at Wilberforce – South Creek WWTPs (St Marys, Quakers Hill and Riverstone) and Richmond WWTP

- South Creek WWTPs (St Mary's, Quakers Hill and Riverstone) including upstream Richmond WWTP
- Water quality sites:
  - N35 – Hawkesbury River at Wilberforce (downstream of South Creek inflow and WWTPs)
  - N39 – Hawkesbury River at Freemans Reach (upstream of South Creek and Richmond WWTPs)
  - NS04A – Lower South Creek at Fitzroy Bridge

Hawkesbury River at Cattai SRA – Cattai Creek WWTPs (Castle Hill and Rouse Hill WWTPS)

- Cattai Creek WWTPs (Rouse Hill and Castle Hill) including decommissioned Round Corner WWTP (decommissioned and transferred to Castle Hill WWTP)

- Water quality sites:
  - N3001 - Hawkesbury River off Cattai State Recreation Area (downstream of Cattai Creek inflow and WWTPs)
  - N35 – Hawkesbury River at Wilberforce (upstream of Cattai Creek WWTPs)
  - NC11A - Lower Cattai Creek at Cattai Ridge Road

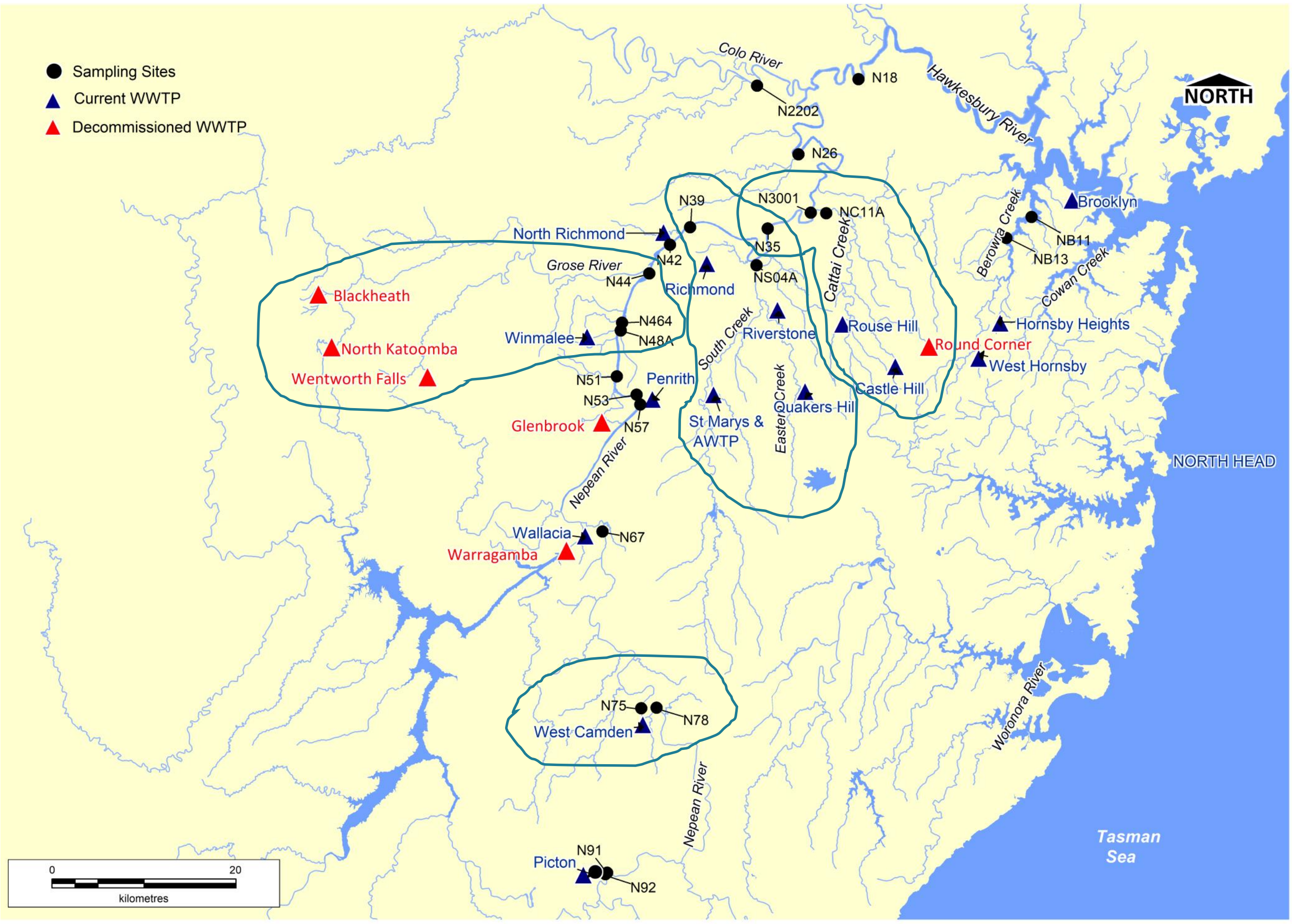

Figure ES-1 Location of Sydney Water WWTPs and water quality monitoring sites; shaded areas are four sub-catchments short-listed for detailed analysis and interpretation

A comprehensive statistical model or data analysis approach was developed in two stages. Firstly, a suitable statistical model was developed based on the long-term monitoring data in the upper Nepean River at Sharpes Weir (N75) and Macquarie Grove Road (N78), and West Camden WWTP. The analytes were limited to total nitrogen, dissolved inorganic nitrogen, total phosphorus and chlorophyll-*a* due to available data and the role of nutrients in plant growth and eutrophication. This Stage 1 pilot study was designed to identify an analysis approach, possible analysis methods, clarify problems and establish objectives/hypotheses going forward. The analysis approach developed as a pilot was further refined in Stage 2 with a reduced and final version of the model.

The finalised modelling approach was then applied in all four zones of the river (including the zone analysed in Stage 1).

The final statistical model assessed if:

WWTPs

- key nutrient loads differ between time periods defined by upgrades, population pressure and other changes to treatment processes at the WWTPs
- there are long-term trends in key nutrient loads within each period, and if so, the shape of these trends (ie increasing or decreasing, linear or curvilinear trends).

Receiving water sites

- there is a relationship between the upstream catchment (flow and nutrient concentrations) on key nutrient and chlorophyll-*a* concentrations at four mainstream sites of the river
- there is a relationship between nutrient concentration at the main river site and nutrient load from each associated WWTP
- nutrient concentrations differ between the periods defined for the associated WWTPs
- there are long-term trends within each period, and if so, the shape of these trends (ie increasing or decreasing linear or curvilinear trends).

Downstream-upstream receiving water sites

- the nutrients and chlorophyll-*a* concentrations differ between site in each period
- the relationship between the site-specific river/creek flow on nutrients and chlorophyll-*a* concentrations differ between the downstream and upstream river site
- the long-term trends within each period differ between sites, and if so, the relative difference between the trends.

WWTP nutrient loads

Decommissioning the poorer performing WWTPs and upgrading/amplifying wastewater treatment processes, has reduced the nutrient loads discharged to the Hawkesbury-Nepean catchment. However by mid-2020, nutrient loads from the majority of the WWTPs had increased, mostly due to increased wastewater inflows from rapid population growth in the catchment:

- The modelled geometric mean for total nitrogen and/or dissolved inorganic nitrogen loads showed an overall increase since the latest upgrade at four WWTPs (West Camden, Quakers Hill, Castle Hill and Rouse Hill) and decrease at three WWTPs (Winmalee, St Marys and Riverstone)
- The modelled geometric mean total phosphorus load showed an overall increase since the last upgrade at five WWTPs (West Camden, Winmalee, Quakers Hill, Riverstone and Castle Hill) and decrease at two WWTPs (St Marys and Rouse Hill).

The temporal trends in nutrient loads between the latest upgrade and mid-2020 were mixed and varied by WWTP:

- As of mid-2020, total nitrogen and dissolved inorganic nitrogen loads were significantly increasing at most WWTPs. The exceptions were no trends for Riverstone WWTP total nitrogen and dissolved inorganic nitrogen loads, and decreasing trends in total nitrogen loads from Quakers Hill and Rouse Hill WWTPs.
- By 2020, total phosphorus loads were decreasing from four WWTPs (West Camden, Winmalee, Quakers Hill and Richmond), stable (St Marys and Riverstone WWTPs) or increasing marginally at two WWTPs (Castle Hill and Rouse Hill).

The benefit of decommissioning the poorer performing WWTPs and upgrading the wastewater nutrient treatment resulted in a decrease in overall nutrient loads discharged from seven WWTPs within the Hawkesbury-Nepean River catchment. Nutrient load data for the pre-upgrade period was not available for the Richmond WWTP to make a comparison. Over time, the nutrient loads from some of these WWTPs has increased, mostly in response to increased wastewater inflows from rapid population growth in the catchment.

A nitrogen process deterioration at West Camden WWTP in 2015, combined with population growth in the catchment (139%), increased the modelled geometric mean total nitrogen load to 269% of the pre-process deterioration load (ie comparing the geometric load from 2015–2020 with 2008-2015). The West Camden WWTP catchment population almost doubled since the last phosphorus treatment upgrade in 2009, and by mid-2020, the geometric mean total phosphorus load had increased to 185% of the pre-upgrade load (ie comparing the geometric load from 2009–2020 with 1995-2009). Total nitrogen and dissolved inorganic nitrogen loads from West Camden WWTP have been significantly increasing since around 2018, while total phosphorus loads started to decrease from around 2016.

After the transfer of Blackheath WWTP to Winmalee WWTP in 2008, there was a significant decrease in modelled geometric mean total nitrogen and dissolved inorganic nitrogen loads from Winmalee WWTP (75% and 77% of pre-transfer load, respectively, ie comparing the geometric load from 1995–2008 with 2008-2020). However, there was a significant increase in the geometric mean total phosphorus load (189% of pre-commissioning load since the phosphorus upgrade in

2000; comparing the geometric load from 2000-2008 with 2008-2020, respectively). The increase in total phosphorus load was linked with essential structural repairs impacting phosphorus treatment, and connection of additional residential areas from Hawkesbury Heights and Yellow Rocks. While total nitrogen and dissolved inorganic nitrogen loads from Winmalee WWTP initially decreased after the Blackheath WWTP transfer, loads started to increase from 2016. The trend in total phosphorus load was the opposite ie increased slightly after the Blackheath WWTP transfer till around 2012, before gradually decreasing.

After the commissioning of St Marys AWTP in 2010, the modelled geometric mean total nitrogen, dissolved inorganic nitrogen and total phosphorus loads from St Marys WWTP decreased to 42%, 37% and 56% of pre-commissioning loads, respectively. This was due to the transfer of a portion of the St Marys wastewater to the AWTP for high level treatment and discharge via Penrith WWTP. Since this initial sharp drop in loads, there has been an overall increasing trend in total nitrogen and dissolved inorganic nitrogen loads from St Marys WWTP (2010-2020). The total phosphorus load trend was stable statistically in this period (2010-2020).

There was a slight increase in the modelled geometric mean total nitrogen and dissolved inorganic nitrogen load from Quakers Hill WWTP after the commissioning of St Marys AWTP (102% and 110% of pre-commissioning load), likely due to the increase in catchment population (121%). The total phosphorus load from Quakers Hill WWTP almost doubled to 189% of pre-commissioning level. A different period of pre-AWTP commissioning is considered for total phosphorus load that excluded pre-1999 data (1999-2010).

The nutrient treatment upgrade and amplification of Riverstone WWTP in 2019 reduced the modelled geometric mean total nitrogen and dissolved inorganic nitrogen load to 75% and 9% of the pre-upgrade load respectively, despite a sharp increase in the catchment population (338% of pre-upgrade population). While the total phosphorus load showed an instant improvement following the upgrade in 2019, the load remained well above the 2010 level, resulting in an overall increase of 200% of the pre-upgrade load (ie comparing loads between 2019-20 with 2010-2019). Statistical analysis on the limited nutrient load data available after the latest nutrient treatment upgrade at Riverstone WWTP (2019-2020) did not show any significant trends, but an increasing trend was identified in the previous period (2010-2019).

Richmond WWTP nutrient loads could not be compared between pre and post the 2005 upgrade due to limited pre-upgrade data.

After the transfer of Round Corner WWTP to Castle Hill WWTP in 2000, the modelled geometric mean total nitrogen, dissolved inorganic nitrogen and total phosphorus loads from Castle Hill WWTP increased to 105%, 112% and 117% of pre-upgrade load, respectively. Catchment population increased to 123% of the pre-upgrade population in this period. After the initial load increase following the decommissioning of Round Corner WWTP, Castle Hill WWTP nutrient loads (both nitrogen and phosphorus) decreased slightly before gradually increasing by 2020.

After the nitrogen treatment process upgrade at Rouse Hill WWTP in 2009, the modelled geometric mean total nitrogen and dissolved inorganic nitrogen loads increased to 239% and 259% of pre-upgrade load respectively, by mid-2020. The benefit of the nitrogen upgrade was lost due to increased population (234% of pre-upgrade population). The total nitrogen loads increased initially after the nitrogen treatment upgrade in 2009 but then gradually started to decrease. The trend in total phosphorus load increased for the entire period after the upgrade (2006-2020).

Receiving water quality

Receiving water response to WWTP upgrades/changed treatment processes

The benefit of decommissioning the poorer performing WWTPs and upgrading/amplifying treatment processes was reflected in reduced nutrient concentrations at the downstream receiving water sites. A similar reduction in chlorophyll-*a* concentration was not found at most sites.

- Nutrient treatment upgrades at upstream WWTPs contributed to reduced modelled geometric mean total nitrogen, dissolved inorganic nitrogen and total phosphorus concentrations at most downstream river sites (92% to 42% of pre-upgrade levels)
- The nitrogen process deterioration at West Camden WWTP in 2015 resulted in an increased geometric mean total nitrogen concentration at the downstream Nepean River at Sharpes Weir (128% of pre-process deterioration)
- The benefit of the nutrient upgrade at Riverstone WWTP was not recognised at the downstream Hawkesbury River site (Wilberforce) due to wet weather dominated data after the upgrade. The chlorophyll-*a* concentration decreased to 51% of pre-upgrade level due to algal washout
- Decreased total phosphorus loads from upstream WWTPs had minimal to no benefit on downstream chlorophyll-*a* concentrations, with the exception of West Camden WWTP (chlorophyll-*a* 91% of pre-total phosphorus upgrade concentration).

The benefit of decommissioning the poorer performing WWTPs combined with treatment upgrades and amplification was generally reflected in reduced modelled geometric mean nutrients concentrations at the downstream sites of the Hawkesbury-Nepean River. However, there were cases when the geometric mean nutrient concentrations increased due to other reasons such as increased WWTP nutrient loads due to population increase, upstream catchment influences or extreme weather. Despite the reduced nutrient loads from WWTPs and the reduced instream nutrient concentrations, a reduction in geometric mean chlorophyll-*a* concentrations was rarely evident and even increased in some cases.

The benefit of the nutrient load reductions from West Camden WWTP in response to upgrades in 2008-2009 was reflected in lower nutrient concentrations downstream in the Nepean River at Sharpes Weir (N75). The modelled geometric mean total nitrogen and total phosphorus concentration dropped to approximately half the pre-upgrade concentration (43% and 53%, respectively). In contrast, after the nitrogen treatment process deterioration at West Camden WWTP the geometric mean total nitrogen concentration at N75 increased to 128% of the concentration prior to the process deterioration. There was a slight reduction in the chlorophyll-*a* concentration in response to the phosphorus treatment upgrade, with the geometric mean concentration dropping to 91% of pre-upgrade concentration.

There was an apparent benefit in total nitrogen and dissolved inorganic nitrogen concentrations in the Nepean River at Yarramundi Bridge (N44) after the commissioning of St Marys AWTP with the geometric mean concentrations decreasing to 68% and 42% of the pre-commissioning level respectively. However, the changes in total phosphorus and chlorophyll-*a* concentrations were the opposite, with both showing an overall increase in geometric mean after the commissioning (123% and 170% respectively). Both total phosphorus and chlorophyll-*a* concentrations showed a decreasing trend from around 2015.

The benefit of WWTP nutrient load reductions in response to the nutrient treatment upgrades at St Marys and Quakers Hill WWTPs in 1999, Richmond WWTP upgrade in 2005 and St Marys AWTP commissioning 2010, was reflected in lower geometric mean nutrient (both nitrogen and phosphorus) concentrations at the downstream Hawkesbury River site at Wilberforce (N35) (63% to 92% of pre-upgrade/pre- AWTP commissioning). However, such a benefit was not identified for geometric mean chlorophyll-*a* concentrations, which increased to 117% of the pre-upgrade level after the first two interventions. After the commissioning of St Marys AWTP, the chlorophyll-*a* concentration at N35 was comparable to pre-commissioning levels (101% of pre-commissioning level).

The limited data following the Riverstone WWTP nutrient upgrade in 2019 indicated an increase in geometric mean total nitrogen and total phosphorus concentrations (120% and 112% respectively) and a decrease in chlorophyll-*a* concentration (51%) at the downstream Hawkesbury River site at Wilberforce site (N35). An extreme wet weather event in early 2020 was likely linked with the increasing nutrient loads due to runoff from the surrounding catchment. The decreased chlorophyll- *a* concentration was not unexpected as algal washout commonly occurs after wet weather events.

The data set for the Hawkesbury River site off Cattai SRA (N3001) was limited to the 2008 to 2020 period. As such, no comparison was made on the geometric mean nutrient and chlorophyll-*a* concentrations to identify the benefit of the decommissioning and transfer of flow from Round Corner WWTP to Castle Hill WWTP, or the Rouse Hill WWTP total nitrogen treatment upgrade in 2009.

Recent trends

Significantly increasing trends were detected in total nitrogen and/or dissolved inorganic nitrogen at the majority of receiving water sites as of mid-2020 after the latest upgrades or interventions at the upstream WWTPs. However, the trend in total phosphorus was mostly decreasing and chlorophyll-*a* concentrations remained steady or increasing. As of mid-2020:

- Significantly increasing trends were detected in total nitrogen and/or dissolved inorganic nitrogen concentrations at three of the four key receiving water sites since last upgrade or intervention
- The Hawkesbury River at Wilberforce, downstream of South Creek, was the exception where no trend in in total nitrogen and/or dissolved inorganic nitrogen concentrations was detected within the short period after Riverstone WWTP upgrade in 2019, but an increasing trend was detected in the previous period (2010-2019)
- Total phosphorus concentrations showed a decreasing trend at two Nepean River sites (Sharpes Weir and Yarramundi)
- No trend in total phosphorus concentration was detected in the Hawkesbury River at Wilberforce downstream of South Creek since 2019, but a decreasing trend was detected in the previous period (2010-2019)
- Total phosphorus concentrations were increasing in the Hawkesbury River off Cattai SRA, downstream of the Cattai Creek catchment WWTPs
- Chlorophyll-*a* concentrations remained steady in the Nepean River at Sharpes Weir, downstream of West Camden WWTP
- Chlorophyll-*a* concentrations showed a decreasing trend in the Nepean River at Yarramundi, downstream of Winmalee WWTP and the Hawkesbury River off Cattai SRA, downstream of Cattai Creek WWTPs
- Chlorophyll-*a* concentrations were increasing in the short period from 2019 at Wilberforce Hawkesbury River, downstream of South Creek but significantly decreased in the previous period (2010-2019)

The total phosphorus concentration in the Nepean River at Sharpes Weir (N75) decreased significantly between 2009 and 2020, after the phosphorus treatment upgrade at West Camden WWTP. During this period, there was a nitrogen treatment process deterioration at West Camden WWTP (2015), which resulted in a significant increase in total nitrogen concentration at the downstream site. However, no trend (increasing or decreasing) was identified in the chlorophyll-*a* concentration at this site between 2009 and 2020.

After the commissioning of St Marys AWTP in 2010, total nitrogen and dissolved inorganic nitrogen concentrations in the Nepean River at Yarramundi Bridge (N44) showed an overall significantly increasing trend, after an initial sharp decline. Total phosphorus and chlorophyll-*a* concentrations showed the opposite trend, increasing until around 2015 before decreasing.

In the recent 15-17 month period after the Riverstone WWTP nutrient treatment upgrade (2019-2020), no significant temporal trend was identified in nutrient concentrations (total nitrogen, dissolved inorganic nitrogen and total phosphorus) in the Hawkesbury River at Wilberforce (N35), downstream of South Creek. The trend in chlorophyll-*a* concentration was increasing significantly in last 15 months (2019-2020). In the previous period, (ie after Riverstone WWTP reached design capacity/increased discharge and the AWTP was commissioned, 2010-2019), there was an initial sharp decrease in total nitrogen at N35, followed by an increasing trend. Total phosphorus and chlorophyll-*a* concentrations at N35 increased until around 2016 when concentrations plateaued (total phosphorus) or decreased (chlorophyll-*a*) by 2019.

There were significantly increasing long-term (2008-2020) trends in total nitrogen and total phosphorus concentrations in the Hawkesbury River off Cattai SRA (N3001), downstream of Cattai Creek. There was a small but significant decreasing trend in chlorophyll-*a*.

Comparison with upstream river and tributary

- Nutrient and chlorophyll-*a* concentrations were mostly higher at the downstream river water sites compared to the upstream concentrations confirming an impact of upstream WWTPs or tributary catchments
- Nutrient concentrations were lower and chlorophyll-*a* concentrations were higher at two downstream Hawkesbury River sites compared to concentrations in the respective upstream tributaries (South Creek or Cattai Creek).

The modelled geometric mean nutrient (total nitrogen, dissolved inorganic nitrogen and total phosphorus) and chlorophyll-*a* concentrations were mostly higher at the downstream river sites compared to the upstream concentrations, with the difference varying by each zone of the river. In the upper Nepean River upstream and downstream of Matahil Creek and West Camden WWTP, the comparison was limited to 18 month dry weather period of 2018-2019 due to minimal data from the upstream site. Although nutrient concentrations, particularly nitrogen, were much higher at the downstream site, the chlorophyll-*a* concentration was lower indicating no direct influence of elevated nutrients on algal growth at this site.

In the Nepean River upstream and downstream of Winmalee WWTP, nutrients and chlorophyll-*a* concentrations were significantly lower at the upstream site on the Nepean River at Smith Road (N48A) compared to the downstream concentrations at Yarramundi Bridge (N44), with a more pronounced difference in the period before the commissioning of St Marys AWTP. This indicates a consistent impact of nutrient discharges from Winmalee WWTP and the benefit of the commissioning AWTP.

Nutrients and chlorophyll-*a* concentrations were significantly lower at the upstream site on the Hawkesbury River at Freemans Reach (N39) compared to downstream concentrations at Wilberforce (N35), with the largest differences identified in phosphorus and chlorophyll-*a* concentrations. This was not unexpected given the addition of nutrient rich inflows via South Creek, and the wider river with tidal influence being a more conducive environment for algal growth. The exception was the final period (2019-2020) which was dominated by wet weather, where the difference in geometric mean chlorophyll-*a* was the opposite: the downstream concentration was only 33% of upstream concentrations indicating algal washout at the downstream site.

The nutrients and chlorophyll-*a* concentrations differed only slightly between the Hawkesbury River off Cattai SRA (N3001) downstream of Cattai Creek, with the concentrations from upstream site in the Hawkesbury River at Wilberforce (N35).

Downstream river nutrient concentrations in the Hawkesbury River at Wilberforce (N35) and Off Cattai SRA (N3001) were much lower than concentrations in the upstream South Creek (NS04A) and Cattai Creek (NC11A), respectively. Chlorophyll-*a* concentrations were higher at the downstream river sites compared to levels in the respective creeks.

Factors contributing to high nutrients and chlorophyll-*a*

- Nutrient and chlorophyll-*a* concentrations at the downstream river sites were significantly correlated with the respective concentrations at the upstream river sites ie upstream catchment influenced the nutrient and chlorophyll-*a* concentrations at all three downstream receiving water sites
  - no such analysis was carried out for the downstream Nepean River at Sharpes Weir due to limited data available for the upstream Macquarie Grove Road site
- There were significant positive correlations between the upstream WWTP nitrogen and phosphorus loads, and the respective downstream concentrations in all four zones of the river confirming an impact of WWTP discharges
- A positive relationship between the site-specific total nitrogen load or total phosphorus load with the downstream chlorophyll-*a* concentration was rarely found and sometimes gave a negative relationship
- A significant positive correlation was found between the flow (upstream river flow or tributary flow) with the downstream nutrient concentrations confirming the contribution of nutrients during wet weather
- The relationship of river/creek flow with chlorophyll-*a* was significantly negative confirming algal washout and reduced residence time during wet weather, and elevation in dry weather at all downstream sites.

The statistical model for the downstream site on the Nepean River at Sharpes Weir (N75) did not fit the limited data for the upstream site at Macquarie Grove Road (N78) to determine an influence of upstream catchment factors. Nutrients (total nitrogen, dissolved inorganic nitrogen and total phosphorus) and chlorophyll-*a* concentrations at the three other downstream river sites were significantly and positively correlated with the respective nutrient concentrations at upstream site. This confirmed that, in addition to WWTP discharges and major tributaries, upstream river catchment also influenced the nutrient and chlorophyll-*a* concentrations at three downstream receiving water sites.

West Camden WWTP total nitrogen and total phosphorus loads were significantly and positively correlated with the total nitrogen and total phosphorus concentrations in the Nepean River at Sharpes Weir (N75) downstream of Matahil Creek, indicating a direct impact of wastewater discharge on nutrient elevation. However, neither the total nitrogen nor total phosphorus load from West Camden WWTP was significantly correlated to the chlorophyll-*a* concentrations at N75. This indicates that, although nutrient concentrations in the river increased in recent years due to increased nutrient loads, there was no detectable influence on chlorophyll-*a* concentrations.

Winmalee WWTP nutrient loads (both nitrogen and phosphorus) were significantly correlated with the nutrient concentrations at the downstream receiving water site. Chlorophyll-*a* was only correlated with the total phosphorus load (not total nitrogen load).

Total phosphorus loads from all three individual South Creek catchment WWTPs (St Marys, Quakers Hill and Riverstone) were significantly and positively correlated with the total phosphorus concentration at downstream Hawkesbury River at Wilberforce receiving water site (N35). Such a significant positive relationship was also identified for the St Marys and Riverstone WWTP total nitrogen loads downstream at Hawkesbury River at Wilberforce (N35), and St Marys WWTP dissolved inorganic nitrogen load with the dissolved inorganic nitrogen concentration at N35. However, the relationship between individual WWTP nutrient loads with the chlorophyll-*a* concentrations was mixed; increased with St Marys WWTP total nitrogen loads, decreased with St Marys WWTP total phosphorus loads and decreased/no relationship with Quakers Hill WWTP total nitrogen load.

The relationship between nutrient loads discharged from the Cattai Creek catchment WWTPs (Castle Hill and Rouse Hill) with total respective nutrient concentrations in the downstream Hawkesbury River (N3001) was mostly insignificant. The only exception was the total nitrogen load from the Castle Hill WWTP, which was significantly and positively correlated with the total nitrogen concentrations at N3001.

The total nitrogen load from Castle Hill WWTP was significantly and inversely correlated to the concentration of chlorophyll-*a* at N3001. That is, chlorophyll-*a* concentration decreased with an increase in total nitrogen load from Castle Hill WWTP.

A significant positive correlation was found between the total phosphorus concentration in the Nepean River at Sharpes Weir (N75) and upstream river flow at Camden Weir or flow from Matahil Creek. This indicates in wet weather, the upstream catchment (both Nepean River and Matahil Creek) contribute to phosphorus elevation. Upstream river (Camden Weir) flow was significantly and negatively correlated with the total nitrogen and dissolved inorganic nitrogen concentration at N75 indicating upstream river flow in wet weather is diluting the nitrogen concentrations downstream. However, the Matahil Creek catchment contributed to the downstream receiving water in terms of dissolved inorganic nitrogen, as confirmed by the positive significant relationship between Matahil Creek flow and dissolved inorganic nitrogen concentrations.

Comparative statistical analysis on the short-term dataset (2018-2019) of Camden Weir flow and river nutrient concentrations indicated that, in wet weather increased river flow impacted the upstream site (N78) with nitrogen (total nitrogen and dissolved inorganic nitrogen) enrichment. However, at downstream site (N75), high river/creek flow was beneficial, reducing the nitrogen (total nitrogen and dissolved inorganic nitrogen) concentrations significantly. Flow was significantly and inversely correlated with the chlorophyll-*a* concentration at this site indicating algal washout during wet weather and lower retention time for algal growth.

In the middle zone near Penrith, the analysis identified a significant negative correlation with upstream river flow on total nitrogen, dissolved inorganic nitrogen and chlorophyll-*a* concentrations downstream at Nepean River at Yarramundi (N44). No such significant relationship was found between the upstream flow and total phosphorus concentrations. This indicated that the upstream site transported diluted nitrogen concentrations during higher flow to sites downstream of Winmalee WWTP discharge. Generally, dry weather nitrogen and chlorophyll-*a* enrichment occurred at N44.

The relationship between the South Creek catchment flow on total nitrogen and total phosphorus concentrations at the downstream Hawkesbury River site (N35) was significant and positive; with increasing flow from the tributary, nutrient concentrations increased at the downstream river site. This indicates in wet weather with high flows, the upstream tributary catchment is transporting these nutrients downstream to N35. The South Creek tributary flow was negatively correlated with the chlorophyll-*a* concentration at N35 confirming a wet weather algal washout was contributed from creek flow.

Comparative statistical analysis between upstream river flow and nutrient concentrations at the upstream (N39) and downstream (N35) sites indicated an influence at both upstream and downstream river sites. The influence of flow on South Creek (NS04A) nutrients was only evident for total phosphorus levels confirming phosphorus enrichment in wet weather.

In the furthermost downstream zone near Cattai Creek, upstream river flow influenced the total nitrogen and total phosphorus concentrations at the downstream river (N3001), but no such influence was identified with the Cattai Creek flow. This indicates nutrient concentrations at N3001 are more influenced by upstream (N35) concentrations than the water transported by Cattai Creek.

Comparative statistical analysis between upstream river flow and nutrient concentrations with the upstream (N35) and downstream (N3001) sites indicated a positive influence at both upstream and downstream river sites. The influence of flow on Cattai Creek (NC11A) nutrient concentrations was evident for both total nitrogen and total phosphorus levels confirming elevation in wet weather.

Way forward

Sydney Water has consistently complied with the vast majority of EPL conditions for wastewater discharge volumes, nutrient concentrations and overall loads to the Hawkesbury-Nepean catchment. The exception was a recent non-compliance for the combined total phosphorus load from three South Creek WWTPs (St Marys, Quakers Hill and Riverstone) in 2019-2020 year. This was mostly due to an extreme weather condition in 2020 when the WWTPs were unable to treat excessive wastewater to the same standard temporarily.

Wastewater treatment upgrades are underway or planned for the majority of the Hawkesbury-Nepean catchment WWTPs to accommodate population growth. These include:

- Picton WWTP – tertiary denitrification upgrade to enhance the nutrient removal capability is in the planning phase. Expected completion is June 2023. Planning is also underway to augment the effluent management capability to service population growth. Various options are being considered including enhanced treatment and reuse. Completion is aimed for 2024
- West Camden WWTP – amplification and treatment upgrade is currently underway to accommodate population growth and enhance the level of treatment to comply with the new

nutrient licence limits which will come into effect in 2024. Expected completion is December 2023

- Penrith WWTP – planning is underway for the renewal of the bioreactors. This will improve the aeration system performance and therefore ammonia removal. Expected completion is March 2024
- Winmalee WWTP – treatment upgrade is currently underway to improve the nutrient removal capability to comply with the new nutrient licence limits which will come into effect in 2024. Expected completion is March 2022
- Richmond WWTP and North Richmond WWTP – the decommissioning of North Richmond WWTP and transfer of flow to Richmond WWTP is in the planning phase. This will enhance the nutrient removal capability to meet the revised licence discharge limits which will come into effect in 2024. Expected completion is October 2024
- St Marys WWTP – treatment upgrade to improve reliability and service growth is currently underway. The upgrade will also improve the nitrogen removal performance. Expected completion is April 2022
- Quakers Hill WWTP - treatment upgrade to improve reliability and service growth is currently underway. The upgrade will also improve the nitrogen removal performance. Expected completion is April 2022
- Riverstone WWTP – the treatment upgrade and amplification in 2019 improved the treatment level and capacity of Riverstone WWTP. Flow from Rouse Hill WWTP is planned to be transferred to Riverstone WWTP for treatment and discharge by December 2022. While this will increase the load discharged to South Creek, it will result in an overall load reduction in the Hawkesbury-Nepean system due to the higher level of treatment
- Upper South Creek Advanced Water Recycling Centre (AWRC) – a new treatment plant to service growth in the South Creek catchment is in the planning phase. The AWRC will have advanced treatment for dry weather discharge. Expected completion is April 2026
- Castle Hill WWTP – treatment upgrade to facilitate growth and improve nutrient removal performance is currently underway. Expected completion is June 2024
- Rouse Hill WWTP – investigating the interim transfer of flow from Rouse Hill WWTP to Riverstone WWTP to facilitate servicing growth (Stage 1) and allow planning and delivery for future amplification (Stage 2). Stage 1 expected completion is December 2022
- No major treatment upgrades are planned for Wallacia, West Hornsby, Hornsby Heights or Brooklyn WWTPs in the immediate future.

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1 Introduction

1.1 Background

The Hawkesbury-Nepean River is one of the longest coastal rivers in eastern Australia and its catchment covers approximately 21,400 km^2. The catchment provides a major source of drinking water for over five million people living across Sydney, the Blue Mountains and the Illawarra. It also supports a diverse range of industries including agriculture, mining, recreation and tourism. The long stretches of the river are ideal for recreational uses such as swimming, water skiing, canoeing and fishing.

The river is sustained by flows from its catchment via multiple tributaries along the river, upstream water storages which either spill over or have controlled releases for environmental flows, and regular discharges of treated wastewater from multiple wastewater treatment plants.

Historically there have been concerns and media coverage about the deteriorating water quality of the Hawkesbury-Nepean River due to algal blooms and excessive macrophyte growth (Sun Herald 1992, Sydney Morning Herald 1993, Sydney Morning Herald 1994, Sydney Morning Herald 2003, Sydney Morning Herald 2004, Industry and Investment 2009, Daily Telegraph 2016, NSW EPA 2019). In recent years, multiple government agencies, including Sydney Water, along with private stakeholders have been working collaboratively to reduce the nutrient loads and improve the water quality of the river (OEH 2009, WaterNSW 2013).

Algal blooms and excessive macrophyte growth are a direct consequence of a combination of river morphology and excess nutrients entering the river system from various diffuse and point sources. The main diffuse sources include runoff from agriculture and urban areas, while the main point sources include wastewater treatment plant discharges, agricultural waste, mining wastes, council swimming pool backwash effluent and colliery waste.

Sydney Water currently serves over 5 million people (5.41 M) with its wastewater network. The bulk of this wastewater (90%) is disposed via ocean outfalls. The remaining 10% is treated to a high standard (tertiary treated) and discharged into the Hawkesbury-Nepean River and its tributaries. Currently, seven wastewater treatment plants (WWTPs), eight water recycling plants (WRPs) and one Advanced Water Treatment Plant (St Marys AWTP) operate in the Hawkesbury-Nepean catchment. For simplicity, these are called WWTPs hereafter in this document.

In the 2019-2020 reporting year, an average of 167 megalitres/day (ML/day) of treated wastewater (including highly treated recycled water) was discharged daily into the river and its tributaries from these WWTPs (Sydney Water 2020b, 2020c). Hawkesbury City Council also operate two WWTPs near Windsor (South Windsor and McGraths Hill) that produce tertiary treated wastewater discharged directly or via a constructed wetland to South Creek.

Since the early 1990’s, Sydney Water has invested heavily in improved wastewater treatment and operational strategies to reduce the nutrient loads from its wastewater activities into the Hawkesbury-Nepean River catchment. Two recent significant investments in the catchment were the upgrade/amplification of Riverstone WWTP in 2018 and the establishment of the St Marys Advanced Water Treatment Plant (AWTP) in 2010. The AWTP takes treated wastewater from Penrith, Quakers Hill and St Marys WWTPs for further treatment using reverse osmosis following discharge of highly treated recycled water into the Hawkesbury-Nepean River via Boundary Creek. The benefit of these strategies has been a significant decrease in overall nutrient loads from Sydney Water's operational activities to the river. The strategies include improved wastewater treatment processes, production of recycled water and decommissioning of poor performing WWTPs. A previous case study on long-term trend analysis demonstrated total nitrogen and total phosphorus loads from Sydney Water's wastewater discharges to the river decreased by 76% and 94%, respectively between 1992 and 2017, whilst the population grew by 73% over the same period in the Hawkesbury-Nepean River catchment (Sydney Water 2018). Both nitrogen and phosphorus (total nitrogen, dissolved inorganic nitrogen, total phosphorus and filterable total phosphorus) concentrations significantly decreased between 1992 and 2017 at most water quality monitoring sites (13% to 72% decrease). Despite the reduced nutrient loads from WWTPs since 1992 and the reduced instream nutrient concentrations, chlorophyll-*a*, a key indicator of algal biomass, showed little change (Sydney Water 2018). The same study also revealed a short term increase in overall WWTP total nitrogen load in the latest period (2011 to 2017) in all five sub-catchments and WWTP total phosphorus loads in four sub-catchments.

Further population growth in recent years resulted in increasing inflows of wastewater to WWTPs for treatment. This reduces the available capacity of WWTPs and nutrient removal performance declines as they approach the limits of their design. This accounted for the increased nutrient concentrations, especially nitrogen, in the discharges. Two third of inland WWTPs operating in the Hawkesbury-Nepean River catchment had an increasing trend in nitrogen compounds in discharges when compared with previous nine year's results (Sydney Water 2018b). Despite the increase in nutrient concentrations in the discharge from these WWTPs, concentrations remained well within the EPL limits.

The analysis approach for the 2020 Interpretive Report is designed to assess the long-term trends in Sydney Water's WWTP nutrient loads and water quality of the Hawkesbury-Nepean River. It aims to investigate the site-specific conditions at priority sites with respect to wastewater related nutrient loads and downstream water quality especially in terms of nutrients and chlorophyll-*a*.

1.2 Purpose

A requirement of Sydney Water's Environment Protection Licences (EPLs) is to undertake an ongoing Sewage Treatment System Impact Monitoring Program (STSIMP) to identify and quantify environmental impacts associated with Sydney Water's wastewater services across our area of operations. The program aims to monitor the environment within Sydney Water's area of operations to:

- determine general trends in water quality over time
- monitor Sydney Water's performance

- determine where Sydney Water's contribution to water quality may pose a risk to environmental ecosystems and human health.

The sampling program is designed to provide a longitudinal and spatial dataset that allows the identification of statistically significant changes in water quality or ecosystem health parameters that may be related to discharges from wastewater systems.

As part of our EPL's conditions (M5.1), Sydney Water is required to produce two types of reports:

1. Annual data report: presents the latest data and data summaries from the monitoring program on a yearly basis; data trends and exceptions are also explored with limited interpretation
2. Interpretive report: compiled every four years to identify and assess the impact on water quality and ecosystem health that may be related to Sydney Water's wastewater systems.

This year's focus for the interpretive report was on the Hawkesbury-Nepean River catchment where Sydney Water's 15 inland WWTPs discharge tertiary treated wastewater into the catchment. The WWTP discharge patterns or trends over time were assessed in terms of nutrient concentrations and loads. These patterns may change over time in response to the impact of treatment plant improvements or process changes. At receiving water sites, the impact of upstream catchment concentrations and flows, any tributary flows, nutrient loads from associated WWTPs, the presence of any long-term trends within the periods defined for the WWTPs and any annual variation in nutrient concentrations were assessed.

Comprehensive statistical analysis and interpretation of the long-term datasets were conducted for all the inland WWTPs and receiving water quality data for the Hawkesbury-Nepean River and tributaries. This will improve Sydney Water's understanding on the current receiving water quality conditions, trends and potential influence of wastewater discharge on downstream water quality.

Based on the NSW Environment Authority's (EPA's) feedback on previous STSIMP data and interpretive reports, Sydney Water engaged Shimsco Consulting Pty Ltd and Tricky Solutions Pty Ltd to develop the new statistical models to interrogate the data and provide biometrical data analysis support for this year's Hawkesbury-Nepean River Interpretive Report.

A comprehensive statistical modelling approach was developed in two stages. Firstly, a suitable statistical model was developed based on the long-term monitoring data of Upper Nepean River at Sharpes Weir and West Camden WWTP. This Stage 1 pilot study was designed to identify an analysis approach, possible analysis methods, clarify problems and establish objectives/hypotheses going forward (Sydney Water 2020a). The analysis approach developed as a pilot was further refined in Stage 2 with a reduced and final version of the model. The finalised modelling approach was then applied in all four zones of the rivers (including the zone analysed in Stage 1). Altogether, data from eight WWTPs and nine water quality monitoring sites from four zones along the Hawkesbury-Nepean River were analysed and are comprehensively interpreted in this report

1.3 Aim

The overall aim of the Hawkesbury-Nepean River Interpretive Report is to understand the long-term trends in WWTP nutrient loads and the water quality of the river. The impact of short-listed or prioritised WWTPs and their influence on nutrients and chlorophyll-*a* concentrations in the Hawkesbury-Nepean River was further explored with in-depth analysis and interpretation.

More specifically the objectives of this report were to:

1. understand the long-term temporal trends in key nutrient concentrations and loads from each inland WWTP and recent performance against their respective EPL
2. understand the long-term temporal trends in receiving water quality conditions (all analytes tested and all routine monitored sites) and comparison against respective Australian and New Zealand Water Quality Guidelines for Fresh and Marine Waters (ANZG 2018) guideline values
3. select WWTPs and water quality sites for comprehensive analysis, assessment and interpretation
4. develop a suitable statistical model or data analysis method based on one WWTP to determine the impact of discharges on downstream receiving water quality (Stage 1)
5. refine and apply the statistical model development process for one site to four short-listed zones of the river with site-specific data and information (Stage 2)
6. interpret the data analysis outcomes together to understand the overall condition of the river and impact of wastewater discharges
7. use the findings from this report to inform future planning to reduce the impact of WWTP discharges.

1.4 Structure of this report

The STSIMP 2020 interpretive report is produced in two volumes:

Volume 1 STSIMP Interpretive Report 2020: this is the main volume of the 2020 Hawkesbury-Nepean River interpretive report. It reports in detail, the rationale, data analysis techniques, and assessment and interpretation of trends in WWTP nutrient loads and associated impacts on receiving water quality at four short-listed zones of the Hawkesbury-Nepean River

Volume 2 STSIMP Interpretive Report 2020 (Appendices): provides detailed supporting information, method details, charts and statistical analyses outcomes for each components of the Hawkesbury-Nepean River interpretive report 2020.

This report forms Volume 1.

2 Monitoring program and methods

2.1 Monitoring program

This study used data collected under multiple current and historical monitoring programs.

The EPLs for each WWTP and St Marys AWTP have specific monitoring requirements for discharge volume and discharge quality in terms of key nutrients, suspended solids, faecal indicator bacteria etc. A comprehensive monitoring program is in place to comply with the EPLs and routinely collect data for these components (Sydney Water 2020d).

The STSIMP is another core monitoring program which aims to measure the impact of Sydney Water's wastewater operations on the environment (Sydney Water 2010). It details monitoring activities and methods for all catchments in Sydney Water's area of operations. The STSIMP Hawkesbury-Nepean sub-program collects a range of physico-chemical parameters including nutrients, chlorophyll-*a* and algal species data (only for samples when chlorophyll-*a* is greater than 7 µg/L) from 18 monitoring sites along the river and its tributaries (Sydney Water 2020e).

The STSIMP succeeded the historic Environmental Indicators Monitoring Program (EIMP, Sydney Water 1995) which had similar broad objectives. It ran consistently for a period of 14 years from July 1994 to June 2008.

Sydney Water has also conducted multiple targeted campaign monitoring programs over the years in relation to capital work projects such as WWTP amplification or upgrades, the Replacement Flows Program and Pollution Reduction Programs (PRP).

2.2 Monitoring sites and frequency of monitoring

Fifteen WWTPs and the St Marys AWTP currently discharge into the Hawkesbury-Nepean River catchment. An additional six WWTPs discharged into the catchment in the past, but were progressively decommissioned from 1996 to 2008. The locations of these WWTPs and St Marys AWTP are shown in Figure 2-1. A complete list of current and historical WWTPs discharging into the Hawkesbury-Nepean catchment since 1995, with information on discharge locations, operating history and data availability is included Volume 2 (Appendix A: Table A-1 and Table A-2).

Treated (routine) or partially treated (bypass) wastewater discharge volumes from each WWTP are continuously monitored using *in-situ* electronic data loggers. Nutrient concentrations in the treated wastewater are measured every six days from a 24-hour composite sample collected from the discharge point. Nutrient concentrations of partially treated wastewater (bypasses) are also measured when these discharges are triggered. Additional WWTP nutrient data are also collected from non-routine monitoring, with monitoring frequencies as low as daily.

Sydney Water's water quality monitoring of the Hawkesbury-Nepean River was mostly focused on areas where Sydney Water's WWTPs discharge. Due to this targeted and cost-effective monitoring approach, there are large stretches of the river and its tributaries where monitoring does not occur. This makes evaluation of other catchment influences on river water quality more challenging.

The STSIMP monitors water quality and algae at 13 sites along the Hawkesbury-Nepean River from the upstream freshwater reaches of the Nepean River at Maldon to downstream Hawkesbury River at Leets Vale and five sites in four major tributaries (South Creek, Cattai Creek, Colo River and Berowra Creek). An additional three sites are monitored in the mainstream Nepean River and a peripheral lagoon site (Winmalee) for operational purposes. The locations of these 22 sites are shown in Figure 2-1 with shaded areas showing location of four sub-catchments short-listed for detailed analysis and interpretation. Further site details such as description, significance, data history etc are included in Volume 2 (Appendix A: Table A-3).

The current water quality monitoring frequency under the STSIMP is three-weekly. Prior to July 2008 under the EIMP, monitoring frequency was four-weekly. To avoid sampling on the same day of the week, the interval between sampling varied plus/minus four days. The monitoring frequency for the other historical or targeted programs ranged between daily and monthly.

Daily flow data (KL/day) are collected by 15 *in-situ* hydrometric monitoring stations in the Hawkesbury-Nepean River catchment. Six of these stations are currently owned and operated by WaterNSW, further details about these stations are included in Volume 2 (Appendix A: Figure A-1 and Table A-4).

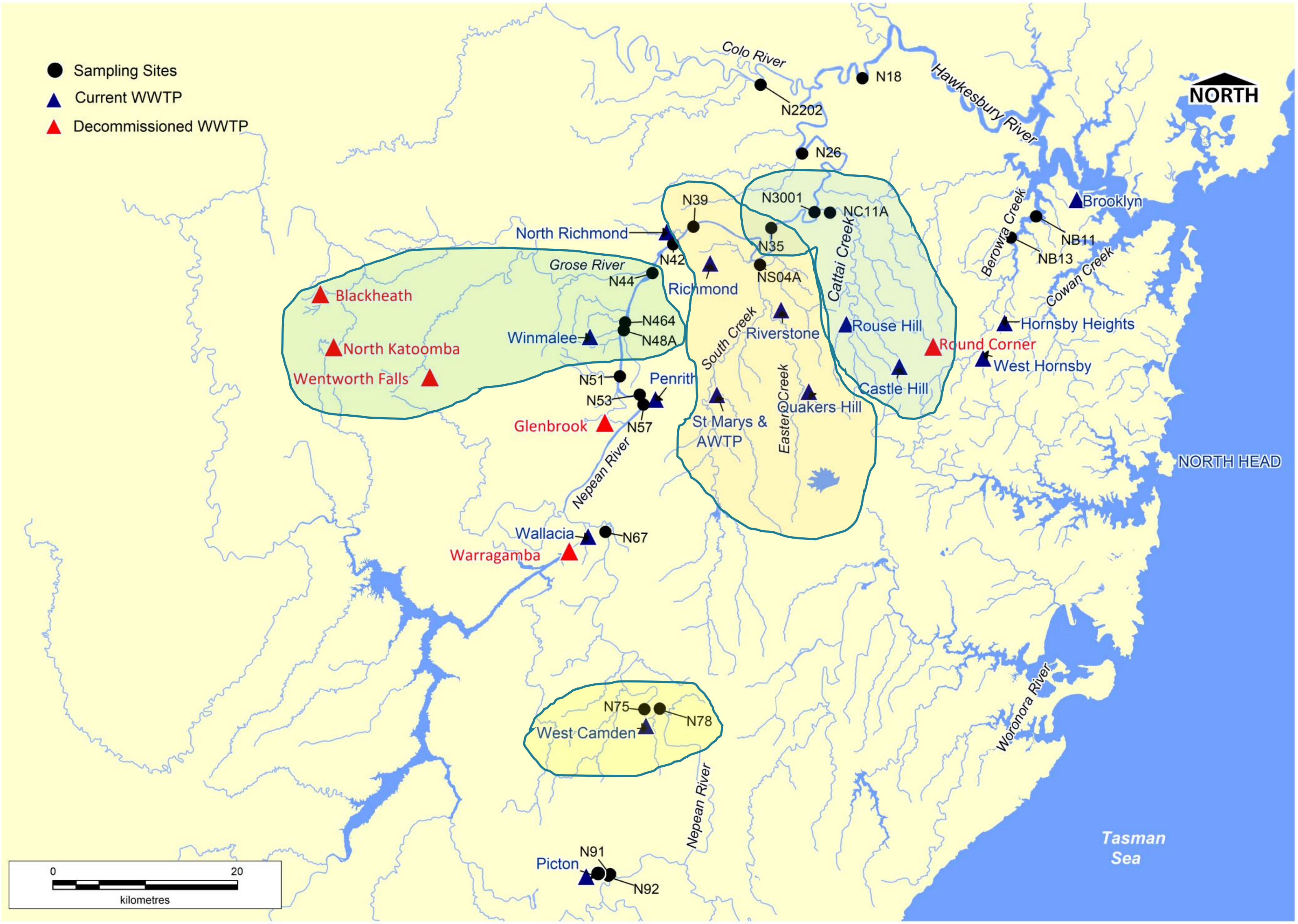

Figure 2-1 Location of Sydney Water WWTPs and key water quality monitoring sites; shaded areas are four sub-catchments short-listed for detailed analysis and interpretation

2.3 Analytes and methods of measurement

Treated wastewater from each WWTP discharge was analysed for a variety of pollutants as specified in the EPL. For this study, nutrients such as total nitrogen, dissolved available forms of nitrogen (ammonia nitrogen, oxidised nitrogen) and total phosphorus were considered as key parameters/variables. A list including the details of analytical method for these analytes are presented in Volume 2 (Appendix A: Table A-5). Only total nitrogen and total phosphorus concentrations were analysed consistently for all WWTPs throughout the period (1995-2020). There were large gaps in data for ammonia nitrogen, oxidised nitrogen and soluble reactive phosphorus.

The STSIMP collects duplicate receiving water quality samples to minimise the local variability. Depending on the waterway and local conditions, replicate samples were obtained either by one of two methods. The first method is to obtain samples approximately 100 m apart while the second method is to obtain samples from one site approximately five minutes apart. Each replicate is made up of a composite of the two samples collected, where possible, at a depth of 0.5 m below the surface. Field measurements of conductivity, turbidity, pH, dissolved oxygen, dissolved oxygen saturation and temperature are mostly taken on a single sample/location at each sampling point. Duplicate samples are analysed for a list of nutrient analytes, chlorophyll-*a* and algae (Volume 2: Appendix A, Table A-6).

Algal biovolume and species count data was not continuous as this analysis was chlorophyll-*a* dependent. Algal abundance and identification to genus level was determined when chlorophyll-*a* concentrations exceeded 7 µg/L. This is a site-specific trigger based on the Healthy Rivers Commission water quality objective for the Hawkesbury-Nepean River (HRC, 1998).

Quality control samples were also collected and analysed as part of this program. A duplicate was collected on each run and a field blank/trip blank was collected on alternate runs. That is, if a field blank was collected one month, a trip blank was collected the following month. The earlier EIMP also followed the same sampling methodology, that is, collected duplicate samples from each site for all the analytes that are monitored currently. The other non-routine programs usually collected duplicate samples from each site but were composited into a single sample for analysis.

The chemical analysis of samples was undertaken by a NATA (National Association of Testing Authorities) accredited laboratory, generally Sydney Water Laboratory Services or a suitably qualified external laboratory. Each laboratory was required to analyse a range of quality control samples (method blank, laboratory duplicates, laboratory fortified blank, surrogate etc). The number, type and frequency of these samples varied depending on the size and range of chemical analyses required.

3 Data analysis methods

3.1 General preparation of data

3.1.1 Data availability

Historical wastewater discharge volume and quality data for Sydney Water's current and decommissioned WWTPs is available from the late 1980s. However, the quality of some of the earlier data is poor, with data gaps for multiple WWTPs and water quality monitoring sites or inconsistency in monitoring sites, monitoring frequency, type of analytes or analytical methods. Based on data quality, completeness and consistency, this study used long-term wastewater and water quality data for a 25-year period from July 1995 to June 2020.

Considering the key objective of this study was to determine the influence of WWTPs nutrient loads on downstream water quality, key nutrient analytes (ammonia nitrogen, oxidised nitrogen, total nitrogen and total phosphorus) that are essential for plant growth and eutrophication were selected for the analysis. Receiving water quality data for all current routine analytes including nutrients (ammonia nitrogen, oxidised nitrogen, total nitrogen, and total phosphorus) and chlorophyll-*a* concentrations and results on physico-chemical condition (conductivity, dissolved oxygen saturation pH and turbidity) were considered for the analysis.

Algal counts or biovolume data for these sites were not considered for further analysis due to limited/patchy data. Algal counts or biovolume were only measured when chlorophyll-*a* exceeded a threshold. Soluble reactive phosphorus was not monitored at receiving water sites and very limited data was available for WWTPs. Consistent filterable total phosphorus data was available for receiving water sites but not monitored for WWTPs. Data for both of these analytes were not considered for further analysis.

3.1.2 Sampling and analytical methods

The sampling and analytical methods need to be consistent and reliable over the time-period so that actual trends in the data can be determined. The sampling techniques and analytical methods used for wastewater volume and quality data were similar throughout the 25-year period. In earlier years, wastewater quality was determined as ammonia nitrogen, oxidised nitrogen and Total Kjeldahl Nitrogen (TKN). Total nitrogen concentrations were derived from this data by adding TKN and oxidised nitrogen concentrations (pre 2002 period).

The exact sampling locations for the following four receiving water quality sites were not consistent throughout the monitoring period:

1. South Creek at Fitzroy Bridge (NS04): from July 2011 the site was moved to about 20 m upstream at Fitzroy pedestrian bridge (NS04A)
2. Cattai Creek site (NC11): from July 2011 the site was moved from Cattai Road to a new location 100 metres downstream (NC11A).

3. Nepean River at Smith Road (N48) was moved 500 metres downstream (N48A) from October 2017
4. Stonequarry Creek upstream of Picton WWTP discharges (N911A): from September 2019, the site was moved to about 50 metres further upstream (N911B).

Locations for the first three sites (NS04, NC11A and N48) were reviewed following safety and accessibility concerns. For each new site, duplicate datasets were collected for comparison for up to the first five sampling occasions with results indicating no statistical differences.

The location of the fourth site (N911A) was reviewed in September 2019 due to possible contamination from the commencement of the Emergency Operation Protocol (EOP) discharge regime during low flow (Sydney Water 2020f). The study confirmed contamination of discharges during low flow conditions or dry weather at the site immediately upstream of discharge (N911A). Historically, Picton WWTP only discharged during high creek flow conditions (>8 ML/day) when there were no chances of contamination.

For consistency, the current site codes (NS04A, NC11A, N48A and N911B) were used in all graphics and tables for this report.

Until December 1995, chlorophyll-*a* samples were analysed by the sonication extraction method. Since then, the grinding extraction method has been employed. The relationship between sonication and grinding extraction was previously established and documented (AWT 1997) and based on this relationship, a correction factor of 1.18 times was applied to July to December 1995 chlorophyll-*a* data to make this dataset compatible for long-term analysis.

3.1.3 Duplicate data

Duplicate values are rare for the wastewater quality data, however where present, were averaged. Receiving water quality samples were analysed in duplicate by the two core monitoring programs (EIMP and STSIMP). If additional samples were collected on the same day as part of a separate monitoring program, the raw data was averaged by date and site to derive a representative value for the sampling date.

3.1.4 Censored data

Some data were reported as being less than the detection limit, for example chlorophyll-*a* as <0.2 μg/L, ammonia nitrogen, oxidised nitrogen and total nitrogen as <0.01 mg/L, total phosphorus as <0.002 mg/L. All such data points were converted to half of the detection limit for analysis purpose. Data points less than the detection limit were rare except for ammonia nitrogen concentrations, where about 10% of the total data points were less than the detection limit.

Statistical analysis was also carried out on dissolved inorganic nitrogen (DIN) data, a total product of ammonia nitrogen and oxidised nitrogen. There were about 2% dissolved inorganic nitrogen data points, when both ammonia and oxidised nitrogen were less than the detection limit. Therefore, this method of treating the Less Than Detection Limit data is not expected to influence the analysis outcomes.

3.1.5 Data transformation

All WWTP analytes (discharge volume and concentrations) and all water quality variables except dissolved oxygen saturation and pH were log-transformed ($\log_{10}$) prior to analysis.

This is a common approach for values that can only take a positive value and are expected to have a right skewed distribution, regardless of what the sample or error distribution shows (assuming the transformed data's errors are sufficiently normal). This is because the log transformation usually gives errors that better meet the assumption of normality and constant variance required for the linear modelling approach taken for the statistical analysis without the need to specify other variance distributions. It also allows for the population geometric mean to be estimated and ensures that the lower limit of any confidence intervals estimated is positive.

The geometric mean is the natural equivalent to the median when the underlying distribution of the outcome is positively skewed (ie approximately log-normal) and is a more appropriate measure of central tendency for skewed data than the mean. The way to estimate geometric means is to log transform the data, undertake the analyses on the transformed scale and then back-transform the estimated means to become the geometric means. If a data transformation is applied, the log transformation is the only one that results in interpretable differences between means. For example, the absolute difference between two means on the log scale becomes the relative difference on the back-transformed or original scale. For the analyses where flow, load and upstream concentration were added as explanatory variables of interest, the log transformation of these explanatory variables allows a linear relationship on the transformed scale to be interpreted as a percentage change on the natural scale allowing for the possibility that the natural relationship is non-linear. For example, as flow increases, the concentration of the outcome may decrease or increase in an exponential-type fashion.

Rather than transform a variable at some sites and not others, the aim was to apply a consistent approach that works reasonably well for all similar datasets (ie the same variable at all sites) since they are each a sample from the larger population, and then results can be interpreted in the same fashion regardless of site (Wymer 2007; Helsel and Hirsch 1992).

No values of zero were recorded in the data, hence no adjustments were required for the log transformation. Values below the detection limit were replaced with half the detection limit and log transformed accordingly. The possible over-transformation of these small results was assessed during the review of the model fit via residual plots.

Observed data and GAM trends are presented on plots using the natural scale of measurement to allow easy visual identification of outlying values and general trends. Observed data and more detailed statistical model results for the analyses within each of the four representative zones or catchments of interest (ie Nepean River at Sharpes Weir, Nepean River at Yarramundi, Hawkesbury River at Wilberforce and Hawkesbury River at Cattai SRA) are presented in plots using a logarithmic scale to improve the visual identification of trends and differences between periods identified at the analysis level.

3.1.6 Derived variables

Dissolved inorganic nitrogen

Considering the importance of available nitrogen to plant (algae and macrophyte) growth, an additional variable, dissolved inorganic nitrogen (DIN) which is the sum of ammonia nitrogen and oxidised nitrogen concentrations was derived.

WWTP nutrient loads

Nutrient loads for each WWTP were calculated by applying any of the following three WWTP specific scenarios:

Category 1: No bypass discharges

For the majority of the WWTPs there were no bypass discharges. Discharge volume/flow and characteristics for these WWTPs were determined at the same location at the final outlet before discharge. The final discharge flow data for these WWTPs was merged with the discharge quality data that includes key nutrient analytes measured at six day intervals. The dates without a discharge concentration data were discarded.

The nutrient load at six days interval at each WWTP was then estimated using the following formula:

Nutrient load (kg/day) = [(c*d)/1000)]

where: c = concentration of nutrients (mg/L)

d = total discharge volume (KL/day)

This approach was taken for Warragamba, Wallacia, Glenbrook, Penrith, Blackheath, North Katoomba, Wentworth Falls, North Richmond, Richmond, Quakers Hill, Riverstone, Round Corner, Hornsby Heights and Brooklyn WWTPs.

Category 2: Only bypass discharges

No routine discharges, bypass discharge volume and characteristics at the final outlet before discharge. This approach was taken for Picton WWTP. The nutrient load calculation protocol is the same as above.

Category 3: Partially treated volume (bypass) mixed with fully routine treated volume before final discharge

There are cases when fully treated routine discharge volume and partial treated bypass discharge volume (if any) are measured separately before mixing at a final discharge quality monitoring point. In those cases, routine discharge volume was added to the bypass discharge volume to derive the final discharge volume. Nutrient concentrations are measured at the final destination before release. Nutrient loads for these WWTPs were determined using the above formula with the combined discharge volume and nutrient concentration data.

This approach was taken for West Camden and Castle Hill WWTPs.

Category 3: Bypass volume and concentrations measured separately

These are exceptions where the bypass discharge outlet is different from the routine discharge outlet (Winmalee, St Marys, Rouse Hill and West Hornsby WWTPs) and discharge quality is monitored at both outlets.

There are also cases of bypass discharge volume data with no corresponding concentration data monitored for these discharges. These missing concentration data for bypass discharges were derived using any of the following approaches:

1. use yearly average concentration of bypass for those dates
2. use an emission factor if no bypass concentrations were determined in a financial year. The NSW EPA's predetermined concentrations for load calculation: St Marys total nitrogen 13 mg/L and total phosphorus 1.9 mg/L. This approach was taken for St Marys WWTP.
3. use average concentration data of bypass and preceding routine discharge concentration.

Nutrient loads for the bypass discharges were calculated separately for these WWTPs and finally added together to get the combined load for the WWTP.

Further details of the load equation for each WWTP are provided in Volume 2 (Appendix E: Table E-3).

3.2 Temporal trends in WWTP nutrients and receiving water quality

3.2.1 Temporal trends in WWTP nutrient concentrations and loads, and EPL performance

To understand the generalised long-term trends and current performance of discharge from all 15 WWTPs and one AWTP the following tasks were carried out:

- determine the data availability for each WWTP and analyte
- identify any trends and step changes by fitting a Generalised Additive Model (GAM) with smoothing functions on nutrient (total nitrogen, dissolved inorganic nitrogen and total phosphorus) concentrations and loads from each individual WWTP and plot with the observed data
- determine the performance of each WWTP with respect to EPL limits by visual inspection.

3.2.2 Temporal trends in receiving water quality and comparison with the guidelines

To understand the generalised long-term trends in receiving water quality at 22 sites of the river and tributaries in comparison with guidelines, the following tasks were carried out:

- determine the data availability for each site and analyte/variable

- identify any trend or step changes by fitting a Generalised Additive Model (GAM) with smoothing function on nutrients (ammonia nitrogen, oxidised nitrogen, dissolved inorganic nitrogen, total nitrogen and total phosphorus) and chlorophyll-*a* concentrations and other physico-chemical analyte concentrations/levels at each site and plot with the observed data
- assess the receiving water quality at each site with respect to ANZG default level by visual inspection.

3.2.3 Selection of analytes/variables

Based on consistency, six key nutrient analytes/variables were selected for exploring the general trend for each WWTP:

- dissolved inorganic nitrogen (DIN) concentration
- DIN load
- total nitrogen (TN) concentration
- TN load
- total phosphorus (TP) concentration and
- TP load.

Ten key analytes/variables were selected to determine the general trend at each receiving water quality site of the Hawkesbury-Nepean River and tributaries:

- ammonia nitrogen
- oxidised nitrogen
- DIN
- TN
- TP
- Chl-*a* (chlorophyll-*a*)
- conductivity
- DO Sat (dissolved oxygen saturation)
- pH and
- turbidity.

3.2.4 Trend plots

All nutrient load and concentration measures were $\log_{10}$ transformed prior to analysis, a common approach for values that can only take a positive value and are expected to have a right skew (See Section 3.1.5 for more details).

Long-term trend plots were drawn for each of the selected variables for each WWTP and receiving water quality monitoring site that included:

- data
- a fitted GAM smoothing function to assist in identifying step changes and other trends in the series
- horizontal reference lines at the EPL limits for each WWTP or ANZG default level for each water quality monitoring site.

A generalised additive model (GAM) approach extends a parametric general linear model (GLM) by including cubic splines that can identify changes within a series without formally modelling them. The default *mgcv* function in the *ggplot2* R package was used to fit the GAM smoother using the REML (restricted maximum likelihood) method with the default spline basis defined by a modest size set of knots spread evenly across the quantiles of time (Wood 2011):

Formula = y ~ s(x),

Where:

- y = outcome
- x =date
- s(x) = spline across x

Long-term trend plots on nutrient (dissolved inorganic nitrogen, total nitrogen and total phosphorus) concentrations and loads for all 15 current WWTPs and one AWTP are provided in Volume 2 (Appendix B).

3.3 Selection of WWTPs and water quality sites

3.3.1 Approach

The approach for selecting the WWTPs, water quality sites and, analytes for comprehensive data analysis, assessment, and reporting was based on one or more of the following key conditions:

- consistent data collection
- increasing or deteriorating trends:
    - increasing or deteriorating recent trends observed in the long-term temporal GAM plots (Volume 2: Appendix B and C)
    - statistically significant increasing/deteriorating trend in the latest year, 2019-2020 data was compared statistically with the previous nine year’s data (Sydney Water 2020b)
- EPL exceedances for nutrient concentrations or loads in WWTP discharges
- consistent high concentrations of nutrients in WWTP discharges (even if below the EPL licence limit)

- ANZG 2018 default level exceedances
    - consistent guideline exceedance
    - 2019-2020 median value exceeded the ANZG default level
- water quality concentrations consistently exceeding the ANZG default level or 2019-2020 median value exceeded the default level
- represents a zone of the river subject to future change or other special significance (eg impact by growth areas)
- priority analytes associated with nutrient enrichment ie eutrophication, algal bloom or macrophyte infestations.

Long-term trend plots of nutrient concentrations and loads (dissolved inorganic nitrogen, total nitrogen and total phosphorus) from all current 15 WWTPs and St Marys AWTP are provided in Volume 2 (Appendix B).

Long-term trend plots of nutrients (ammonia nitrogen, oxidised nitrogen, dissolved inorganic nitrogen, total nitrogen and total phosphorus) and chlorophyll-*a* concentrations and other physico-chemical analyte (conductivity, dissolved oxygen saturation, pH and turbidity) levels from all water quality monitoring sites are provided in Volume 2 (Appendix C).

3.3.2 Selection of final WWTPs/sites and analytes

WWTPs

The EPL limits for each individual WWTP and 2019-2020 performance is included in Volume 2 (Appendix D: Table D-1). The overall performance of each WWTP and analytes against some of the key selection criteria (Section 3.3.1) is summarised in Table 3-1.

Eight WWTPs were chosen for comprehensive data analysis, namely West Camden, Winmalee, Richmond, St Marys, Quakers Hill, Riverstone, Castle Hill and Rouse Hill. While Quakers Hill and Riverstone WWTPs are performing well, they are included in the final list as important components of the larger South Creek assessment.

Five WWTPs were excluded from detailed analysis despite poor performance against some of the assessment criteria:

- Picton WWTP is currently being assessed separately as a part of an Environmental Impact Statement (EIS) for a Licence variation application
- Wallacia and Hornsby Heights WWTPs were excluded because of no suitable downstream water quality site for a comprehensive analysis and assessment
- Penrith WWTP was excluded due to the comparatively small discharge volume compared to the recycled water from the St Marys AWTP, and the good water quality at the downstream site (compared to other sites)
- North Richmond WWTP has a small discharge volume and load.

The analysis for West Camden WWTP in Stage 1 included both nutrient concentrations and nutrient loads. Nutrient concentrations consistently showed the same trend as load results but to a lesser degree. As such it was agreed to focus on nutrient load variables only for the remaining WWTP analysis.

Table 3-1 WWTP performance and priority group

WWTP	Ammonia	DIN conc	DIN load	TN conc	TN load	TP conc	TP load	Comments
Picton	2	1	1	1, 2	3	0	0	Subject to separate assessment for the Picton EIS
West Camden*	0	0	0	1, 2	1	0	0	Selected for complete analysis
Wallacia	0	1	1	1, 2	1	1, 2	1	No suitable downstream site for comparison (N57 is influenced by other inflows)
Penrith	0	0	0	1, 2	0	0	0	Highly treated recycled water is discharged from this location
Winmalee*	2	1	1	1, 2	0	0	0	Selected for complete analysis
North Richmond	2	0	0	2	0	1, 2	1	Small WWTP discharge volume (0.9 ML/day)
Richmond*	0	0	0	0	0	2	0	Small discharge volume (2.2 ML/day). Part of the South Creek analysis
St Marys*	2	0	0	1, 2	0	0	0	Selected for complete analysis. Part of South Creek catchment/growth area
Quakers Hill*	0	0	0	0	0	0	0	Selected for complete analysis. Part of South Creek catchment/growth area
Riverstone*	0	0	0	0	0	0	0	Selected for complete analysis. Part of South Creek catchment/growth area
Castle Hill*	0	4	0	2, 4	0	0	0	Selected for complete analysis
Rouse Hill*	0	1	1	1, 2	1	0	0	Selected for complete analysis
Hornsby Heights	0	1	1	1, 2	1	1	0	No suitable upstream downstream sites for comparison
West Hornsby	0	0	0	0	0	0	0	No suitable upstream downstream sites for comparison
Brooklyn	0	0	0	0	0	0	0	No exceedances or elevated trends

*	Selected for full comprehensive analysis
0	No negative trends/exceedances
1	Increasing/deteriorating GAM trend in recent years
2	Significant deteriorating trend in 2019-2020 data report
3	Recent running median or other values above EPL limits (concentrations or load)
4	Consistently high concentration

Water quality sites

The 50th percentile value for the 2019-2020 year for each site and analyte were compared against the site-specific guideline (Volume 2: Appendix D, Table D-2). The performance of each receiving water quality site and analytes based on all selection criteria (Section 3.3.1) is summarised in Table 3-2.

Water quality data from nine sites from the four zones of the Hawkesbury-Nepean River were considered relevant for a complete assessment on the short-listed WWTPs. These locations were within the major EPA zones of the river (ie Yarramundi subzone 1 and subzone 2; Sackville subzone 1, subzone 2 and subzone 3) and subject to impact by growth areas (eg South Creek catchment). The Berowra subzone has not been included as there is no suitable upstream downstream site-pair for comparison.

Prioritised WWTPs and water quality sites

The final short-listed WWTPs, water quality sites and analytes for detailed analyses are:

Nepean River at Sharpes Weir – West Camden WWTP (Stage 1 pilot study zone)

- West Camden WWTP
- Water quality sites:
  - N75 – Sharpes Weir (downstream of West Camden WWTP)
  - N78 – Nepean River at Macquarie Grove Road (upstream of West Camden WWTP)

Nepean River at Yarramundi – Winmalee WWTP

- Winmalee WWTP (includes Blackheath, North Katoomba and Wentworth Falls WWTPs decommissioned and transferred to Winmalee)
- Water quality sites:
  - N44 – Nepean River at Yarramundi (downstream of Winmalee WWTP)
  - N48A – Nepean River at Smith Road (upstream of Winmalee WWTP)

Hawkesbury River at Wilberforce – South Creek WWTPs (St Marys, Quakers Hill and Riverstone) and Richmond WWTP

- South Creek WWTPs (St Mary's, Quakers Hill and Riverstone) including upstream Richmond WWTP
- Water quality sites:
  - N35 – Hawkesbury River at Wilberforce (downstream of South Creek inflow and WWTPs)
  - N39 – Hawkesbury River at Freemans Reach (upstream of South Creek inflow and WWTPs)

- NS04A – Lower South Creek at Fitzroy Bridge

Hawkesbury River at Cattai SRA – Cattai Creek WWTPs (Castle Hill and Rouse Hill WWTPS)

- Cattai Creek WWTPs (Rouse Hill and Castle Hill) including decommissioned Round Corner WWTP (decommissioned and transferred to Castle Hill WWTP)
- Water quality sites:
  - N3001 - Hawkesbury River off Cattai State Recreation Area (downstream of Cattai Creek inflow and WWTPs)
  - N35 – Hawkesbury River at Wilberforce (upstream of Cattai Creek inflow and WWTPs)
  - NC11A - Lower Cattai Creek at Cattai Ridge Road

Based on data availability and relationship to eutrophication, three nutrient load variables (total nitrogen, dissolved inorganic nitrogen and total phosphorus) were chosen for in-depth statistical data analysis.

Four key water quality variables were chosen for in-depth statistical analysis, namely total nitrogen, dissolved inorganic nitrogen, total phosphorus and chlorophyll-*a*.

Table 3-2 Water quality site performance and priority sites

Site	Associated WWTP	Ammonia nitrogen	Oxidised nitrogen	DIN	TN	TP	Chl-a	Conductivity	DO Sat (%)	pH	Turbidity
N92	u/s Picton	0	1, 2, 3	1	1, 2, 3	0	0	1, 2	0	1, 2	0
N91	d/s Picton	1	1, 3	1	1, 3	0	0	1	0	1	0
N78*	u/s West Camden	0	0	0	0	0	3	0	0	0	0
N75*	d/s West Camden	1, 2, 3	1, 2, 3	1	1, 2, 3	0	3	1, 2	0	0	0
N67	u/s Wallacia	0	1, 2, 3	1	1, 2, 3	0	3	1, 2	0	0	0
N57	u/s Penrith	1, 2	1, 2, 3	1	1, 2, 3	0	3	1, 2	2	0	0
N53	d/s Penrith	1	1, 3	1	1	0	3	0	0	0	0
N51	d/s Penrith	1, 2	1, 2, 3	1	1, 2, 3	0	3	2	0	0	1
N48A*	u/s Winmalee	2, 3	1, 2, 3	1	1, 2, 3	0	3	0	0	0	0
N464	d/s Winmalee (lagoon)	2	1, 3	1	1, 3	3	3	0	0	0	0
N44*	d/s Winmalee, u/s North Richmond	1, 2, 3	1, 2, 3	1	1, 2, 3	0	3	2	0	0	0
N42	d/s North Richmond	0	1, 2, 3	1	1, 2, 3	0	3	2	2	0	0
N39*	u/s South Creek catchment	1, 2	1, 2, 3	1	1, 2, 3	0	3	2	0	0	0
NS04A*	South Creek lower tributary	3	3	0	3	3	3	0	3	0	0
N35*	d/s South Creek catchment u/s Cattai Creek catchment	3	1, 2, 3	1	1, 2, 3	3	3	2	0	0	0
NC11A*	Cattai Creek lower tributary	1, 3	1, 3	1	1, 3	3	3	0	3	0	0
N3001*	d/s Cattai Creek catchment	0	2, 3	0	1, 2, 3	3	3	2	0	0	0
N26	d/s Cattai Creek catchment	1, 2	1,2, 3	1	1, 2, 3	3	3	1, 2	0	2	0
N2202	Lower Colo River	1, 2	1, 2	1	1, 2	1	0, 2	1, 2	0	0	0
N18	Lower Hawkesbury River	0	1, 3	1	1, 3	3	3	2	0	0	0

Site	Associated WWTP	Ammonia nitrogen	Oxidised nitrogen	DIN	TN	TP	Chl-*a*	Conductivity	DO Sat (%)	pH	Turbidity
NB13	Berowra estuary	0	3	0	3	0	3	0	0	0	0
NB11	Berowra estuary	0	0	0	3	2	3	0	0	0	0

*	Selected for full comprehensive analysis
0	No negative trends/exceedances
1	Increasing or deteriorating (DO Sat trend) GAM trend in recent years
2	Significant deteriorating trend in 2019-2020 data report
3	Recent running median above ANZG default levels

3.4 Statistical analysis – model building approach

3.4.1 Overview

The overall aim of the statistical model building approach for the short-listed inland WWTPs and receiving water sites (Section 3.3) was to fit models to help explain the pattern of the outcome over time, taking into account seasonal effects, upstream impacts and intervention effects from the relevant WWTP(s). This includes differences between the geometric means of each period and temporal trends within each period defined by the interventions.

The modelling approach was undertaken for inference rather than prediction purposes. Modelling for inference assists in understanding the data series eg how outputs (nutrient loads) from a WWTP and river/creek flow influence nutrients and chlorophyll-*a* concentration at the receiving water site. Models for inference are built by determining models with both deterministic and stochastic components that approximate the data series using all data in the series, validating this model using residual analysis and/or goodness of fit tests and then using the features or terms included in this model to understand the data series (Hyndman and Athanasopoulos 2018; Derwin *et al* 2020).

3.4.2 Data categorisation

Step-trends or two separate trends are suitable when data collected before a specific time is clearly from a distinctly different population than the data collected after that time. So, it is more appropriate to use this approach when there is a known event that has occurred at a specific time and is likely to have resulted in a significant change in water quality (Hirsch *et al* 1991). In this situation, the data should be divided into 'pre' and 'post' periods at the time of this known event.

All data were categorised into time periods based on WWTP upgrades or any other distinct process change that may have resulted in a significant change in both the discharge and receiving water quality. Categorisation using the key intervention dates ie WWTP upgrade completion or process change, formed the basis of nutrient-specific time periods.

For example, two intervention dates were considered for total nitrogen and dissolved inorganic nitrogen for the West Camden WWTP and downstream receiving water site:

- nitrogen treatment upgrade (October 2008)
- a process change that resulted in increases in nitrogen concentrations from January 2015

As such, total nitrogen and dissolved inorganic nitrogen was categorised into three periods:

- period 1: date < 3 Oct 2008
- period 2: date ≥ 3 Oct 2008 and < 6 Jan 2015
- period 3: date ≥ 6 Jan 2015

One intervention date was considered for total phosphorus.

- West Camden WWTP phosphorus treatment upgrade (March 2009)

Hence, total phosphorus data of West Camden WWTP and downstream receiving water sites was categorised into two periods based on the above intervention date:

- period 1: date < 1 Mar 2009
- period 2: date ≥ 1 Mar 2009

Data from other WWTPs were categorised into time periods from one to five based on WWTP decommissioning and consolidation, upgrade/amplification or any other distinct process change that may have resulted in a significant change in both the discharge and receiving water quality. Further details about the data categorisation of all WWTPs are included in Volume 2 (Appendix E: Table E-1).

Receiving water quality data for the selected sites were also categorised in line with some of these major changes that may have potentially influenced downstream receiving water quality (Volume 2, Appendix E: Table E-2). Dates separating these major intervention periods along with some other minor events/changes are considered for adding as reference lines in plots.

3.4.3 Derived variables

For analysis purposes, the following derived variables were created in addition to those described in Section 3.1.6.

Daily nutrient loads

Daily nutrient load at each WWTP was estimated to provide loads that could be associated with each river site sampling date. As wastewater nutrient quality was only measured at six-day intervals, the 6th day nutrient concentration was used to patch the preceding five days data to provide relevant nutrient loads for the corresponding water quality data. For example, if discharge concentration was estimated on January 1 and then January 7, concentration for January 2 to 6 is assumed to be that of January 7.

The daily nutrient load at each WWTP was estimated using formula as specified in Section 3.1.6.

Composite nutrient loads

Three Blue-Mountains WWTPs (Blackheath, North Katoomba and Wentworth Falls) were decommissioned and transferred to Winmalee between 1996 to 2008. For a combined nutrient load from Winmalee WWTP, data for these decommissioned WWTPs were summed together by sampling date. Similarly, the load from Castle Hill WWTP included data for Round Corner WWTP that was decommissioned and transferred to Castle Hill in 2000.

Lag nutrient loads

Lag variables were created for a more appropriate estimation of nutrient load impact on downstream receiving water quality. For the two upstream Nepean River models, no lag was applied to the nutrient load variables as it was considered the receiving water site and relevant WWTP were in close proximity eg nutrient load of West Camden WWTP would reach the downstream receiving water site at Sharper Weir Nepean River within a couple of hours. However, a lag of one day was applied to WWTP nutrient loads in the two downstream

Hawkesbury River receiving water models as it was assumed that it could take a day for nutrients from West Camden WWTP to reach these downstream receiving water sites.

Further detail on nutrient load lag for each WWTP are provided in Volume 2 (Appendix E: Table E-4).

River and Creek flow

The analysis of the Nepean River at Sharpes Weir (N75) required river flow values from Matahil Creek and the Nepean River at Camden Weir. There were periods of time across both sets of flow data where there were no records. A series of GAM smoothers were fitted, and missing data imputed with the predicted values from the corresponding GAM.

There were fewer missing records for all other flow gauging stations used to estimate flow at all other receiving water sites. Where they did occur, they have been imputed with the predicted value from a single GAM fitted to the observed series.

Composite flow estimates for the water quality sites were derived considering both the gauged river flow volume and any contributing WWTP discharge or bypass flow volumes. The length of time the water may take to move from the flow gauge or WWTP to the water quality monitoring site was also considered by including lag variables. Lag variables for river flow for one day prior to sampling date were created for use as explanatory variables in models

The details on composite flow volume estimates for all receiving water sites are provided in Volume 2 (Appendix E: Table E-5).

Seasonal, linear and quadratic trend variables

Seasonal trends

Fourier transforms using harmonic functions were used to convert the day of the year from the time domain to a frequency domain to model the cyclical or annual seasonal trends within each year. Each day within a year is mapped to the corresponding point within a 12-month cycle. This approach to fitting cyclical patterns is used in timeseries modelling approaches such as ARIMA (Auto Regressive Integrated Moving Average) models that rely on equally spaced records over time. However, any point within the cycle can be assigned a value in the appropriate domain. The smoothness of the seasonal trend can be controlled by the number of Fourier sine and cosine pairs with a smoother pattern for a smaller number of pairs (Hyndman and Athanasopoulos 2018; Derwin *et al* 2020).

Further details on Fourier transform and example plots are included in Volume 2 (Appendix E, Figure E-1).

Linear and quadratic trends

Linear and quadratic terms were derived for each period defined for the analysis. Period definitions are included in Volume 2 (Appendix E: Table E-1 and Table E-2).

These are fit at the day scale by deriving a different day variable for each period. A segmented (hockey stick) analysis approach is taken since this allows each period to be fitted independently ie each period can or cannot have its own linear and/or quadratic trend, or nothing at all. For example, for Period 1, it will be the number of days since the start of the data series up to the date of the first WWTP process change and 0 thereafter. For Period 2 it will be 0 prior to the first WWTP process change, then the number of days since the process change up to the next process change and 0 thereafter. Quadratic trend terms will be derived by taking this day variable and squaring it.

For example, at West Camden WWTP, there were two intervention dates modelled for total nitrogen: nitrogen upgrade completed on 30 October 2008 and a treatment process change that appeared to result in increases in nitrogen from 6 January 2015. A variable was created to identify which period each sampling date occurred in:

$$Period = \begin{cases} 1\ if\ date < 3Oct2008 \\ 2\ if\ date \geq 3Oct2008\ and < 6Jan2015 \\ 3\ if\ date \geq 6Jan2015 \end{cases}$$

Linear trend measures were then derived as:

$$Period\ 1\ linear\ trend = date - 30June1995\ if\ date < 30Oct2008$$

$$Period\ 2\ linear\ trend \begin{cases} 0\ if\ date < 3Oct2008 \\ date - 3Oct2008 + 1\ if\ date \geq 3Oct2008\ and < 6Jan2015 \\ 0\ if\ date\ \geq 6Jan2015 \end{cases}$$

$$Period\ 3\ linear\ trend = \begin{cases} 0\ if\ date < 6Jan2015 \\ date - 6Jan2015 + 1\ if\ date \geq 6Jan2015 \end{cases}$$

This is different to the ANCOVA (Analysis of Covariance) style parameterisation where a single day variable would be defined across the entire time series (ie ignoring periods) to fit an overall linear trend and a Period by Linear Trend interaction term fitted allowing the trend to differ within each period. Similarly, for a quadratic trend, a Period by Quadratic Trend interaction term would be fitted to allow the curvature to differ within each period. The downside of this being that the terms fitted to each period can't be controlled independently ie either they all have a linear trend or none do and they all have a quadratic trend or none do. To answer the specified hypotheses, control over which trends were included in the analyses within each period was required resulting in an approach where the parameterisation allows the trends to be fitted independently. Which is why the ANCOVA method was not used.

3.4.4 Objectives and hypotheses tested

The data analysis approach is designed to serve three key purposes each with underlying objectives and one or more hypotheses tested:

Individual wastewater treatment plants

- Determine if nutrient loads (TN, DIN and TP) differ between time periods defined by upgrades and other changes to treatment processes at the treatment plant
  - Hypothesis: Do the geometric means of nutrient loads differ between the periods?

- Determine if there are long-term trends in nutrient loads within each period and, if so, the shape of these trends (ie increasing or decreasing linear or curvilinear trends).
    - Hypothesis: Do the linear and quadratic trends in nutrient load differ between periods?

Receiving water sites

- Determine if the nutrients (TN, DIN and TP) and Chl-*a* concentrations at a downstream receiving water site differ between time periods defined by upgrades and other changes to processes at the relevant treatment plant
    - Hypothesis: Do the geometric means of nutrients and Chl-*a* concentrations differ between the periods?
- Determine if there is a relationship between nutrient and Chl-*a* concentrations at the main river site and nutrient load from each associated WWTP of interest
    - Hypothesis: Is there a relationship between main river site nutrient and Chl-*a* concentration and nutrient loads of relevant WWTPs?
- Determine if there is a relationship between the upstream catchment on downstream water quality. This impact is investigated in two parts: the relationship between upstream (i) nutrient concentrations and (ii) creek/river flow on nutrients (TN, DIN, TP) and Chl-*a* concentrations at the mainstream river site.
    - Hypothesis 1: Is there a relationship between main river site nutrient/Chl-*a* concentration and nutrient concentrations at the upstream site? Note: not tested for upper Nepean River zone as there was not enough data for the upstream site
    - Hypothesis 2: Is there a relationship between main river site nutrient and Chl-*a* concentration and its flow?
- Determine if there are long-term trends in nutrients and Chl-*a* concentrations within each period and, if so, the shape of these trends (ie increasing or decreasing linear or curvilinear trends)
    - Hypothesis: Do the linear and quadratic trends in nutrient and Chl-*a* concentrations at the main river site differ between periods?

Downstream - upstream receiving water sites

- Determine if the nutrients (TN, DIN and TP) and Chl-*a* concentrations differ between sites in each period
    - Hypothesis: Do the geometric mean of nutrients and Chl-*a* concentrations differ between the periods?
- Determine if the relationship between the site-specific river/creek flow on nutrients (TN, DIN, TP) and Chl-*a* concentrations differ between the downstream and upstream river site

- Hypothesis: Does the relationship between river/creek site nutrient and Chl-*a* concentration and its flow differ between downstream and upstream site?

- Determine if the long-term trends within each period differ between sites and, if so, the relative difference between the trends
  - Hypothesis: Do the linear and quadratic trends in nutrient concentrations within each period differ between sites?

3.4.5 Model building approach

All analyses were undertaken using R statistical software (R version 4.0.4, 2015).

For each WWTP, the aim was to understand how the nutrient loads (TN, DIN and TP) are changing over time (trends) and whether these trends differ with changes to treatment plant processes before or after adjusting for seasonal trends.

For the receiving water sites, the aim was to understand how the magnitude of different sources of river flow and nutrients affect the concentration (TN, DIN, TP and Chl-*a*) at the site before or after adjusting for seasonal trends and whether the relationship differed in response to process changes at upstream WWTPs.

For each analysis, there were two phases. In the first phase, exploratory data analyses were undertaken to assist in identifying any possible challenges with the modelling process. This step includes but is not limited to:

- the presence and size of any periods with missing data
- number of records within each period and year within period over the data series
- any correlation between possible terms within the model ie multicollinearity
- checking for outliers and data entry mistakes
- estimating the geometric means for each period based on the data.

In the second phase, a fixed effects general linear modelling approach was undertaken to consciously determine whether the effects of linear and quadratic trends within each period, the effects of flow and nutrient loads, the seasonal patterns each year and the differences between sites in each downstream/upstream set should remain in the final model.

Multiple steps were undertaken for each outcome of interest (nutrient load at WWTPs or nutrient and chlorophyll-*a* concentration at receiving water sites). The model reduction process was undertaken to achieve a final model containing predictors that are likely to be impacting the analytes and provide answers for the stated hypotheses. The aim is to obtain the most parsimonious model that captures the main patterns within the observed data while not necessarily capturing the extremely high or low values. Any model that fits outliers could be considered to be over parameterized or over fitted (ie with too many terms in the model suggesting the components have been selected more by the observed data than scientific understanding.

Answers to the hypotheses and hence, objectives will allow informed decisions to be made on things such as: are there differences between periods, what trends exist within a period (linear or curvilinear), and what tributaries are impacting the main river sites. The *glm* function in the *stats* R package was used to fit the models and the *emmeans* package (Length R 2020) was used to calculate the estimated marginal means (EMM) and differences between these means on the transformed data. The EMMs and differences were back transformed to represent the estimated geometric means (that approximate the median) and ratios between these geometric means (approximately the ratio between medians) on the natural scale.

A number of publications discuss choice of significance level in model building and recommend significance levels as high as 0.20 or even 0.25 for initial variable selection (eg Bendel and Afifi 1977; Hosmer 2013, Menard 2002). They show that the use of more traditional levels such as 0.05 often fails to identify variables known to be important and the higher levels have the disadvantage of including variables of questionable importance, then go on to suggest it is important to review all variables added to or removed from a model critically before a decision is reached regarding the final model. It is not uncommon for blocking and other experimental design variables or those known to impact the response to be retained even if not 'significant'. However rather than totally ignore the data's evidence on their need for inclusion a decision was made to include those where there was at least weak evidence ie $p<0.15$. A level of 0.15 was applied for p-values to keep a term in the model as a conservative approach to ensure that the model matched the known experimental design while also providing some opportunity to reduce the complexity of the model to obtain a more parsimonious model

Step 1: Model the initial full model

Wastewater treatment plants (WWTPs)

A general linear model (GLM) was fitted to the nutrient loads for each WWTP including terms to capture the effect of improvements or other process changes at the corresponding WWTP, linear and curvilinear trends over time within each period defined by the changes at the WWTP and any remaining seasonal trends that can change each year. This was defined as the full model. The number of periods may differ between type of nutrient load within each WWTP (Section 3.4.2). The treatment plants and general linear model components included in each river zone are shown in Table 3-3.

WWTPs have the simplest model structure containing a factor defining periods and continuous variables for the linear and quadratic trends within each period and for the seasonal trends that can differ by year. Although harmonic terms were included in the model, their estimated parameters were not included as they are of little value for interpretative purposes.

Table 3-3 General linear model components for nutrient loads at WWTPs

River zone	Model explanatory variables		
Model outcome variable: WWTP nutrient load	WWTP impact		Seasonal trends by year
	Periods[1]	Trends within periods	
Upper Nepean River – West Camden			
West Camden WWTP	Yes	Yes	Yes
Lower Nepean River - Yarramundi			
Winmalee WWTP	Yes	Yes	Yes
Hawkesbury River – South Creek			
Quakers Hill WWTP	Yes	Yes	Yes
St Mary's WWTP	Yes	Yes	Yes
Riverstone WWTP	Yes	Yes	Yes
Richmond WWTP	Yes	Yes	Yes
Hawkesbury River – Cattai Creek			
Rouse Hill WWTP	Yes	Yes	Yes
Castle Hill WWTP	Yes	Yes	Yes

1 Details of the period definitions are presented in Volume 2 Appendix E Table E-1. The number of periods may differ between type of nutrient load within each WWTP

Receiving water sites

This analysis aimed to investigate the relationship between the nutrient (TN, DIN and TP) and chlorophyll-*a* concentrations at the river site and the upstream catchment as represented by:

- the analyte concentration from this upstream site (N48A for N44, N39 for N35 and N35 for N3001). Note, no upstream site concentration was included for N75 as there was insufficient data recorded for N78
- the derived composite flow appropriate for the upstream site.
- the state of any tributary as measured by:
  - the base flow from that tributary (eg South Creek for N35 and Cattai Creek for N3001).
  - the analyte nutrient load of any WWTPs on the tributary
- the analyte nutrient load of any other specified WWTP on the Hawkesbury-Nepean River

The TN, DIN and TP model included relevant WWTP TN, DIN and TP loads, respectively. For Chl-*a*, nutrient loads included both TN and TP loads from the relevant WWTPs. DIN loads were also considered for inclusion due to the potential influence on Chl-*a*, however, due to the large periods of time with no DIN data, these terms were not included.

The impact of the WWTPs were also assessed by fitting a categorical Period effect and continuous linear and quadratic trend variables within each period as for the analyses of the individual WWTPs. However, there were different period definitions (Section 3.4.2), and hence different linear and quadratic trend variables that consider the multiple WWTPs of interest (ie Winmalee WWTP for N44, St Marys, Quakers Hill and Riverstone WWTPs for N35, and Castle Hill and Rouse Hill WWTPs for N3001). Also, as for the WWTP analyses, harmonic variables were fitted in the model to capture any remaining seasonal trends that can change each year. Although these harmonic terms have been included in the model, their estimated parameters are not included as they are of little value for interpretative purposes.

The inclusion of these explanatory variables allows the investigation to focus on the effect of the WWTPs after adjusting for the effect of the upper catchment on the receiving water site concentrations.

The general linear model components for concentrations (TN, DIN, TP, Chl-*a*) for the full model at receiving water sites are provided in Table 3-5.

Table 3-4 General linear model components for nutrient and chlorophyll-*a* concentrations at individual receiving water sites.

River zone	Model explanatory variables					
Model outcome variable: main river site nutrient concentration	Upstream catchment[1]	Tributary catchment[1]	WWTP impact			Seasonal trends by year
			Load[2, 5]	Periods[3]	Trends within periods	
Upper Nepean River – West Camden						
N75	• Flow at N78[4]	Flow at Matahil Creek	West Camden WWTP	Yes	Yes	Yes
Lower Nepean River - Yarramundi						
N44	• Concentration at N48A • Flow at N48A	NA	Winmalee WWTP	Yes	Yes	Yes
Hawkesbury River – South Creek						
N35	• Concentration at N39 • Flow at N39	Base flow at South Creek	Quakers Hill WWTP St Mary's WWTP Riverstone WWTP	Yes	Yes	Yes
Hawkesbury River – Cattai Creek						
N3001	• Concentration at N35 • Flow at N35	Base flow Cattai Creek	Rouse Hill WWTP Castle Hill WWTP	Yes	Yes	Yes

NA = Not applicable

[1] Details of the flow calculations are presented in Volume 2, Appendix E: Table E-5

[2] Details of the load calculations are presented in Volume 2, Appendix E: Table E-3 and Table E-4

[3] Details of the period definitions are presented in Volume 2, Appendix E: Table E-1 and Table E-2

[4] No upstream concentration was fitted to N75 as there was insufficient data at Site N78

[5] For Chl-*a* analyses both TN and TP loads are included in the model

Downstream-upstream receiving water sites

The general linear model components of the full model for nutrient (TN, DIN and TP) and Chl-*a* concentrations at receiving water sites for the downstream-upstream analyses are provided in Table 3-5. The outcome is the concentration at each of the sites included in the downstream-upstream combination. When there is a tributary that contains WWTPs between the upstream and downstream sites, the concentration in the tributary water quality monitoring site is also included ie South Creek and Cattai Creek. The Site factor in the model accounts for differences between sites. With a GLM approach, estimated marginal means for each level of a factor after adjusting for other terms in the model were obtained directly, removing the need for the coefficients of these terms in the model to be directly interpretable. In addition, since trends were being fitted, the coefficients of the Site factor do not have a directly interpretable meaning as the site average, they represent the y-intercept for each site model. To adjust for the trends, the estimated marginal means approach needs to be taken. Hence while it might be natural to identify the upstream site as the reference site in the model, it is not necessary. In these downstream/upstream models a streamlined approach to the analyses was planned whereby the same model structure could be applied for any concentration measure at any main river site. When there was a tributary site the question became ‘what is the correct upstream site?’ A comparison between the tributary site with the upstream main river site was of no interest, hence the reference site in the modeling process was deliberately identified as the downstream site.

The period definitions, and hence linear and quadratic trend variables are those related to the model for the downstream receiving water site analyses above and are assigned to each upstream, tributary or downstream site in the model. The seasonal variables and their interaction with Year were based on the sampling dates specific to each site.

The composite flow volume corresponding to each site is also included. The addition of the seasonal trend terms and the composite flow volume to the model allows the effect of the WWTP(s) on the downstream sites to be investigated after adjusting for seasonal and flow effects. Interaction terms between site and the Period and linear and quadratic trend terms were fitted to investigate the hypotheses of interest.

Table 3-5 General linear model components for nutrients and chlorophyll-*a* concentrations at receiving water sites in the downstream-upstream analyses

River zone	Model explanatory variables				
Main river site	**Upstream and downstream Site**	**Flow[1]**	**WWTP impact**		**Seasonal trends by year**
			Periods[2]	**Trends within periods[3]**	
Upper Nepean River – West Camden					
N75	• N75 • N78	• Flow at N75 • Flow at N78	Yes	Yes	Yes
Lower Nepean River - Yarramundi					
N44	• N44 • N48A	• Flow at N44 • Flow at N48A	Yes	Yes	Yes
Hawkesbury River – South Creek					
N35	• N35 • NS04 • N39	• Flow at N35 • Flow at NS04 • Flow at N39	Yes	Yes	Yes
Hawkesbury River – Cattai Creek					
N3001	• N3001 • NC11A • N35	• Flow at N3001 Flow at NC11A • Flow at N35	Yes	Yes	Yes

[1] Details of the flow calculations are presented in Volume 2 Appendix E, Table E-5

[2] Details of the load calculations are presented in Volume 2 Appendix E, Table E-3 and Table E-4

[3] Details of the period definitions are presented in Volume 2 Appendix E, Table E-1

Step 2: Building the final Model

Model reduction process

The order in which terms are included in the model is important for the model reduction process. This provided the ability to test specific hypothesis about the impact of various factors and make inferential decisions eg once the impact of site/period was considered do we need to account for additional trends such as linear, curvilinear or seasonal

Term order for the analyses of WWTP loads:

1. period effect to assess if there was a difference between the level at the start of each period
2. linear terms fitted for each period
3. quadratic terms fitted for each period
4. seasonal trend terms to capture any remaining explainable variability in the data series

Term order for the analysis of downstream receiving water river sites:

1. upstream catchment (concentration and flow)
2. any tributary flow
3. any associated WWTP loads
4. period effect
5. linear terms fitted for each period
6. quadratic terms fitted for each period
7. seasonal trend terms

Term order for the analyses of the downstream-upstream receiving water river sites:

1. categorical factor identifying the site
2. a site by flow interaction term to allow the relationship between flow and analyte concentration to differ between sites
3. interaction terms between site and period
4. interaction terms between linear, quadratic and seasonal trend terms with site

The type I sums of squares (SS) was used to choose the terms that remain in the model. The type I sums of squares, also known as the sequential sums of squares, estimate the amount of remaining variation in the data explained by the addition of the specified variable after accounting for the variability explained by the preceding variables in the model. For example, if a linear trend term is fitted first, the type I sums of squares for the addition of the quadratic term gives an indication of how important it is to include a term to capture any curvature in the trend. Hence the if all the type I sums of squares are added together, the result equals the total variability in the data.

Linear and quadratic trend terms were retained in the model if the p value associated with the type I SS was $p \le 0.15$ except for the following condition. If quadratic terms were significant then linear terms were retained regardless of their p value. The shape of the trends are reported as up/down arrows in a summary table. A conservative p-value of 0.15 was chosen as the determining cut-point as is commonly used for model selection processes.

Seasonal trends were modelled using Fourier transform terms derived as 1st, 2nd and 3rd order sine and cosine harmonic curves. Main effect terms for each harmonic were included to fit the same seasonal trend each year. Interaction terms for each harmonic with Year were included to test if there was a different seasonal trend for each year. While these terms were included in the model to provide a more complete representation of the trends over time and a more accurate estimate of the variability around any mean effects or long-term trends, they were not interpreted. However, they gave an indication of which years were driving any complexity of the model and roughly when the peaks and troughs of the cycles occurred. If the harmonic by year terms were significant, the main effect terms were removed from the model for simplicity. Terms were retained in the model if the p value associated with the type I SS was $p \le 0.15$ for at least one sine-cosine pair except if higher order harmonic terms were significant, in which case all lower harmonic terms were retained regardless of their p value.

For the analyses of the receiving water sites, the river and tributary flow volumes, upstream receiving water site concentration, period and WWTP load variables were retained in the model regardless of their p values as they formed part of the study design and answered the hypotheses of interest.

For the analyses of the downstream-upstream receiving water sites, the interaction term between site and Period and between site and flow was retained in the model regardless of their p values. These terms provide the test of the hypotheses of interest. Interaction terms between site and linear, quadratic or harmonic by year terms were removed from the model if $p>0.15$. The linear term was only removed if the quadratic term was also not significant.

The final, reduced models were checked for goodness of fit and assumptions by reviewing:

- Goodness of fit plots
  - Plot of residuals vs predicted values
  - A normal Q-Q plot
  - Scale-location plot
  - Residuals vs leverage plot that also includes Cooks distance measure for influential outliers
  - A histogram of the residuals
  - Kernel density plot of the residuals
- R^2 and adjusted R^2 to assess the proportion of variation explained by the regressors in the model both unadjusted and adjusted for the number of independent variables in the model
- Sense check of the geometric means estimated from the model (ie adjusted for the various trends) compared to the geometric means estimated from the observed data and a comparison with the information provided on the figure containing the observed data and fitted model.

Reduced model output

Once the model was finalised, a figure was produced that included the observed data, the fitted model, the 95% confidence interval of the fitted model, the 95% prediction interval for the observed data and a smooth estimate of the long-term trends within each period. Vertical reference lines were included to identify the interventions defining the periods.

For the receiving water river sites, some of the reference lines identified the major WWTP upgrades or changes that may be useful to interpret the patterns over time but were not deemed to be of significant impact to define a period that would need to be assessed in more detail. Horizontal reference lines are included to identify EPL limits at WWTPs and ANZG default levels for the receiving water river sites.

As all analyses were undertaken with data on the log scale, the vertical axis of the figures are in the logarithmic scale to display the results using their natural units. As a result, the tick marks and values on the vertical axis are not equally spaced. This enables the reader to see the results on the scale in which the analyte is measured eg kg/day rather than $\log_{10}$(kg/day) while also being able to clearly see the range of records including extreme events, fitted model etc.

Estimated regression coefficients, their standard errors and corresponding p-values from the final model are presented in Volume 2 (Appendix F to Appendix I). Note that the estimates for the annual trend parameters (ie the harmonic interaction terms) have not been presented in these tables. The Appendices also include a table for each model detailing the type I and type III sums of squares and corresponding p-values. The type III sums of squares estimate the amount of variation in the data explained by the addition of the specified variable after accounting for the variability explained by all other variables in the model. The type III sums of squares are also called the adjusted sums of squares. As the data being analysed come from records over time, not a balanced study design, the type III sums of squares for each term in the model will not be independent and will not sum to the total variation in the data series. However, they do give insight as to how other terms in the model are affecting the estimate of the variable of interest and, hence a greater understanding of the interplay between variables.

The p values from the type I sums of squares were used to determine the significance level of each term in the model when order was important eg linear and quadratic trends and the order of fitting nutrient loads from multiple WWTPs in the river analyses. Regression coefficients were used to determine the direction or impact of the continuous explanatory variables on the outcome. The p-value from the type III sums of squares was used to determine if the importance of the explanatory variable seen via the type I sums of squares continued after adjusting for all terms in the model.

The relationship between an outcome on the original scale and a continuous explanatory variable on the original scale, when both have been analysed on the log transformed scale is relative. However, the relative relationship also depends on the magnitude of the explanatory variable of interest. Examples have been provided for pre-specified changes at a low, medium and high value of the explanatory variable.

Geometric marginal means and 95% confidence intervals were used to summarise the levels of each analyte in each period. Estimating the geometric marginal mean loads or concentrations for each period from the model (ie adjusted or estimated marginal means) using the automated default procedure was not appropriate for the way the linear and quadratic trend terms have been parameterised for these analyses. The default approach estimates the period mean of interest at the mean level of each term in the model ie at the mean of the day variable (linear term) for period 1 and the mean of the day variable for period 2 and the mean of each harmonic term and so on until all terms in the model have been accounted for. If the standard ANCOVA parameterisation had been used this approach would have been appropriate. Because the approach used here fits linear terms using the hockey stick approach, the mean of the day variable applicable for period 1 across the complete series of data will include all the days outside of period 1 where a 0 has been assigned, thereby underestimating or overestimating its mean. The R package provides the facility to specify how the mean for each variable is to be derived and hence included in the estimate of the mean of interest.

Specifications for estimating the means from the model include:

- Using the average of the day variable for the period of interest, with the other day variables set to 0 ie the mean is an estimate of the load or concentration for the middle day of the period.
- Setting the mean for each harmonic term to 0 - an assumption has been made that across a year period the cyclical nature of the harmonic terms would result in a mean of 0
- Including only those years in each period, with each year having an equal weight rather than biased towards its sample size eg we don't want to include the extreme deviations of a flood period in a drought period that didn't occur in a period to be included.

Estimating effects and answering the hypotheses

Hypotheses for the WWTPs to determine if nutrient loads differ between periods, for the river sites to determine if nutrient concentrations differ between periods and for the downstream-upstream analyses to determine if nutrient concentrations differ between sites within each period are assessed by comparing estimated geometric marginal mean loads and concentrations. Estimated mean loads and concentrations on the log scale for each period from the model and the corresponding 95% confidence intervals (CI) were back transformed to represent the estimated geometric mean loads and concentrations and 95% CI on the original scale. The geometric mean load is the appropriate measure of the mean of a log normal distribution and approximates the median. The difference between the estimated mean in a period compared to the estimated mean in the preceding period along with the corresponding 95% CI was calculated and back transformed to represent the relative difference between periods as a percent. If the confidence interval for the relative difference included 100% then the conclusion was that there was not enough evidence to conclude the periods were different based on their geometric marginal mean. Note that, even though the geometric marginal means may be similar or not statistically significantly different, the trends may be different.

Hypotheses for the trends within periods at each WWTP or river site analyses were assessed by reviewing the direction of the regression coefficient and the p-value from the type I SS for each trend within each period. Results have been presented in a table as an up, down or horizontal arrow, shaded in relation to the p-value from the type I SS in categories of ≤0.0001, >0.0001 and ≤0.001, >0.001 and ≤0.01, >0.01 and ≤0.05. P-values >0.05 and ≤0.15 were also shaded as these terms have been included in the model based on their p-value being ≤0.15. Trends with p≤0.05 are deemed statistically significant for hypothesis testing.

The hypotheses investigating the relationship between the upper catchment variables (upstream concentration, upstream flow) and the outcome looked at the corresponding regression coefficient, its sign (positive or negative) and its corresponding p-value. Results have been presented in a table similar to the trend table. However, in this case all upper catchment variables are included in the reduced model regardless of the p-value because they form part of the design of the analyses and are the hypotheses of interest. Relationships with a type I or type III SS or regression coefficient p-value of ≤0.05 are deemed statistically significant for hypothesis testing. Discrepancies between the conclusions based on the different p-values have been discussed. Examples have been provided for pre-specified changes at a low, medium and high values of the upstream concentration and upstream flow variables and the relative change in the outcome for those coefficients where one or both p-values are ≤0.05. Further details on interpretation of coefficients are provided in Volume 2 (Appendix E).

The hypotheses investigating the relationship between the WWTP load variables and the outcome were also answered by looking at the corresponding regression coefficient, its sign (positive or negative) and its corresponding p-values. Relationships with a type I or type III SS or regression coefficient p-value of ≤0.05 were deemed statistically significant for hypothesis testing. Discrepancies between the conclusions based on the different p-values have been discussed. Examples have been provided for pre-specified changes at a low, medium and high values of the WWTP load variables and the relative change in the outcome.

For the downstream-upstream analyses, the hypotheses to investigate the presence of an interaction between site and flow ie does the relationship between flow and concentration differ between sites, and the presence of an interaction between site and linear or quadratic trend for each period ie do the linear or quadratic trends differ between sites, was assessed by the type I SS p-value for the interaction term in the model as order is important. The hypotheses for the presence of linear or quadratic trends within each period at each site was assessed by reviewing the direction of the regression coefficient and its corresponding p-value for each trend within each site and period. Results have been presented in a table with the interaction term shaded in relation to the significance of the p-value from the type I SS and the relationships at each site for flow and linear and quadratic trends presented as an up or down arrow or horizontal line for no trend, shaded in relation to the significance of the p-value from the regression coefficients table. Trends with p≤0.05 have been deemed statistically significant for hypothesis testing.

3.4.6 Checking multicollinearity

Multicollinearity occurs when the predictors are highly correlated with each other. This can affect the interpretability of the parameter estimates due to lower stability (higher standard error). This was minimised by:

- Identifying that flow and load would likely be correlated. Therefore, nutrient concentration was more preferable than nutrient load
- Reporting both SS I and SS III. Comparing them allows us to understand the impact of multicollinearity on p-values and where there may be issues with interpreting the parameters
- As part of the initial Exploratory Data Analysis creating a scatterplot matrix for all predictors along with suitable metrics (eg R, its p-value, R^2) to assess the extent of multicollinearity.

The one area where there may still be multicollinearity is between flow predictors due to rainfall ie when it rains they will likely all go up. Accounting for this is beyond the scope of this work. However, it is important to identify if it is a possible problem both so we can identify parameters where this should be accounted for when interpreting them, and to understand the extent of the problem (if any) so decisions can be made on whether future work needs to include time to account for this.

3.4.7 Quality control and assurance

At all stages during the data preparation process, quality control checking was undertaken to ensure the expected quality of the data, both observed and derived was met. Checks included:

- Review of data types eg numeric, dates, character, missing data
- Identifying and managing duplicate dates – mean values derived where dates were duplicated
- Sense checking eg gaps in dissolved inorganic nitrogen series corresponded with gaps in NOx.

Furthermore, the following additional checks and processes were used to ensure the analysis and models were correctly applied.

1. R Code
   - Code review was performed for sections where the primary coder did not have extensive experience eg the code calculating estimated means was different to that conventionally used so had extensive input, core review and checking by a senior statistician.
   - Automation
     - Unit tests for automated sections.
2. Common Sense Checks
   - Methods and Code
     - Senior Statistician detailed review of analysis results
     - Independent Senior Statistician high level review of analysis results
     - Comparison of the estimated adjusted geometric means, unadjusted geometric means and the fitted model and a review of the R EMM data matrix
   - Data
     - Final review by experienced Monitoring and Analysis Lead (Sydney Water) to confirm the series of data being used and the fitted model choice matches and behaves as expected.

4 Results

This chapter presents the step-by-step statistical modelling results for each variable and site (relevant WWTP or water quality site) for four key zones of the Hawkesbury-Nepean River (Section 4.1 to 4.4). The detailed statistical analysis outcomes are included in Volume 2 (Appendix F to Appendix I). For simplicity, analytes/variables are often abbreviated in this chapter: total nitrogen (TN), dissolved inorganic nitrogen (DIN), total phosphorus (TP) and chlorophyll-*a* (Chl-*a*).

4.1 Nepean River at Sharpes Weir – West Camden WWTP

The following sub-sections present the results of the model building steps, and key outcomes for 11 models fitted on data from the Nepean River at Sharpes Weir and West Camden WWTP. A summary is included to interpret the variability in the outcomes due to explanatory variables fitted or any other supplementary changes eg demography, weather etc.

The detailed results of all statistical models fitted for the Nepean River at Sharpes Weir (N75) and West Camden WWTP are included in Volume 2: Appendix F. Estimated regression coefficients, standard errors, p values, type I and type III sum of squares details are provided in Table F-1 to Table F-22. Residual plots on all models are provided in Figure F-1 to Figure F-11. The model and model adjusted R^2 are provided to assess the goodness of fit of the models (Table F-23). Examples of relative changes in water quality concentrations (total nitrogen, dissolved inorganic nitrogen, total phosphorus or chlorophyll-*a*) with respect to prespecified ranges of nutrient loads and river and creek flow are included in Table F-24 and Table F-25.

4.1.1 West Camden WWTP – Total nitrogen load

There were 1522 total nitrogen load records for the West Camden WWTP in this data series. Prior to the nitrogen upgrade in 2008 there were 807 records (period 1), after the upgrade and before the nitrogen process deterioration there were 381 records (period 2), and after the process deterioration in 2015 there were 334 records (period 3). All records are included in the analyses. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included the three periods defined by the nitrogen upgrade and process deterioration, linear and quadratic trends within each period and 1^{st}, 2^{nd} and 3^{rd} order harmonic main effects and by year interaction terms to model the seasonal trends.

The model:

Log_{10}(TN load) = period + linear trend in period 1 + linear trend in period 2 + linear trend in period 3 + quadratic trend in period 1 + quadratic trend in period 2 + quadratic trend in period 3 + 1^{st} order sine + 1^{st} order cosine + 2^{nd} order sine + 2^{nd} order cosine + 3^{rd} order sine + 3^{rd} order cosine + 1^{st} order sine trend by year + 1^{st} order cosine trend by year + 2nd order sine trend by year + 2nd order cosine trend by year + 3rd order sine trend by year + 3rd order cosine trend by year

Where:

period and year are categorical factors.

Model reduction decisions:

- Retain all harmonic interaction terms as the p-values for the 3rd order terms from the type I SS were <0.15
- Remove the main effect harmonic terms since they can be included in the harmonic interaction terms.

Step 2: Fit the final, reduced model

Log_{10}(TN load) = period + linear trend in period 1 + linear trend in period 2 + linear trend in period 3 + quadratic trend in period 1 + quadratic trend in period 2 + quadratic trend in period 3 + 1st order sine trend by year + 1st order cosine trend by year + 2nd order sine trend by year + 2nd order cosine trend by year

Where:

period and year are categorical factors.

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-1.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix F). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table F-1 and Table F-2, respectively. The residual plots for this model are shown in Figure F-1.

All terms in the final, reduced model had a p-value for the corresponding type I SS <0.15 except for the linear trend in period 3 with a p-value of 0.23. This term was included in the model as the corresponding quadratic term was significant (p<0.0001). Each term in the model had a similar p-value after adjusting for all other terms in the model (type III SS) except for the linear trend in period 2 that became not significant with p=0.2 and the linear trend in period 3 that became significant p<0.0001. In period 2, this suggested that the seasonal terms may also be explaining the pattern and for period 3, there may be an underlying linear component to the curvilinear trend that is not obvious when the seasonal trend is not accounted.

The model fitted the data well (R^2=0.75 and adjusted R^2=0.72) except for those at extremely high loads, and, to a lesser extent extremely low loads. Four values showed a high leverage (ie terms in the model are included because of their contribution to the variability in the data). The distribution of the residuals was approximately Normal, and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

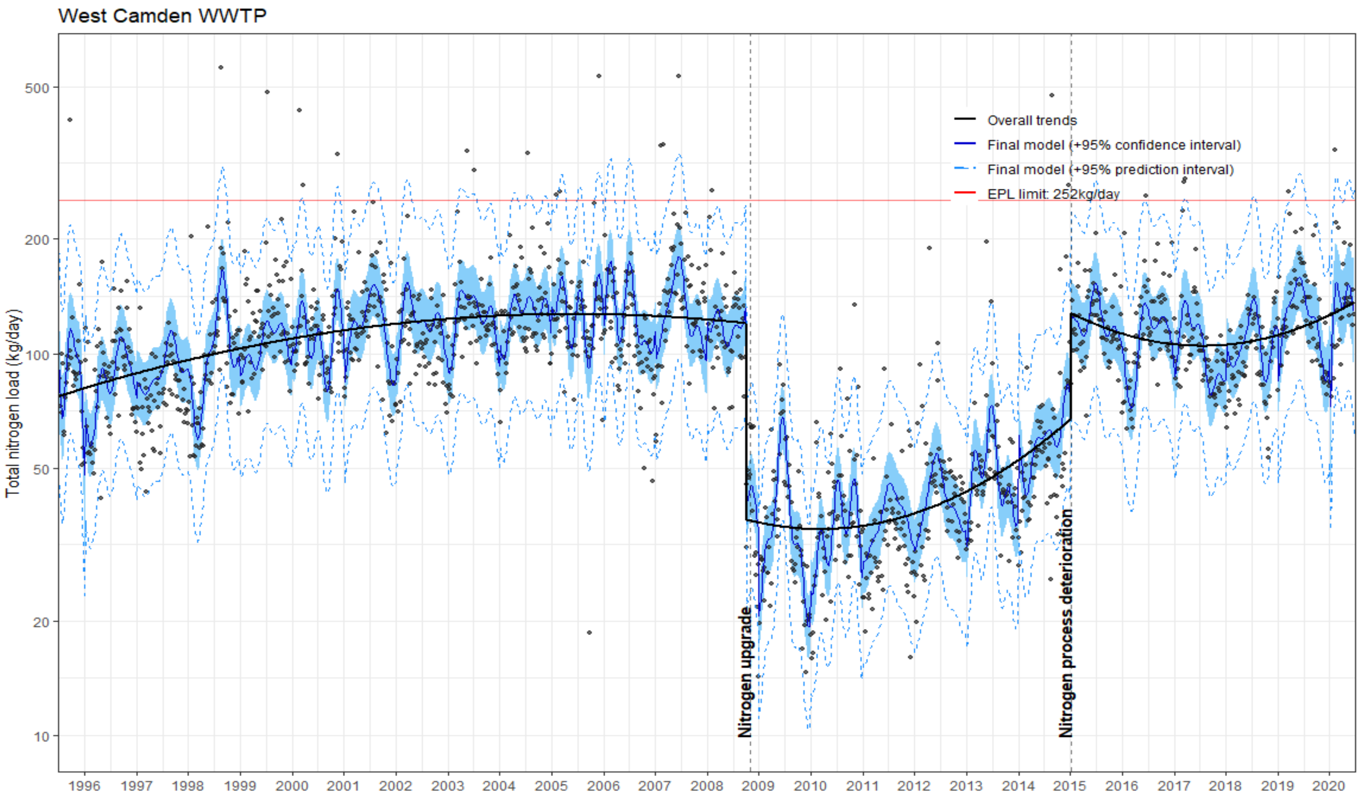

Figure 4-1 Total nitrogen load from West Camden WWTP: fitting terms to model interventions, linear and quadratic trends within each period and seasonal trends overlaid with the trends in each period

Key outcomes

- Total nitrogen load:
  - The majority of loads recorded were less than the current total nitrogen EPL limit of West Camden WWTP (252 kg/day)
  - The final reduced model fitted well with R^2=0.75 and adjusted R^2=0.72. However, the residual plots showed the model did not capture the extremely high or low total nitrogen loads.
- Long term trends:
  - Significant curvilinear trends were observed in each period
    - Before the nitrogen upgrade in 2008, the total nitrogen load curved upwards until around 2005 when the load started to flatten out and curve slightly downwards
    - After the nitrogen upgrade and before the process deterioration (2008-2015), there was a large increasing curvilinear trend. This pattern was also accounted for by the seasonal trend over the period.

    - After the process deterioration, the trend curved downwards until around 2018 before curving upwards
    - As of mid-2020, the trend in total nitrogen load was increasing.
- Seasonal trends:
  - First, second and third order sine and cosine terms by year interactions were included to capture a more complex pattern of three total nitrogen load peaks per year, capturing the largest one in February, and with two smaller ones around late May/early June and September. The lowest trough was around late October/early November. The magnitude of these peaks and troughs differed between years.
- After adjusting for seasonal trends, the total nitrogen geometric mean loads:
  - Prior to the upgrade (period 1) was 119.5 kg/day of total nitrogen (95% CI=115.7 to 123.4 kg/day)
  - After the upgrade and before the process deterioration (period 2) was 37.9 kg/day of total nitrogen (95% CI=36.2 to 39.7 kg/day)
  - After the process change (period 3) was 101.9 kg/day of total nitrogen (95% CI=96.7 to 107.4 kg/day).
- Comparing the total nitrogen geometric mean loads between periods:
  - The total nitrogen load in the period after the upgrade was 32% of the pre upgrade load (95% CI=30 to 34%)
  - After the process change in 2015, the load increased by 269% compared to the period before the process change (95% CI=251 to 289%).

4.1.2 Nepean River at Sharpes Weir (N75) – Total nitrogen concentration

There were 583 total nitrogen concentration records in this data series. Prior to the nitrogen upgrade in 2008 there were 381 records (period 1), after the upgrade and before the process change in 2015 there were 106 records (period 2), and after the process deterioration there were 96 records (period 3). All records are included in the analyses. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included flow from the Nepean River at Camden Weir, flow from Matahil Creek, West Camden TN load, the three periods defined by the nitrogen upgrade and process deterioration at West Camden WWTP, linear and quadratic trends within each period and 1st, 2nd and 3rd order harmonic main effects and harmonic interaction terms to model the seasonal trends. Note that the TN concentration for the upstream site was not included in the full model. The upstream site (N78) did not have enough records to be included in the model.

The model:

Log_{10}(TN concentration) = log_{10}(flow at Camden Weir) + log_{10}(flow at Matahil Creek) + log_{10}(TN load at West Camden WWTP) + period + linear in period 1 + linear in period 2 + linear in period 3 + quadratic in period 1 + quadratic in period 2 + quadratic in period 3+ 1^{st} order sine + 1^{st} order cosine + 2^{nd} order sine + 2^{nd} order cosine + 3^{rd} order sine + 3^{rd} order cosine + 1^{st} order sine trend by year + 1^{st} order cosine trend by year + 2^{nd} order sine trend by year + 2^{nd} order cosine trend by year + 3^{rd} order sine trend by year + 3^{rd} order cosine trend by year

Where:

period and year are categorical factors.

Model reduction decisions:

- Remove the main effect harmonic terms since they can be included in the harmonic interaction terms.
- Remove the 3^{rd} order harmonic interaction terms
- Remove the linear and quadratic trend terms in period 2

Step 2: Fit the final, reduced model

Log_{10}(TN concentration) = log_{10}(flow at Camden Weir) + log_{10}(flow at Matahil Creek) + log_{10}(TN load at West Camden WWTP) + period + linear in period 1 + linear in period 3 + quadratic in period 1 + quadratic in period 3+ 1^{st} order sine trend by year + 1^{st} order cosine trend by year + 2^{nd} order sine trend by year + 2^{nd} order cosine trend by year

Where:

period and year are categorical factors.

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-2.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix F). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table F-3 and Table F-4, respectively. The residual plots for this model are shown in Figure F-2.

The period parameter as well as the flow at Camden Weir, the flow at Matahil Creek and the WWTP TN load estimates were retained in the model as part of the study design. The p-values corresponding to the type III SS vary compared with the type I SS. The linear trend in period 1 did not meet the <0.15 cut-off based on the type I SS. It is included in the model because the quadratic trend for period 1 had $p<0.0001$. However, the linear trend was significant after adjusting for all terms in the model ($p=0.02$) suggesting, that after accounting for the seasonal trends there was an additional underlying linear component to the curvilinear trend. Matahil Creek flow was also significant after adjusting for all terms in the model.

The model fitted the data well (R^2=0.78 and adjusted R^2=0.72) except for those at extremely high concentrations and the very low concentrations at or near the limit of quantification. Two values showed a high leverage (ie terms in the model are included because of their contribution to the variability in the data). The distribution of the residuals was approximately Normal with a long left tail for the very low concentrations and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

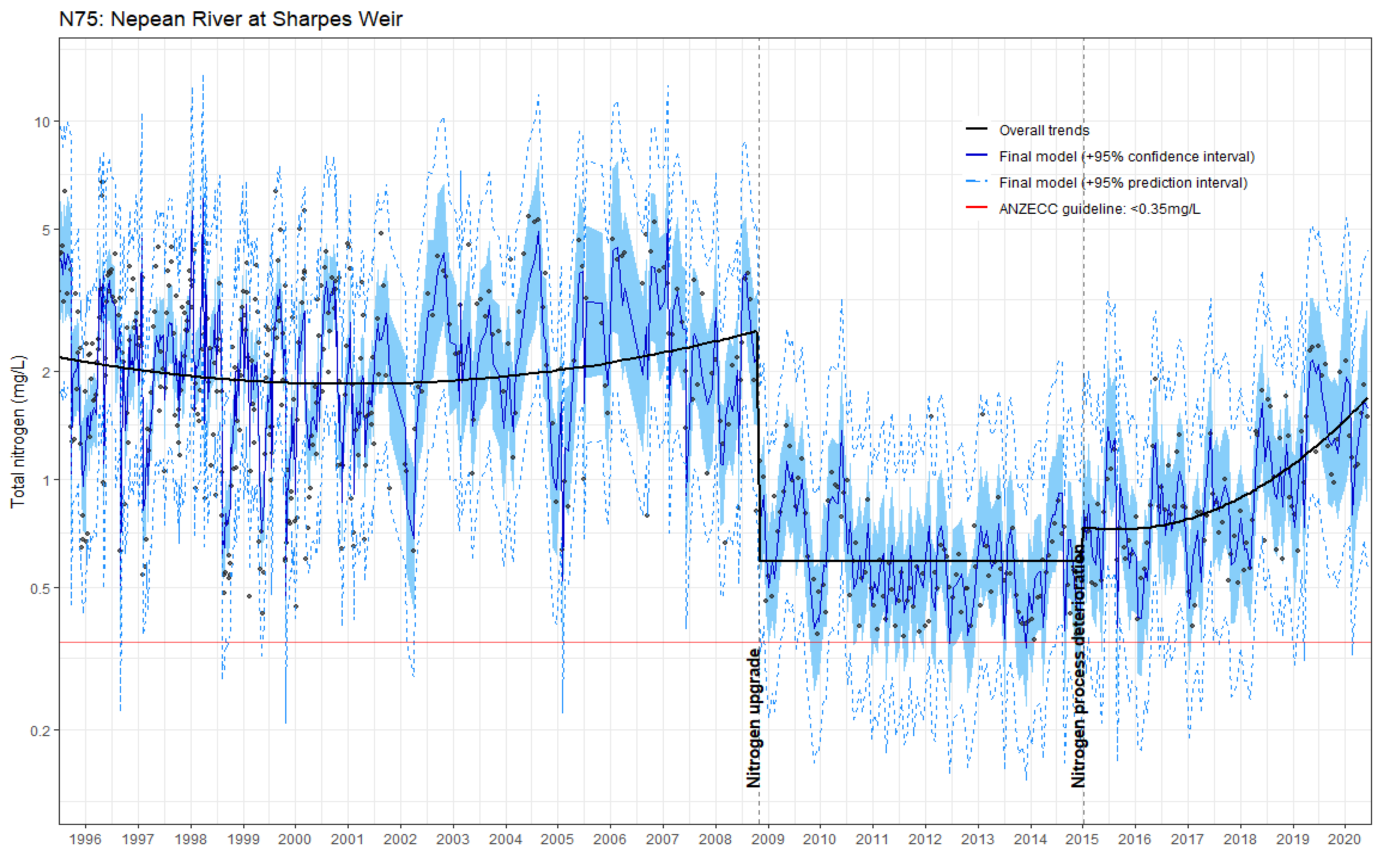

Figure 4-2 Total nitrogen concentrations at Sharpes Weir (N75): fitting terms to model Camden Weir and Matahil Creek flow, TN load from West Camden WWTP, along with linear and quadratic trends within each period and seasonal trends overlaid with the trends in each period

Key outcomes

- Total nitrogen concentration:
  - The majority of records were above the total nitrogen ANZG default level of <0.35 mg/L
  - The final reduced model fitted well with R^2=0.78 and adjusted R^2=0.72. However, the residual plots showed the model did not capture the extremely high TN concentrations.

- Impact of flow:
  - Flow at Camden Weir was significantly correlated to the concentration of TN at Sharpes Weir N75 ($p<0.0001$ on its own or after adjusting for all terms in the model):
    - when flow at Camden Weir was low eg 80 ML/day, a 10 ML increase in flow decreased the total nitrogen concentration at N75 by 2.5%
    - when flow at Camden Weir was moderate eg 100 ML/day, a 10 ML increase in flow decreased the concentration at N75 by 2.3% and
    - when flow at Camden Weir was high eg 150 ML/day, a 10 ML increase in flow decreased concentration at N75 by 1.6%.
  - Flow at Matahil Creek shows no relationship to the concentration of TN at Sharpes Weir N75 after accounting for the effect of Camden Weir ($p=0.4$) but did help to explain some of the remaining variability in concentration after adjusting for all terms in the model ($p=0.01$):
    - when flow at Matahil Creek was low eg 5 ML/day, a 1 ML increase in flow increased the concentration at N75 by 1.8%
    - when flow at Matahil Creek was moderate eg 10 ML/day, a 1 ML increase in flow increased the concentration at N75 by 0.9%
    - when flow at Matahil Creek was high eg 15 ML/day, a 1 ML increase in flow increased the concentration at N75 by 0.6%.
- Impact of WWTPs:
  - TN load from West Camden WWTP was significantly correlated to the concentration of TN at Sharpes Weir N75 after taking into account the effect of flow from Camden Weir and Matahil Creek ($p<0.0001$) and after adjusting for all terms in the model ($p=0.0009$):
    - when the load from West Camden WWTP was low eg 80 kg/day, a 10 kg/day increase in load increased the total nitrogen concentration at N75 by 2.6%
    - when the load from West Camden WWTP was moderate eg 100 kg/day, a 10 kg/day increase in load increased the concentration at N75 by 2.1%
    - when the load from West Camden WWTP was high eg 150 kg/day, a 10 kg/day increase in load increased the concentration at N75 by 1.4%.
- Long term trends:
  - Total nitrogen concentration showed a gradual decreasing trend prior to the nitrogen upgrade till around 2002 before gradually increasing (period 1)
  - There was no trend after the upgrade and before the nitrogen process deterioration (period 2)
  - After the nitrogen process deterioration there was an increasing trend in total nitrogen concentration (period 3)
  - As of mid-2020, the trend in total nitrogen concentration was increasing.

- Seasonal trends:
  - First and second order sine and cosine terms by year interactions were included to capture a pattern of two peaks of total nitrogen concentration per year, capturing the largest one in February and a smaller one around August/September. The magnitude of the peaks and troughs differed between years.
- After adjusting for seasonal trends, flow and load from West Camden WWTP, the geometric mean total nitrogen concentration at Sharpes Weir (N75):
  - Before the nitrogen upgrade (period 1) was 1.13 mg/L (95% CI = 1.03 to 1.23 mg/L)
  - After the nitrogen upgrade and before the process deterioration (period 2) was 0.48 mg/L (95% CI = 0.45 to 0.52 mg/L)
  - After the nitrogen process deterioration (period 3) was 0.62 mg/L (95% CI = 0.54 to 0.71 mg/L).
- Comparing the total nitrogen geometric mean concentrations between periods:
  - The total nitrogen concentration at Sharpes Weir (N75) in the period after the upgrade and before the process deterioration (period 2) was 43% (95% CI=39 to 47%) of the period before the upgrade (period 1)
  - The total nitrogen concentration in the period after the process deterioration (period 3) was 128% (95% CI=109 to 150%) of the previous period (period 2).

4.1.3 Nepean River at Sharpes Weir (N75) and Macquarie Grove Rd (N78) – Total nitrogen concentration (downstream/upstream)

There were no total nitrogen concentration records for the Nepean River at Macquarie Grove Road (N78) between mid-2011 and 2018, or after June 2019 as this is not a routine monitoring site. The data collected during the 2018-2019 period were for a special investigation. Hence the downstream-upstream analysis was undertaken on the 18-month time-period common to both series. There were 35 total nitrogen concentration records in the series for N75, and 23 at N78 included in the analyses. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included site, site by flow interaction, site by linear and quadratic trends interactions, 1^{st} order harmonic main effects and site by harmonic interaction terms to model different seasonal trends at each site. Note that only first order harmonic patterns with no Year term were fitted due to the small number of records and short time-period.

The model:

$\log_{10}$(TN concentration) = site + 1^{st} order sine + 1^{st} order cosine + site by $\log_{10}$flow + site by linear trend + site by quadratic trend + site by 1^{st} order sine trend + site by 1^{st} order cosine trend

Where:

period and year are categorical factors.

Model reduction decisions:

- Remove the main effect harmonic terms
- Retain the 1st order main effect harmonic terms
- Retain the quadratic trend

Step 2: Fit the final, reduced model

Log_{10}(TN concentration) = site + site by $\log_{10}$(flow) + site by linear trend + site by quadratic trend + site by 1st order sine trend + site by 1st order cosine trend

Where:

period and year are categorical factors.

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-3.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix F). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table F-5 and Table F-6, respectively. The residual plots for this model are shown in Figure F-3.

The site and site by flow parameters were retained in the model as they formed part of the study design. The p-values corresponding to the type III SS varied compared with the type I SS for all terms, which is not unexpected. For example, the site term was no longer significant ($p=0.39$) suggesting that different seasonal trends were accounting for the difference between sites.

The model fitted the data well ($R^2=0.88$ and adjusted $R^2=0.85$) except for those at extremely high concentrations. A few values showed a high leverage (ie terms in the model are included because of their contribution to the variability in the data). The distribution of the residuals was approximately Normal and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

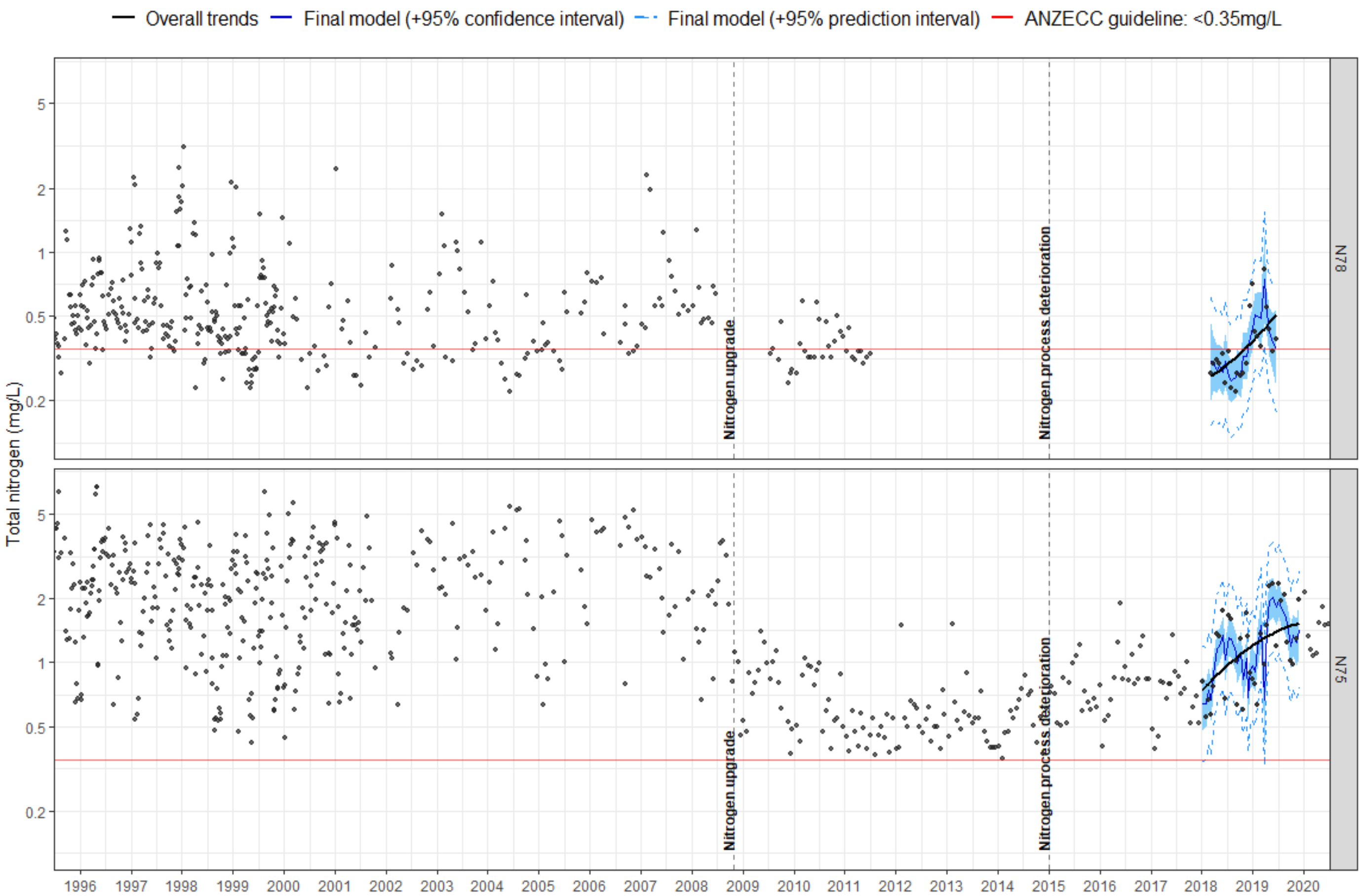

Figure 4-3 Total nitrogen concentrations at Macquarie Grove Road (N78) and Sharpes Weir (N75), Nepean River: fitting terms to model site differences, associated flow and linear and quadratic trends and seasonal trends overlaid with the trend

Key outcomes

- Total nitrogen concentration:
  - TN concentrations were consistently lower at N78 (upstream) compared with N75 (downstream)
  - TN concentrations remained above the ANZG default level of <0.35 mg/L at N75 and were also above the guideline at N78 since 2019
  - The large gap in the data series at site N78 resulted in a comparison of the two data series for the 18-month period across both sites from January 2018 to July 2019
  - The period of data for analysis was fully contained in the period after the process change at the West Camden WWTP so no investigation of the differences between sites in the various periods identified for the N75 analyses was required
  - The 18-month period was long enough to account for some seasonal trends

- The final reduced model fitted well with R^2=0.88 and adjusted R^2=0.85. However, the residual plots showed the model did not capture the extremely high total nitrogen concentrations.

- Flow:
  - The relationship between flow and TN concentration differed between sites ($p<0.0001$ after adjusting for site differences and 0.002 after adjusting for all terms in the model). There was a negative relationship with N75 ($p=0.001$) and a suggestion of a positive relationship with N78 ($p=0.12$).
    - when flow was low eg 80 ML/day, an increase of 10 ML/day decreased TN concentrations at N75 by 3.7%, whereas at N78 concentrations were increased by 1.5%
    - when flow was medium, eg 100 ML/day, an increase of 10 ML/day decreased TN concentrations at N75 by 3.0% and increased concentrations at N78 by 1.2%
    - when flow was high, eg 150 ML/day, an increase of 10 ML/day decreased concentrations at N75 by 2.1% and increased concentrations at N78 by 0.8%.
- Long term trends:
  - There was a significant interaction between site and linear trend after adjusting for site differences and site by flow differences ($p<0.0001$), and between site and quadratic trend ($p=0.06$)
  - The TN concentration showed an overall increasing trend at both sites, with a steeper trend at N78. However, the negative coefficients for the quadratic component capture the decreasing trend at the end of the data series. This could be capturing the decrease in concentration expected during the winter period.
- Seasonal trends:
  - The seasonal trend differed between sites as measured by the first order sine and cosine terms. Particularly the first order cosine trend captured a trough around July 2018 at N78, whereas it was a peak at N75.
- Site total nitrogen geometric mean concentrations:
  - After adjusting for seasonal trends and stream flow, the geometric mean TN concentration at site N78 was 0.40 mg/L (95% CI=0.32 to 0.50 mg/L), and at site N75 was 1.15 mg/L (95% CI=1.00 to 1.32 mg/L).
- Comparing the total nitrogen geometric mean concentrations between sites:
  - The geometric mean TN concentration at site N75 was 289% times as large as that at site N78 (95%CI = 223 to 374).

4.1.4 West Camden WWTP – Dissolved inorganic nitrogen load

There were 691 dissolved inorganic nitrogen load records for West Camden WWTP in this data series. Prior to the nitrogen upgrade in 2008 there were 548 records up until mid-2007 (period 1), there were no records after the upgrade and before the process deterioration in 2015 (period 2), and after the process deterioration in 2015 there were 143 records (period 3). All records are included in the analyses. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included the three periods defined by the nitrogen upgrade and process deterioration, linear and quadratic trends within each period and 1st, 2nd and 3rd order harmonic main effects and by year interaction terms to model the seasonal trends. Note, Period 2 was not included in the model as there were no records during this period.

The model:

Log_{10}(DIN load) = period + linear trend in period 1 + linear trend in period 3 + quadratic trend in period 1 + quadratic trend in period 3 + 1st order sine + 1st order cosine + 2nd order sine + 2nd order cosine + 3rd order sine + 3rd order cosine + 1st order sine trend by year + 1st order cosine trend by year + 2nd order sine trend by year + 2nd order cosine trend by year + 3rd order sine trend by year + 3rd order cosine trend by year

Where:

period and year are categorical factors.

Model reduction decisions:

- Retain all harmonic interaction terms as the p-values for the 3rd order terms from the type I SS were <0.15
- Remove the main effect harmonic terms since they can be included in the harmonic interaction terms.

Step 2: Fit the final, reduced model

Log_{10}(DIN load) = period + linear trend in period 1 + linear trend in period 3 + quadratic trend in period 1 + quadratic trend in period 3 + 1st order sine trend by year + 1st order cosine trend by year + 2nd order sine trend by year + 2nd order cosine trend by year + 3rd order sine trend by year + 3rd order cosine trend by year

Where:

period and year are categorical factors.

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-4.

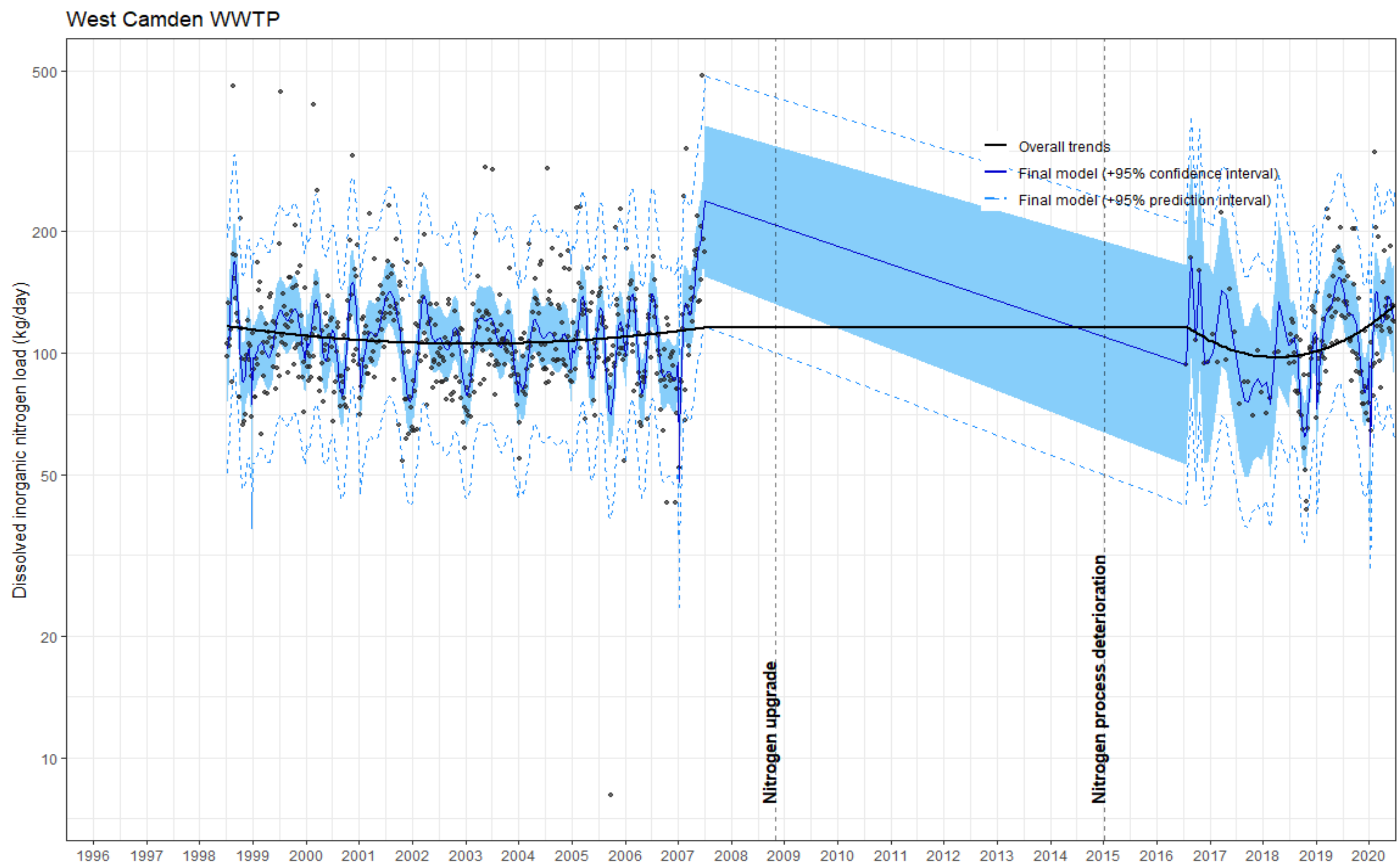

Figure 4-4 West Camden WWTP dissolved inorganic nitrogen load: fitting terms to model interventions, linear and quadratic trends within each period and seasonal trends overlaid with the trends in each period

The detailed statistical outcomes of this model are included in Volume 2 (Appendix F). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value was shown in Table F-7 and Table F-8, respectively. The residual plots for this model are shown in Figure F-4.

All terms in the final, reduced model had a p-value for the corresponding type I SS <0.15 except for the linear trend in period 1 with a p-value of 0.85. This term was included in the model as the corresponding quadratic term was significant (p=0.02). The linear and quadratic trend terms in both periods had different p-values between the type I and type III SS suggesting that the seasonal trends may also explain the trends within both period 1 and period 3.

The model fitted the data (R^2=0.35 and adjusted R^2=0.25) except for those at extremely high and low loads. Six values showed a leverage of 1 ie the model fitted these values exactly in the second half of 2016. The distribution of the residuals was approximately Normal and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

Key outcomes

- Dissolved inorganic nitrogen load:
  - There was no EPL limit for DIN load
  - The final reduced model fitted with R2=0.35 and adjusted R2=0.25. However, the residual plots showed the model did not capture the extremely high or low total nitrogen loads. There were six records that the model fitted exactly (ie a leverage of 1) in the second half of 2016.
- Long term trends:
  - There was a curvilinear trend in the DIN load before the nitrogen upgrade (period 1) that was also explained by the seasonal trend
  - No trend was fitted after the nitrogen upgrade and before the process deterioration (period 2) as there were no records during this period
  - After the process deterioration (period 3), there were no records until June 2016 when the DIN load decreased until around 2018 before increasing
  - As of mid-2020, the trend in DIN load was increasing.
- Seasonal trends:
  - First, second and third order sine and cosine terms by year interactions were included to capture a more complex pattern of three DIN peaks per year, capturing the largest one in February and two smaller ones in late May/early June and September. The lowest trough was around the late October/early November. The magnitude of these peaks and troughs differed between years.
- After adjusting for seasonal trends, the dissolved inorganic nitrogen geometric mean load:
  - prior to the upgrade was 107.1 kg/day (95% CI=103.0 to 111.4 kg/day),
  - after the process deterioration was 104.1 kg/day (95% CI=94.9 to 114.1 kg/day)
- No comparison of the loads between periods was undertaken as period 2 had no records.

4.1.5 Nepean River at Sharpes Weir (N75) – Dissolved inorganic nitrogen concentration

There were 583 dissolved inorganic nitrogen concentration records for the Nepean River at Sharpes Weir (N75) in this data series. However, due to limited number of records from West Camden WWTP, only the 210 records prior to the nitrogen upgrade (period 1) coincided with the period of DIN values at West Camden WWTP and the 41 records after the process deterioration (period 3) were included in the analyses. All records from N75 are plotted for completeness. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included flow at Camden Weir, flow at Matahil Creek, West Camden DIN load, the three periods defined by the nitrogen upgrade and process deterioration at West Camden WWTP, linear and quadratic trends within each period and 1st, 2nd and 3rd order harmonic main effects and harmonic interaction terms to model the seasonal trends. Note that no concentration for DIN at an upstream site is included in the full model. The upstream site (N78) did not have enough records to be included in this model. Note also, that Period 2 is not fitted to the model based on no DIN estimates being available for West Camden WWTP.

The model:

Log_{10}(DIN concentration) = log_{10}(flow at Camden Weir) + log_{10}(flow at Matahil Creek) + log_{10}(DIN load at West Camden WWTP) + period + linear in period 1 + quadratic in period 1 + linear in period 2 + quadratic in period 2 + linear in period 3 + quadratic in period 3+ 1st order sine + 1st order cosine + 2nd order sine + 2nd order cosine + 3rd order sine + 3rd order cosine + 1st order sine trend by year + 1st order cosine trend by year + 2nd order sine trend by year + 2nd order cosine trend by year + 3rd order sine trend by year + 3rd order cosine trend by year

Where:

period and year are categorical factors.

Model reduction decisions:

- Remove the main effect harmonic terms since they can be included in the harmonic interaction terms
- Remove 2nd and 3rd order harmonic interaction terms
- Remove linear and quadratic terms for period 3.

Step 2: Fit the final, reduced model

Log_{10}(DIN concentration) = log_{10}(flow at Camden Weir) + log_{10}(flow at Matahil Creek) + log_{10}(DIN load at West Camden WWTP) + period + linear in period 1 + quadratic in period 1 + 1st order sine trend by year + 1st order cosine trend by year

Where:

period and year are categorical factors.

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-5.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix F). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table F-9 and Table F-10, respectively. The residual plots for this model are shown in Figure F-5.

The period parameter as well as the flow at Camden Weir, the flow at Matahil Creek and the WWTP DIN load estimates were retained in the model as part of the study design. The p-values corresponding to the type III SS varied compared with the type I SS. West Camden DIN load had a p-value of 0.004 when fitted after Camden Weir and Matahil Creek flows. However, it had a p-value of 0.99 after fitting all other terms in the model, suggesting that the difference between periods or the harmonic interaction terms accounted for this.

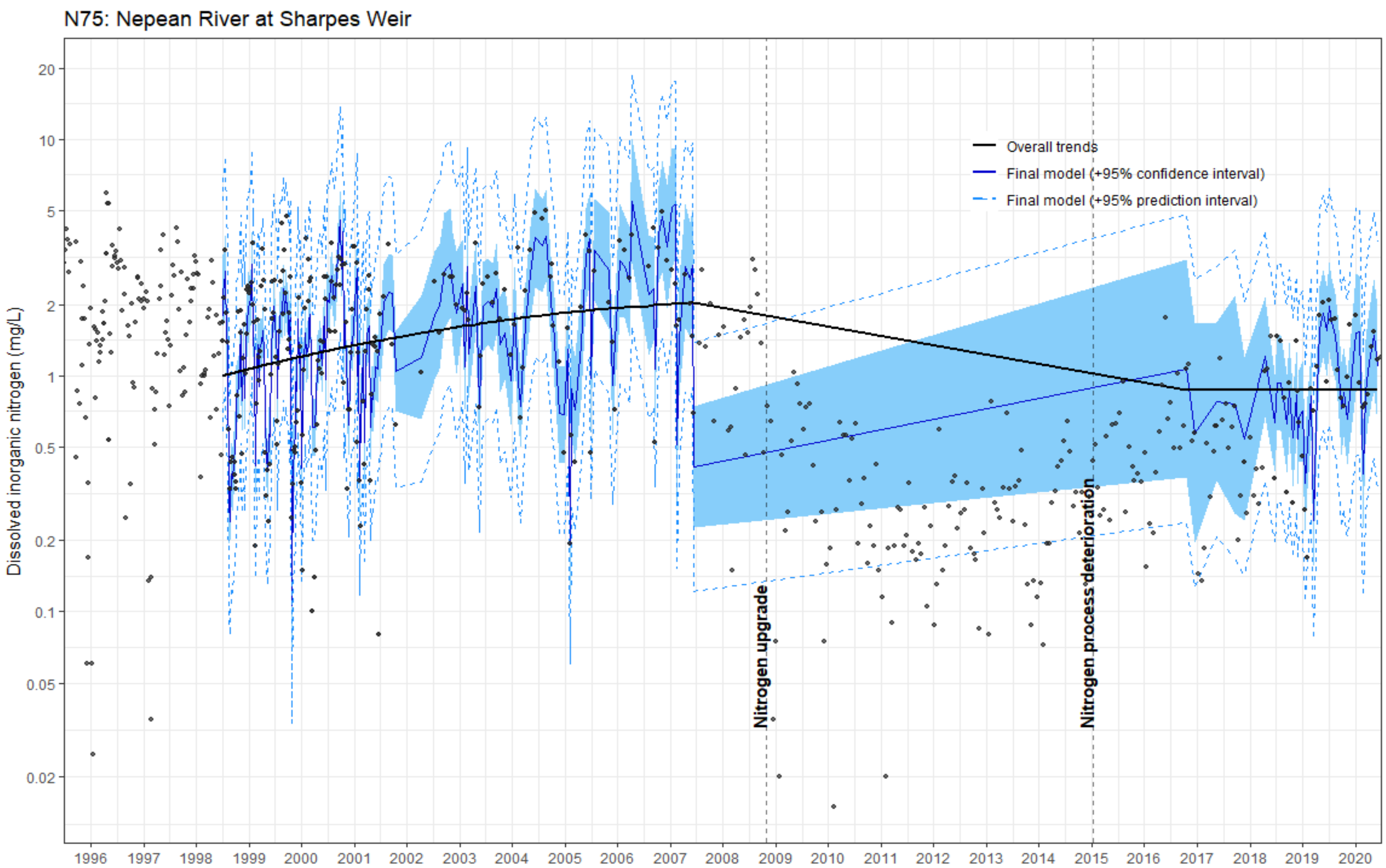

Figure 4-5 Dissolved inorganic nitrogen concentrations at Sharpes Weir (N75): fitting terms to model Camden Weir and Matahil Creek flow, DIN load from West Camden WWTP, along with linear and quadratic trends within each period and seasonal trends overlaid with the trends in each period

The model fitted the data well (R^2=0.63 and adjusted R^2=0.56) except for those at extremely low concentrations. One value showed a high leverage (ie terms in the model are included because of their contribution to the variability in the data). The distribution of the residuals was approximately Normal with a long left tail for the very low concentrations and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

Key outcomes

- Dissolved inorganic nitrogen concentration:

  - There was no ANZG default level for DIN concentration
  - The final reduced model fitted well with R^2=0.63 and adjusted R^2=0.56. However, the residual plots showed the model did not capture the extremely low DIN concentrations.
- Impact of flow:
  - Flow at Camden Weir was significantly correlated to the concentration of DIN at N75 ($p<0.0001$ on its own or after adjusting for all terms in the model)
    - when flow at Camden Weir is low eg 80 ML/day, a 10 ML increase in flow decreased the concentration at N75 by 4.9%
    - when flow at Camden Weir is moderate eg 100 ML/day, a 10 ML increase in flow decreased the concentration at N75 by 4%
    - when flow at Camden Weir is high eg 150 ML/day, a 10 ML increase in flow decreased the concentration at N75 by 2.7%.
  - Flow at Matahil Creek was significantly correlated to the concentration of DIN at N75 ($p=0.02$ after accounting for the effect of Camden Weir and $p=0.004$ after adjusting for all terms in the model).
    - when flow at Matahil Creek is low eg 5 ML/day, a 1 ML increase in flow increased the concentration at N75 by 4.1%
    - when is moderate eg 10 ML/day, a 1 ML increase in flow increased the concentration at N75 by 2.1%
    - when high eg 15 ML/day, a 1 ML increase in flow increased the concentration at N75 by 1.4%.
- Impact of WWTPs:
  - The DIN load from West Camden WWTP was significantly correlated to the concentration of DIN at N75 after taking into account the effect of flow from Camden Weir and Matahil Creek ($p=0.004$). However, it provided no additional information after adjusting for all terms in the model ($p=0.99$). No estimates of the effect of load on DIN concentrations at N75 were undertaken.
- Long term trends:
  - There was an increasing trend in DIN concentration prior to the nitrogen upgrade at West Camden WWTP (period 1).
  - There was no trend fitted before and after the nitrogen process deterioration (period 2 and Period 3)
  - As of mid-2020, the trend for DIN concentration was stable.

- Seasonal trends:
    - First order sine and cosine terms by year interactions were included to capture a pattern of one peak per year in February and one trough around August with a magnitude that differed between years.
- After adjusting for seasonal trends, flow and load from West Camden WWTP, the DIN geometric mean concentration:
    - Before the nitrogen upgrade at West Camden WWTP (period 1) was 0.61 mg/L (95% CI = 0.51 to 0.73 mg/L)
    - After the nitrogen process deterioration at West Camden WWTP (period 3) was 0.47 mg/L ((95% CI = 0.38 to 0.60 mg/L).
    - No comparison of the DIN loads between periods was undertaken because there were no records in period 2.

4.1.6 Nepean River at Sharpes Weir (N75) and Macquarie Grove Rd (N78) – Dissolved inorganic nitrogen concentration (downstream/upstream)

There were no dissolved inorganic nitrogen concentration records for the Nepean River at Sharpes Weir (N78) between mid-2011 and 2018 or after June 2019 as this is not a routine monitoring site. The data collected during the 2018-2019 period were for a special investigation. Hence the downstream-upstream analysis was undertaken on the 18-month time-period common to both series. There were 35 records in the series for the downstream site at N75, and 23 for the upstream site at N78 included in the analyses. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included site, site by flow interaction, site by linear and quadratic trends interactions, 1st order harmonic main effects and site by harmonic interaction terms to model different seasonal trends at each site. Note that only first order harmonic patterns with no Year term were fitted due to the small number of records and short time-period.

The model:

Log_{10}(DIN concentration) = site + 1st order sine + 1st order cosine + site by $\log_{10}$(flow) + site by linear trend + site by quadratic trend + site by 1st order sine trend + site by 1st order cosine trend

Where:

period and year are categorical factors.

Model reduction decisions:

- Remove the site by harmonic interaction terms
- Retain the 1st order main effect harmonic terms
- Remove the site by quadratic trend

Step 2: Fit the final, reduced model

Log_{10}(DIN concentration) = site + site by log_{10}flow + site by linear trend + 1^{st} order sine + 1^{st} order cosine

Where:

period and year are categorical factors.

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-6.

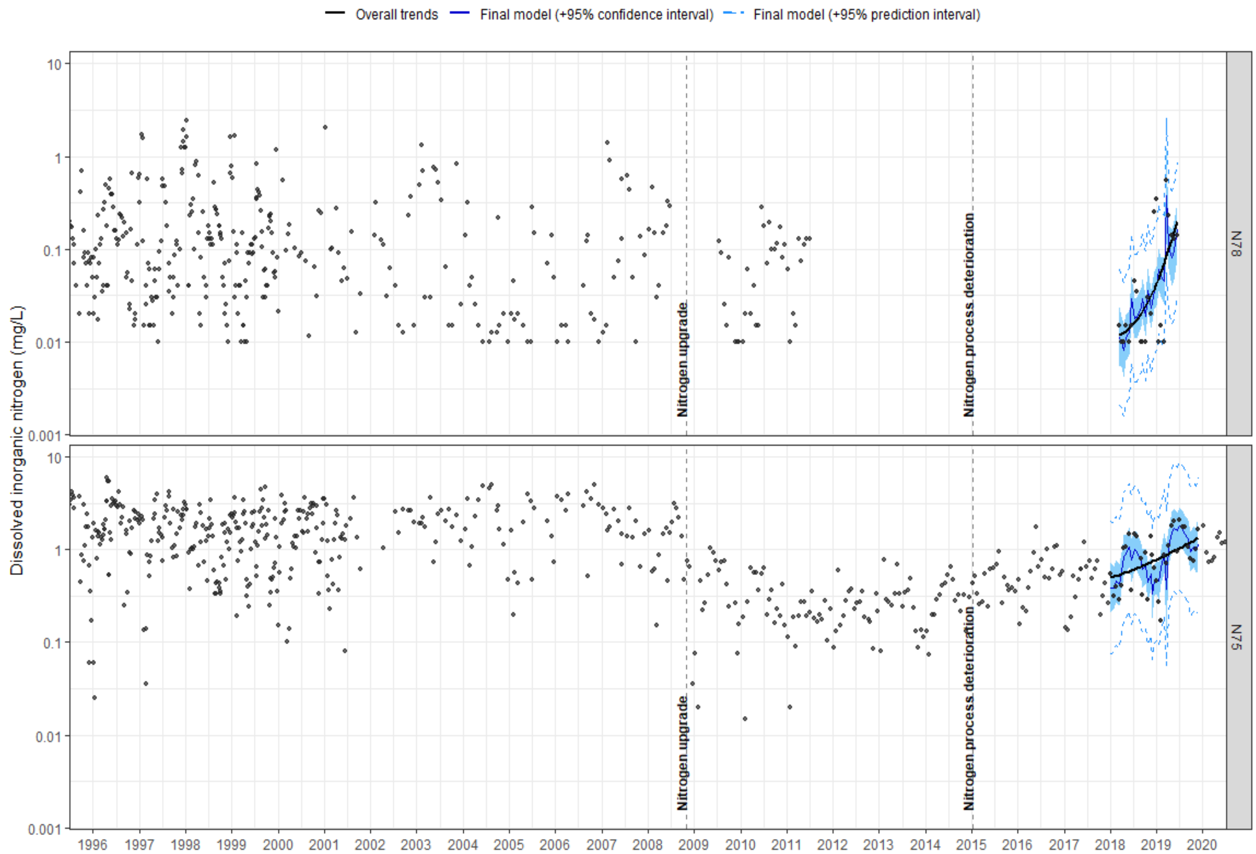

Figure 4-6 Dissolved inorganic nitrogen concentrations at Macquarie Grove Road (N78) and Sharpes Weir (N75), Nepean River: fitting terms to model site differences, associated flow and linear and quadratic trends and seasonal trends overlaid with the trend overlaid with the trend

The site and site by flow parameters were retained in the model as they were part of the study design. The p-values corresponding to the type III SS varied compared with the type I SS for all terms but retained the same conclusion. For example, the main effect harmonic terms had smaller p-values after adjusting for differences between sites in flow and linear trend.

The model fitted the data well (R^2=0.85 and adjusted R^2=0.83) except for those at extremely high and low concentrations. A few values showed a high leverage (ie terms in the model were included because of their contribution to the variability in the data). The distribution of the residuals was approximately Normal with a long tail for the low values. Residuals plotted against the fitted values showed no remaining pattern in the data series. However, the Scale-Location plot highlighted an unusual pattern of the variances of records in the middle of the predicted values to be higher than those at either end. This could be due to the small number of records in this series.

Key outcomes

- Dissolved inorganic nitrogen concentration:
  - DIN was consistently lower at the upstream site (N78) compared to the downstream site (N75)
  - There was no ANZG default level for DIN concentration
  - The large gap in the data series at site N78 resulted in a comparison of the two data series for the 18-month period across both sites from January 2018 to July 2019
  - The period of data for analysis was fully contained in the period after the nitrogen process deterioration at the West Camden WWTP (period 3) so no investigation of the differences between sites in the various periods identified for the N75 analyses was required.
- The final reduced model fitted well with R^2=0.85 and adjusted R^2=0.83. However, the residual plots showed the model did not capture the extremely high DIN concentrations
- Flow:
  - The relationship between flow and DIN concentration differed between sites (p=0.002 after adjusting for site differences and an overall seasonal pattern, and 0.008 after adjusting for all terms in the model). The relationship was negative at N75 (p=0.10) and positive at N78 (p=0.01)
    - when flow is low eg 80 ML/day, an increase of 10 ML/day decreased the DIN concentrations at N75 by 4.4%, whereas at N78 concentrations were increased by 6.8%.
    - when flow is medium, eg 100 ML/day, an increase of 10 ML/day decreased the DIN concentrations at N75 by 3.6% and increased concentrations at N78 by 5.5%.
    - when flow is high, eg 150 ML/day, an increase of 10 ML/day decreased DIN concentrations at N75 by 2.4% and increased concentrations at N78 by 3.7%.
- Long term trends:
  - There was a significant interaction between site and linear trend after adjusting for site differences, site by flow differences and an overall seasonal pattern (p<0.0001)
  - The DIN concentration showed an increasing trend at both sites, with a steeper trend at N78
- Seasonal trends:

- A seasonal trend was modelled, however, this was similar at each site. That is, a peak around late January/February months and trough around late June/July.

- Site dissolved inorganic nitrogen geometric mean concentrations:
  - After adjusting for seasonal trends and stream flow, the geometric mean DIN concentration at site N78 was 0.04 mg/L (95% CI=0.03 to 0.06 mg/L), and at site N75 was 0.72 mg/L (95% CI=0.54 to 0.95 mg/L).
- Comparing dissolved inorganic nitrogen geometric mean concentrations between sites:
  - The geometric mean DIN concentration at site N75 was 1679% times as large as that at site N78 (95%CI = 1063 to 2651%). Note the confidence interval is extremely large due to the small number of records.

4.1.7 West Camden WWTP – Total phosphorus load

There were 1522 total phosphorus load records from West Camden WWTP in this data series. Prior to the phosphorus upgrade (period 1) there were 832 records, after the upgrade (period 2) there were 690 records. All records are included in the analyses. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included the two periods defined by the phosphorus upgrade, linear and quadratic trends within each period and 1st, 2nd and 3rd order harmonic main effects and by year interaction terms to model the seasonal trends.

The model:

Log_{10}(TP load) = period + linear trend in period 1 + linear trend in period 2 + quadratic trend in period 1 + quadratic trend in period 2 + 1st order sine + 1st order cosine + 2nd order sine + 2nd order cosine + 3rd order sine + 3rd order cosine + 1st order sine trend by year + 1st order cosine trend by year + 2nd order sine trend by year + 2nd order cosine trend by year + 3rd order sine trend by year + 3rd order cosine trend by year

Where:

period and year are categorical factors.

Model reduction decisions:

- Retain all harmonic interaction terms as the p-values for the 3rd order terms from the type I SS were <0.15
- Remove the main effect harmonic terms since they can be included in the harmonic interaction terms.

Step 2: Fit the final, reduced model

Log_{10}(TP load) = period + linear trend in period 1 + linear trend in period 2 + quadratic trend in period 1 + quadratic trend in period 2 + 1^{st} order sine trend by year + 1^{st} order cosine trend by year + 2^{nd} order sine trend by year + 2^{nd} order cosine trend by year

Where:

period and year are categorical factors.

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-7.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix F). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table F-13 and Table F-14, respectively. The residual plots for this model are shown in Figure F-7.

All terms in the final, reduced model had a p-value for the corresponding type I SS <0.15. Each term in the model had a similar p-value after adjusting for all other terms in the model (type III SS) suggesting that each term was explaining different parts of the variability of the data series.

The model fitted the data (R^2=0.35 and adjusted R^2=0.27) except for those at extremely high and low loads. Four values showed a very high leverage estimate (ie terms in the model are included because of their contribution to the variability in the data). The distribution of the residuals was approximately Normal and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

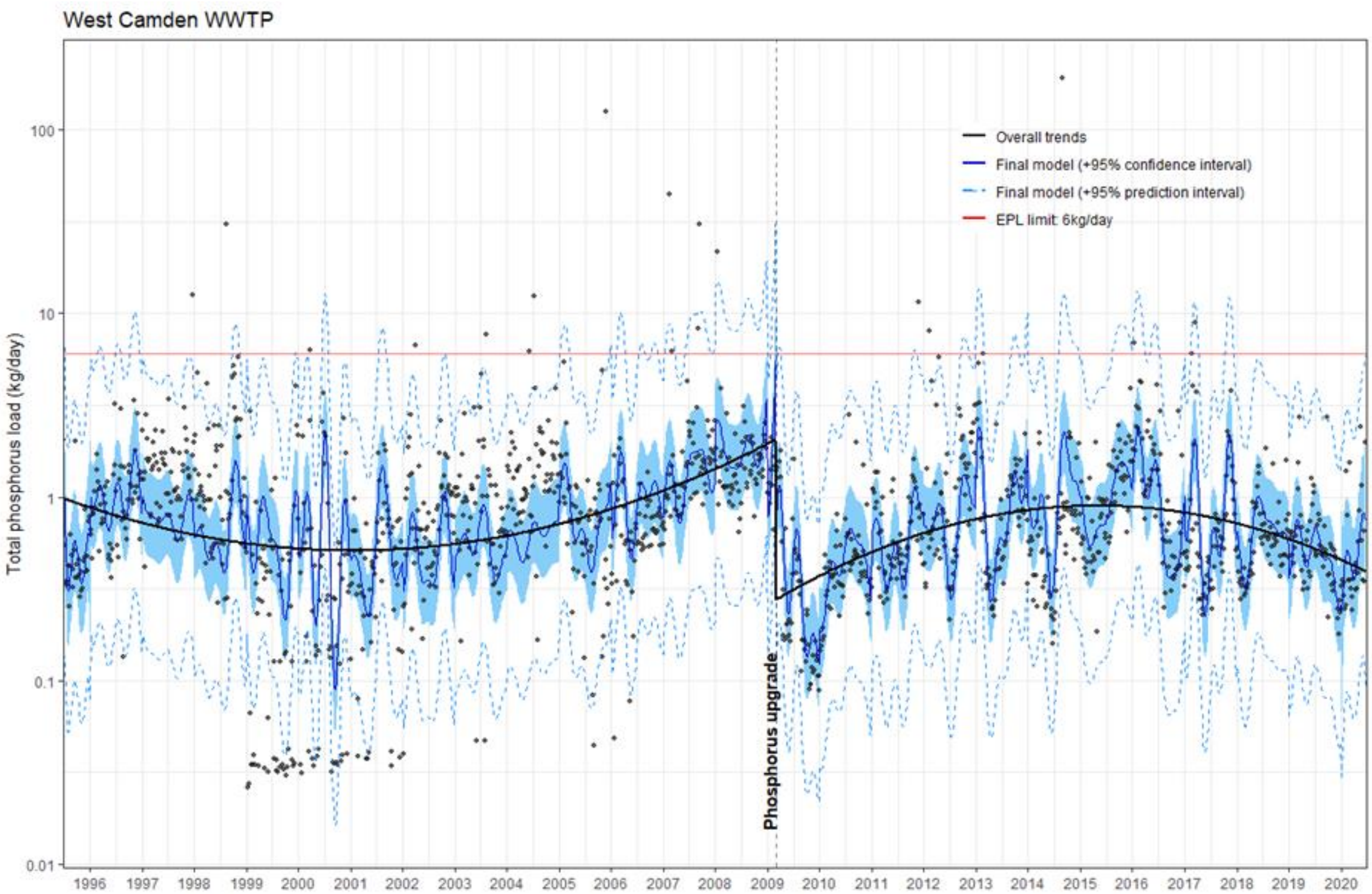

Figure 4-7 Total phosphorus load from West Camden WWTP: fitting terms to model interventions, linear and quadratic trends within each period and seasonal trends overlaid with the trends in each period

Key outcomes

- Total phosphorus load:
  - The majority of the records were less than the current EPL limit of 6 kg/day
  - The final reduced model fitted with R2=0.35 and adjusted R2=0.27. However, the residual plots showed the model did not capture the extremely high or low total phosphorus loads, particularly prior to the upgrade (period 1).
- Long term trends:
  - Significant curvilinear trends were observed in each period
    - Before the phosphorus upgrade (period 1), the TP load gradually decreased until around 2002 before increasing

    - There was an immediate reduction in TP load after the upgrade (period 2). The trend increased until around 2015 before the load started to decrease
    - As of mid-2020, the total phosphorus load trend was decreasing

- Seasonal trends:
  - First, second and third order sine and cosine terms by year interactions were included to capture a more complex pattern of three total phosphorus load peaks per year, capturing the largest one February and two smaller ones in late May/ early June and September. The lowest trough was around the late October/early November. The magnitude of these peaks and troughs differed between years.
- After adjusting for seasonal trends, the modelled geometric mean total phosphorus load:
  - prior to the upgrade (period 1) was 0.495 kg/day (95% CI=0.454 to 0.541 kg/day)
  - after the upgrade (period 2) was 0.914 kg/day (95% CI=0.830 to 1.007 kg/day).
- Comparing the total phosphorus loads between periods:
  - The total phosphorus load in the period after the upgrade increased by 185% compared to the period before the upgrade (95% CI=162 to 210%).

4.1.8 Nepean River at Sharpes Weir (N75) – Total phosphorus concentration

There were 581 total phosphorus concentration records from the Nepean River at Sharpes Weir (N75) in the data series. Prior to the phosphorus upgrade in 2009 (period 1) there were 385 records, and after the upgrade there were 196 records (period 2). Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included flow at Camden Weir, flow at Matahil Creek, West Camden TP load, the two periods defined by the phosphorus upgrade at West Camden WWTP, linear and quadratic trends within each period and 1st, 2nd and 3rd order harmonic main effects and harmonic interaction terms to model the seasonal trends. Note that no concentration for TP at an upstream site was included in the full model. The upstream site (N78) did not have enough records to be included in this model.

The model:

Log_{10}(TP concentration) = log_{10}(flow at Camden Weir) + log_{10}(flow at Matahil Creek) + log_{10}(TP load at West Camden WWTP) + period + linear in period 1 + linear in period 2 + quadratic in period 1 + quadratic in period 2 + 1st order sine + 1st order cosine + 2nd order sine + 2nd order cosine + 3rd order sine + 3rd order cosine + 1st order sine trend by year + 1st order cosine trend by year + 2nd order sine trend by year + 2nd order cosine trend by year + 3rd order sine trend by year + 3rd order cosine trend by year

Where:

period and year are categorical factors.

Model reduction decisions:

- Remove the main effect harmonic terms since they can be included in the harmonic interaction terms.

Step 2: Fit the final, reduced model

Log_{10}(TP concentration) = $\log_{10}$(flow at Camden Weir) + $\log_{10}$(flow at Matahil Creek) + $\log_{10}$(TP load at West Camden WWTP) + period + linear in period 1 + quadratic in period 1 + linear in period 2 + quadratic in period 2 + 1st order sine trend by year + 1st order cosine trend by year + 2nd order sine trend by year + 2nd order cosine trend by year + 3rd order sine trend by year + 3rd order cosine trend by year

Where:

period and year are categorical factors.

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-8.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix F). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table F-15 and Table F-16, respectively. The residual plots for this model are shown in Figure F-8.

The period parameter as well as the flow at Camden Weir, the flow at Matahil Creek and the WWTP TP load estimates were retained in the model as part of the study design. The p-values corresponding to the type III SS varied compared with the type I SS. The linear trend in period 1 did not meet the <0.15 cut-off based on the type I SS, but was included in the model because the quadratic trend for period 1 had $p<0.0001$. However, the linear trend was significant after adjusting for all terms in the model ($p<0.0001$) suggesting, that after accounting for the seasonal trends there was an additional underlying linear component to the curvilinear trend.

The model fitted the data well (R^2=0.71 and adjusted R^2=0.60) except for those at extremely high concentrations and the very low concentrations at or near the limit of quantification. One value showed a high leverage (ie terms in the model are included because of their contribution to the variability in the data). The distribution of the residuals was approximately Normal with a long left tail for the very low concentrations and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

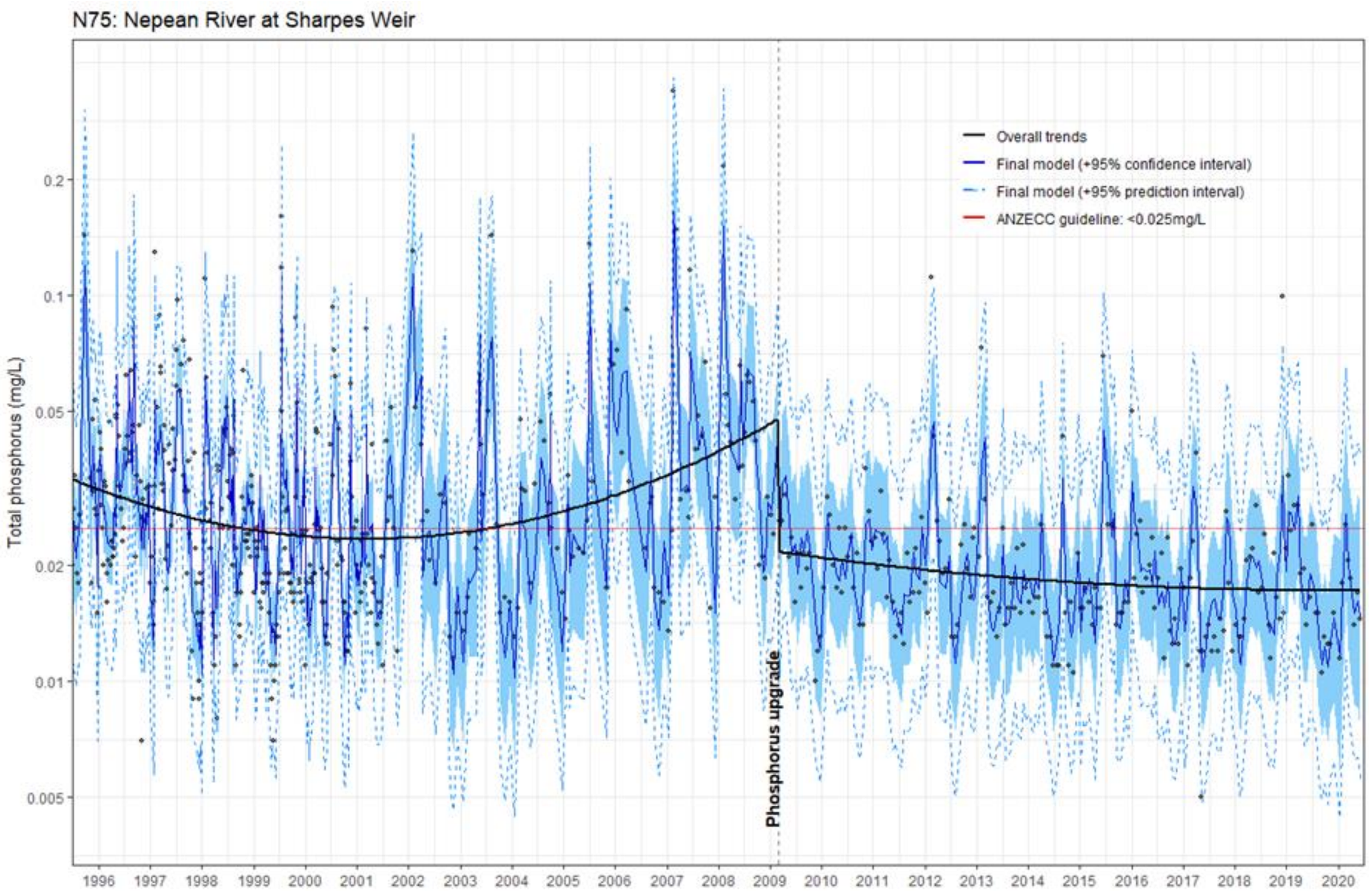

Figure 4-8 Total phosphorus concentrations at Sharpes Weir (N75): fitting terms to model Camden Weir and Matahil Creek flow, TN load from West Camden WWTP, along with linear and quadratic trends within each period and seasonal trends overlaid with the trends in each period

Key outcomes

- Total phosphorus concentration:
  - The majority of records after the phosphorus upgrade (period 2) were below the ANZG default level of <0.025 mg/L
  - The final reduced model fitted well with R^2=0.71 and adjusted R^2=0.60. However, the residual plots showed the model did not capture the extremely high TP concentrations.
- Impact of flow:
  - Camden Weir flow
    - Flow at Camden Weir was significantly correlated to the concentration of TP at N75 ($p<0.0001$ on its own or after adjusting for all terms in the model).

- when flow at Camden Weir is low eg 80 ML/day, a 10 ML increase in flow increased the TP concentration at N75 by 1.2%
- when flow at Camden Weir is moderate eg 100 ML/day, a 10 ML increase in flow increased the concentration at N75 by 1%
- when flow at Camden Weir is high eg 150 ML/day, a 10 ML increase in flow increased the concentration at N75 by 0.6%.

  - Matahil Creek
    - Flow at Matahil Creek was significantly correlated to the concentration of TP at N75 ($p=0.002$ after accounting for the effect of Camden Weir and $p<0.0001$ after adjusting for all terms in the model).
      - when flow at Matahil Creek is low eg 5 ML/day, a 1 ML increase in flow increased the concentration at N75 by 4.3%
      - when flow is moderate eg 10 ML/day, a 1 ML increase in flow increased the concentration at N75 by 2.2%
      - when flow is high eg 15 ML/day, a 1 ML increase in flow increased the concentration at N75 by 1.4%.

- Impact of WWTPs:
  - The TP load from West Camden WWTP was significantly correlated to the concentration of TP at N75 after taking into account the effect of flow from Camden Weir and Matahil Creek ($p<0.0001$) and after adjusting for all terms in the model ($p=0.0006$)
    - when the load from West Camden WWTP is low eg 0.5 kg/day, a 0.1 kg/day increase in load increased the TP concentration at N75 by 1.1%
    - when the load from West Camden WWTP is moderate eg 0.8 kg/day, a 0.1 kg/day increase in load increased the concentration at N75 by 0.7%
    - when the load from West Camden WWTP is high eg 1.1 kg/day, a 0.1 kg/day increase in load increased the concentration at N75 by 0.5%.
- Long term trends:
  - There was a curvilinear trend in TP concentration prior to the phosphorus upgrade at West Camden WWTP (period 1), decreasing to around 2002, before increasing.
  - After the phosphorus upgrade (period 2) the TP concentration gradually decreased.
  - As of mid-2020, the trend in total phosphorus concentration at the downstream site was slightly decreasing.
- Seasonal trends:
  - First, second and third order sine and cosine terms by year interactions were included to capture a more complex pattern of three peaks per year, capturing the largest one in February and two smaller ones in late May/early June and September. The lowest

trough was around the late October/early November. The magnitude of these peaks and troughs differed between years.

- After adjusting for seasonal trends, flow and load from West Camden WWTP, the modelled geometric mean total phosphorus concentration:
  - Before the phosphorus upgrade at West Camden WWTP (period 1) was 0.035 mg/L (95% CI = 0.032 to 0.039 mg/L)
  - After the phosphorus upgrade (period 2) was 0.019 mg/L (95% CI = 0.017 to 0.020 mg/L)
- Comparing the total phosphorus concentrations between periods:
  - The TP concentrations in the period after the upgrade was 53% of the period before the upgrade (95% CI=47 to 59%).

4.1.9 Nepean River at Sharpes Weir (N75) and Macquarie Grove Rd (N78)–Total phosphorus concentration (downstream/upstream)

There were no total phosphorus concentration records from the Nepean River at Macquarie Grove Road (N78) between mid-2011 and 2018 or after June 2019 as this is not a routine monitoring site. The data collected during the 2018-2019 period were for a special investigation. Hence the downstream-upstream analysis was undertaken on the 18-month time-period common to both series. There were 35 total phosphorus concentration records in the series for the downstream site at N75 and 23 from the upstream site at N78 included in the analyses. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included site, site by flow interaction, site by linear and quadratic trends interactions, 1^{st} order harmonic main effects and site by harmonic interaction terms to model different seasonal trends at each site. Note that only first order harmonic patterns with no Year term were fitted due to the small number of records and short time-period.

The model:

Log_{10}(TP concentration) = site + 1^{st} order sine + 1^{st} order cosine + site by log_{10}(flow) + site by linear trend + site by quadratic trend + site by 1^{st} order sine trend + site by 1^{st} order cosine trend

Model reduction decisions:

- Remove the main effect harmonic terms.
- Retain the quadratic trend

Step 2: Fit the final, reduced model

Log_{10}(TP concentration) = site + site by log_{10}flow + site by linear trend + site by quadratic trend + site by 1^{st} order sine trend + site by 1^{st} order cosine trend

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-9.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix F). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table F-17 and Table F-18, respectively. The residual plots for this model are shown in Figure F-9.

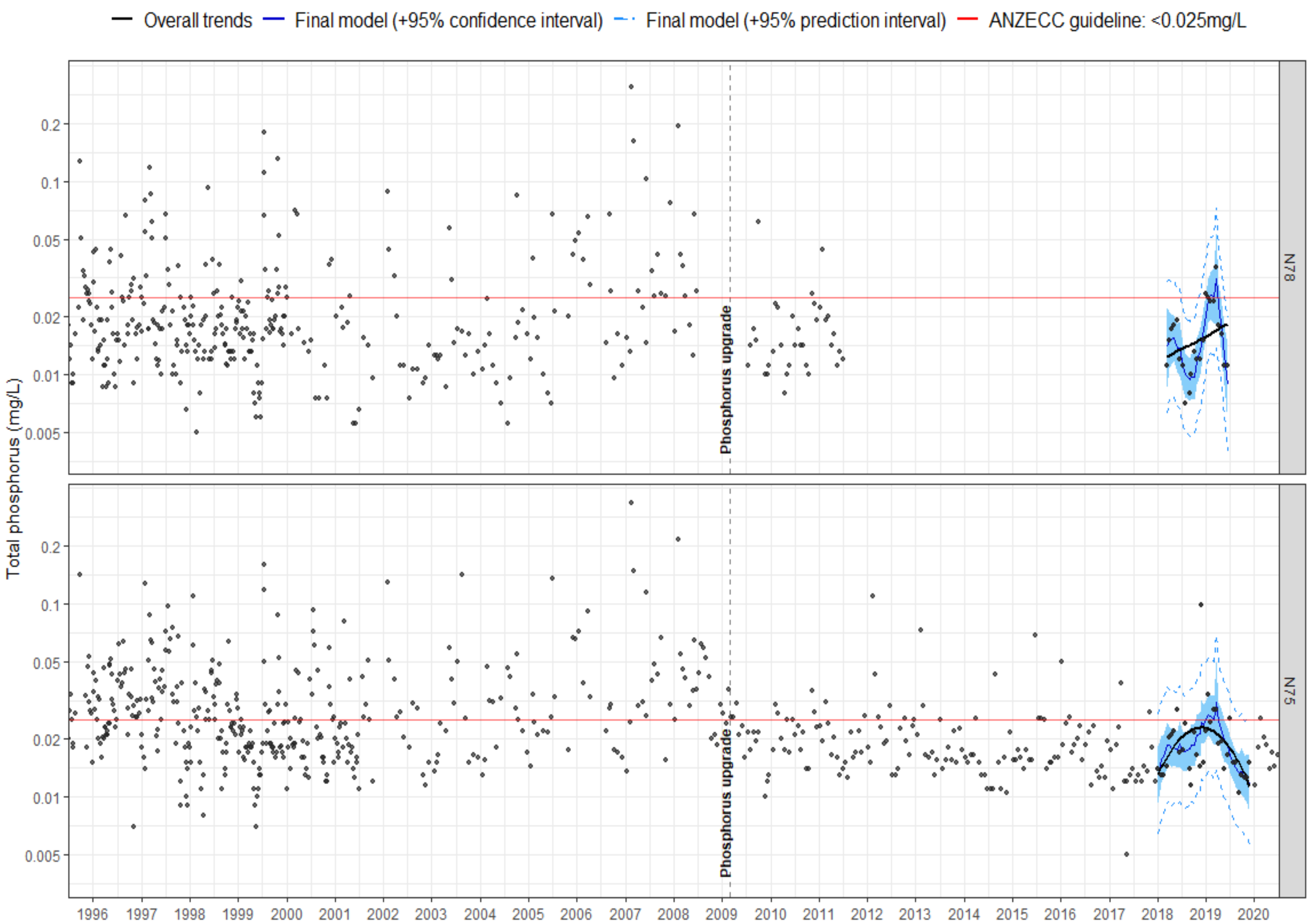

Figure 4-9 Total phosphorus concentrations at Macquarie Grove Road (N78) and Sharpes Weir (N75), Nepean River: fitting terms to model site differences, associated flow and linear and quadratic trends and seasonal trends overlaid with the trend

The site and site by flow parameters were retained in the model as they formed part of the study design. The site by linear trend parameter was retained in the model as the site by quadratic trend was significant (p=0.02). The p-values corresponding to the Type III SS varied compared with the type I SS for the site, site by flow and site by linear trend terms. Differences between sites overall and adjusted for flow were not significant after adjusting for all terms in the model suggesting that the different seasonal trends accounted for the differences. This was not unexpected due to the short time period for this analysis.

The model does not fit the data as well as for nitrogen; however, it is still good (R^2=0.55 and adjusted R^2=0.45). A few values showed a high leverage (ie terms in the model are included because of their contribution to the variability in the data). The distribution of the residuals was approximately Normal with a few extremely high values. Residuals plotted against the fitted values showed no remaining pattern in the data series.

Key outcomes

- Total phosphorus concentrations:
    - Were generally lower than the ANZG default level of <0.025 mg/L at both sites
    - The large gap in the data series at site N78 resulted in a comparison of the two data series for the 18-month period across both sites from January 2018 to July 2019
    - The period of data for analysis was fully contained in the period after the process change at the West Camden WWTP so no investigation of the differences between sites in the various periods identified for the N75 analyses was required
- The final reduced model provided a reasonable fit with R^2=0.55 and adjusted R^2=0.45. However, the residual plots showed the model did not capture the few extremely high total phosphorus concentrations. These values were so high that if the model were to account for them it could be considered to be an over-parameterised or over-fitting model (ie a model with too many terms in it that has been driven by the sample observations rather than the scientific understanding).
- Flow:
    - The relationship between flow and TP concentration differed between sites (p=0.002) after adjusting for site differences. However, it did not differ after adjusting for all terms in the model (p=0.36).
    - The coefficient at N75 was not significant (p=0.25), hence no estimates of the relationship between flow and TP concentration at N75 was undertaken
    - The coefficient for N78 was also not significant (p=0.40), hence no estimates were undertaken
- Long term trends:
    - There was a significant interaction between site and quadratic trend after adjusting for site differences, site by flow differences and site by linear trend differences (p=0.02). However, there was no significant interaction between site and linear trend after adjusting for site differences and site by flow differences (p=0.24) but was retained in the model due to the significant quadratic trend. After accounting for all terms in the model the differences in linear trends became significant (p=0.002)
    - There is an increasing linear trend at both sites, with a much larger trend seen at N78.

    - Both sites also have significantly decreasing quadratic trends suggesting that the model is on a downward trend at the end of the series, possibly reflecting the decrease in concentration expected during the winter period as was seen with TN.

- Seasonal trends:
  - First order sine and cosine terms by site interactions were included to allow the seasonal trend to differ between sites and to capture one peak per year around February
- Site total phosphorus geometric mean concentrations:
  - After adjusting for seasonal trends and stream flow, the geometric mean TP concentration at site N78 was 0.019 mg/L (95% CI=0.015 to 0.024 mg/L), and at site N75 was 0.023 mg/L (95% CI=0.020 to 0.027 mg/L).
- Comparing modelled geometric mean total phosphorus concentrations between sites:
  - Although both series were generally less than the ANZG default level, the geometric mean TP concentration at site N75 was 123% of that at site N78 (95%CI = 92 to 164%).

4.1.10 Nepean River at Sharpes Weir (N75) – Chlorophyll-*a* concentration

There were 579 chlorophyll-*a* records from the Nepean River at Sharpes Weir (N75) in the data series. Prior to the phosphorus upgrade in 2009 there were 384 records, and after the upgrade there were 195 records. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included flow at Camden Weir, flow at Matahil Creek, West Camden TN and TP loads, the two periods defined by the phosphorus upgrade at West Camden WWTP, linear and quadratic trends within each period and 1^{st}, 2^{nd} and 3^{rd} order harmonic main effects and harmonic interaction terms to model the seasonal trends.

The model:

Log_{10}(Chl-*a* concentration) = $\log_{10}$(flow at Camden Weir) + $\log_{10}$(flow at Matahil Creek) + $\log_{10}$(TN load at West Camden WWTP)+ $\log_{10}$(TP load at West Camden WWTP) + period + linear in period 1 + linear in period 2 + quadratic in period 1 + quadratic in period 2 + 1^{st} order sine + 1^{st} order cosine + 2^{nd} order sine + 2^{nd} order cosine + 3^{rd} order sine + 3^{rd} order cosine + 1^{st} order sine trend by year + 1^{st} order cosine trend by year + 2^{nd} order sine trend by year + 2^{nd} order cosine trend by year + 3^{rd} order sine trend by year + 3^{rd} order cosine trend by year

Where:

period and year are categorical factors.

Model reduction decisions:

- Remove the main effect harmonic terms since they can be included in the harmonic interaction terms.
- Remove the linear and quadratic trends in Period 2

Step 2: Fit the final, reduced model

Log_{10}(Chl-*a* concentration) = log_{10}(flow at Camden Weir) + log_{10}(flow at Matahil Creek) + log_{10}(TN load at West Camden WWTP)+ log_{10}(TP load at West Camden WWTP) + period + linear in period 1 + quadratic in period 1 + 1st order sine trend by year + 1st order cosine trend by year + 2nd order sine trend by year + 2nd order cosine trend by year + 3rd order sine trend by year + 3rd order cosine trend by year

Where:

period and year are categorical factors.

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-10.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix F). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table F-19 and Table F-20, respectively. The residual plots for this model are shown in Figure F-10.

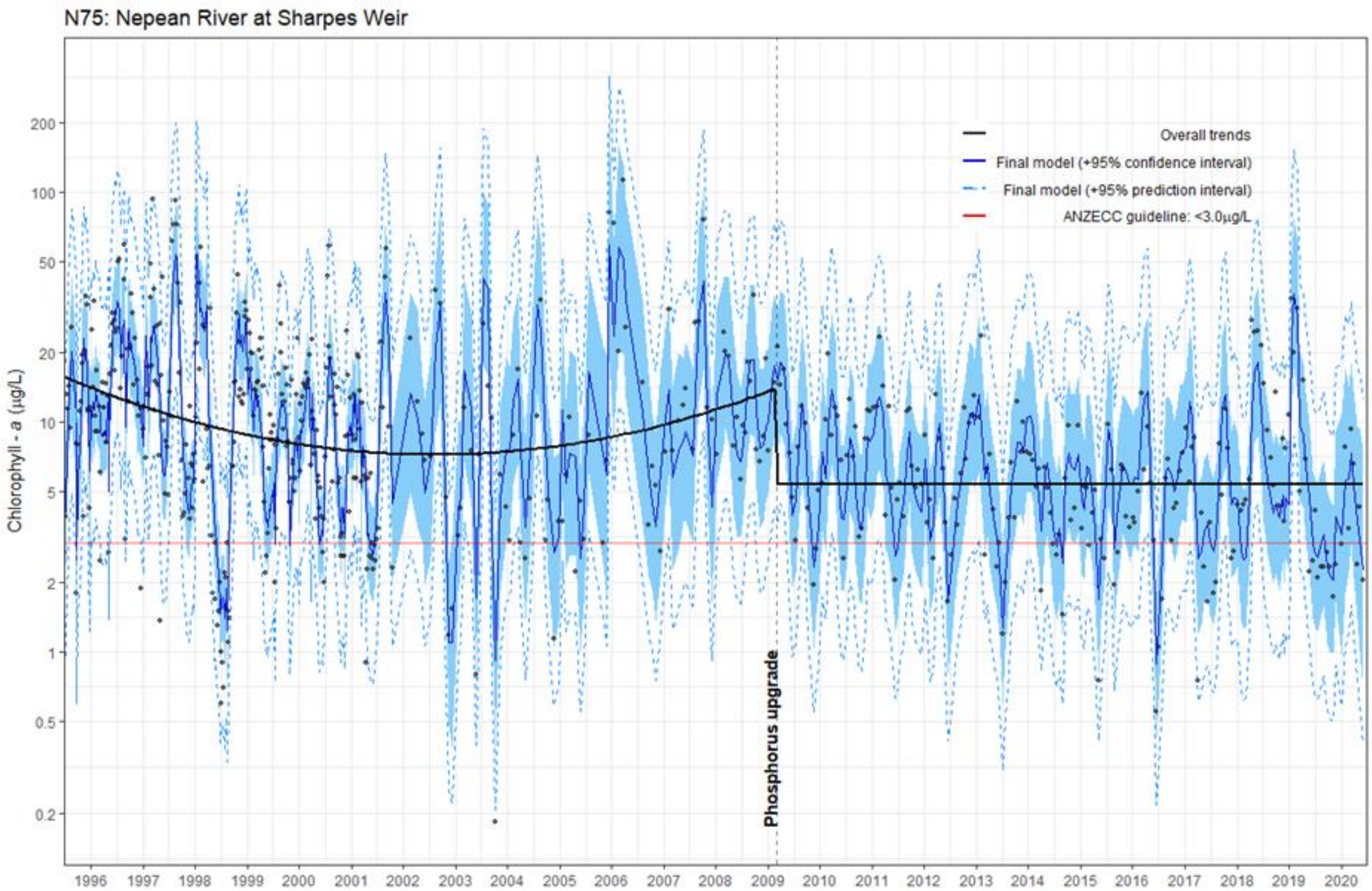

Figure 4-10 Chlorophyll-*a* concentrations at Sharpes Weir (N75): fitting terms to model Camden Weir and Matahil Creek flow, TN and TP loads from West Camden WWTP, along with linear and quadratic trends within each period and seasonal trends overlaid with the trends in each period

The period parameter as well as the flow at Camden Weir, the flow at Matahil Creek and the WWTP TN and TP load estimates were retained in the model as part of the study design. The p-values corresponding to the Type III SS varied compared with the type I SS. The linear trend in period 1 did not meet the <0.15 cut-off based on the type I SS, but was included in the model because the quadratic trend for period 1 had p<0.0001. However, the linear trend was significant after adjusting for all terms in the model (p<0.0001) suggesting, that after accounting for the seasonal trends there was an additional underlying linear component to the curvilinear trend. There was also a difference for Matahil Creek flow.

The model fitted the data well (R^2=0.68 and adjusted R^2=0.56) except for those at extremely high concentrations and the very low concentrations at or near the limit of quantification. A few values showed a high leverage (ie terms in the model are included because of their contribution to the variability in the data). The distribution of the residuals was approximately Normal with a long left tail for the very low concentrations. Residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

Key outcomes

- Chlorophyll-*a* concentration:
  - The majority of the Chl-*a* records were above the ANZG default level of <3.0 µg/L
  - The final reduced model fitted well with R^2=0.68 and adjusted R^2=0.56. However, the residual plots showed the model did not capture the extremely high or low Chl-*a* concentrations.
- Impact of flow:
  - Camden Weir flow
    - Flow at Camden Weir was significantly correlated to the concentration of Chl-*a* at N75 (p<0.0001 on its own or after adjusting for all terms in the model).
      - when flow at Camden Weir is low eg 80 ML/day, a 10 ML increase in flow decreased the Chl-*a* concentration at N75 by 1.6%
      - when flow at Camden Weir is moderate eg 100 ML/day, a 10 ML increase in flow decreased the Chl-*a* concentration at N75 by 1.3%
      - when flow at Camden Weir is high eg 150 ML/day, a 10 ML increase in flow decreased the Chl-*a* concentration at N75 by 0.9%.
  - Matahil Creek flow
    - Flow at Matahil Creek was significantly correlated to the concentration of Chl-*a* at N75 (p<0.0001) after accounting for the effect of Camden Weir and p=0.38 after adjusting for all terms in the model suggesting that the seasonal trend accounts for some of the relationship with flow at Matahil Creek.
      - when flow at Matahil Creek is low eg 5 ML/day, a 1 ML increase in flow decreased the Chl-*a* concentration at N75 by 1.3%
      - when flow is moderate eg 10 ML/day, a 1 ML increase in flow decreased the Chl-*a* concentration at N75 by 0.7% and
      - when flow is high eg 15 ML/day, a 1 ML increase in flow decreased the Chl-*a* concentration at N75 by 0.5%.
- Impact of WWTPs:
  - The TN and TP loads from West Camden WWTP were not significantly correlated to the concentration of Chl-*a* at N75 after taking into account the effect of flow from Camden Weir and Matahil Creek (p=0.3 and 0.8 respectively).
  - After adjusting for all terms in the model, there was still no relationship evident with TN load (p=0.65) but there was a suggestion of a relationship with TP load (p=0.06).

- No estimates of the relationship between TN or TP loads from West Camden WWTP and concentrations of Chl-*a* at N75 were undertaken.

- Long term trends:
  - There was a curvilinear trend prior to the phosphorus upgrade at West Camden WWTP, with Chl-*a* gradually decreasing to around 2003, before increasing.
  - There was no trend in Chl-*a* concentration after the phosphorus upgrade.
  - As of mid-2020, the Chl-*a* trend was flat.
- Seasonal trends:
  - First, second and third order sine and cosine terms by year interactions were included to capture a more complex pattern of three peaks per year, capturing the largest one in February and two smaller ones in late May/ early June and September. The lowest trough was around the late October/early November. The magnitude of these peaks and troughs differed between years.
- After adjusting for seasonal trends, flow and load from West Camden WWTP, the Chl-*a* geometric mean concentration:
  - Before the phosphorus upgrade at West Camden WWTP was 5.48 µg/L (95% CI = 4.67 to 6.44 µg/L)
  - After the phosphorus upgrade was 5.00 µg/L (95% CI = 4.49 to 5.56 µg/L)
- Comparing the Chl-*a* concentrations between periods:
  - The Chl-*a* concentration in the period after the upgrade was 91% of the period before the upgrade (95% CI=76 to 109%).

4.1.11 Nepean River at Sharpes Weir (N75) and Macquarie Grove Rd (N78) – Chlorophyll-*a* concentration (downstream/upstream)

There were no chlorophyll-*a* concentration records from the Nepean River at Macquarie Grove Road (N78) between mid-2011 and 2018 or after June 2019 as this is not a routine monitoring site. The data collected during the 2018-2019 period were for a special investigation. Hence the downstream-upstream analysis was undertaken on the 18-month time-period common to both series. There were 35 records in the series for the downstream site at N75 and 23 for the upstream site at N78 included in the analyses. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included site, site by flow interaction, site by linear and quadratic trends interactions, 1^{st} order harmonic main effects and site by harmonic interaction terms to model different seasonal trends at each site. Note that only first order harmonic patterns with no Year term were fitted due to the small number of records and short time-period.

The model:

Log_{10}(Chl-*a* concentration) = site+ 1st order sine + 1st order cosine + site by log_{10}(flow) + site by linear trend + site by quadratic trend + site by 1st order sine trend + site by 1st order cosine trend

Model reduction decisions:

- Remove the main effect harmonic terms.

Step 2: Fit the final, reduced model

Log_{10}(Chl-*a* concentration) = site + site by log_{10}flow + site by linear trend + site by quadratic trend + site by 1st order sine trend + site by 1st order cosine trend

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-11.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix F). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table F-21 and Table F-22, respectively. The residual plots for this model are shown in Figure F-11.

The site and site by flow parameters were retained in the model as they were part of the study design. The p-values corresponding to the Type III SS varied compared with the type I SS, in particular for the site and site by flow terms. After adjusting for all terms in the model, the site term became significant (p=0.02) and the site by flow term had p=0.06 suggesting that after accounting for the relationships between the various trends, there was a difference between sites on average and the relationship with flow differed between sites.

The model fitted the data well (R^2=0.60 and adjusted R^2=0.50). A few values showed a high leverage (ie terms in the model are included because of their contribution to the variability in the data). The distribution of the residuals was approximately Normal. Residuals plotted against the fitted values and the Scale-Location plots showed that, as low predicted values increase, the size of the residual decreases and the variance decreases. However, there were few records, particularly at the lower levels of Chl-*a*, so this is more likely applicable to just this set of data, rather than violating the *a priori* decision that Chl-*a* concentrations were log normally distributed.

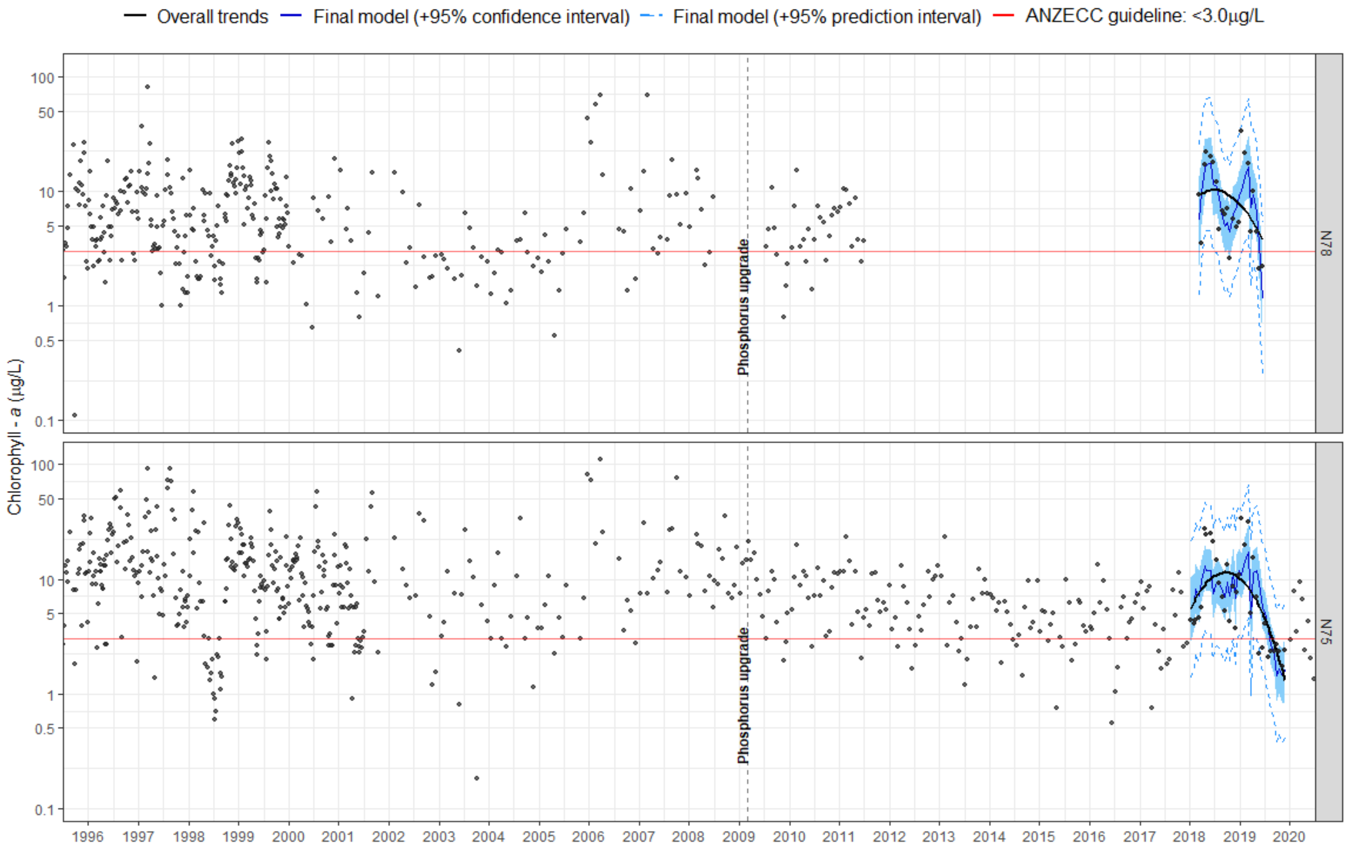

Figure 4-11 Chlorophyll-*a* concentrations at Macquarie Grove Road (N78) and Sharpes Weir (N75), Nepean River: fitting terms to model site differences, associated flow and linear and quadratic trends and seasonal trends overlaid with the trend

Key outcomes

- Chlorophyll-*a* concentration:
  - Was generally higher than the ANZG default level of <3.0 µg/L at both sites
  - The large gap in the data series at site N78 resulted in a comparison of the two data series for the 18-month period across both sites from January 2018 to July 2019
  - The period of data for analysis was fully contained in the period after the TP upgrade at West Camden WWTP so no investigation of the differences between sites in the various periods identified for the N75 analyses was required.
- The final reduced model fitted well with R^2=0.60 and adjusted R^2=0.50. However, the residual plots showed the model did not capture the extremely high or low Chl-*a* concentrations

- Flow:
  - The relationship between flow and Chl-a concentration showed no difference between sites (p=0.85) after adjusting for site and 0.060 after adjusting for all terms in the model.
  - The coefficient at N75 was significant (p=0.03)
    - when flow is low eg 80 ML/day, an increase of 10 ML/day decreased the Chl-a concentrations at N75 by 5.1%.
    - when flow is medium, eg 100 ML/day, an increase of 10 ML/day decreased the Chl-a concentrations at N75 by 4.1%
    - when flow is high, eg 150 ML/day, an increase of 10 ML/day decreased Chl-a concentrations at N75 by 2.8%
- The coefficient at N78 was not significant (p=0.27), hence no estimates of this relationship were undertaken.
- Long term trends:
  - There was a significant interaction between site and linear trend after adjusting for site differences and site by flow differences (p=0.0001) that is also seen after accounting for all terms in the model (p<0.0001)
  - There was also a significant interaction between site and quadratic trend both after adjusting for site differences, site by flow differences and linear trends and after adjusting for all terms in the model (p=0.0001 and p<0.0001 respectively)
  - At both sites there was an increasing trend in Chl-*a* before decreasing from around late 2018 suggesting that the model is on a downward trend at the end of the series, possibly reflecting the decrease in concentration expected during the winter period as was seen with TN.
  - As of mid-2020, the Chl-*a* trend at both sites was decreasing. However, the additional data plotted for N75 that was not included in the analysis because there were no comparative records at N78, suggest that the trend is flattening out as the series moves into later seasons.
- Seasonal trends:
  - First order sine and cosine terms by site interactions were included to allow the seasonal trend to differ between sites and to capture one peak per year around February.
- Site Chl-*a* geometric mean concentrations:
  - After adjusting for seasonal trends and stream flow, the geometric mean Chl-*a* concentration at site N78 was 13.8 µg/L (95% CI=8.6 to 22.2 µg/L), and at site N75 was 10.4 µg/L (95% CI=7.7 to 13.9 µg/L).
- Comparing Chl-*a* geometric mean concentrations between sites:

- The geometric mean Chl-*a* concentration at site N75 was 75% of that at site N78 (95%CI = 43 to 131%). Note, the confidence interval was large due to the small number of records.

4.1.12 West Camden WWTP and the Nepean River at Sharpes Weir (N75) – Summary

Nutrient loads

The approach for analysing the nutrient loads data in sub-categories enabled the trends in periods between the interventions to be identified more accurately. The distinct interventions that split the nitrogen load data into three categories and phosphorus load data into two categories are:

- nitrogen treatment upgrade completed by October 2008
- phosphorus treatment upgrade completed by February 2009 and
- process deterioration on nitrogen treatment in January 2015.

The modelled geometric mean nutrient loads for West Camden WWTP for each period and comparisons between periods are shown in Table 4-1. The trend and percent change in population served by the West Camden WWTP are provided in Table 4-2. The results are discussed in the detail in Section 5.1.

A summary of the final model outcomes on temporal trends for West Camden WWTP nutrient (total nitrogen, dissolved inorganic nitrogen and total phosphorus) loads by each period of intervention is included in Table 4-3. . The models identified both seasonal and non-seasonal variation in nutrient load. The results are discussed in the detail in Section 5.1.

Table 4-1 Geometric mean (95% CI) West Camden WWTP nutrient loads (kg/day) for each period and the comparisons (95% CI) between periods

Period	TN (kg/day)	DIN (kg/day)	TP (kg/day)
1	119.5 (115.7, 123.4)	107.1 (103.0, 111.4)	0.495 (0.454, 0.541)
2	37.9 (36.2, 39.7)		0.914 (0.830, 1.007)
3	101.9 (96.7, 107.4)	104.1 (94.9, 114.1)	
2:1	32% (30%, 34%)		185% (162%, 210%)
3:2	269% (251%, 289%)		

Table 4-2 Average catchment population serviced by West Camden WWTP and percent change by period

Period for TN and DIN	Population	Percent increase
Period 1: 1995-2008	37,266	
Period 2: 2009-2015	63,140	
Period 3: 2016-2020	88,052	
Period 2: Period 1		169%
Period 3: Period 2		139%
Period for TP	**Population**	**Percent increase**
Period 1: 1995-2009	38,234	
Period 2: 2090-2020	75,671	
Period 2: Period 1		198%

Data source: 2001-2021: forecast data by the Australian Bureau of Statistics and the Department of Planning, Industry and Environment
1995-2000: Sydney Water's internal estimates based on local government area data, sewer and unsewered areas

Table 4-3 Summary of final West Camden WWTP models with detailed results on increasing or decreasing trends and significance levels in each period

Parameter	TN	DIN	Parameter	TP
Period 1: Linear trend	→	→	Period 1: Linear trend	↘
Period 2: Linear trend	↘	NA	Period 2: Linear trend	↗
Period 3: Linear trend	→	↘		
Period 1: Quadratic trend	↘	↗	Period 1: Quadratic trend	↗
Period 2: Quadratic trend	↗	NA	Period 2: Quadratic trend	↘
Period 3: Quadratic trend	↗	↗		

Legend Keys:

	≤0.0001		≤0.001		≤0.01		≤0.05		≤0.15

↗	Upward trend	↘	Downward trend	→	no trend, p>0.15

NA	Not applicable, p>0.15, term removed from the model during the model reduction process

Notes: Significance level was based on type I SS p-values and the direction of trend (upward/downward/flat) was determined by the regression coefficient estimates (positive, negative or stable)

Receiving water quality

The receiving water quality data was analysed after dividing the data into two or three sub-categories to better understand the trends and impact/benefit of interventions. The modelled geometric mean water quality of Nepean River at Sharpes Weir (N75) for each period and comparisons between periods are shown in Table 4-4. The results are discussed in the detail in Section 5.2.

Table 4-4 Geometric mean (95% CI) nutrient (TN, DIN, TP and Chl-*a*) concentrations at Nepean River at Sharpes Weir (N75) for each period and the comparisons (95% CI) between periods

Period	TN (mg/L)	DIN (mg/L)	TP (mg/L)	Chl-*a* (µg/L)
	Geometric Mean (95% CI)	Geometric Mean (95% CI)	Geometric Mean (95% CI)	Geometric Mean (95% CI)
1	1.13 (1.03, 1.23)	0.61 (0.51, 0.73)	0.035 (0.032, 0.039)	5.5 (4.7, 6.4)
2	0.48 (0.45, 0.52)		0.019 (0.017, 0.02)	5.0 (4.5, 5.6)
3	0.62 (0.54, 0.71)	0.47 (0.38, 0.60)		
Comparison	**% (95% CI)**	**% (95% CI)**	**% (95% CI)**	**% (95% CI)**
2:1	43% (39%, 47%)		53% (47%, 59%)	91% (76%, 109%)
3:2	128% (109%, 150%)			

A summary of the final model outcomes on temporal trends in the water quality of the Nepean River at Sharpes Weir (N75), and the relationship with the upstream river/creek flow and nutrient loads from WWTP is included in Table 4-5. The results are discussed in the detail in Section 5.2.

Table 4-5 Overall summary table for Nepean River at Sharpes Weir (N75) – final models with detailed results on increasing or decreasing trends, significance levels in each period

Parameter	TN	DIN	Parameter	TP	Parameter	Chl-a
Camden Weir flow	↘	↘	Camden Weir flow	↗	Camden Weir flow	↘
Matahil Creek flow	→	↗	Matahil Creek flow	↗	Matahil Creek flow	↘
West Camden load (kg/day)	↗	↘	West Camden load (kg/day)	↗	West Camden TN load (kg/day)	→
Period 1: Linear trend	→	↘	Period 1: Linear trend	→	West Camden TP load (kg/day)	→
Period 3: Linear trend	↘	NA	Period 2: Linear trend	↘	Period 1: Linear trend	→
Period 1: Quadratic trend	↗	↗	Period 1: Quadratic trend	↗	Period 2: Linear trend	NA
Period 3: Quadratic trend	↗	NA	Period 2: Quadratic trend	↗	Period 1: Quadratic trend	↗
					Period 2: Quadratic trend	NA

Legend Keys:

(green)	≤0.0001	(blue)	≤0.001	(yellow)	≤0.01	(grey)	≤0.05	(light blue)	≤0.15

↗	Upward trend or positive correlation	↘	Downward trend or negative correlation	→	no trend, p>0.15

NA	Not applicable, p>0.15, term removed from the model during the model reduction process

(magenta) Load increases DIN concentration after taking into account Camden Weir and Matahil Creek flows. This relationship is not sustained after adjusting for all terms in the mode (p=0.99)l

Notes: Significance level was based on type I SS p-values and the direction of trend (upward/downward/flat) was determined by the regression coefficient estimates (positive, negative or stable)

Receiving water quality – downstream and upstream comparison

Water quality data for the upstream site (Nepean River at Camden Weir, N78) was very limited, only available for a dry weather period of 18 months during 2018-2019. Comparative analysis was made between the upstream and downstream site on these limited data. The modelled geometric mean downstream water quality of the Nepean River at Sharpes Weir (N75) and comparison with the upstream site at Macquarie Grove Road (N78) for each period and comparisons between periods are shown in Table 4-6. The results are discussed in the detail in Section 5.2.

Table 4-6 Geometric mean (95% CI) nutrient (TN, DIN, TP and Chl-*a*) concentrations Nepean River at Sharpes Weir (N75) and Macquarie Grove Rd (N78) for each period and the comparisons (95% CI) between periods

Variable	N75	N78	N75/N78
TN (mg/L)	1.15 (1.00, 1.32)	0.40 (0.32, 0.50)	289% (223%, 374%)
DIN (mg/L)	0.72 (0.54, 0.95)	0.04 (0.03 to 0.06)	1679% (1063%, 2651%)
TP (mg/L)	0.023 (0.020, 0.027)	0.019 (0.015, 0.024)	123% (92 to 164%)
Chl-*a* (µg/L)	10.4 (7.7, 13.9)	13.8 (8.6, 22.2)	75% (43 to 131%)

A summary of the final model outcomes on temporal trends in the water quality of Nepean River at Sharpes Weir (N75) and comparison with the upstream site of Nepean River at Macquarie Grove Road (N78) is included in Table 4-7. The results are discussed in the detail in Section 5.2.

Table 4-7 Summary of final models for the Nepean River at Sharpes Weir (N75) – upstream/downstream comparison with detailed results on increasing or decreasing trends, significance levels in each period

Parameter	TN	DIN	TP	Chl-*a*
Site by Flow				
N75	↘	↘	→	↘
N78	↗	↗	→	→
Site by linear trends				
N75	↗	↗	↗	↗
N78	→	↗	↗	↗
Site by quadratic trends				
N75	↘		↘	↘
N78	→		↘	↘

Legend Keys:

	≤0.0001		≤0.001		≤0.01		≤0.05		≤0.15

↗	Upward trend or positive correlation	↘	Downward trend or negative correlation	→	no trend, p>0.15

Notes: Significance level was based on type I SS p-values and the direction of trend (upward/downward/flat) was determined by the regression coefficient estimates (positive, negative or stable)

4.2 Nepean River at Yarramundi – Winmalee WWTP

The following sub-sections present the results of the model building steps, and key outcomes for 11 models fitted on data from the Nepean River at Yarramundi and Winmalee WWTP. A summary is included to interpret the variability in the outcomes due to explanatory variables fitted or any other supplementary changes eg demography, weather etc.

The detailed results of all statistical models fitted for the Nepean River at Yarramundi (N44) and Winmalee WWTP are included in Volume 2: Appendix G. Estimated regression coefficients, standard errors, p values, type I and type III sum of squares details are provided in Table G-1 to Table G-22. Residual plots on all models are provided in Figure G-1 to Figure G-11. The model and model adjusted R^2 are provided to assess the goodness of fit of the models (Table G-23). Examples of relative changes in water quality concentrations (total nitrogen, dissolved inorganic nitrogen, total phosphorus or chlorophyll-*a*) with respect to prespecified ranges of nutrient load, upstream concentrations and, river and creek flow are included in Table G-24 and Table G-25.

4.2.1 Winmalee WWTP – Total nitrogen load

Winmalee WWTP total nitrogen load includes loads from North Katoomba, Wentworth Falls and Blackheath WWTPs prior to their decommissioning.

There were 1524 total nitrogen load records for Winmalee WWTP in this data series. Prior to decommissioning of North Katoomba and Wentworth Falls WWTPs in 1996 there were 58 records, after the decommissioning and before the decommissioning of Blackheath WWTP in 2008 there were 735 records, and after decommissioning of Blackheath there were 731 records. All records were included in the analyses. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included the three periods defined by the decommissioning of North Katoomba and Wentworth Falls WWTPs and decommissioning of Blackheath WWTP, linear and quadratic trends within each period and 1^{st}, 2^{nd} and 3^{rd} order harmonic interaction terms to model the seasonal trends.

The model:

Log_{10}(TN load) = period + linear trend in period 1 + linear trend in period 2 + linear trend in period 3 + quadratic trend in period 1 + quadratic trend in period 2 + quadratic trend in period 3 + 1^{st} order sine + 1^{st} order cosine + 2^{nd} order sine + 2^{nd} order cosine + 3^{rd} order sine + 3^{rd} order cosine + 1^{st} order sine by year + 1^{st} order cosine by year + 2^{nd} order sine by year + 2^{nd} order cosine by year + 3^{rd} order sine by year + 3^{rd} order cosine by year

Where:

period and year are categorical factors.

Model reduction decisions:

- Period 1: the linear and quadratic trend terms were removed (both p-values from the type I SS were > 0.15)
- Periods 2 and 3: retain the linear and quadratic trend terms as the p-values for the quadratic terms using the type I SS were <0.15
- Retain all harmonic interaction terms as the p-values for the 3rd order terms from the type I SS were <0.15 (ie <0.0001 and 0.0023 for cosine and sine respectively)
- Remove the main effect harmonic terms since they can be included in the harmonic interaction terms.

Step 2: Fit the final, reduced model

Log_{10}(TN load) = period + linear trend in period 2 + linear trend in period 3 + quadratic trend in period 2 + quadratic trend in period 3 + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

period and year are categorical factors.

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends tends in composite total nitrogen loads from Winmalee WWTP shown in Figure 4-12.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix G). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table G-1 and Table G-2, respectively. The residual plots for this model are shown in Figure G-1.

All terms in the final, reduced model have a p-value for the corresponding type I SS <0.15 except for the linear trend in period 2 with a p-value of 0.56. This term was included in the model as the corresponding quadratic term was significant (p<0.0001). Each term in the model had a similar p-value after adjusting for all other terms in the model (type III SS) except for the linear trend in Period 2 that became significant with p<0.0001 and the second order harmonic interaction terms that were still significant, but less so. This suggested that there may be some correlation between these terms and that, after adjusting for all the seasonal terms there may be an underlying linear component to the curvilinear trend that is not obvious when the seasonal trend is not accounted for. Or after adjusting for the third order harmonic by Year seasonal trend, there is less variability accounted for by the second order harmonic interaction terms.

The model generally fitted the data well (R^2=0.45 and adjusted R^2=0.38) except for those at extremely high loads. Three values showed a high leverage (ie terms in the model are included because of their contribution to the variability in the data). However, the variability in the loads appeared to be smaller since the decommissioning of Blackheath WWTP. The distribution of the residuals was approximately Normal and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

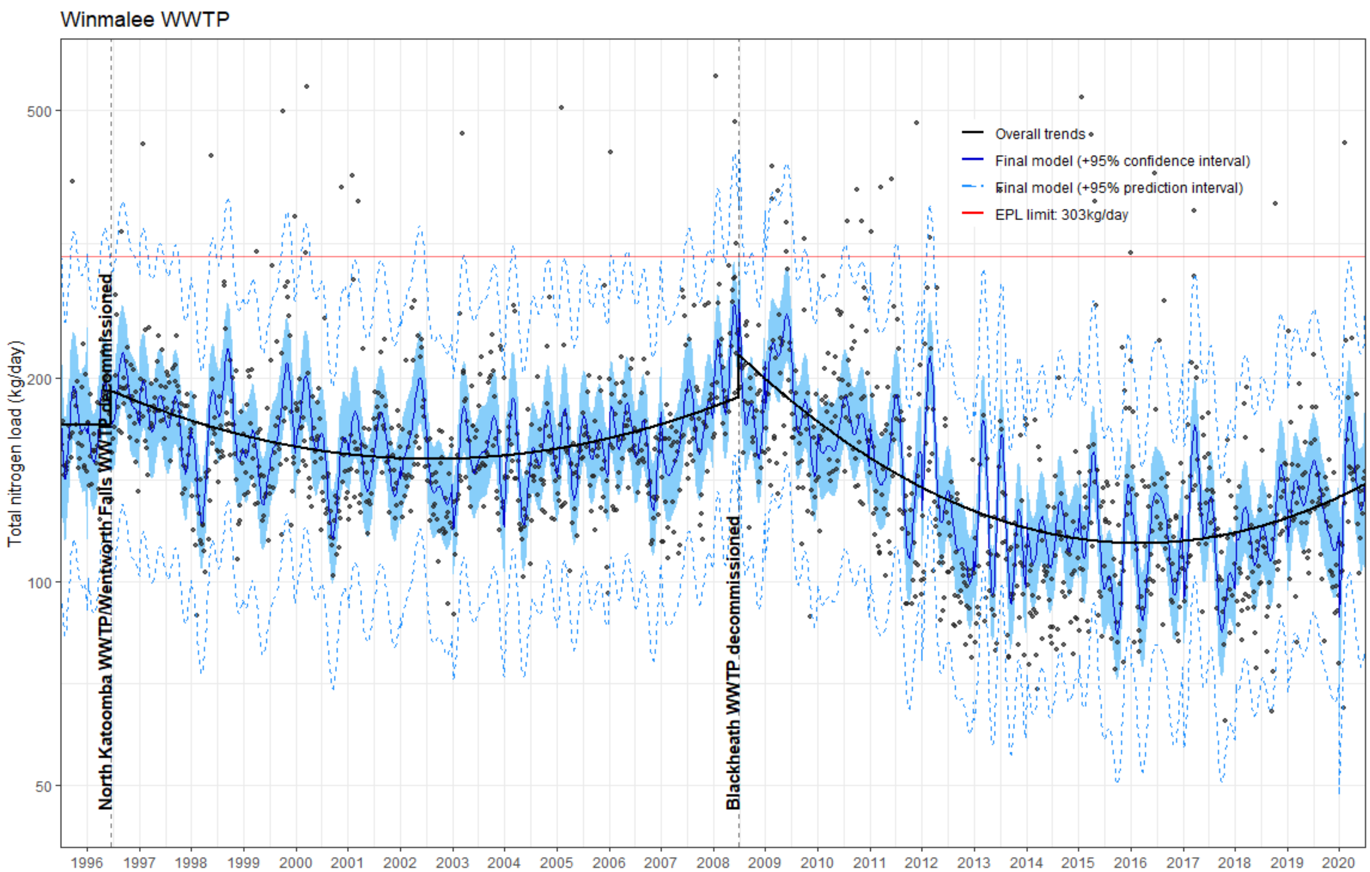

Figure 4-12 Total nitrogen load from Winmalee, North Katomba, Wentworth Falls and Blackheath WWTPs: fitting terms to model interventions, linear and quadratic trends within each period and seasonal trends overlaid with the trends in each period

Key outcomes

- Total nitrogen load:
  - Winmalee WWTP total nitrogen load included loads from North Katoomba, Wentworth Falls and Blackheath WWTPs prior to their decommissioning
  - The majority of the records were less than the current EPL limit of 303 kg/day
- The final reduced model fitted reasonably well with R^2=0.45 and adjusted R^2=0.38. However, the residual plots showed the model did not capture the extremely high total nitrogen loads
- Long term trends:
  - No trend was observed in the short period prior to the decommissioning of North Katoomba and Wentworth Falls WWTPs

    - Significant curvilinear trends were observed in the two periods after the decommissioning of North Katoomba and Wentworth Falls WWTPs in 1996 and Blackheath WWTP in 2008
    - After decommissioning of North Katoomba and Wentworth Falls WWTPs and before the decommissioning of the Blackheath WWTP, total nitrogen load had a decreasing trend until around 2003 when load started to increase
    - After decommissioning of Blackheath WWTP, there was a larger decreasing trend until around 2016 when total nitrogen load started to increase again
    - As of mid-2020, the trend in total nitrogen load was increasing
- Seasonal trends:
    - First, second and third order sine and cosine terms by year interactions were included to capture a more complex pattern of three peaks per year, capturing the largest one in February and two smaller ones around late May/early June and September. The lowest trough was around the late October/early November. The magnitude of these peaks and troughs differed between years.
- After adjusting for seasonal trends, the total nitrogen geometric mean load:
    - Prior to the decommissioning of North Katoomba and Wentworth Falls WWTPs (period 1) was 183.5 kg/day of nitrogen (95% CI =158.8 to 212.1 kg/day)
    - After the decommissioning of North Katoomba and Wentworth Falls WWTPs (period 2) was 153.9 kg/day of nitrogen (95% CI = 149.7 to 158.3 kg/day)
    - After decommissioning Blackheath WWTP (period 3) was 116.2 kg/day of nitrogen (95% CI = 112.9 to 119.5 kg/day)
- Comparing the modelled total geometric nitrogen loads between periods:
    - The geometric mean for the period after North Katoomba and Wentworth Falls WWTPs were decommissioned (period 2) was 84% (95% CI = 73 to 97%) of the geometric mean for the period before North Katoomba and Wentworth Falls WWTPs were decommissioned (period 1).
    - The geometric mean after Blackheath WWTP was decommissioned (period 3) was 75% (95% CI = 72 to 79%) of the geometric mean for the period before Blackheath WWTP was decommissioned (period 2)

4.2.2 Nepean River at Yarramundi (N44) – Total nitrogen concentration

There were no total nitrogen concentration records from the Nepean River at Yarramundi (N44) from mid-2001 to mid-2008 when Blackheath WWTP was decommissioned. The analysis models include data from 2008 ie 221 records from N44. However, the data prior to 2001 are plotted for completeness. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included TN concentration at the upstream site N48A, the flow at N48A, Winmalee WWTP TN load, the two periods defined by the commissioning of St Marys AWTP, linear and quadratic trends within each period and 1st, 2nd and 3rd order harmonic interaction terms to model the seasonal trends.

The model:

Log_{10}(N44 TN concentration) = log_{10}(N48A TN concentration) + log_{10}(flow at N48A) + log_{10}(Winmalee WWTP TN load) + period + linear trend in period 1 + linear trend in period 2 + quadratic trend in period 1 + quadratic trend in period 2 + 1st order sine + 1st order cosine + 2nd order sine + 2nd order cosine + 3rd order sine + 3rd order cosine + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

- period and year are categorical factors
- Winmalee WWTP TN load is a composite of North Katoomba, Wentworth Falls and Blackheath WWTPs up until the time of their being decommissioned as well as Winmalee WWTP TN load

Model reduction decisions:

- Retain only 1st order harmonic interaction terms. Even though the 2nd and 3rd order harmonic interaction terms could have been included based on the p-value cut-off, these terms only captured the unusual patterns in 2013, 2014 and 2020. Due to the small number of records and the risk of overfitting, these terms were excluded.
- Remove the main effect harmonic terms since they can be included in the harmonic interaction terms.

Step 2: Fit the final, reduced model

Log_{10}(N44 TN concentration) = log_{10}(N48A TN concentration) + log_{10}(flow at N48A) + log_{10}(Winmalee WWTP TN load) + period + linear trend in period 1 + linear trend in period 2 + quadratic trend in period 1 + quadratic trend in period 2 + 1st order sine by year + 1st order cosine by year

Where:

- period and year are categorical factors.
- Winmalee WWTP TN load is a composite of North Katoomba, Wentworth Falls and Blackheath WWTPs up until the time of their being decommissioned as well as Winmalee WWTP TN load.
- Flow at N48A is derived as described in Volume 2: Appendix E (Table E-5)

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-13.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix G). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table G-3 and Table G-4, respectively. The residual plots for this model are shown in Figure G-2.

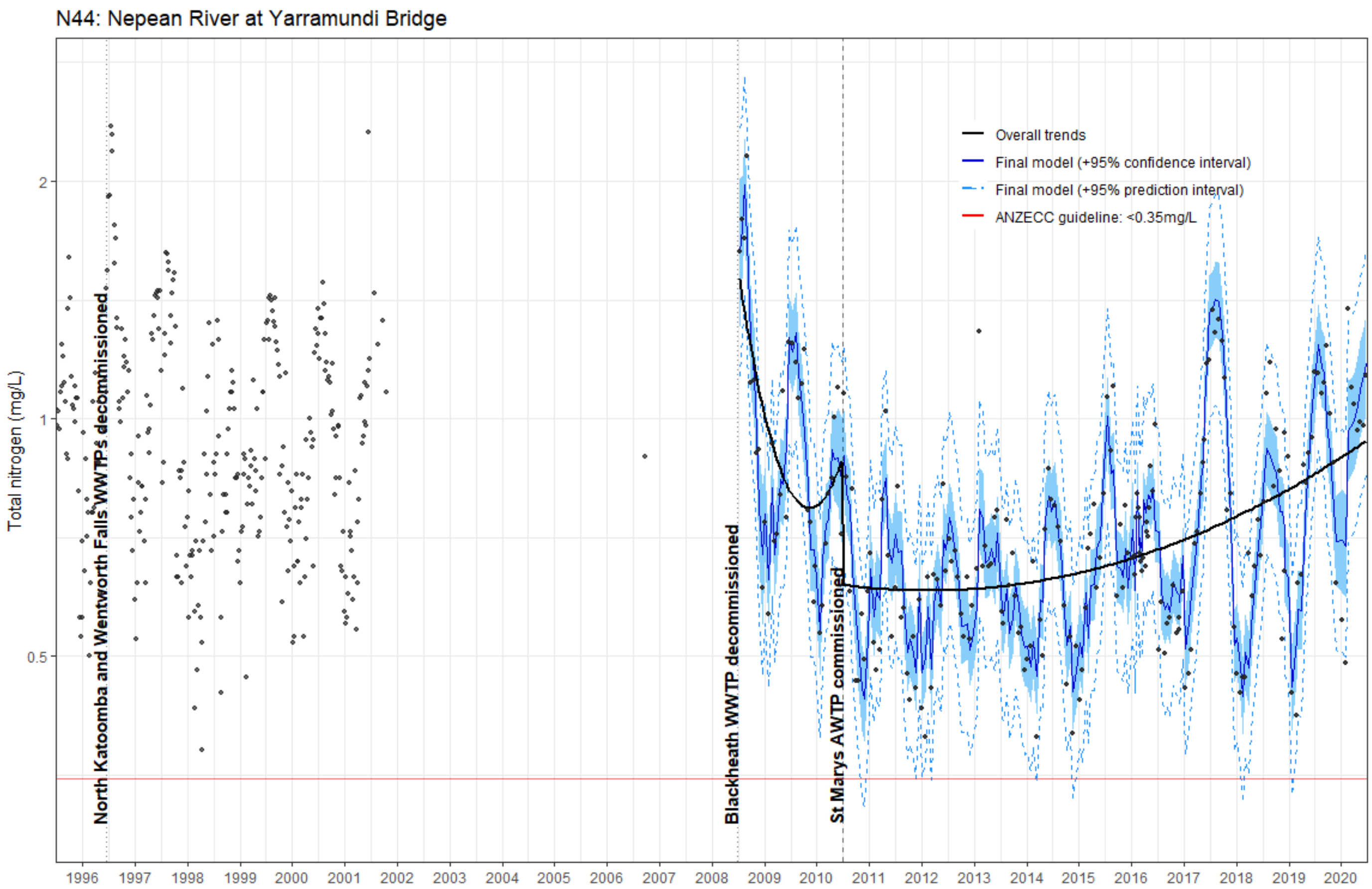

Figure 4-13 Total nitrogen concentrations at Yarramundi, Nepean River (N44): fitting terms to model upstream concentration, upstream river flow, TN load from Winmalee WWTP, along with linear and quadratic trends within each period and seasonal trends overlaid with the trends in each period

The period parameter as well as the upstream concentration at N48A, flow corresponding to N48A and the WWTP TN load estimates were retained in the model as part of the study design. The p-values corresponding to the Type III SS varied compared with the type I SS. The linear and quadratic trends in period 1 had type III SS p-values >0.3, suggesting that the harmonic interaction terms accounted for these trends in the short timespan for this period. The upstream concentration at N48A, flow corresponding to N48A and the Winmalee WWTP TN load have p<0.0001 for both type I and type III SS.

The model fitted the data well (R^2=0.82 and adjusted R^2=0.79) except for those at extremely high concentrations or, to a lesser extent, low concentrations. Three values showed a high leverage (ie terms in the model are included because of their contribution to the variability in the data). The distribution of the residuals was approximately Normal and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

Key outcomes

- Total nitrogen concentration:
  - The TN concentration was consistently above the ANZG default level of <0.35mg/L
  - The final reduced model fitted well with R^2=0.82 and adjusted R^2=0.79. However, the residual plots showed the model did not capture the extremely high total nitrogen concentration
- Impact of upstream catchment:
  - The TN concentration at the upstream site (N48A) was significantly correlated to the concentration at the downstream site at Yarramundi (N44) ($p<0.0001$)
    - when the TN concentration at N48A is low eg 0.35 mg/L, a 0.1 mg/L increase of TN concentration increased the concentration at N44 by 8%
    - when TN concentration at N48A is moderate eg 0.45 mg/L, a 0.1 mg/L increase in concentration increased the concentration at N44 by 6%
    - when TN concentration at N48A is high eg 0.65 mg/L, a 0.1 mg/L increase in concentration increased the concentration at N44 by 4.5%.
  - Flow in the Nepean River at N48A was significantly correlated to the concentration of TN at N44 ($p<0.0001$).
    - when flow at N48A is low eg 800 ML/day, a 100 ML increase in flow decreased the concentration at N44 by 0.7%
    - when flow at N48A is moderate eg 1100 ML/day, a 100 ML increase in flow decreased the concentration at N44 by 0.5%
    - when flow at N48A is high eg 1500 ML/day, a 100 ML increase in flow decreased the concentration at N44 by 0.4%.
- Impact of WWTPs:
  - TN load from Winmalee WWTP was significantly correlated to the concentration of TN at Yarramundi (N44) ($p<0.0001$).
    - when the load from Winmalee WWTP is low eg 90 kg/day, a 10 kg/day increase in load increased the concentration at N44 by 1.9%
    - when the load from Winmalee WWTP is moderate eg 125 kg/day, a 10 kg/day increase in load increased the concentration at N44 by 1.4%

    - when the load from Winmalee WWTP is high eg 225 kg/day, a 10 kg/day increase in load increased the concentration at N44 by 0.9%

- Long term trends:
  - The curvilinear trend seen after decommissioning Blackheath WWTP and before the commissioning of St Marys AWTP (period 1) is also explained by the seasonal trend by year.
  - After the commissioning of St Marys AWTP, there was a significantly increasing curvilinear trend in total nitrogen concentration.
  - As of mid-2020, the trend in total nitrogen concentration was increasing.
- Seasonal trends:
  - First order sine and cosine terms by year interactions were included to capture a pattern of one peak per year in February and one trough around August with a magnitude that differed between years.
- After adjusting for seasonal trends, flow and concentration at the upstream site and load from Winmalee WWTP, the total nitrogen geometric mean concentration at Yarramundi (N44):
  - After decommissioning Blackheath WWTP (period 1) was 0.90 mg/L (95% CI = 0.82 to 0.99 mg/L)
  - After commissioning of St Marys AWTP (period 2) the geometric mean was 0.61 mg/L (95% CI = 0.58 to 0.64 mg/L).
- Comparing the total nitrogen geometric mean concentration between periods:
  - The total nitrogen geometric mean concentration for the period after commissioning St Marys AWTP (period 2) was 68% (95% CI = 61 to 75%) of the geometric mean for the period prior to the commissioning (period 1).

4.2.3 Nepean River at Yarramundi (N44) and Smith Rd (N48A) – Total nitrogen concentration (downstream/upstream)

There were no total nitrogen concentration records from the upstream Nepean River site at Smith Road (N48A) from 2002 to mid-2008. The analysis was undertaken on data from 2008 which included 222 records from N44, and 214 from N48A. However, the data prior to this time are plotted for completeness. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included a factor for site identifier, site by flow interaction term to allow the relationship with flow to differ between sites, a site by period interaction term to allow the site means to differ in each of the two periods defined by the commissioning of St Marys AWTP, interaction terms for site by linear and quadratic trends to allow them to differ within each period and 3-factor interaction terms for site by 1st, 2nd and 3rd order harmonic interaction terms to model the seasonal trends and allow them to differ between sites.

The model:

Log_{10}(TN concentration) = site (N44 or N48A) + site by flow + site by period + site by linear trend in period 1 + site by linear trend in period 2 + site by quadratic trend in period 1 + site by quadratic trend in period 2 + site by 1st order sine by year + site by 1st order cosine by year + site by 2nd order sine by year + site by 2nd order cosine by year + site by 3rd order sine by year + site by 3rd order cosine by year

Where:

- site, period and year are categorical factors.
- Flow consists of the flow corresponding to the site identified in the site variable as defined in Volume 2: Appendix E (Table E-5)

Model reduction decisions:

- No further model reduction is undertaken

Step 2: Fit the final, reduced model

Log_{10}(TN concentration) = site (N44 or N48A) + site by flow + site by period + site by linear trend in period 1 + site by linear trend in period 2 + site by quadratic trend in period 1 + site by quadratic trend in period 2 + site by 1st order sine by year + site by 1st order cosine by year + site by 2nd order sine by year + site by 2nd order cosine by year + site by 3rd order sine by year + site by 3rd order cosine by year

Where:

- site, period and year are categorical factors.
- Flow consists of the flow corresponding to the site identified in the site variable as defined in Volume 2: Appendix E (Table E-5)

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-14.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix G). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table G-5 and Table G-6, respectively. The residual plots for this model are shown in Figure G-3.

The site, site by flow and site by period parameters were retained in the model as they were part of the study design. The p-values corresponding to the Type III SS varied compared with the type I SS for the site by period and site by linear and quadratic trends in period 1. The site by linear and quadratic trends in period 1 had type III SS p-values >0.3, suggesting that the seasonal trend within each site was also accounting for these trends in the short timespan for this period. For the period 2 trends, the p-values were larger for the type III SS but still significant, suggesting that the seasonal trend within each site was partly accounting for these trends. The flow corresponding to each site and the linear trends in period 2 continued to have a p-value of <0.15 for both type I and type III SS.

The model fitted the data well (R^2=0.84 and adjusted R^2=0.74) except for those at extremely high concentrations or, to a lesser extent, low concentrations. A few values showed a high leverage (ie terms in the model were included because of their contribution to the variability in the data). The distribution of the residuals was approximately Normal and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

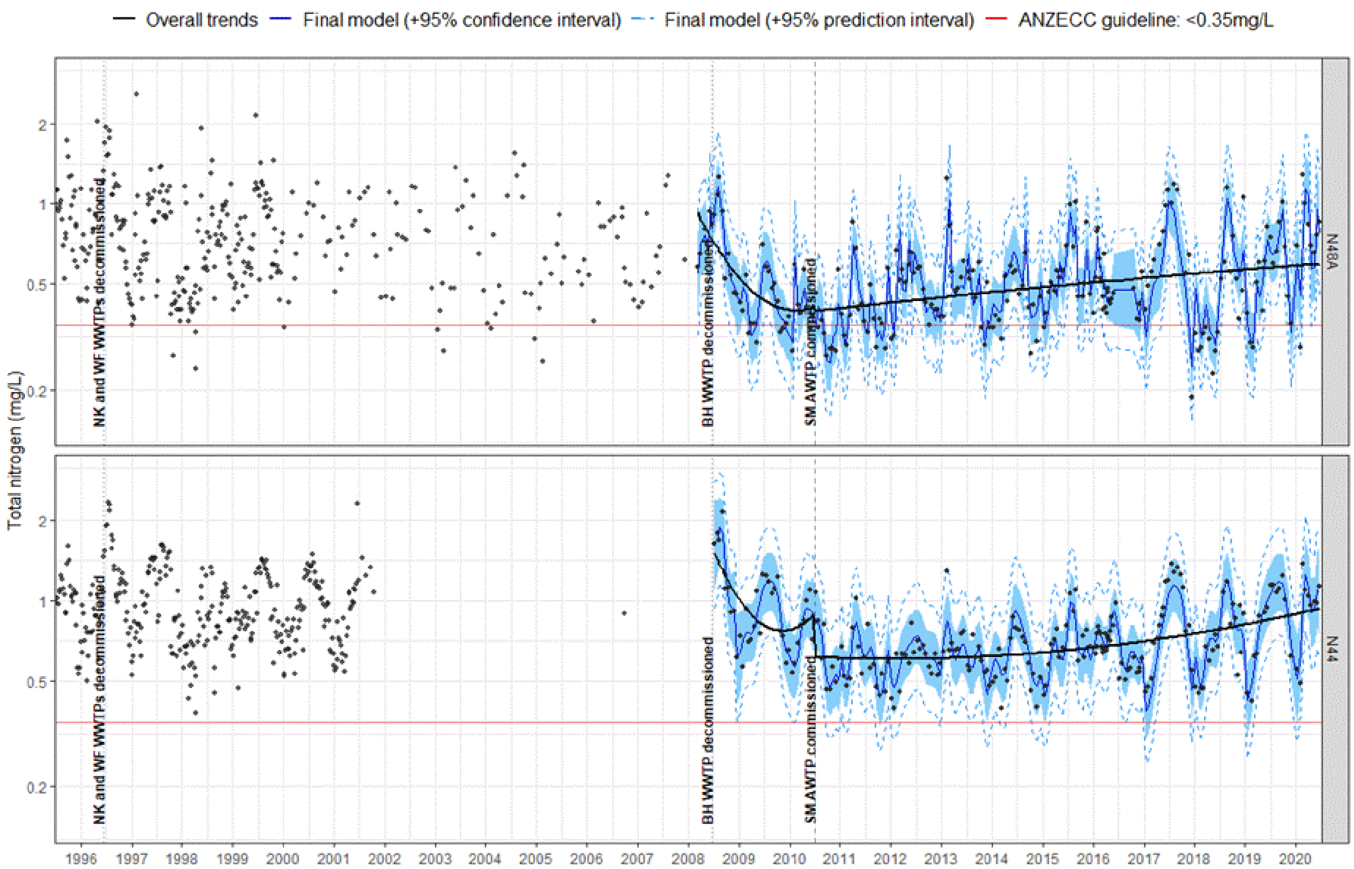

Figure 4-14 Total nitrogen concentrations at Smith Road (N48A) and Yarramundi (N44), Nepean River: fitting terms to model site differences and associated flow along with linear and quadratic trends and seasonal trends overlaid with the trends in each period

Key outcomes

- Total nitrogen concentration:
  - TN concentration were consistently above the ANZG default level of <0.35mg/L for both the downstream site of N44 and the upstream site of N48A.

    - The final reduced model fitted well with R^2=0.84 and adjusted R^2=0.74. However, the residual plots showed the model did not capturing the extremely high total nitrogen concentrations.
- Flow:
    - The relationship between flow and TN concentration differed between sites ($p<0.0001$).
    - There was no apparent relationship between flow and the TN concentration at the downstream site (N44) ($p=0.8$).
    - Flow significantly increased the TN concentration at N48A ($p<0.0001$).
        - when flow at N48A is low eg 800 ML/day, a 100 ML/day increase in flow increased the TN concentration at N48A by 2%
        - when flow at N48A is moderate eg 1100 ML/day, a 100 ML/day increase in flow increased the concentration at N48A by 1.5%
        - when flow at N48A is high eg 1500 ML/day, a 100 ML/day increase in flow increased the concentration at N48A by 1.1%.
- Long term trends:
    - There is a significant interaction between site and linear trends in period 1 and 2 ($p<0.0001$), and between site and quadratic trend in period 1 ($p=0.0005$) and period 2 ($p=0.008$).
    - There was a curvilinear trend at both sites in the period after decommissioning of Blackheath WWTP and before commissioning of St Marys AWTP (period 1) that differed between sites. At both sites, the total nitrogen concentration decreased until mid-2009. After 2009 the trend at N48A flattens out, whereas at N44 the trend in total nitrogen concentration increased. This pattern was also explained by the seasonal trend by year interaction term.
    - After the commissioning of St Marys AWTP (period 2), there was also a slight difference between the curvilinear trends at each site, although they both showed an increase in the total nitrogen concentration. This pattern was partly explained by the seasonal trend by year.
    - As of mid-2020, the trend in total nitrogen concentration at both sites was increasing.
- Seasonal trends:
    - All site by 1st, 2nd and 3rd order sine and cosine terms by year interactions were included to capture a more complex pattern of three peaks in total nitrogen concentration per year, capturing the largest one in February and two smaller ones in late May/early June and September. The lowest trough was around late October/early November that differed between years and sites.
- Site by period total nitrogen geometric mean concentrations:
    - There was a significant interaction between site and period ($p<0.0001$).

- After adjusting for linear, quadratic and seasonal trends:
  - After decommissioning Blackheath WWTP, the modelled total nitrogen geometric mean concentration at N44 was 0.91 mg/L (95% CI = 0.79 to 1.03 mg/L) and at N48A was 0.51 mg/L (95% CI = 0.45 to 0.58 mg/L).
  - After commissioning of St Marys AWTP the modelled total nitrogen geometric mean concentration at N44 was 0.66 mg/L (95% CI = 0.63 to 0.70 mg/L) and at N48A was 0.61 mg/L (95% CI = 0.57 to 0.65 mg/L).
- Comparing the total nitrogen concentrations between sites within periods:
  - The geometric mean for N44 in the period before commissioning St Marys AWTP (period 1) was 177% (148 to 211%) of the geometric mean for N48A
  - The geometric mean for N44 in the period after commissioning St Marys AWTP (period 2) was 109% (100 to 119%) of the geometric mean for N48A
- Comparing the total nitrogen concentrations between periods:
  - The geometric mean for the period after commissioning St Marys AWTP (period 2) was 73% (95% CI = 64 to 84%) of the geometric mean for the period prior to the commissioning (period 1) at site N44
  - The geometric mean for the period after commissioning St Marys AWTP (period 2) was 119% (95% CI = 104 to 136%) of the geometric mean for the period prior to the commissioning (period 1) at site N48A
  - The percentage difference between periods 2 and 1 for the geometric mean concentration at N44 was 62% (95% CI 51 to 75%) of the percentage difference at N48A.

4.2.4 Winmalee WWTP – Dissolved inorganic nitrogen load

Winmalee WWTP dissolved inorganic nitrogen load includes loads from North Katoomba, Wentworth Falls and Blackheath WWTPs prior to their decommissioning.

There were 1390 dissolved inorganic load records from Winmalee WWTP in this data series. Prior to decommissioning of North Katoomba and Wentworth Falls WWTPs in 1996 there were 58 records, after the decommission and before decommissioning of Blackheath WWTP in 2008 there were 603 records and after decommissioning of Blackheath there were 729 records. There were no records from mid-1996 to mid-1998. All records are included in the analyses.

The analysis models do not fit any terms during the time where there are missing records and hence, does not predict any loads during this period. Key outcomes of the analysis are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included the three periods defined by the decommissioning of North Katoomba and Wentworth Falls WWTPs and decommissioning of Blackheath WWTP, linear and quadratic trends within each period and 1st, 2nd and 3rd order harmonic interaction terms to model the seasonal trends.

The model:

Log_{10}(DIN load) = period + linear trend in period 1 + linear trend in period 2 + linear trend in period 3 + quadratic trend in period 1 + quadratic trend in period 2 + quadratic trend in period 3 + 1st order sine + 1st order cosine + 2nd order sine + 2nd order cosine + 3rd order sine + 3rd order cosine + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

period and year are categorical factors.

Model reduction decisions:

- Period 1: the linear and quadratic trend terms were removed (both p-values from the type I SS were > 0.15)
- Periods 2 and 3: retain the linear and quadratic trend terms as the p-values for the quadratic terms using the type I SS were <0.15
- Retain all harmonic interaction terms as the p-values for the 3rd order terms from the type I SS were <0.15
- Remove the main effect harmonic terms since they can be included in the harmonic interaction terms.

Step 2: Fit the final, reduced model

Log_{10}(DIN load) = period + linear trend in period 2 + linear trend in period 3 + quadratic trend in period 2 + quadratic trend in period 3 + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

period and year are categorical factors.

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-15. A straight line on the figure was included to join the predicted value for the last data point prior to the missing data period from mid-1996 to mid-1998 and the predicted value for the first data point after this missing data period.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix G). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table G-7 and Table G-8, respectively. The residual plots for this model are shown in Figure G-4.

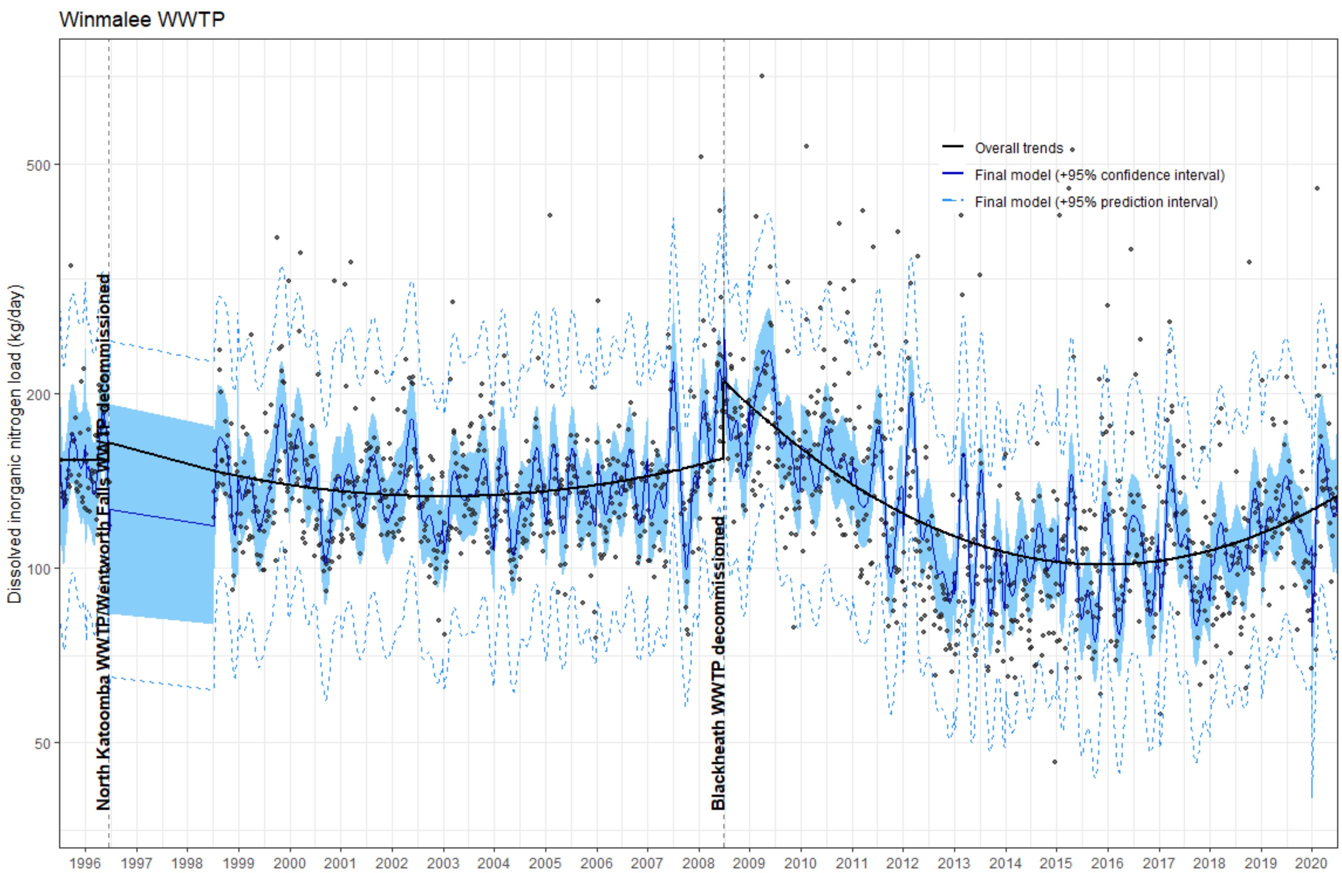

Figure 4-15 Combined dissolved inorganic nitrogen load from Winmalee, North Katoomba, Wentworth Falls and Blackheath WWTPs: fitting terms to model interventions, linear and quadratic trends within each period and seasonal trends overlaid with the trends in each period

All terms in the final, reduced model had a p-value for the corresponding type I SS <0.15 except for the linear trend in period 2 with a p-value of 0.30. This term was included in the model as the corresponding quadratic term was significant (p=0.0002). Most of the terms in the model had a similar p-value after adjusting for all other terms in the model (type III SS) except for the linear trend in period 2 that became significant with p=0.03, the corresponding quadratic trend that became less significant with p=0.03 and the second order sine by Year term that also became less significant with p=0.05. This suggested a similar interplay between the terms in the model as for total nitrogen load.

The model generally fitted the data well (R^2=0.43 and adjusted R^2=0.36) except for those at extremely high loads. A few values showed a high leverage (ie terms in the model are included because of their contribution to the variability in the data). The distribution of the residuals was approximately Normal and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

Key outcomes

- Dissolved inorganic nitrogen load:
  - The Winmalee WWTP DIN load includes loads from North Katoomba, Wentworth Falls and Blackheath WWTPs prior to their decommissioning.
  - There was no EPL limit for DIN load
  - The final reduced model fitted reasonably well with R^2=0.43 and adjusted R^2=0.36. However, the residual plots showed the model did not capture the extremely high DIN loads.
- Long term trends:
  - No trend was observed prior to the decommissioning of North Katoomba and Wentworth Falls WWTPs in 1996
  - Significant curvilinear trends were observed in the two periods after the decommissioning of North Katoomba and Wentworth Falls WWTPs
    - After decommissioning of North Katoomba and Wentworth Falls WWTPs and before the decommissioning of the Blackheath WWTP, the dissolved inorganic nitrogen load had a decreasing curvilinear trend until around 2003 when the load started to increase
    - After decommissioning of Blackheath WWTP, there was a larger decreasing curvilinear trend until around 2016 when the dissolved inorganic nitrogen load started to increase again.
    - As of mid-2020, the trend in dissolved inorganic nitrogen load was increasing
- Seasonal trends:
  - First, second and third order sine and cosine terms by year interactions were included to capture a more complex pattern of three peaks per year, capturing the largest one in February and two smaller ones in late May/early June and September. The lowest trough was around late October/early November. The magnitude of the peaks and troughs differed between years.
- After adjusting for seasonal trends, the dissolved inorganic nitrogen geometric mean load:
  - Prior to the decommissioning of North Katoomba and Wentworth Falls WWTPs (period 1) was 245.6 kg/day (95% CI =109.6 to 550.4 kg/day), noting the width of the confidence interval was large due to the small number of records in this period.
  - After the decommissioning of North Katoomba and Wentworth Falls WWTPs (period 2) was 133.5 kg/day (95% CI = 129.2 to 138.1 kg/day)
  - After the decommissioning of Blackheath WWTP (period 3) was 103.0 kg/day (95% CI = 100.0 to 106.2 kg/day)

- Comparing the dissolved inorganic nitrogen loads between periods:
  - The geometric mean for the period between North Katoomba and Wentworth Falls WWTPs was decommissioned (period 2) was 54% (95% CI = 24 to 123%) of the geometric mean for the period prior to North Katoomba and Wentworth Falls WWTPs were decommissioned (period 1). Again, the confidence interval is wide due to the small number of records in period 1
  - The geometric mean after Blackheath WWTP was decommissioned (period 3) was 77% (95% CI = 74 to 81%) of the geometric mean for the period before Blackheath WWTP was decommissioned (period 2)

4.2.5 Nepean River at Yarramundi (N44) – Dissolved inorganic nitrogen concentration

There were no dissolved inorganic nitrogen records for the Nepean River at Yarramundi (N44) from mid-2001 to mid-2008 when Blackheath WWTP was decommissioned. The analysis models included data from 2008 with 221 records from N44. However, the data prior to 2001 has been plotted for completeness. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included DIN concentration at the upstream site N48A, the flow at N48A, Winmalee DIN load, the two periods defined by the commissioning of St Marys AWTP, linear and quadratic trends within each period and 1^{st}, 2^{nd} and 3^{rd} order harmonic interaction terms to model the seasonal trends.

The model:

Log_{10}(N44 DIN concentration) = log_{10}(N48A DIN concentration) + log_{10}(flow at N48A) + log_{10}(Winmalee WWTP DIN load) + period + linear trend in period 1 + linear trend in period 2 + quadratic trend in period 1 + quadratic trend in period 2 + 1^{st} order sine + 1^{st} order cosine + 2^{nd} order sine + 2^{nd} order cosine + 3^{rd} order sine + 3^{rd} order cosine + 1^{st} order sine by year + 1^{st} order cosine by year + 2^{nd} order sine by year + 2^{nd} order cosine by year + 3^{rd} order sine by year + 3^{rd} order cosine by year

Where:

- period and year are categorical factors.
- Winmalee WWTP DIN load is a composite of North Katoomba, Wentworth Falls and Blackheath WWTPs up until the time before decommissioning as well as Winmalee WWTP DIN load.
- Flow at N48A is derived as described in Table Volume 2: Appendix E (Table E-5)

Model reduction decisions:

- Period 1: remove linear and quadratic trends in Period 1 as both p-values for the type I SS were >0.15

- Retain only 1st order harmonic interaction terms. Even though the 2nd and 3rd order harmonic interaction terms could have been included based on the p-value cut-off, these terms only captured the unusual patterns in 2013, 2014 and 2020. Due to the small number of records and the risk of overfitting, these terms were excluded.
- Remove the main effect harmonic terms since they can be included in the harmonic interaction terms.

Step 2: Fit the final, reduced model

Log_{10}(N44 DIN concentration) = log_{10}(N48A DIN concentration) + log_{10}(flow at N48A) + log_{10}(Winmalee WWTP DIN load) + period + linear trend in period 2 + quadratic trend in period 2 + 1st order sine by year+ 1st order cosine by year

Where:

- period and year are categorical factors.
- Winmalee WWTP DIN load is a composite of North Katoomba, Wentworth Falls and Blackheath WWTPs up until the time of their being decommissioned as well as Winmalee WWTP DIN load.
- Flow at N48A is derived as described in Volume 2: Appendix E (Table E-5)

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-16.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix G). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table G-9 and Table G-10, respectively. The residual plots for this model are shown in Figure G-5.

The period parameter as well as the upstream concentration at N48A, flow corresponding to N48A and the WWTP DIN load estimates were retained in the model as part of the study design. The p-values corresponding to the type III SS were similar to those from the type I SS.

The model fitted the data well (R^2=0.82 and adjusted R^2=0.79) except for those at extremely high and low concentrations. The distribution of the residuals was approximately Normal and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

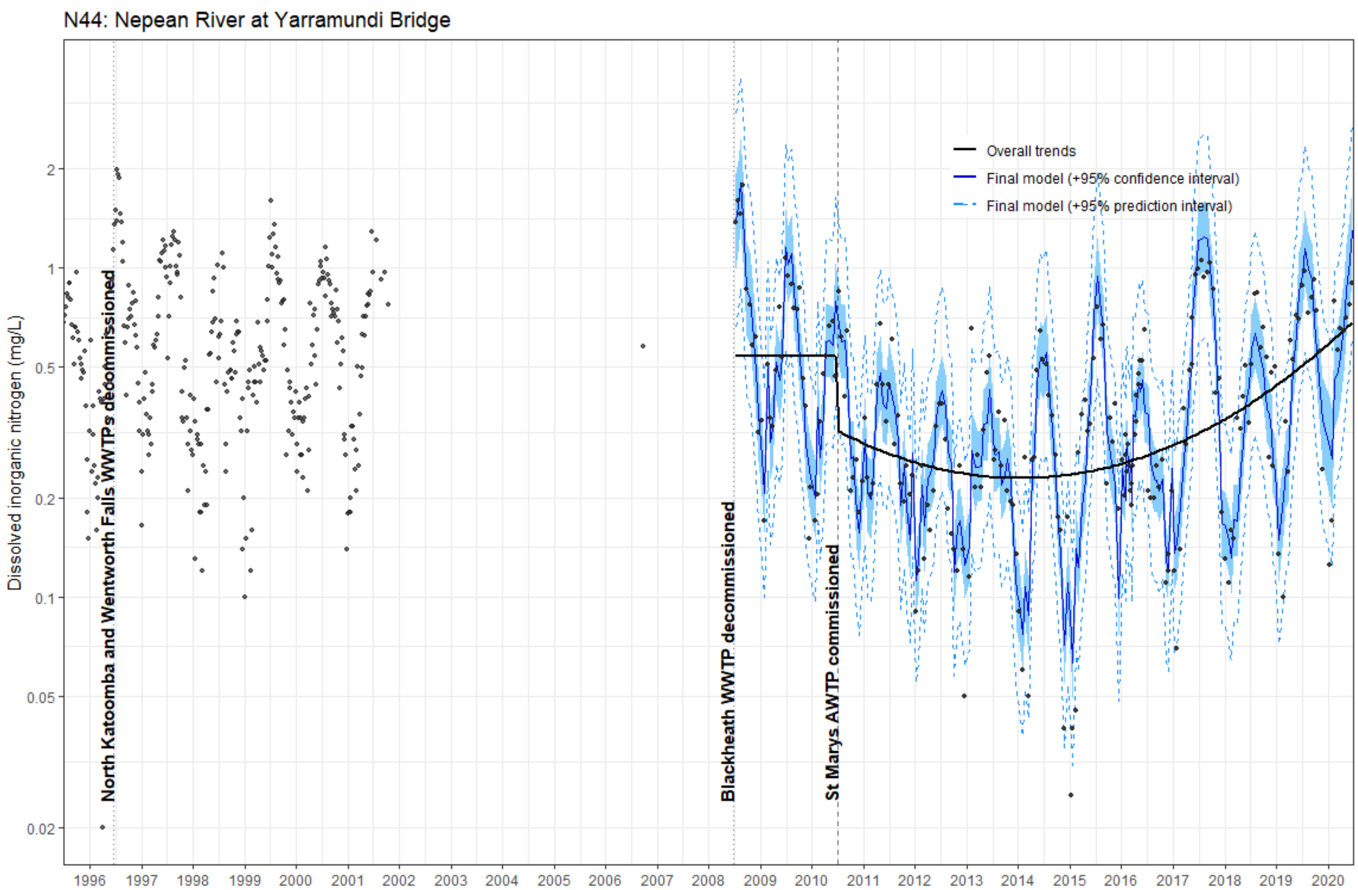

Figure 4-16 Dissolved inorganic nitrogen concentrations at Yarramundi, Nepean River (N44): fitting terms to model upstream concentration, upstream river flow, DIN load from Winmalee WWTP, along with linear and quadratic trends within each period and seasonal trends overlaid with the trends in each period

Key outcomes

- Dissolved inorganic nitrogen concentration:
  - There was no ANZG default level for dissolved inorganic nitrogen concentration
  - The final reduced model fitted well with R^2=0.82 and adjusted R^2=0.79. However, the residual plots showed the model did not capture the extremely high or low dissolved inorganic nitrogen concentrations.
- Impact of upstream catchment:
  - The DIN concentration at N48A was significantly correlated to the concentration at N44 ($p<0.0001$).
    - when DIN concentration at N48A is low eg 0.03 mg/L, a 0.01 mg/L increase of DIN concentration increased the concentration at N44 by 9%

        - when DIN concentration at N48A is moderate eg 0.15 mg/L, a 0.01 mg/L increase in concentration increased the concentration at N44 by 2%
        - when DIN concentration at N48A is high eg 0.3 mg/L, a 0.01 mg/L increase in concentration increased the concentration at N44 by 1%.
    - Flow in the Nepean River at N48A was significantly correlated to the concentration of DIN at N44 ($p<0.0001$).
        - when flow at N48A is low eg 800 ML/day, a 100 ML increase in flow decreased the concentration at N44 by 1.3%
        - when flow at N48A is moderate eg 1100 ML/day, a 100 ML increase in flow decreased the concentration at N44 by 1.0%
        - when flow at N48A is high eg 1500 ML/day, a 100 ML increase in flow decreased the concentration at N44 by 0.7%.
- Impact of WWTPs:
    - The DIN load from Winmalee WWTP was significantly correlated to the concentration of DIN at N44 ($p<0.0001$ when adjusting for upstream catchment variables and 0.001 when adjusting for all variables in the model).
        - when the load from Winmalee WWTP is low eg 90 kg/day, a 10 kg/day increase in load increased the concentration at N44 by 3.2%
        - when the load from Winmalee WWTP is moderate eg 125 kg/day, a 10 kg/day increase in load increased the concentration at N44 by 2.3% and
        - when the load from Winmalee WWTP is high eg 225 kg/day, a 10 kg/day increase in load increased the concentration at N44 by 1.3%.
- Long term trends:
    - There was no trend seen after decommissioning Blackheath WWTP and before commissioning of St Marys AWTP (period 1)
    - After the commissioning of St Marys AWTP, there was a significantly increasing curvilinear trend.
    - As of mid-2020, the trend in dissolved inorganic nitrogen concentration was increasing.
- Seasonal trends:
    - First order sine and cosine terms by year interactions were included to capture a pattern of one peak per year in February and one trough around August with a magnitude that differed between years.
- After adjusting for seasonal trends, flow and concentration at the upstream site and load from Winmalee WWTP, the dissolved inorganic nitrogen geometric mean concentration:
    - After decommissioning Blackheath WWTP (period 1) was 0.58 mg/L (95% CI = 0.50 to 0.67 mg/L) at N44

- After commissioning of St Marys AWTP (period 2) the geometric mean was 0.24 mg/L (95% CI = 0.22 to 0.26 mg/L) at N44

- Comparing the dissolved inorganic nitrogen concentrations between periods:
  - The geometric mean for the period after commissioning St Marys AWTP (period 2) was 42% (95% CI = 34 to 52%) of the geometric mean for the period prior to the commissioning (period 1).

4.2.6 Nepean River at Yarramundi (N44) and Smith Rd (N48A) – Dissolved inorganic nitrogen concentration (downstream/upstream)

There were no dissolved inorganic nitrogen concentration records for the upstream Nepean River site at Smith Road (N48A) from 2002 to mid-2008. The analysis models included data from 2008, with 222 records from N44 and 214 records from N48A. However, the data prior to this time has been plotted for completeness. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included a factor for site identifier, site by flow interaction term to allow the relationship with flow to differ between sites, a site by period interaction term to allow the site means to differ in each of the two periods defined by the commissioning of St Marys AWTP, interaction terms for site by linear and quadratic trends to allow them to differ within each period and 3-factor interaction terms for site by 1st, 2nd and 3rd order harmonic interaction terms to model the seasonal trends and allow them to differ between sites.

The model:

Log_{10}(DIN concentration) = site (N44 or N48A) + site by flow + site by period + site by linear trend in period 1 + site by linear trend in period 2 + site by quadratic trend in period 1 + site by quadratic trend in period 2 + site by 1st order sine by year + site by 1st order cosine by year + site by 2nd order sine by year + site by 2nd order cosine by year + site by 3rd order sine by year + site by 3rd order cosine by year

Where:

- site, period and year are categorical factors.
- Flow consists of the flow corresponding to the site identified in the site variable as defined in Volume 2: Appendix E (Table E-5)

Model reduction decisions:

- No further model reduction is undertaken

Step 2: Fit the final, reduced model

Log_{10}(DIN concentration) = site (N44 or N48A) + site by flow + site by period + site by linear trend in period 1 + site by linear trend in period 2 + site by quadratic trend in period 1 + site by quadratic trend in period 2 + site by 1st order sine by year + site by 1st order cosine by year + site by 2nd order sine by year + site by 2nd order cosine by year + site by 3rd order sine by year + site by 3rd order cosine by year

Where:

- site, period and year are categorical factors.
- Flow consists of the flow corresponding to the site identified in the site variable as defined in Volume 2: Appendix E (Table E-5)

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-17.

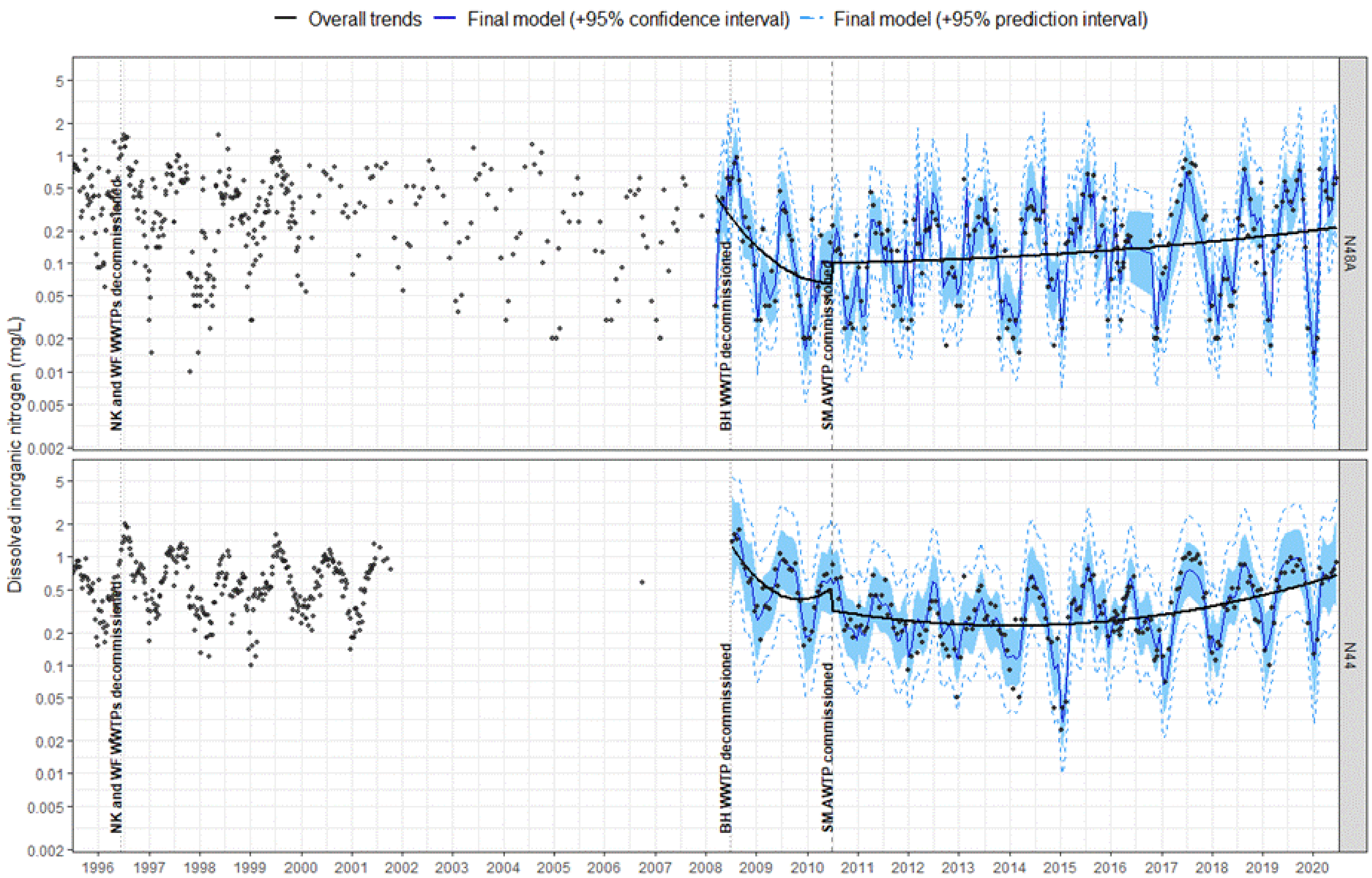

Figure 4-17 Dissolved inorganic nitrogen concentrations at Smith Road (N48A) and Yarramundi (N44), Nepean River: fitting terms to model site differences and associated flow along with linear and quadratic trends and seasonal trends overlaid with the trends in each period

The detailed statistical outcomes of this model are included in Volume 2 (Appendix G). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table G-11 and Table G-12, respectively. The residual plots for this model are shown in Figure G-6.

The site, site by flow and site by period parameters were retained in the model as they were part of the study design. A similar pattern as for TN was seen with the difference between the type I and type III SS. The site by linear and quadratic trends in period 1 had type III SS p-values >0.3, suggesting that the site by harmonic interaction terms accounted for these trends in the short timespan for this period. The flow corresponding to each site and the linear trends in period 2 continued to have a p-value of <0.15 for both type I and type III SS.

The model fitted the data well (R^2=0.86 and adjusted R^2=0.77) except for those at extremely high concentrations or, to a lesser extent, low concentrations. A few values showed a high leverage (ie terms in the model are included because of their contribution to the variability in the data). The distribution of the residuals was approximately Normal and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

Key outcomes

- Dissolved inorganic nitrogen concentration:
  - There was no ANZG default level for DIN concentration
  - The final reduced model fitted well with R^2=0.86 and adjusted R^2=0.77. However, the residual plots showed the model did not capture the extremely high DIN concentrations.
- Flow:
  - The relationship between flow and DIN concentration differed between sites (p<0.0001).
  - There was no apparent relationship at N44 (p=0.9).
  - Flow significantly increased concentration at N48A (p<0.0001).
    - when flow at N48A is low eg 800 ML/day, a 100 ML/day increase in flow increased DIN concentration by 5%
    - when flow at N48A is moderate eg 1100 ML/day, a 100 ML/day increase in flow increased the concentration at N48A by 3.8%
    - when flow at N48A is high eg 1500 ML/day, a 100 ML/day increase in flow increased the concentration at N48A by 2.8%.
- Long term trends:
  - There was a significant interaction between site and linear trends in periods 1 and 2 and between site and quadratic trend in period 2 (p<0.0001), and between site and quadratic trend in period 1 (p=0.04).
  - There was a curvilinear trend at both sites seen in the period after decommissioning of Blackheath WWTP and before commissioning of St Marys AWTP (period 1) that differed between sites. At both sites, the dissolved inorganic nitrogen concentration decreased until mid-2009. At N48A the concentration continued to decrease, whereas at N44 the

concentration started to increase. This pattern was also explained by the seasonal trend by year.

  - After the commissioning of St Marys AWTP (period 2), there was also a difference between the curvilinear trends at each site, although they both showed an overall increase in dissolved inorganic nitrogen concentration. This pattern was partly explained by the seasonal trend by year.
  - As of mid-2020, the dissolved inorganic nitrogen concentration trend at both sites was increasing.

- Seasonal trends:
  - All site by 1st, 2nd and 3rd order sine and cosine terms by year interactions were included to capture a more complex pattern of three peaks per year, capturing the largest one in February and two smaller ones in late May/ early June and September. The lowest trough was around late October/ early November. The magnitude of the peaks and troughs differed between years and sites.
- Site by period modelled geometric means:
  - There was a significant interaction between site and period ($p<0.0001$).
  - After adjusting for linear, quadratic and seasonal trends:
    - After decommissioning Blackheath WWTP and prior to the commissioning St Marys AWTP the dissolved inorganic nitrogen geometric mean concentration at N44 was 0.49 mg/L (95% CI = 0.35 to 0.68 mg/L) and at N48A was 0.13 mg/L (95% CI = 0.10 to 0.17 mg/L)
    - After commissioning of St Marys AWTP the dissolved inorganic nitrogen geometric mean concentration at N44 was 0.25 mg/L (95% CI = 0.21 to 0.28 mg/L) and at N48A was 0.22 mg/L (95% CI = 0.18 to 0.26 mg/L).
  - Comparing the modelled geometric mean dissolved inorganic nitrogen concentrations between sites within periods
    - The geometric mean for N44 in the period before commissioning St Marys AWTP (period 1) was 377% (242 to 586%) of the geometric mean for N48A
    - The geometric mean for N44 in the period after commissioning St Marys AWTP (period 2) was 113% (91 to 140%) of the geometric mean for N48A
  - Comparing the dissolved inorganic nitrogen concentrations between periods:
    - The geometric mean for the period after commissioning St Marys AWTP (period 2) was 50% (95% CI = 35 to 72%) of the geometric mean for the period prior to the commissioning (period 1) at site N44.
    - The geometric mean for the period after commissioning St Marys AWTP (ie period 2) was 168% (95% CI = 120 to 234%) of the geometric mean for the period prior to the commissioning (period 1) at site N48A

- The percentage difference between periods 2 and 1 for the geometric mean concentration at N44 was 30% (18 to 49%) of the percentage difference at N48A

4.2.7 Winmalee WWTP – Total phosphorus load

There were 1523 total phosphorus load records from Winmalee WWTP in this data series. Prior to the decommissioning of North Katoomba and Wentworth Falls WWTPs in 1996 there were 58 records, after the decommissioning of these WWTPs and a phosphorus upgrade at Winmalee WWTP in 2000 there were 216 records, after the phosphorus upgrade and before the decommissioning of Blackheath WWTP in 2008 there were 519 records and after the decommissioning there were 730 records. All records are included in the analyses. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included the four periods defined by the decommissioning of North Katoomba and Wentworth Falls WWTPs, a phosphorus upgrade at Winmalee WWTP in 2000 and decommissioning of Blackheath WWTP, then linear and quadratic trends within each period and 1st, 2nd and 3rd order harmonic interaction terms to model the seasonal trends.

The model:

Log_{10}(TP load) = period + linear trend in period 1 + linear trend in period 2 + linear trend in period 3 + linear trend in period 4 + quadratic trend in period 1 + quadratic trend in period 2 + quadratic trend in period 3 + quadratic trend in period 4 + 1st order sine + 1st order cosine + 2nd order sine + 2nd order cosine + 3rd order sine + 3rd order cosine + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

period and year are categorical factors.

Model reduction decisions:

- Period 1: the linear and quadratic trend terms were removed (both p-values from the type I SS were > 0.15)
- Periods 2, 3 and 4: retain the linear and quadratic trend terms as the p-values for the quadratic terms using the type I SS were <0.15
- Retain all harmonic interaction terms as the p-values for the 3rd order terms from the type I SS were <0.15
- Remove the main effect harmonic terms since they can be included in the harmonic interaction terms.

Step 2: Fit the final, reduced model

Log_{10}(TP load) = period + linear trend in period 2 + linear trend in period 3 + linear trend in period 4 + quadratic trend in period 2 + quadratic trend in period 3 + quadratic trend in period 4 + 1st order sine by Year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

period and year are categorical factors.

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-18.

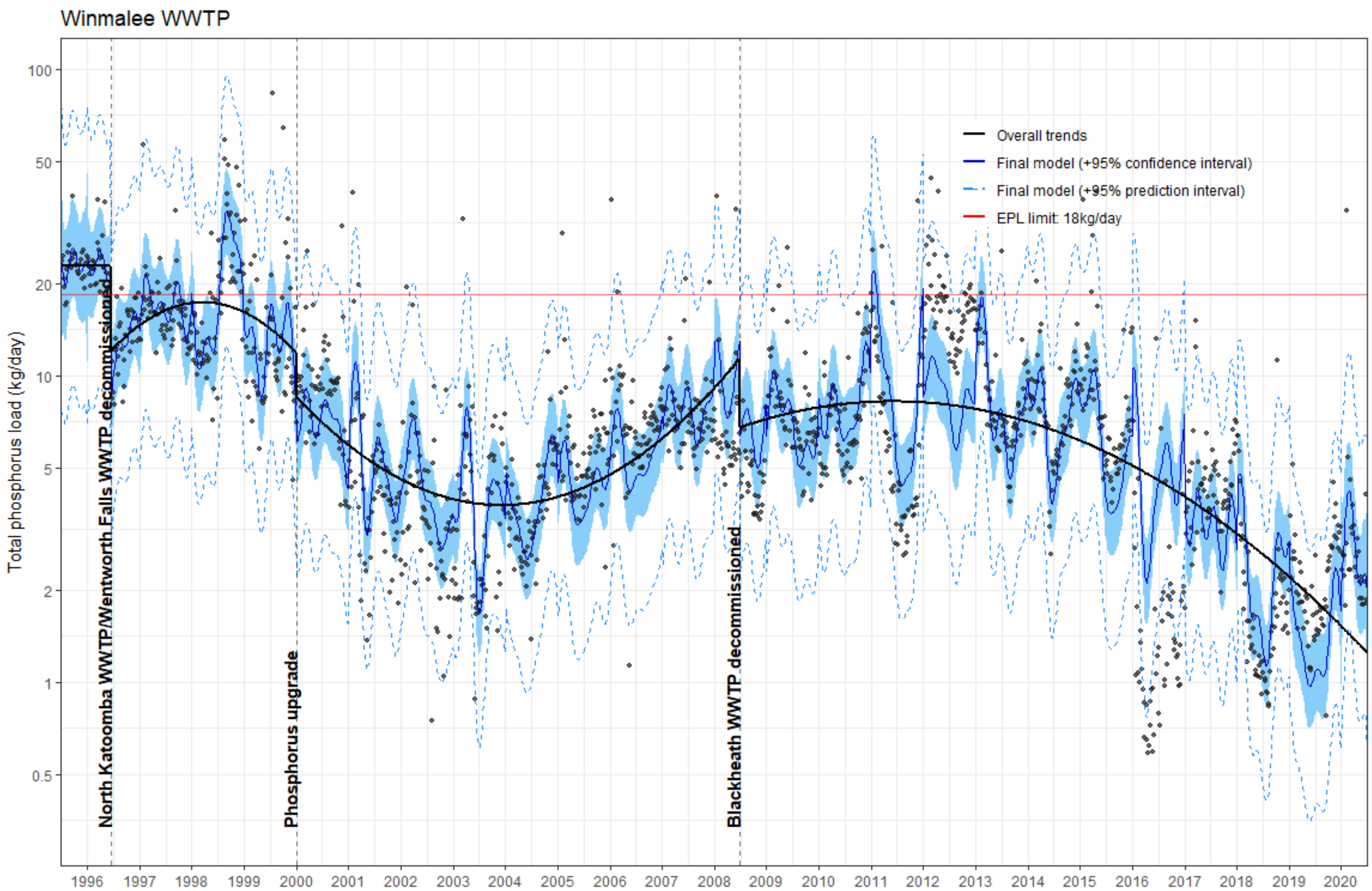

Figure 4-18 Total phosphorus load from Winmalee, North Katoomba, Wentworth Falls and Blackheath WWTPs: fitting terms to model interventions, linear and quadratic trends within each period and seasonal trends overlaid with the trends in each period

The detailed statistical outcomes of this model are included in Volume 2 (Appendix G). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table G-13 and Table G-14, respectively. The residual plots for this model are shown in Figure G-7.

All terms in the final, reduced model had a p-value for the corresponding type I SS <0.15 except for the linear trend in period 2 with a p-value of 0.90 and the 3rd order cosine by Year term with a p-value of 0.33. The linear trend term was included in the model as the corresponding quadratic term was significant (p=0.001) and the cosine term was included as its partner, the 3rd order sine by Year term had p=0.12 (ie <0.15). Each term in the model had a similar p-value after adjusting for all other terms in the model (type III SS) except for the linear trend in period 2 that became significant with p=0.007. This suggested that, after adjusting for all the seasonal terms there was an underlying linear component to the curvilinear trend that was not obvious when the seasonal trend is not accounted for.

The model fitted the data well (R^2=0.69 and adjusted R^2=0.66) except for those at extremely high or low loads. Four values showed a high leverage (ie terms in the model are included because of their contribution to the variability in the data). The distribution of the residuals was approximately Normal and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

Key outcomes

- Total phosphorus load:
    - Winmalee WWTP total phosphorus load included loads from North Katoomba, Wentworth Falls and Blackheath WWTPs prior to their decommissioning.
    - Since the phosphorus upgrade in 2000, the majority of records were below the current EPL limit of 18 kg/day.
    - The final reduced model fitted well with R^2=0.69 and adjusted R^2=0.66. However, the residual plots showed the model did not capture the extremely high or low total phosphorus loads.
- Long term trends:
    - No trend was observed prior to the decommissioning of North Katoomba and Wentworth Falls WWTPs
    - Significant curvilinear trends were observed in the three periods after the decommissioning of North Katoomba and Wentworth Falls WWTPs
        - After decommissioning of North Katoomba and Wentworth Falls WWTPs, the total phosphorus load had an increasing curvilinear trend driven by the high loads seen in the second half of 1998 before decreasing to end the period at a similar level to the start of the period.
        - After the phosphorus upgrade, the total phosphorus load had a decreasing curvilinear trend until around 2004 when load started to increase again.

    - After decommissioning Blackheath WWTP there was a slightly increasing curvilinear trend until approximately 2012 when total phosphorus load started to decrease.
    - As of mid-2020, the phosphorus load trend was decreasing.
- Seasonal trends:
  - First, second and third order sine and cosine terms by year interactions were included to capture a more complex pattern of three peaks per year, capturing the largest one in February and two smaller ones in late May/ early June and September. The lowest trough was around late October/ early November. The magnitude of the peaks and troughs differed between years.
- After adjusting for seasonal trends, the modelled geometric mean total phosphorus load:
  - Prior to the decommissioning of North Katoomba and Wentworth Falls WWTPs (period 1) was 24.6 kg/day (95% CI =17.2 to 35.3 kg/day), the confidence interval was wide due to the small number of records in the period prior to the decommissioning of North Katoomba and Wentworth Falls WWTPs
  - After the decommissioning of North Katoomba and Wentworth Falls WWTPs (period 2) was 18.9 kg/day (95% CI = 16.9 to 21.1 kg/day)
  - After the phosphorus upgrade at Winmalee WWTP (period 3) was 3.8 kg/day (95% CI = 3.5 to 4.0 kg/day)
  - After the decommissioning of Blackheath WWTP (period 4) was 7.1 kg/day (95% CI = 6.7 to 7.5 kg/day).
- Comparing the modelled geometric mean total phosphorus loads between periods:
  - The geometric mean for the period after North Katoomba and Wentworth Falls WWTPs (period 2) were decommissioned was 68% (95% CI = 29 to 162%) of the geometric mean for the period before North Katoomba and Wentworth Falls WWTPs were decommissioned (period 1).
  - The geometric mean for the for the period after the phosphorus upgrade (period 3) was 20% (95% CI = 18 to 23%) of the geometric mean before the phosphorus upgrade at Winmalee WWTP (period 2)
  - The geometric mean after Blackheath WWTP was decommissioned (period 4) was 189% (95% CI = 173 to 206%) of the geometric mean for the period before Blackheath WWTP was decommissioned (period 3).

4.2.8 Nepean River at Yarramundi (N44) – Total phosphorus concentration

There were no total phosphorus concentration records from the Nepean River at Yarramundi (N44) from mid-2001 to mid-2008 when Blackheath WWTP was decommissioned. The analysis models included data from 2008, with 221 records from N44. However, the data prior to 2001 has been plotted for completeness. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included TP concentration at the upstream site N48A, the flow at N48A, Winmalee TP load, the two periods defined by the commissioning of St Marys AWTP, linear and quadratic trends within each period and 1st, 2nd and 3rd order harmonic interaction terms to model the seasonal trends.

The model:

Log_{10}(N44 TP concentration) = log_{10}(N48A TP concentration) + log_{10}(flow at N48A) + log_{10}(Winmalee WWTP TP load) + period + linear trend in period 1 + linear trend in period 2 + quadratic trend in period 1 + quadratic trend in period 2 + 1st order sine + 1st order cosine + 2nd order sine + 2nd order cosine + 3rd order sine + 3rd order cosine + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

- period and year are categorical factors.
- Winmalee WWTP TP load is a composite of North Katoomba, Wentworth Falls and Blackheath WWTPs up until the time of their being decommissioned as well as Winmalee WWTP TP load.
- Flow at N48A is derived as described in Volume 2: Appendix E (Table E-5)

Model reduction decisions:

- Retain only 1st order harmonic interaction terms. Even though the 2nd and 3rd order harmonic interaction terms could have been included based on the p-value cut-off, these terms only captured the unusual patterns in 2013, 2014 and 2020. Due to the small number of records and the risk of overfitting, these terms were excluded.
- Remove the main effect harmonic terms since they can be included in the harmonic interaction terms.

Step 2: Fit the final, reduced model

Log_{10}(N44 TP concentration) = log_{10}(N48A TP concentration) + log_{10}(flow at N48A) + log_{10}(Winmalee WWTP TP load) + period + linear trend in period 1 + linear trend in period 2 + quadratic trend in period 1 + quadratic trend in period 2 + 1st order sine by year + 1st order cosine by year

Where:

- period and year are categorical factors.
- Winmalee WWTP TP load is a composite of North Katoomba, Wentworth Falls and Blackheath WWTPs up until the time of their being decommissioned as well as Winmalee WWTP TP load.
- Flow at N48A is derived as described in Volume 2: Appendix E (Table E-5)

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-19.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix G). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table G-15 and Table G-16, respectively. The residual plots for this model are shown in Figure G-8.

The period parameter as well as the upstream concentration at N48A, flow corresponding to N48A and the WWTP TP load estimates were retained in the model as part of the study design. The p-values corresponding to the Type III SS varied compared with the type I SS. The linear and quadratic trends in period 1 had type III SS p-values >0.3, suggesting that the harmonic interaction terms accounted for these trends in the short timespan for this period. The upstream concentration at N48A, flow corresponding to N48A and the Winmalee WWTP TP load had $p<0.0001$ for both type I and type III SS.

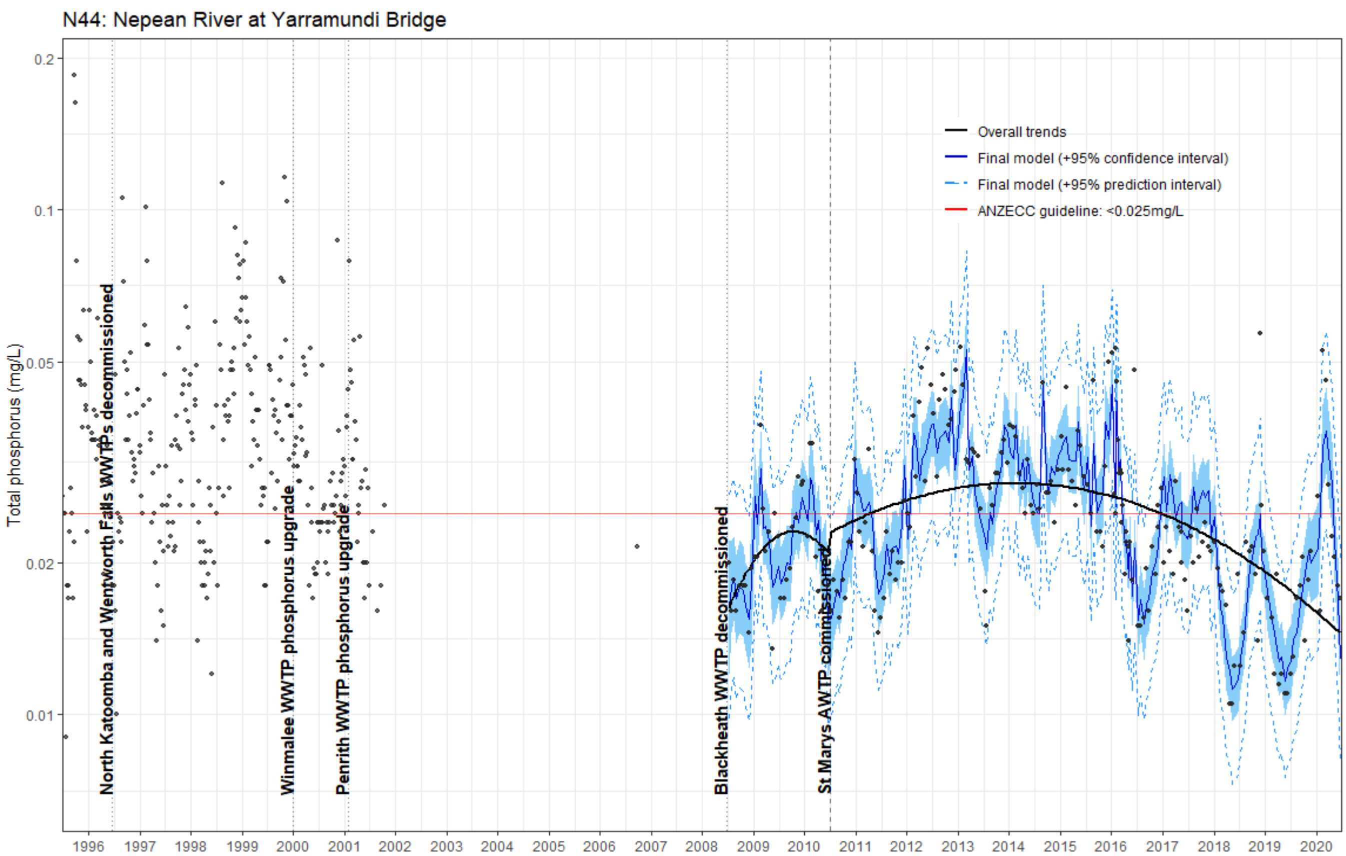

Figure 4-19 Total phosphorus concentrations at Yarramundi, Nepean River (N44): fitting terms to model upstream concentration, upstream river flow, TP load from Winmalee WWTP, along with linear and quadratic trends within each period and seasonal trends overlaid with the trends in each period

The model fitted the data well (R^2=0.73 and adjusted R^2=0.68) except for those at extremely high and low concentrations. There were three records with high leverage. The distribution of the residuals was approximately Normal and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

Key outcomes

- Total phosphorus concentration:
  - TP concentration in the Nepean River at Yarramundi varied around the ANZG default level of <0.025 mg/L
  - The final reduced model fitted well with R^2=0.73 and adjusted R^2=0.68. However, the residual plots showed the model did not capture the extremely high or low total phosphorus concentrations
- Impact of upstream catchment
  - The TP concentration at N48A was significantly correlated to the concentration at downstream site (N44) ($p<0.0001$).
    - when TP concentration at N48A is low eg 0.015 mg/L, a 0.001 mg/L increase of TP concentration increased the concentration at N44 by 2.4%
    - when TP concentration at N48A is moderate eg 0.02 mg/L, a 0.1 mg/L increase in concentration increased the concentration at N44 by 1.8%
    - when TP concentration at N48A is high eg 0.025 mg/L, a 0.1 mg/L increase in concentration increased the concentration at N44 by 1.4%.
  - Flow in the Nepean River at N48A was not correlated to the concentration of TP at N44 after taking into account the correlation between TP concentration at N48A and N44 ($p<0.6$).
- Impact of WWTPs:
  - TP load from Winmalee WWTP was significantly correlated to the concentration of TP at the downstream site (N44) after accounting for the effects of TP concentration at N48A and flow in the Nepean River at N48A, and after adjusting for all terms in the model ($p<0.0001$).
    - When the load from Winmalee WWTP is low eg 2 kg/day, a 1 kg/day increase in load increased the concentration at N44 by 6.7%
    - when the load from Winmalee WWTP is moderate eg 6 kg/day, a 1 kg/day increase in load increased the concentration at N44 by 2.5%
    - when the load from Winmalee WWTP is high eg 10 kg/day, a 1 kg/day increase in load increased the concentration at N44 by 1.5%.

- Long term trends:
    - The curvilinear trend seen after decommissioning of Blackheath WWTP and before commissioning of St Marys AWTP (period 1) was also explained by the seasonal trend by year.
    - After the commissioning of St Marys AWTP, there was a significantly decreasing curvilinear trend.
    - As of mid-2020, the trend in total phosphorus concentration was decreasing.
- Seasonal trends:
    - First order sine and cosine terms by year interactions were included to capture a pattern of one peak per year in February and one trough around August with a magnitude that differed between years.
- After adjusting for seasonal trends, flow and concentration at the upstream site and load from Winmalee WWTP, the geometric mean total phosphorus concentration:
    - After decommissioning Blackheath WWTP (period 1) was 0.023 mg/L (95% CI = 0.021 to 0.026 mg/L)
    - After commissioning of St Marys AWTP (period 2) was 0.029 mg/L (95% CI = 0.027 to 0.031 mg/L).
- Comparing the total phosphorus concentration between periods:
    - The geometric mean for the period after commissioning St Marys AWTP (period 2) was 123% (95% CI = 108 to 140%) of the geometric mean for the period prior to the commissioning (period 1).

4.2.9 Nepean River at Yarramundi (N44) and Smith Rd (N48A) – Total phosphorus concentration (downstream/upstream)

There were no total phosphorus concentration records for the Nepean River upstream site at N48A from 2002 to mid-2008. The analysis models included data from 2008 with 222 records from N44 and 214 records from N48A. However, the data prior to this time has been plotted for completeness. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included a factor for site identifier, site by flow interaction term to allow the relationship with flow to differ between sites, a site by period interaction term to allow the site means to differ in each of the two periods defined by the commissioning of St Marys AWTP, interaction terms for site by linear and quadratic trends to allow them to differ within each period and 3-factor interaction terms for site by 1^{st}, 2^{nd} and 3^{rd} order harmonic interaction terms to model the seasonal trends and allow them to differ between sites.

The model:

Log_{10}(TP concentration) = site (N44 or N48A) + site by flow + site by period + site by linear trend in period 1 + site by linear trend in period 2 + site by quadratic trend in period 1 + site by quadratic trend in period 2 + site by 1st order sine by year + site by 1st order cosine by year + site by 2nd order sine by year + site by 2nd order cosine by year + site by 3rd order sine by year + site by 3rd order cosine by year

Where:

- site, period and year are categorical factors.
- Flow consists of the flow corresponding to the site identified in the site variable as defined in Volume 2: Appendix E (Table E-5)

Model reduction decisions:

- No further model reduction is undertaken

Step 2: Fit the final, reduced model

Log_{10}(TP concentration) = site (N44 or N48A) + site by flow + site by period + site by linear trend in period 1 + site by linear trend in period 2 + site by quadratic trend in period 1 + site by quadratic trend in period 2 + site by 1st order sine by year + site by 1st order cosine by year + site by 2nd order sine by year + site by 2nd order cosine by year + site by 3rd order sine by year + site by 3rd order cosine by year

Where:

- site, period and year are categorical factors.
- Flow consists of the flow corresponding to the site identified in the site variable as defined in Volume 2: Appendix E (Table E-5)

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-20.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix G). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table G-17 and Table G-18, respectively. The residual plots for this model are shown in Figure G-9.

The site, site by flow and site by period parameters were retained in the model as they were part of the study design. A similar pattern as for TN was seen with the difference between the type I and type III SS. The site by linear and quadratic trends in period 1 had type III SS p-values >0.3, suggesting that the site by harmonic interaction terms accounted for these trends in the short timespan for this period. The flow corresponding to each site and the linear trends and quadratic trends in period 2 continued to had a p-value of <0.15 for both type I and type III SS.

The model fitted the data well (R^2=0.74 and adjusted R^2=0.58) except for those at extremely high concentrations or, to a lesser extent, low concentrations. A few values showed a high leverage (ie terms in the model are included because of their contribution to the variability in the data). The distribution of the residuals was approximately Normal and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

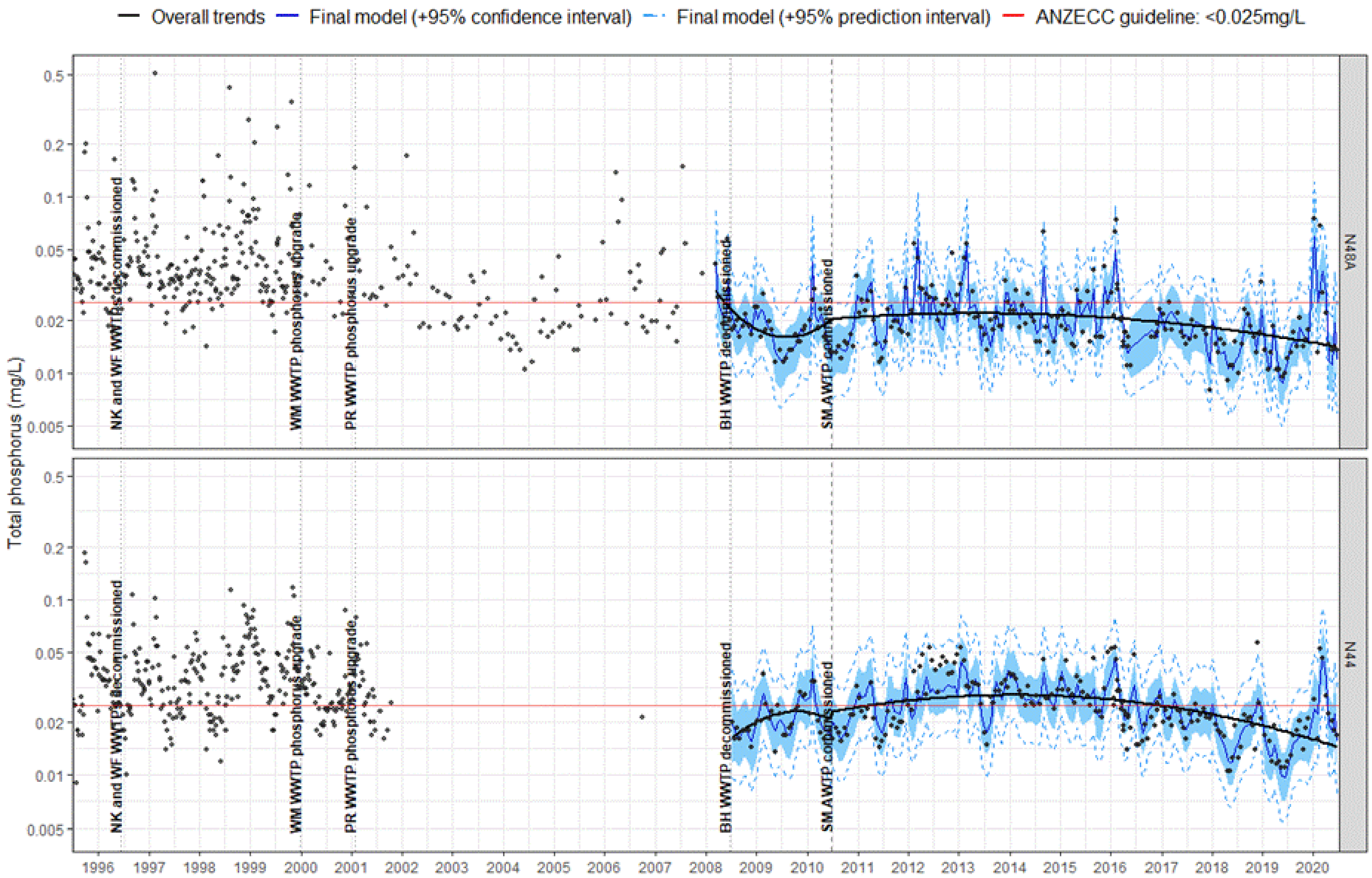

Figure 4-20 Total phosphorus concentrations at Smith Road (N48A) and Yarramundi (N44), Nepean River: fitting terms to model site differences and associated flow along with linear and quadratic trends and seasonal trends

Key outcomes

- Total phosphorus concentration:
  - Total phosphorus concentration was generally below the ANZG default level of <0.025mg/L at the upstream site of N48A and was below during 2018 to 2019. However, there was a peak in TP above the guideline at the downstream site of N44 during the first half of 2020.
  - The final reduced model fitted well with R^2=0.74 and adjusted R^2=0.58. However, the residual plots showed the model did not capture the extremely high total phosphorus concentrations.

- Flow:
  - Although flow increased the TP concentration at both sites, the relationship differed in terms of significance between sites ($p<0.0001$).
  - Flow increased concentration at N44 ($p=0.01$).
    - when flow at N44 is low eg 800 ML/day, a 100 ML/day increase in flow increased the TP concentration by 0.8%
    - when flow at N44 is moderate eg 1100 ML/day, a 100 ML/day increase in flow increased the concentration at N44 by 0.6%
    - when flow at N44 is high, eg 1500 ML/day, a 100 ML/day increase in flow increased the concentration at N44 by 0.5%.
  - Flow increased concentration at N48A more significantly ($p<0.0001$).
    - When flow at N48A is low eg 800 ML/day, a 100 ML/day increase in flow increased the TP concentration by 2.4%
    - when flow at N48A is moderate eg 1100 ML/day, a 100 ML/day increase in flow increased the concentration at N48A by 1.8%
    - when flow at N48A is high, eg 1500 ML/day, a 100 ML/day increase in flow increased the concentration at N48A by 1.3%.
- Long term trends:
  - There was a significant interaction between site and linear trends in period 1 ($p=0.007$) and between site and quadratic trend in period 1 ($p=0.01$). Also in period 2, there was a significant interaction between site and linear and quadratic trend ($p<0.0001$).
  - There was a curvilinear trend at both sites in the period after decommissioning of Blackheath WWTP and before commissioning of St Marys AWTP (period 1) that differed between sites. At N48A the total phosphorus concentration decreased until mid-2009 before increasing. At N44 the total phosphorus concentration increased until mid-2009 before decreasing. This pattern was also explained by the seasonal trend by year.
  - After the commissioning of St Marys AWTP (period 2), there was also a difference between the curvilinear trends at each site, although both sites showed an overall decrease in total phosphorus concentration.
  - As of mid-2020, the total phosphorus concentration trend at both sites was decreasing.
- Seasonal trends:
  - All site by 1st, 2nd and 3rd order sine and cosine terms by year interactions were included to capture a more complex pattern of three peaks per year, capturing the largest one in February and two smaller ones in late May/ early June and September. The lowest trough was around late October/ early November. The magnitude of the peaks and troughs differed between years and sites.

- Site by period modelled geometric mean total phosphorus concentrations:
  - The interaction between site and period had a p-value of 0.09. While not significant if $p<0.05$ is used as a cut-point, the individual geometric means and comparisons were undertaken for consistency with the rest of the report.
  - After adjusting for linear, quadratic and seasonal trends:
    - After decommissioning Blackheath WWTP, the geometric mean at N44 was 0.025 mg/L (95% CI = 0.021 to 0.029 mg/L) and at N48A was 0.019 mg/L (95% CI = 0.016 to 0.022 mg/L).
    - After commissioning of St Marys AWTP, the geometric mean at N44 was 0.030 mg/L (95% CI = 0.028 to 0.033 mg/L) and at N48A was 0.025 mg/L (95% CI = 0.023 to 0.028 mg/L).
  - Comparing the total phosphorus concentrations between sites within periods:
    - The geometric mean TP concentration for N44 in the period before commissioning St Marys AWTP (period 1) was 129% (102 to 161%) of the geometric mean for N48A
    - The geometric mean TP concentration for N44 in the period after commissioning St Marys AWTP (period 2) was 120% (107 to 134%) of the geometric mean for N48A
  - Comparing the total phosphorus concentrations between periods:
    - The geometric mean TP concentration for the period after commissioning St Marys AWTP (period 2) was 123% (95% CI = 103 to 147%) of the geometric mean for the period prior to the commissioning (period 1) at site N44
    - The geometric mean TP concentration for the period after commissioning St Marys AWTP (period 2) was 132% (95% CI = 111 to 156%) of the geometric mean for the period prior to the commissioning (period 1) at site N48A
    - The percentage difference between periods 2 and 1 for the geometric mean concentration at N44 was 93% (72 to 120%) of the percentage difference at N48A.

4.2.10 Nepean River at Yarramundi (N44) –Chlorophyll-*a* concentration

There were no chlorophyll-*a* concentration records for the Nepean River at Yarramundi from mid-2001 to mid-2008 when Blackheath WWTP was decommissioned. The analysis models include data from 2008, with 219 records from N44. However, the data prior to 2001 has been plotted for completeness. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included Chl-*a* concentration at the upstream site N48A, the flow at N48A, Winmalee TN and TP loads, the two periods defined by the commissioning of St Marys AWTP, linear and quadratic trends within each period and 1st, 2nd and 3rd order harmonic interaction terms to model the seasonal trends.

The model:

Log_{10}(N44 Chl-*a*) = $\log_{10}$(N48A Chl-*a*) + $\log_{10}$(flow at N48A) + $\log_{10}$(Winmalee WWTP TN load) + $\log_{10}$(Winmalee WWTP TP load) + period + linear trend in period 1 + linear trend in period 2 + quadratic trend in period 1 + quadratic trend in period 2 + 1st order sine + 1st order cosine + 2nd order sine + 2nd order cosine + 3rd order sine + 3rd order cosine + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

- period and year are categorical factors.
- Winmalee WWTP TN and TP loads are a composite of North Katoomba, Wentworth Falls and Blackheath WWTPs up until the time of their being
- Flow at N48A is derived as described Volume 2: Appendix E (Table E-5)

Model reduction decisions:

- Retain only 1st order harmonic interaction terms. Even though the 2nd and 3rd order harmonic interaction terms could have been included based on the p-value cut-off, these terms only captured the unusual patterns in 2013, 2014 and 2020. Due to the small number of records and the risk of overfitting, these terms were excluded.
- Remove the main effect harmonic terms since they can be included in the harmonic interaction terms.

Step 2: Fit the final, reduced model

Log_{10}(N44 Chl-*a*) = $\log_{10}$(N48A Chl-*a*) + $\log_{10}$(flow at N48A) + $\log_{10}$(Winmalee WWTP TN load) + $\log_{10}$(Winmalee WWTP TP load) + period + linear trend in period 1 + linear trend in period 2 + quadratic trend in period 1 + quadratic trend in period 2 + 1st order sine by year + 1st order cosine by year

Where:

- period and year are categorical factors.
- Winmalee WWTP TN and TP loads are a composite of North Katoomba, Wentworth Falls and Blackheath WWTPs up until the time of their being decommissioned
- Flow at N48A is derived as described in Volume 2: Appendix E (Table E-5)

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-21.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix G). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table G-19 and Table G-20, respectively. The residual plots for this model are shown in Figure G-10.

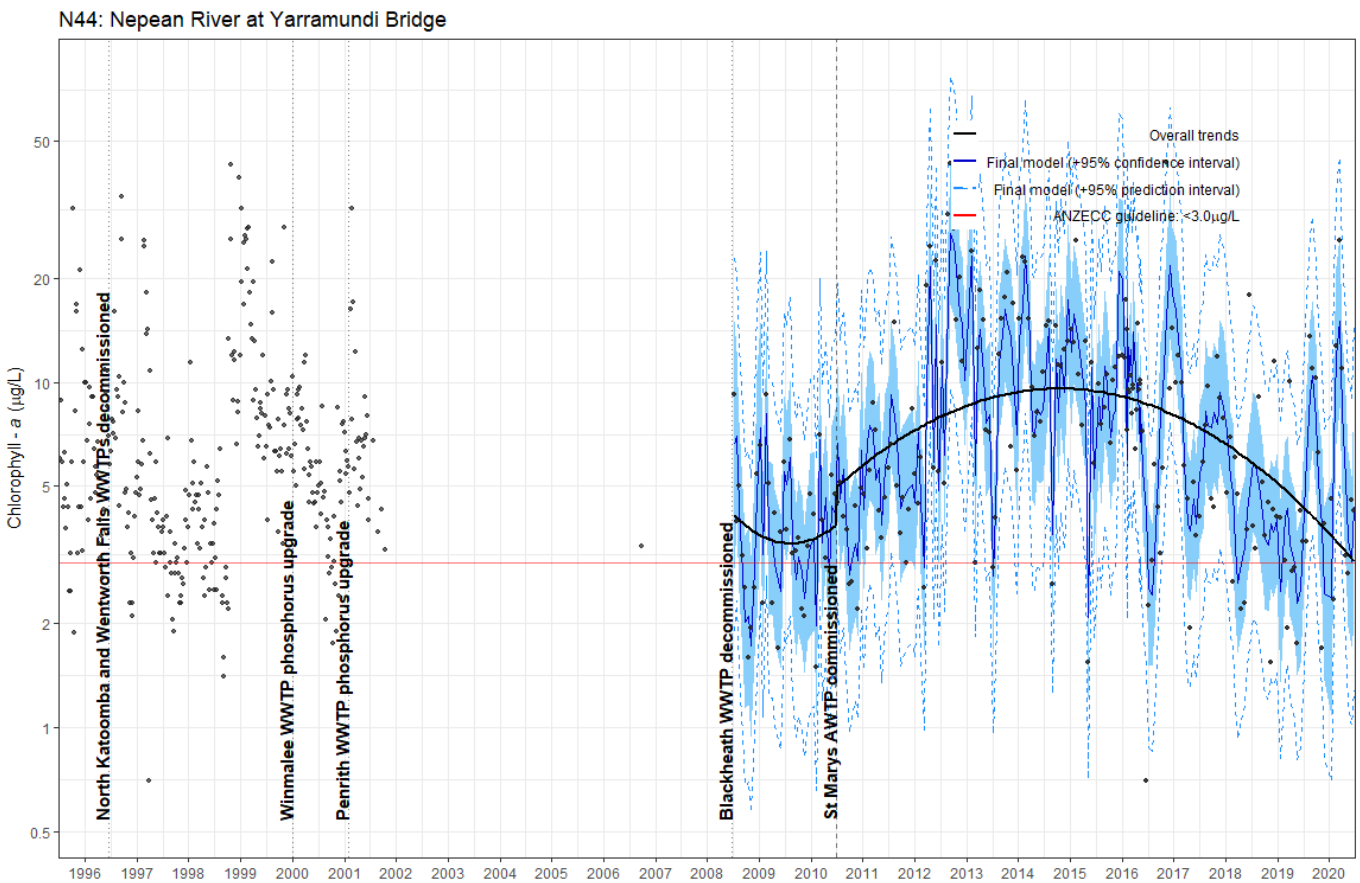

Figure 4-21 Chlorophyll-*a* concentrations at Yarramundi, Nepean River (N44): fitting terms to model upstream concentration, upstream river flow, TN and TP loads from Winmalee WWTP, along with linear and quadratic trends within each period and seasonal trends overlaid with the trends in each period

The period parameter as well as the upstream concentration at N48A, flow corresponding to N48A and the WWTP TN and TP load estimates were retained in the model as part of the study design. The p-values corresponding to the Type III SS varied compared with the type I SS. The linear and quadratic trends in period 1 had type III SS p-values >0.3, suggesting that the harmonic interaction terms accounted for these trends in the short timespan for this period. The upstream concentration at N48A, flow corresponding to N48A and the Winmalee WWTP TP load had p<0.0001 for both type I and type III SS.

The model fitted the data well (R^2=0.71 and adjusted R^2=0.59) except for those at extremely high and low concentrations. There were a few records with high leverage. The distribution of the residuals was approximately Normal and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

Key outcomes

- Chlorophyll-*a* concentration:
  - Chl-*a* concentrations were above the ANZG default level of <3.0 µg/L
  - The final reduced model fitted well with R^2=0.71 and adjusted R^2=0.59. However, the residual plots showed the model did not capture the extremely high or low Chl-*a* concentration.
- Impact of upstream catchment:
  - The Chl-*a* concentration at N48A was significantly correlated to the concentration at N44 ($p<0.0001$).
    - when the Chl-*a* concentration at N48A is low eg 5 µg/L, a 1 µg/L increase of Chl-*a* concentration increased the concentration at N44 by 12.6%
    - when Chl-*a* concentration at N48A is moderate eg 7 µg /L, a 1 µg /L increase in concentration increased the concentration at N44 by 9.1%
    - when Chl-*a* concentration at N48A is high eg 10 µg /L, a 1 µg /L increase in concentration increased the concentration at N44 by 6.4%.
  - Flow in the Nepean River at N48A was significantly correlated to the concentration of Chl-*a* at N44 ($p<0.05$).
    - When flow at N48A is low eg 800 ML/day, a 100 ML increase in flow decreased the concentration at N44 by 1.2%
    - when flow at N48A is moderate eg 1100 ML/day, a 100 ML increase in flow decreased the concentration at N44 by 0.9%
    - when flow at N48A is high eg 1500 ML/day, a 100 ML increase in flow decreased the concentration at N44 by 0.6%.
- Impact of WWTPs:
  - The TN load from Winmalee WWTP was not significantly correlated to the concentration of Chl-*a* at N44 after adjusting for upstream variables ($p=0.12$) and after adjusting for all terms in the model ($p=0.27$).
  - The TP load from Winmalee WWTP was significantly correlated to the concentration of Chl-*a* at N44 after adjusting for upstream variables and TN load from Winmalee WWTP and after adjusting for all terms in the model ($p=0.001$).
    - when the load at Winmalee WWTP is low eg 2 kg/day, a 1 kg/day increase in load increased the concentration at N44 by 8.9%
    - when the load from Winmalee WWTP is moderate eg 6 kg/day, a 1 kg/day increase in load increased the concentration at N44 by 3.3%
    - when the load from Winmalee WWTP is high eg 10 kg/day, a 1 kg/day increase in load increased the concentration at N44 by 2.0%.

- Long term trends:
    - The curvilinear trend seen after decommissioning of Blackheath WWTP and before commissioning of St Marys AWTP (period 1) is also explained by the seasonal trend by year.
    - After the commissioning of St Marys AWTP, there was a significantly decreasing curvilinear trend in Chl-*a* concentration.
    - As of mid-2020, the Chl-*a* concentration was decreasing.
- Seasonal trends:
    - First order sine and cosine terms by year interactions were included to capture a pattern of one peak per year in February and one trough around August with a magnitude that differed between years.
- After adjusting for seasonal trends, flow and concentration at the upstream site and load from Winmalee WWTP, the geometric mean Chl-*a* concentration:
    - After decommissioning Blackheath WWTP and prior to the commissioning St Marys AWTP (period 1) was 4.9 µg/L (95% CI = 3.6 to 6.7 µg/L)
    - After commissioning of St Marys AWTP (period 2) was 8.5 µg/L (95% CI = 7.5 to 9.6 µg/L)
- Comparing the modelled geometric mean Chl-*a* concentration between periods:
    - The geometric mean for the period after commissioning St Marys AWTP (period 2) was 170% (95% CI = 110 to 270%) of the geometric mean for the period prior to the commissioning (period 1).

4.2.11 Nepean River at Yarramundi (N44) and Smith Rd (N48A)– Chlorophyll-*a* concentration (upstream/downstream)

There were no chlorophyll-*a* concentration records for the Nepean River upstream site at Smith Road (N48A) from 2002 to mid-2008. The analysis models included data from 2008 with 222 records from N44, and 214 records from N48A. However, the data prior to this time has been plotted for completeness. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included a factor for site identifier, site by flow interaction term to allow the relationship with flow to differ between sites, a site by period interaction term to allow the site means to differ in each of the two periods defined by the commissioning of St Marys AWTP, interaction terms for site by linear and quadratic trends to allow them to differ within each period and 3-factor interaction terms for site by 1^{st}, 2^{nd} and 3^{rd} order harmonic interaction terms to model the seasonal trends and allow them to differ between sites.

The model:

Log_{10}(Chl-*a* concentration) = site (N44 or N48A) + site by flow + site by period + site by linear trend in period 1 + site by linear trend in period 2 + site by quadratic trend in period 1 + site by quadratic trend in period 2 + site by 1st order sine by year + site by 1st order cosine by year + site by 2nd order sine by year + site by 2nd order cosine by year + site by 3rd order sine by year + site by 3rd order cosine by year

Where:

- site, period and year are categorical factors.
- Flow consists of the flow corresponding to the site identified in the site variable as defined in Volume 2: Appendix E (Table E-5)

Model reduction decisions:

- Remove the site by 3rd order harmonic interaction terms

Step 2: Fit the final, reduced model

Log_{10}(Chl-*a* concentration) = site (N44 or N48A) + site by flow + site by period + site by linear trend in period 1 + site by linear trend in period 2 + site by quadratic trend in period 1 + site by quadratic trend in period 2 + site by 1st order sine by year + site by 1st order cosine by year + site by 2nd order sine by year + site by 2nd order cosine by year + site by 3rd order sine by year + site by 3rd order cosine by year

Where:

- site, period and year are categorical factors.
- Flow consists of the flow corresponding to the site identified in the site variable as defined in Volume 2: Appendix E (Table E-5)

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-22.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix G). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table G-21 and Table G-22, respectively. The residual plots for this model are shown in Figure G-11.

The site, site by flow and site by period parameters were retained in the model as they form part of the study design. The site by linear and quadratic trends in period 1 had type III SS p-values that were larger than their type I SS and were still <0.15, suggesting that the site by harmonic interaction terms accounted for some, but not all of these trends in the short timespan for this period. The site by flow interaction term was not significant for the type I SS (p=0.6) and was for the type III SS (p=0.0003). This suggested that after adjusting for differences between the mean level at each site, the linear, quadratic and seasonal trends, flow provided additional information to explain the pattern in Chl-*a* concentrations over time.

The model fitted the data well (R^2=0.60 and adjusted R^2=0.45) except for those at extremely high concentrations or, to a lesser extent, low concentrations. A few values showed a high leverage (ie terms in the model are included because of their contribution to the variability in the data). The distribution of the residuals was approximately Normal and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

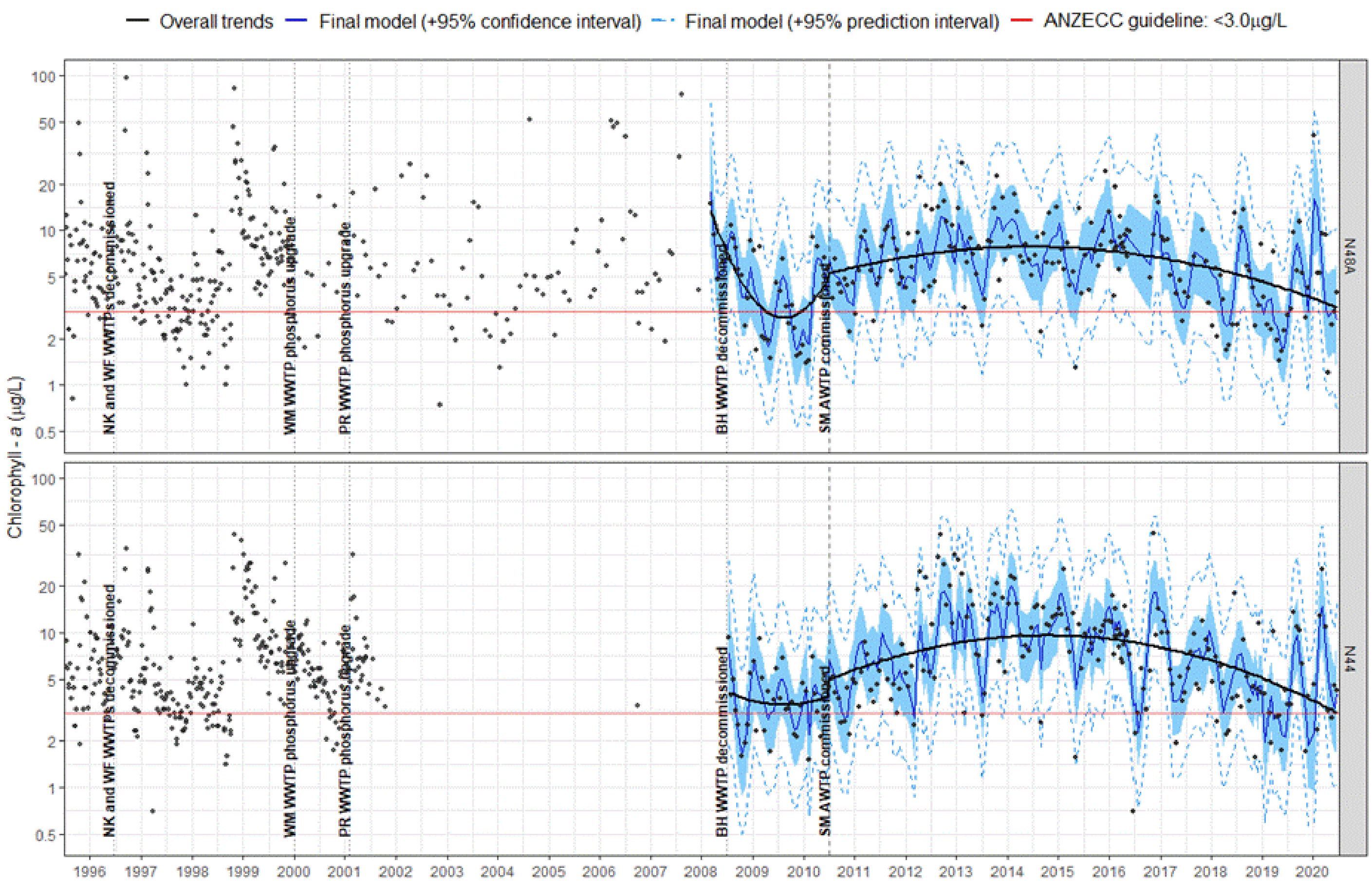

Figure 4-22 Chlorophyll-*a* concentrations at Smith Road (N48A) and Yarramundi (N44), Nepean River: fitting terms to model site differences and associated flow along with linear and quadratic trends and seasonal trends overlaid with the trends in each period

Key outcomes

- Chlorophyll-*a* concentration:
  - The Chl-*a* concentration remained above the ANZG default level of <3 µg/L for both the downstream site of N44 and the upstream site of N48A.
  - The final reduced model fitted well with R^2=0.60 and adjusted R^2=0.45. However, the residual plots showed the model did not capture the extremely high Chl-*a* concentrations.

- Flow:
    - Although flow decreased the Chl-*a* concentration at both sites, the relationship differed between sites after adjusting for all terms in the model (p=0.0003).
    - Flow decreased concentration at N44 (p=0.0002).
        - when flow at N44 is low eg 800 ML/day, a 100 ML/day increase in flow decreased Chl-*a* concentration by 2.2%
        - when flow at N44 is moderate eg 1100 ML/day, a 100 ML/day increase in flow decreased the concentration at N44 by 1.6%
        - when flow at N44 is high, eg 1500 ML/day, a 100 ML/day increase in flow decreased the concentration at N44 by 1.2%.
    - Flow decreased concentration at N48A (p=0.08).
        - when flow at N48A is low eg 800 ML/day, a 100 ML/day increase in flow decreased the Chl-*a* concentration by 1.1%
        - when flow at N48A is moderate eg 1100 ML/day, a 100 ML/day increase in flow decreased the concentration at N48A by 0.8%
        - when flow at N48A is high, eg 1500 ML/day, a 100 ML/day increase in flow decreased the concentration at N48A by 0.6%.
- Long term trends:
    - There was a significant interaction between site and linear trends in period 1 (p=0.003) and between site and quadratic trend in period 1 (p=0.0009). Also in period 2, there was a significant interaction between site and linear and quadratic trend (p<0.0001).
    - There was a curvilinear trend at both sites seen in the period after decommissioning of Blackheath WWTP and before commissioning of St Marys AWTP (period 1) that differed between sites. At site N48A, the Chl-*a* concentration decreased until mid-2009 before increasing. At N44 the trend was approximately flat.
    - After the commissioning of St Marys AWTP (period 2), both sites showed an increasing Chl-*a* concentration trend until approximately 2015 before decreasing. However, N48A had a slightly flatter curve than N44.
    - As of mid-2020, the trend in Chl-*a* concentration was decreasing at both sites as directed by the quadratic terms in the model.
- Seasonal trends:
    - The site by 1st and 2nd order sine and cosine terms by year interactions were included to capture a pattern of two peaks per year, capturing the largest one in late January/ early February, and a smaller one around mid-May. The lowest trough around mid-October to early November. The magnitude of the peaks and troughs differed between years and sites.
- Site by period geometric mean Chl-*a* concentrations:

- There was a significant interaction between site and period ($p<0.0001$).
- After adjusting for linear, quadratic and seasonal trends:
  - After decommissioning Blackheath WWTP and prior to the commissioning St Marys AWTP (period 1) the geometric mean at N44 was 3.1 µg/L (95% CI = 2.2 to 4.2 µg/L) and at N48A was 2.7 µg/L (95% CI = 2.0 to 3.7 µg/L)
  - After commissioning of St Marys AWTP (period 2) the geometric mean at N44 was 8.4 µg/L (95% CI = 7.4 to 9.7 µg/L) and at N48A was 6.8 µg/L (95% CI = 5.8 to 8.0 µg/L).
- Comparing the modelled geometric mean Chl-*a* concentrations between sites within periods
  - The geometric mean for N44 in the period after decommissioning Blackheath WWTP and before commissioning St Marys AWTP (period 1) was 114% (73 to 177%) of the geometric mean for N48A
  - The geometric mean for N44 in the period after commissioning St Marys AWTP (period 2) was 124% (101 to 153%) of the geometric mean for N48A
- Comparing the Chl-*a* concentrations between periods within each site:
  - The geometric mean for the period after commissioning St Marys AWTP (period 2) was 274% (95% CI = 194 to 386%) of the geometric mean for the period prior to the commissioning (period 1) at site N44
  - The geometric mean for the period after commissioning St Marys AWTP (period 2) was 251% (95% CI = 179 to 354%) of the geometric mean for the period prior to the commissioning (period 1) at site N48A
  - The percentage difference between periods 2 and 1 for the geometric mean concentration at N44 was 109% (68 to 175%) of the percentage difference at N48A.

4.2.12 Winmalee WWTP and the Nepean River at Yarramundi – Summary

Nutrient loads

The approach for analysing the nutrient load data from Winmalee WWTP in sub-categories enabled the trends in periods between the interventions to be identified more accurately. The distinct interventions that split the nitrogen load data into three categories and phosphorus load data into four categories are:

- North Katoomba and Wentworth Falls WWTPs decommissioning in June 1996
- Winmalee phosphorus treatment upgrade in December 1999
- Blackheath WWTP decommissioned in June 2008

The modelled geometric mean nutrient loads from Winmalee WWTP for each period and comparisons between periods are shown in Table 4-8. The trend and percent change in population served by the Winmalee WWTP are provided in Table 4-9. The results are discussed in the detail in Section 5.1.

Table 4-8 Geometric mean (95% CI) Winmalee WWTP nutrient loads for each period and the comparisons (95% CI) between periods

Period	TN (kg/day)	DIN (kg/day)	TP (kg/day)
	Geometric Mean (95% CI)	Geometric Mean (95% CI)	Geometric Mean (95% CI)
1	183.5 (158.8, 212.1)	245.6 (109.6, 550.4)	24.6 (17.2, 35.3)
2	153.9 (149.7, 158.3)	133.5 (129.2, 138.1)	18.9 (16.9, 21.1)
3	116.2 (112.9, 119.5)	103.0 (100.0, 106.2)	3.8 (3.5, 4.0)
4			7.1 (6.7, 7.5)
	% (95% CI)	% (95% CI)	% (95% CI)
2:1	84% (73%, 97%)	54% (24%, 123%)	68% (29%, 162%)
3:2	75% (72%, 79%)	77% (74%, 81%)	20% (18%, 23%)
4:3			189% (173%, 206%)

Table 4-9 Winmalee WWTP catchment population serviced and percent change by period

Period for TN and DIN	Average population	Percent increase
Period 1: 1995-1996	37,070	
Period 2: 1997-2008	56,381	
Period 3: 2009-2020	60,223	
Period 2 : Period 1		152%
Period 3 : Period 2		107%
Period for TP	**Population**	**Percent increase**
Period 1: 1995-1996	37,070	
Period 2: 1997-1999	54,270	
Period 3: 2000-2008	56,616	
Period 4: 2009-2020	60,223	
Period 2 : Period 1		146%
Period 3 : Period 2		104%
Period 4 : Period 3		106%

Data source: 2001-2021: forecast data by the Australian Bureau of Statistics and the Department of Planning, Industry and Environment
1995-2000: Sydney Water's internal estimates based on local government area data, sewer and unsewered areas

A summary of final model outcomes on temporal trends in Winmalee WWTP nutrient (TN, DIN and TP) loads by each period of intervention is included in Table 4-10. The models identified both seasonal and non-seasonal variation in nutrient load parameters. The results are discussed in the detail in Section 5.1.

Table 4-10 Summary of final Winmalee WWTP models with detailed results on increasing or decreasing trends, significance levels in each period

Parameter	TN	DIN	Parameter	TP
Period 1: Linear trend	NA	NA	Period 1: Linear trend	NA
Period 2: Linear trend	→	→	Period 2: Linear trend	→
Period 3: Linear trend	↘ (≤0.0001)	↘ (≤0.0001)	Period 3: Linear trend	↘ (≤0.0001)
			Period 4: Linear trend	↗ (≤0.0001)
			Period 1: Quadratic trend	NA
Period 2: Quadratic trend	↗ (≤0.0001)	↗ (≤0.01)	Period 2: Quadratic trend	↘ (≤0.001)
Period 3: Quadratic trend	↗ (≤0.0001)	↗ (≤0.0001)	Period 3: Quadratic trend	↗ (≤0.0001)
			Period 4: Quadratic trend	↘ (≤0.0001)

Legend Keys:

Green: ≤0.0001	Blue: ≤0.001	Yellow: ≤0.01	Grey: ≤0.05	Light blue: ≤0.15

↗ Upward trend	↘ Downward trend	→ no trend, p>0.15

NA	Not applicable, p>0.15, term removed from the model during the model reduction process

Notes: Significance level was based on type I SS p-values and the direction of trend (upward/downward/flat) was determined by the regression coefficient estimates (positive, negative or stable)

Receiving water quality

The analysis of receiving water quality for this site was limited to the period from 2008 onwards due to missing data between 2001 to 2008. The commissioning of St Marys AWTP in 2010 was the only intervention examined to identify any benefit of the high quality discharge to the upstream river via Penrith WWTP. The modelled geometric mean water quality data of Nepean River at Yarramundi (N44) for each period and comparisons between periods are shown in Table 4-11. The results are discussed in the detail in Section 5.2.

Table 4-11 Geometric mean (95% CI) nutrient (TN, DIN, TP and Chl-*a*) concentrations at Nepean River – Yarramundi (N44) for each period and the comparisons (95% CI) between periods

Period	TN (mg/L) Geometric Mean (95% CI)	DIN (mg/L) Geometric Mean (95% CI)	TP (mg/L) Geometric Mean (95% CI)	Chl-*a* (µg/L) Geometric Mean (95% CI)
1	0.90 (0.82, 0.99)	0.58 (0.50, 0.67)	0.023 (0.021, 0.026)	4.9 (3.6, 6.7)
2	0.61 (0.58, 0.64)	0.24 (0.22, 0.26)	0.029 (0.027, 0.031)	8.5 (7.5, 9.6)
	% (95% CI)	**% (95% CI)**	**% (95% CI)**	**% (95% CI)**
2:1	68% (61%, 75%)	42% (34%, 52%)	123% (108%, 140%)	170% (110%, 270%)

A summary of the final model outcomes on temporal trends in the water quality of Nepean River at Yarramundi (N44), and the relationship with upstream river flow and concentration, and nutrient loads from Winmalee WWTP is included in Table 4-12. The results are discussed in the detail in Section 5.2.

Table 4-12 Overall summary table for Nepean River at Yarramundi (N44) – final models with detailed results on increasing or decreasing trends, significance levels in each period

Parameter	TN	DIN	TP	Parameter	Chl-*a*
Upstream N48A concentration (mg/L)	↗	↗	↗	Upstream N48A concentration (µg/L)	↗
Upstream N48A flow (ML/day)	↘	↘	→	Upstream N48A flow (ML/day)	↘
Winmalee load (kg/day)	↗	↗	↗	Winmalee TN load (kg/day)	↘
				Winmalee TP load (kg/day)	↗
Period 1: Linear trend	↗	NA	↗	Period 1: Linear trend	→
Period 2: Linear trend	↘	↘	↗	Period 2: Linear trend	↗
Period 1: Quadratic trend	↘	NA	↘	Period 1: Quadratic trend	↘
Period 2: Quadratic trend	↗	↗	↘	Period 2: Quadratic trend	↘

Legend Keys:

	≤0.0001		≤0.001		≤0.01		≤0.05		≤0.15

↗	Upward trend or positive correlation	↘	Downward trend or negative correlation	→	no trend, p>0.15

NA	p>0.15, term removed from the model during the model reduction process

Not significant after adjusting for upstream variables (p=0.12) and after adjusting for all terms in the model (p=0.27).

Notes: Significance level was based on type I SS p-values and the direction of trend (upward/downward/flat) was determined by the regression coefficient estimates positive, negative or stable)

Receiving water quality – downstream and upstream comparison

The modelled geometric mean downstream water quality of Nepean River at Yarramundi (N44) and comparison with the upstream site at Smith Road (N48A) for each period and comparisons between periods are shown in Table 4-13. The results are discussed in the detail in Section 5.2.

A summary of final model outcomes on temporal trends in the water quality of Nepean River at Yarramundi (N44) and comparison with the upstream site Nepean River at Smith Road (N48A) is included in Table 4-14. The results are discussed in the detail in Section 5.2.

Table 4-13 Geometric mean (95% CI) nutrient (TN, DIN, TP and Chl-*a*) concentrations at Nepean River – Yarramundi (N44) and Smith Road (N48A) for each period and the comparisons (95% CI) between periods

Variables	Period	N44	N48A	N44/N48A
TN (mg/L)	1	0.91 (0.79, 1.03)	0.51 (0.45, 0.58)	177% (148%, 211%)
	2	0.66 (0.63, 0.70)	0.61 (0.57, 0.65)	109% (100%, 119%)
	2:1	73% (64%, 84%)	119% (104%, 136%)	62% (51%, 75%)
DIN (mg/L)	1	0.49 (0.35, 0.68)	0.13 (0.10, 0.17)	377% (242%, 586%)
	2	0.25 (0.21, 0.28)	0.22 (0.18, 0.26)	113% (91%, 140%)
	2:1	50% (35%, 72%)	168% (120%, 234%)	30% (18%, 49%)
TP (mg/L)	1	0.025 (0.021, 0.029)	0.019 (0.016, 0.022)	129% (102%, 161%)
	2	0.030 (0.028, 0.033)	0.025 (0.023, 0.028)	120% (107%, 134%)
	2:1	123% (103%, 147%)	132% (111%, 156%)	93% (72%, 120%)
Chl-a (µg/L)	1	3.1 (2.2, 4.2)	2.7 (2.0, 3.7)	114% (73%, 177%)
	2	8.4 (7.4, 9.7)	6.8 (5.8, 8.0)	124% (101%, 153%)
	2:1	274% (194%, 386%)	251% (179%, 354%)	109% (68%, 175%)

Table 4-14 Summary of final models for the Nepean River at Yarramundi (N44) – upstream/downstream comparison with detailed results on increasing or decreasing trends, significance levels in each period

Parameter	TN	DIN	TP	Chl-*a*
Site				
Site by Flow				
N44	→	→	↗	↘
N48A	↗	↗	↗	↘
Site by Period				
Site by P1 Linear trend				
Period 1: N44	→	→	→	→
Period 1: N48A	→	→	↘	↘
Site by P2 linear trend				
Period 2: N44	→	↘	↗	↗
Period 2: N48A	↗	↗	→	↗
Site by P1 quadratic trends				
Period 1: N44	→	→	→	→
Period 1: N48A	→	→	→	↗
Site by P2 quadratic trends				
Period 2: N44	→	↗	↘	↘
Period 2: N48A	↘	→	↘	↘

Legend Keys:

	≤0.0001		≤0.001		≤0.01		≤0.05		≤0.15

↗	Upward trend or positive correlation	↘	Downward trend or negative correlation	→	no trend, p>0.15

Notes: Significance level was based on type I SS p-values and the direction of trend (upward/downward/flat) was determined by the regression coefficient estimates (positive, negative or stable)

4.3 Hawkesbury River at Wilberforce – South Creek (St Marys, Quakers Hill and Riverstone) and Richmond WWTPs

The following sub-sections present the results of the model building steps, and key outcomes on 19 models fitted on data for the Hawkesbury River at Wilberforce and South Creek (St Marys, Quakers Hill and Riverstone WWTPs) and Richmond WWTP. A summary is included to interpret the variability in the outcomes due to explanatory variables fitted or any other supplementary changes eg demography, weather etc.

The detailed results of all statistical models fitted for the Hawkesbury River at Wilberforce and South Creek (St Marys, Quakers Hill and Riverstone) and Richmond WWTPs are included in Volume 2: Appendix H. Estimated regression coefficients, standard errors, p values, type I and type III sum of squares details are provided in Table H-1 to Table H-38. Residual plots on all models are provided in Figure H-1 to Figure H-19. The model and model adjusted R^2 are provided to assess the goodness of fit of the models (Table H-39). Examples of relative changes in water quality concentrations (total nitrogen, dissolved inorganic nitrogen, total phosphorus or chlorophyll-*a*) with respect to prespecified ranges of nutrient load, upstream concentrations and river and creek flow are included in Table H-40 and Table H-41.

4.3.1 St Marys WWTP – Total nitrogen load

There were 1392 total nitrogen load records in the St Marys WWTP data series. There were 274 records prior to the St Marys WWTP nitrogen upgrade in 2000 (period 1), 645 records after this nitrogen upgrade and before the commissioning of the St Marys AWTP (period 2), and 609 records after the commissioning of St Marys AWTP (period 3). All records are included in the analyses. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included the three periods defined by the St Marys WWTP nitrogen upgrade and the commissioning of the St Marys AWTP, linear and quadratic trends within each period and 1st, 2nd and 3rd order harmonic interaction terms to model the seasonal trends.

The model:

Log_{10}(TN load) = period + linear trend in period 1 + linear trend in period 2 + linear trend in period 3 + quadratic trend in period 1 + quadratic trend in period 2 + quadratic trend in period 3 + 1st order sine + 1st order cosine + 2nd order sine + 2nd order cosine + 3rd order sine + 3rd order cosine + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

period and year are categorical factors.

Model reduction decisions:

- Period 1 and 3: retain the linear and quadratic trend terms

- Periods 2: remove the quadratic trend
- Retain all harmonic interaction terms as the p-values for the 3rd order terms from the type I SS were <0.15
- Remove the main effect harmonic terms since they can be included in the harmonic interaction terms.

Step 2: Fit the final, reduced model

Log_{10}(TN load) = period + linear trend in period 1 + linear trend in period 2 + linear trend in period 3 + quadratic trend in period 1 + quadratic trend in period 3 + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

period and year are categorical factors.

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-23.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix H). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table H-1 and Table H-2, respectively. The residual plots for this model are shown in Figure H-1.

All terms in the final, reduced model had a p-value for the corresponding type I SS <0.15. Each term in the model also had a p value <0.15 after adjusting for all other terms in the model (type III SS).

The model fitted the data well (R^2=0.74 and adjusted R^2=0.70) except for those at extremely high and, to a lesser extent the low loads. Three values showed a high leverage (ie terms in the model are included because of their contribution to the variability in the data). The distribution of the residuals was approximately Normal and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

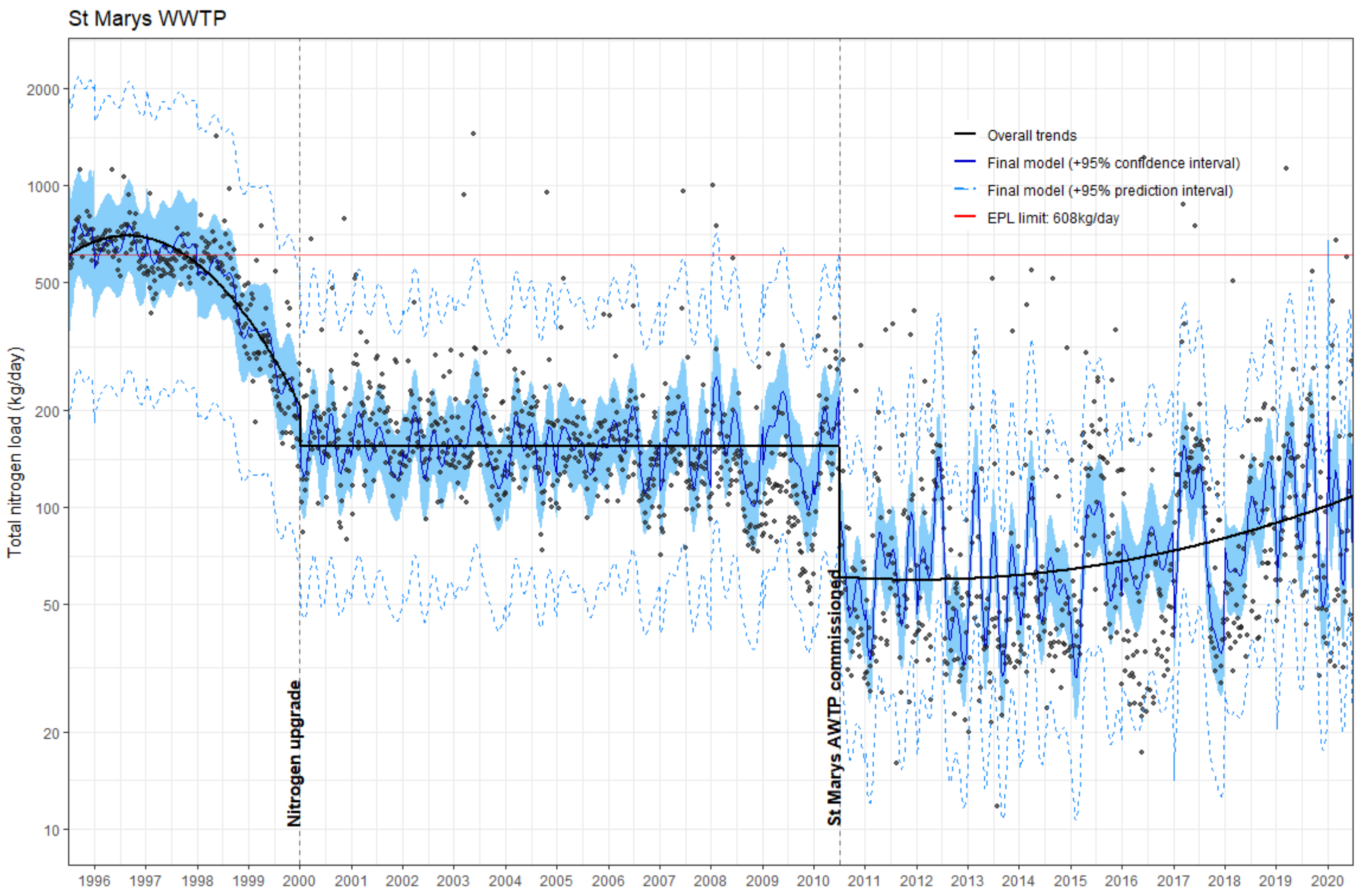

Figure 4-23 St Marys WWTP total nitrogen load: fitting terms to model interventions, linear and quadratic trends within each period and seasonal trends overlaid with the trends in each period

Key outcomes

- Total nitrogen load:
  - Since the nitrogen upgrade in 2000, the majority of the total nitrogen load records were less than the current combined EPL limit of South Creek WWTPs (608 kg/day)
  - The final reduced model fitted well with R^2=0.74 and adjusted R^2=0.70. However, the residual plots showed the model did not capture the extremely high and low total nitrogen loads.
- Long term trends:
  - Prior to the nitrogen upgrade at St Marys WWTP (period 1), the curvilinear trend captured an increase to around 1997 before curving downwards prior to the nitrogen upgrade.
  - After the nitrogen upgrade at St Marys WWTP and before the commissioning of St Marys AWTP (period 2), TN load was increasing in a linear fashion

- After commissioning of St Marys AWTP in 2010 (period 3), there was a large decrease in load that has been gradually increasing since 2014.
- As of mid-2020, the total nitrogen load was increasing.

- Seasonal trends:
  - First, second and third order sine and cosine terms by year interactions were included to capture a more complex pattern of three peaks per year, capturing the largest one in February and two smaller ones in late May/ early June and September. The lowest trough was around late October/ early November. The magnitude of the peaks and troughs differed between years.
- After adjusting for seasonal trends, geometric mean total nitrogen load:
  - Prior to the nitrogen upgrade at St Marys WWTP (period 1) was 621.7 kg/day (95% CI = 563.3 to 686.1 kg/day)
  - After the nitrogen upgrade and before the commissioning of the St Marys AWTP (period 2) was 152.8 kg/day (95% CI = 147.1 to 158.8 kg/day)
  - After commissioning of the St Marys AWTP (period 3) was 64.2 kg/day (95% CI = 60.4 to 68.3 kg/day)
- Comparing the modelled total nitrogen loads between periods:
  - The geometric mean after the commissioning of St Marys AWTP (period 3) was 42% (95% CI = 39 to 45%) of the geometric mean for the period before commissioning of St Marys AWTP (period 2)
  - The geometric mean for the period after the nitrogen upgrade (period 2) was 25% (95% CI = 22 to 27%) of the geometric mean for the period prior to the nitrogen upgrade at St Marys WWTP (period 1).

4.3.2 Quakers Hill WWTP – Total nitrogen load

There were 1529 total nitrogen load records in the Quakers Hill WWTP data series. Prior to commissioning of the St Marys AWTP in 2010 there were 920 records (period 1) and after the commissioning, 609 records (period 2). All records are included in the analyses. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included the two periods defined by the commissioning of the St Marys AWTP, linear and quadratic trends within each period and 1st, 2nd and 3rd order harmonic interaction terms to model the seasonal trends.

The model:

Log_{10}(TN load) = period + linear trend in period 1 + linear trend in period 2 + quadratic trend in period 1 + quadratic trend in period 2 + 1st order sine + 1st order cosine + 2nd order sine + 2nd order cosine + 3rd order sine + 3rd order cosine + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

period and year are categorical factors.

Model reduction decisions:

- Period 1 and 2: retain the linear and quadratic trend terms (all p-values from the type I SS were < 0.15)
- Retain all harmonic interaction terms as the p-values for the 3rd order terms from the type I SS were <0.15
- Remove the main effect harmonic terms since they can be included in the harmonic interaction terms.

Step 2: Fit the final, reduced model

Log_{10}(TN load) = period + linear trend in period 1 + linear trend in period 2 + quadratic trend in period 1 + quadratic trend in period 2 + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

period and year are categorical factors.

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-24.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix H). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table H-3 and Table H-4, respectively. The residual plots for this model are shown in Figure H-2.

All terms in the final, reduced model had a p-value for the corresponding type I SS <0.15. Each term in the model had a similar p-value after adjusting for all other terms in the model (type III SS) except for the quadratic trend in period 2 that was more significant with p=0.006 and the 2nd order harmonic interaction terms which were less significant. This suggested that after adjusting for all the seasonal terms there was an underlying linear component to the curvilinear trend that was not obvious when the seasonal trend was not accounted for and that the 3rd order harmonic interaction terms were slightly correlated with the 2nd order terms.

The model generally fitted the data well (R^2=0.40 and Adjusted R^2=0.33) except for those at extremely high loads and to a lesser extent, those at the extremely low loads. Four values showed a high leverage (ie terms in the model are included because of their contribution to the variability in the data). The distribution of the residuals was approximately Normal with a slightly long tail reflecting the very high loads. The residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

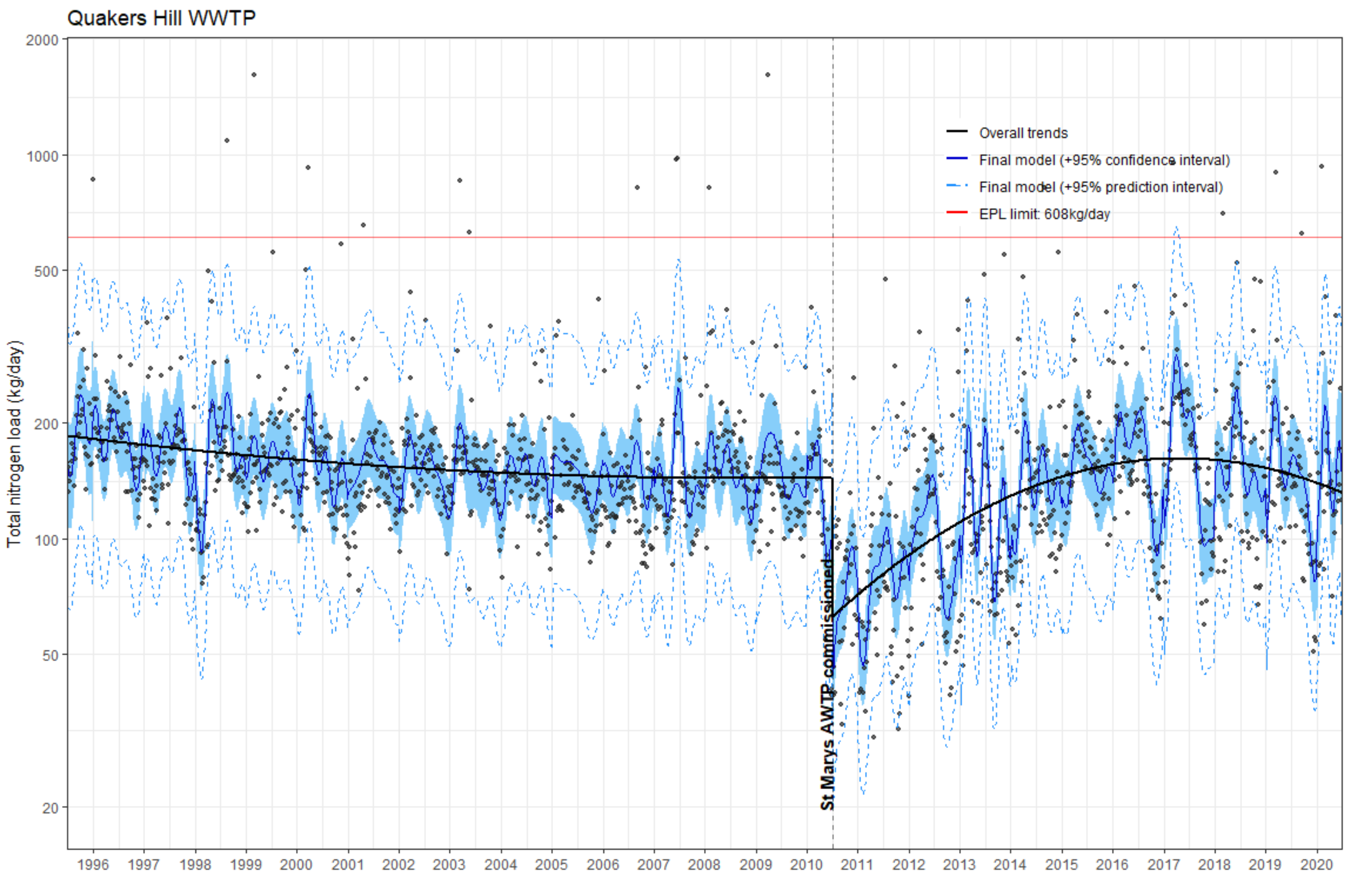

Figure 4-24 Quakers Hill WWTP total nitrogen load: fitting terms to model interventions, linear and quadratic trends within each period and seasonal trends overlaid with the trends in each period

Key outcomes

- Total nitrogen load:
  - The majority of the total nitrogen load records were less than the combined current EPL limit of South Creek WWTPs (608 kg/day)
  - The final reduced model fitted reasonably well with R^2=0.40 and adjusted R^2=0.33. However, the residual plots showed the model did not capture the extremely high total nitrogen loads, and to a lesser extent, the extremely low loads.
- Long term trends:
  - Significant curvilinear trends were observed in both periods
    - Prior to commissioning St Marys AWTP (period 1), total nitrogen load showed a gradual decreasing trend

- After the commissioning of St Marys AWTP (period 2), there was an immediate decrease in total nitrogen load that has been gradually increasing until approximately 2017 when load started to decrease.
- As of mid-2020, the trend in total nitrogen load was decreasing.

- Seasonal trends:
  - First, second and third order sine and cosine terms by year interactions were included to capture a more complex pattern of three peaks per year, capturing the largest one in February and two smaller ones in late May/early June and September. The lowest trough was around late October/early November. The magnitude of the peaks and troughs differed between years.
- After adjusting for seasonal trends, the geometric mean total nitrogen load:
  - prior to the commissioning of St Marys AWTP (period 1) was 148.9 kg/day (95% CI =143.5 to 154.6 kg/day)
  - after the commissioning of St Marys AWTP (period 2) was 152.4 kg/day (95% CI = 145.4 to 159.7 kg/day)
- Comparing the total nitrogen loads between periods:
  - The geometric mean for the period after commissioning of St Marys AWTP (period 2) was 102% (95% CI = 96 to 109%) of the geometric mean for the period prior to the commissioning (period 1)

4.3.3 Riverstone WWTP – Total nitrogen load

There were 729 total nitrogen records in the Riverstone WWTP data series. There were 275 records prior to the first nitrogen upgrade in 2000 (period 1), 640 records after this nitrogen upgrade and before the increase in capacity/increased discharge (period 2), 522 records after the increase in capacity and before the second nitrogen upgrade in 2010 (period 3) and 87 records after the second nitrogen upgrade (period 4). All records are included in the analyses. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included the four periods defined by two nitrogen upgrades and an increase in Riverstone WWTP capacity and discharge, linear and quadratic trends within each period and 1st, 2nd and 3rd order harmonic interaction terms to model the seasonal trends.

The model:

Log_{10}(TN load) = period + linear trend in period 1 + linear trend in period 2 + linear trend in period 3 + linear trend in period 4 + quadratic trend in period 1 + quadratic trend in period 2 + quadratic trend in period 3 + quadratic trend in period 4 + 1st order sine + 1st order cosine + 2nd order sine + 2nd order cosine + 3rd order sine + 3rd order cosine + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

period and year are categorical factors.

Model reduction decisions:

- Periods 1, 2 and 3: retain the linear and quadratic trend terms as the p-values for the quadratic terms using the type I SS were <0.15
- Period 4: remove the quadratic trend
- Retain all harmonic interaction terms as the p-values for the 3rd order terms from the type I SS were <0.15
- Remove the main effect harmonic terms since they can be included in the harmonic interaction terms.

Step 2: Fit the final, reduced model

Log_{10}(TN load) = period + linear trend in period 1 + linear trend in period 2 + linear trend in period 3 + linear trend in period 4 + quadratic trend in period 1 + quadratic trend in period 2 + quadratic trend in period 3 + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

period and year are categorical factors.

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-25.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix H). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table H-5 and Table H-6, respectively. The residual plots for this model are shown in Figure H-3.

All terms in the final, reduced model had a p-value for the corresponding type I SS <0.15. All linear trend terms in each period and the quadratic trend in Period 1 had p-values larger than 0.15 after adjusting for all other terms in the model (type III SS). This suggested that for period 1, the changes in seasonal trends by year accounted for the trend, partly due to the smaller number of records in this period. This also suggests there is multicollinearity between the trends and seasonal trends in period 1. The quadratic trends in periods 2 and period 3 remained statistically significant.

The model fitted the data well (R^2=0.79 and adjusted R^2=0.77) except for those at extremely high loads. Four values showed a high leverage (ie terms in the model are included because of their contribution to the variability in the data). The distribution of the residuals was approximately Normal and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

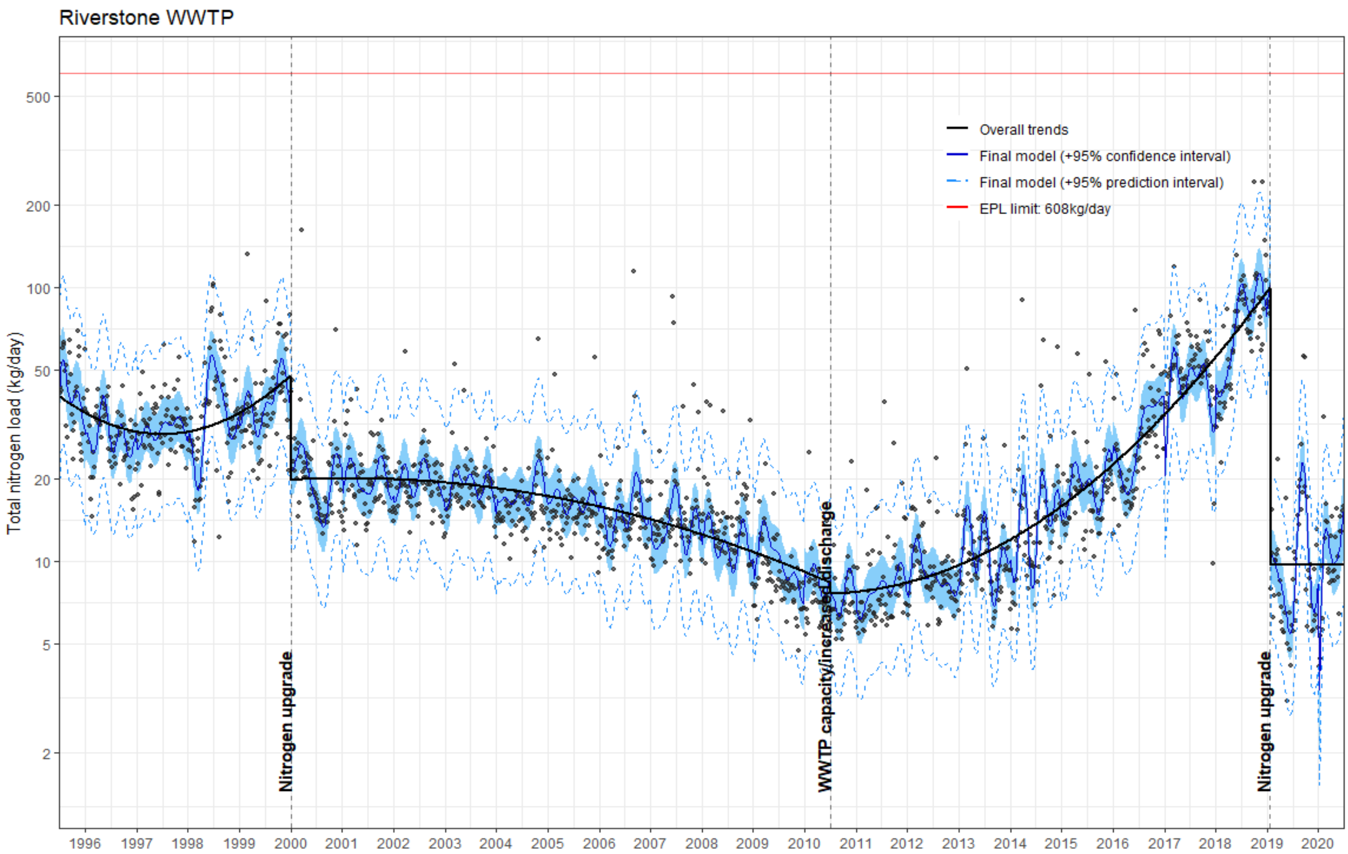

Figure 4-25 Riverstone WWTP total nitrogen load: fitting terms to model interventions, linear and quadratic trends within each period and seasonal trends overlaid with the trends in each period

Key outcomes

- Total nitrogen load:
  - All total nitrogen load records were less than the current combined EPL limit of South Creek WWTPs (608 kg/day)
  - The final reduced model fitted well with R^2=0.79 and adjusted R^2=0.77. The residual plots showed the model did not capture the extremely high total nitrogen loads.
- Long term trends:
  - Before the first nitrogen upgrade (period 1), nitrogen load curved downwards until around 1998 when load started to curve upwards. This trend has also been captured in the change in seasonal trends each year.
  - After the nitrogen upgrade in 2000, there was a large reduction in total nitrogen load discharged from Riverstone WWTP. The load then gradually decreased until the capacity of the WWTP was reached in mid-2010.

- After the increase in capacity/increased discharge, the total nitrogen load notably increased until 2019 when there was another nitrogen upgrade. The second nitrogen upgrade resulted in a large and rapid decline in total nitrogen load.
- As of mid-2020, the trend in total nitrogen load from Riverstone WWTP was stable.

- Seasonal trends:
  - First, second and third order sine and cosine terms by year interactions were included to capture a more complex pattern of three peaks per year capturing the largest one in February and two smaller ones in late May/early June and September. The lowest trough was around late October/early November. The magnitude of the peaks and troughs differed between years.
- After adjusting for seasonal trends, the geometric mean total nitrogen load:
  - Prior to the first nitrogen upgrade (period 1) was 30.6 kg/day (95% CI = 28.7 to 32.7 kg/day)
  - After the first nitrogen upgrade and before the increase in capacity and discharge at Riverstone WWTP (period 2) was 16.9 kg/day (95% CI =16.2 to 17.6 kg/day)
  - After Riverstone WWTP reached design capacity and increased discharge and before the second nitrogen upgrade (period 3) was 14.9 kg/day (95% CI =14.3 to 15.6 kg/day)
  - After the second nitrogen upgrade (period 4) was 11.2 kg/day (95% CI = 8.3 to 15.2 kg/day)
- Comparing the modelled total nitrogen loads between periods:
  - The geometric mean for the period after the first nitrogen upgrade and when Riverstone WWTP reached design capacity and increased discharge (period 2) was 55% (95% CI = 51 to 60%) of the geometric mean for the period prior to the first nitrogen upgrade (period 1).
  - The geometric mean for the period after Riverstone WWTP reached design capacity and increased discharge (period 3) was 89% (95% CI = 84 to 94%) of the geometric mean for the period prior to when Riverstone WWTP reached design capacity and increased and after the first nitrogen upgrade (period 2).
  - The geometric mean for the period after the second nitrogen upgrade (period 4) was 75% (95% CI = 55 to 102%) of the geometric mean for the period prior to the upgrade and after the Riverstone WWTP reached design capacity and increased discharge (period 3).

4.3.4 Richmond WWTP – Total nitrogen load

There were 1063 total nitrogen records in the Richmond WWTP data series. There were 428 records prior to the increase in recycled water use in mid-2000 (period 1), 22 records after the increase in recycled water use and before the nitrogen upgrade (period 2) and 613 records after the nitrogen upgrade (period 3). Due to the large differences in the number of load records, the analysis wis restricted to records from 2007 onwards (N=445 records). Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fit the full model to the data from 2007 onwards, linear and quadratic trends and 1st, 2nd and 3rd order harmonic interaction terms to model the seasonal trends.

The model:

$\log_{10}$(TN load) = linear trend + quadratic trend + 1st order sine + 1st order cosine + 2nd order sine + 2nd order cosine + 3rd order sine + 3rd order cosine + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

year is a categorical factor.

Model reduction decisions:

- Retain the linear and quadratic trend terms as the p-values for the quadratic terms using the type I SS were <0.15
- Retain all harmonic interaction terms as the p-values for the 3rd order terms from the type I SS were <0.15
- Remove the main effect harmonic terms since they can be included in the harmonic interaction terms.

Step 2: Fit the final, reduced model

$\log_{10}$(TN load) = linear trend + quadratic trend + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

year is a categorical factor.

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-26. All data not fitted in the model are also shown.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix H). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table H-7 and Table H-8, respectively. The residual plots for this model are shown in Figure H-4.

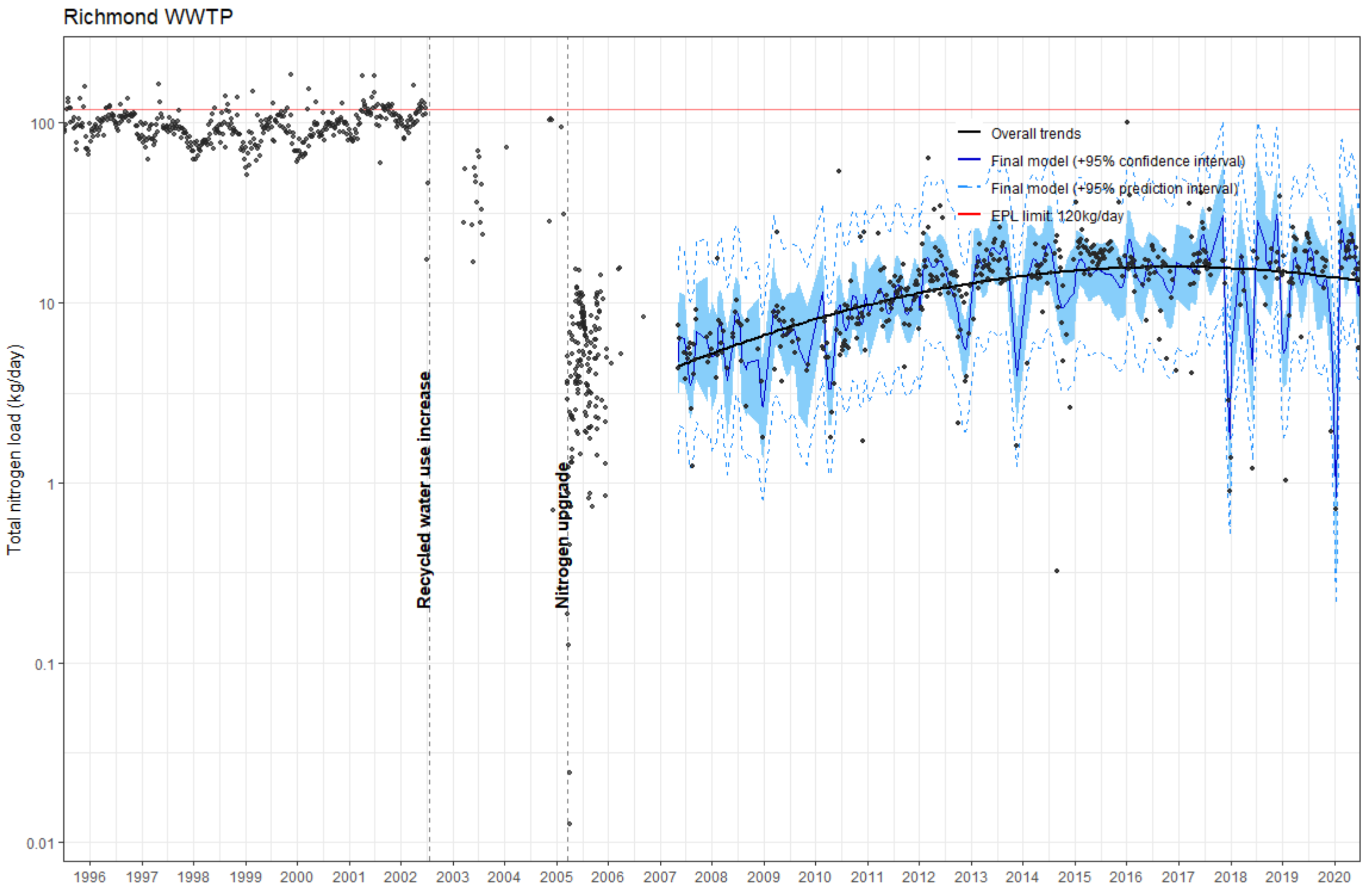

Figure 4-26 Richmond WWTP total nitrogen load: fitting terms to model linear and quadratic trends in the latest period and seasonal trends overlaid with the trends

All terms in the final, reduced model had a p-value for the corresponding type I SS <0.15. All terms also had p-values <0.15 after adjusting for all other terms in the model (type III SS).

The model fitted the data well (R^2=0.55 and adjusted R^2=0.44) except for those at extremely high and low loads. A few values showed a high leverage (ie terms in the model are included because of their contribution to the variability in the data). The distribution of the residuals was approximately Normal with one extremely low load from 2014 with a very small estimated residual value. Residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

Key outcomes

- Total nitrogen load:
  - Since 2002, all the total nitrogen load records were below the current EPL limit of 120 kg/day.
  - The final reduced model fitted reasonably well with R^2=0.55 and adjusted R^2=0.44. However, the Normal Q-Q plot showed the model did not capture the extremely high and

low total nitrogen loads. The distribution of residuals was approximately Normal with one extreme value.

- Long term trends:
  - There was an increase in total nitrogen load until around 2016 when load plateaued and then slightly decreased.
  - As of mid-2020, the trend in total nitrogen load from Richmond WWTP was decreasing slightly.
- Seasonal trends:
  - First, second and third order sine and cosine terms by year interactions were included to capture a more complex pattern of three peaks per year, capturing the largest one in February and two smaller ones in late May/early June and September. The lowest trough was around late October/early November. The magnitude of the peaks and troughs differed between years.
- After adjusting for seasonal trends, the geometric mean total nitrogen load:
  - The geometric mean total nitrogen load was 13.6 kg/day (95% CI = 12.6 to 14.8 kg/day)

4.3.5 Hawkesbury River at Wilberforce (N35) – Total nitrogen concentration

There were 439 total nitrogen concentration records in this data series for the Hawkesbury River at Wilberforce (N35). All records are used in the analysis. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included TN concentration at the upstream site (Hawkesbury River at Freemans Reach N39), the flow at N39, the flow in South and Eastern Creeks, Riverstone WWTP TN load, St Marys WWTP TN load, Quakers Hill WWTP TN load, the five periods defined by the nitrogen upgrades at St Marys and Riverstone WWTPs, the nitrogen upgrade at Richmond WWTP, commissioning of St Marys AWTP and the nitrogen upgrade at Riverstone WWTP, linear and quadratic trends within each period and 1st, 2nd and 3rd order harmonic interaction terms to model the seasonal trends. Note that the aim was to also include TN load from Richmond WWTP, however, the number of records in the Richmond WWTP data series that were able to be matched with data from N35 were few. Hence Richmond WWTP data has been excluded from the analysis dataset.

The model:

$\log_{10}$(N35 TN concentration) = $\log_{10}$(N39 TN concentration) + $\log_{10}$(flow at N39) + $\log_{10}$(Combined flow from South and Eastern Creeks) + $\log_{10}$(lag 1 (Quakers Hill WWTP TN load)) + $\log_{10}$(lag 1 (St Marys WWTP TN load)) + $\log_{10}$(lag 1 (Riverstone WWTP TN load)) + period + linear trend in period 1 + linear trend in period 2 + linear trend in period 3 + linear trend in period 4 + linear trend in period 5 + quadratic trend in period 1 + quadratic trend in period 2 + quadratic trend in period 3+ quadratic trend in period 4 + quadratic trend in period 5 + 1st order sine + 1st order cosine +

2nd order sine + 2nd order cosine + 3rd order sine + 3rd order cosine + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

- period and year are categorical factors.
- Flow at N39 is derived as described in Volume 2: Appendix E (Table E-5)
- Lag 1 for the loads from the WWTPs are loads estimated on the day before the sampling dates at N35.

Model reduction decisions:

- Remove linear and quadratic trends in periods 2, 3 and 5 as all type I SS had p-values >0.15
- Retain only 1st order harmonic interaction terms. Even though the 2nd and 3rd order harmonic interaction terms could have been included based on the p-value cut-off, these terms only captured the unusual patterns in 2013, 2014 and 2020. Due to the small number of records and the risk of overfitting, these terms were excluded.
- Remove the main effect harmonic terms since they can be included in the harmonic interaction terms.

Step 2: Fit the final, reduced model:

Log_{10}(N35 TN concentration) = log_{10}(N39 TN concentration) + log_{10}(flow at N39) + log_{10}(Combined flow from South and Eastern Creeks) + log_{10}(lag 1 (Quakers Hill WWTP TN load)) + log_{10}(lag 1 (St Marys WWTP TN load)) + log_{10}(lag 1 (Riverstone WWTP TN load)) + period + linear trend in period 1 + linear trend in period 4 + quadratic trend in period 1 + quadratic trend in period 4 + 1st order sine by year + 1st order cosine by year

Where:

- period and year are categorical factors.
- Flow at N39 is derived as described in in Table Volume 2: Appendix E (Table E-5)
- Lag 1 for the loads from the WWTPs are loads estimated on the day before the sampling dates at N35.

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-27.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix H). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table H-9 and Table H-10, respectively. The residual plots for this model are shown in Figure H-5.

The period parameter as well as the upstream concentration at N39, flow corresponding to N39 and the three WWTPs TN load estimates were retained in the model as part of the study design.

The p-values corresponding to the Type III SS varied compared with the type I SS. The linear and quadratic trends in period 4 have Type III SS p-values >0.4, suggesting that the harmonic interaction terms accounted for these trends. The TN loads from Riverstone WWTP were significantly correlated to TN concentrations at N35 via the sequential type I SS and were not related after adjusting for St Marys and Quakers Hill WWTP loads. Whereas loads from Quakers Hill WWTP helped to explain more variability in the data after adjusting for all terms in the model including the trends and seasonal trends than they did in the sequential SS.

The model fitted the data well (R^2=0.72 and adjusted R^2=0.67) except for those at extremely high and low concentrations. There were a few records with high leverage. The distribution of the residuals was approximately Normal and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

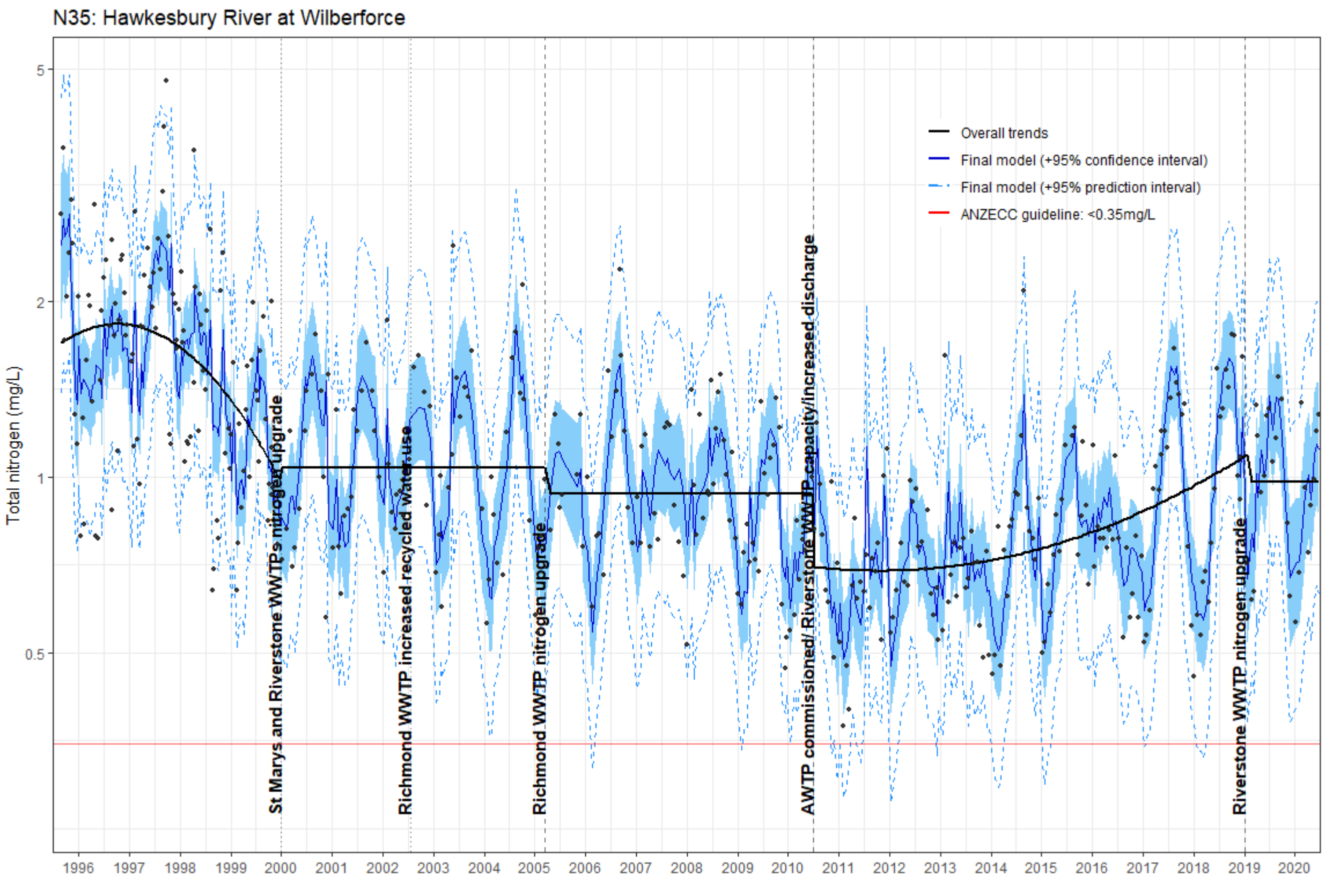

Figure 4-27 Total nitrogen concentrations at Wilberforce Hawkesbury River (N35): fitting terms to model upstream concentration and river flow, South Creek flow, TN loads from St Marys, Quakers Hill, Riverstone and Richmond WWTPs, along with linear and quadratic trends and seasonal trends overlaid with the trends in each period

Key outcomes

- Total nitrogen concentration:
  - All total nitrogen concentration records were above the ANZG default level of <0.35 mg/L
  - The final reduced model fitted well with R^2=0.72 and adjusted R^2=0.67. However, the residual plots showed the model did not capture the extremely high or low total nitrogen concentrations.
- Impact of upstream catchment and tributary
  - TN concentration at the upstream site (N39) was significantly correlated to the concentration at downstream site (N35) ($p<0.0001$).
    - When TN concentration at N39 is low eg 0.3 mg/L, a 0.1 mg/L increase of TN concentration increased the concentration at N35 by 5.6%
    - when TN concentration at N39 is moderate eg 0.6 mg /L, a 0.1 mg /L increase in concentration increased the concentration at N35 by 3%
    - when TN concentration at N39 is high eg 0.9 mg /L, a 0.1 mg /L increase in concentration increased the concentration at N35 by 2.0%.
  - Flow in the Nepean River at the upstream site (N39) was significantly correlated to the concentration of TN at N35 after accounting for TN concentration at N39 ($p<0.0001$) and after accounting for all terms in the model ($p=0.001$)
    - When flow at N39 is low eg 850 ML/day, a 100 ML increase in flow decreased the concentration at N35 by 0.7%
    - when flow at N39 is moderate eg 1150 ML/day, a 100 ML increase in flow decreased the concentration at N35 by 0.5%
    - when flow at N39 is high eg 1550 ML/day, a 100 ML increase in flow decreased the concentration at N35 by 0.4%.
  - Flow in South and Eastern Creeks was not correlated to the concentration of TN at N35 ($p=0.1$ after adjusting for the upper catchment variables and $p=0.06$ after adjusting for all terms in the model)
- Impact of WWTPs:
  - The TN load from Riverstone WWTP was significantly correlated to the concentration of TN at N35 when adjusted only for upstream catchment measures ($p<0.0001$) but was not significantly correlated after adjusting for all variables in the model ($p=0.18$). The load from Riverstone WWTP had no impact after accounting for the effect of WWTPs with larger discharges.
    - when the load from Riverstone WWTP is low eg 5 kg/day, a 1 kg/day increase in load increased the concentration at N35 by 1.1%
    - when the load from Riverstone WWTP is moderate eg 10 kg/day, a 1 kg/day increase in load increased the concentration at N35 by 0.6%

    - when the load from Riverstone WWTP is high eg 80 kg/day, a 10 kg/day increase in load increased the concentration at N35 by 0.1%.
  - The TN load from St Marys WWTP was significantly correlated to the concentration of TN at N35 when adjusted only for upstream catchment measures and Riverstone WWTP load (p<0.0001) and is also significantly correlated after adjusting for all variables in the model (p=0.003).
    - when the load from St Marys WWTP is low eg 30 kg/day, a 10 kg/day increase in load increased the concentration at N35 by 3.2%
    - when the load at St Marys WWTP is moderate eg 90 kg/day, a 10 kg/day increase in load increased the concentration at N35 by 1.2%
    - when the load at St Marys WWTP is high eg 200 kg/day, a 10 kg/day increase in load increased the concentration at N35 by 0.5%.
  - The TN load from Quakers Hill WWTP was not significantly correlated to the concentration of TN at N35 when adjusted for upstream catchment measures and Riverstone and St Marys WWTP TN loads (p=0.96). However, it was significantly correlated after adjusting for all variables in the model (p=0.05). This suggested that, after taking into account any linear and quadratic trends and any seasonal trends, Quakers Hill WWTP load provides additional explanation of the variability in TN concentration at N35.
    - when the load from Quakers Hill WWTP is low eg 80 kg/day, a 10 kg/day increase in load increased the concentration at N35 by 0.9%
    - when the load from Quakers Hill WWTP is moderate eg 150 kg/day, a 10 kg/day increase in load increased the concentration at N35 by 0.5%
    - when the load from Quakers Hill WWTP is high eg 250 kg/day, a 10 kg/day increase in load increased the concentration at N35 by 0.3%.
- Long term trends:
  - In period 1 before St Marys and Riverstone WWTPs TN upgrade there was an overall decreasing trend in total nitrogen concentration
  - In period 2 (after St Marys and Riverstone WWTP TN upgrade) and period 3 (after the Richmond WWTP TN upgrade) there was no trend, only a seasonal trend.
  - In period 4 after St Marys AWTP commissioned and Riverstone WWTP increased discharge there was an increasing trend in total nitrogen concentration at N35
  - In period 5 after Riverstone WWTP's TN upgrade, there was no trend.
- Seasonal trends:
  - First order sine and cosine terms by year interactions were included to capture a pattern of one peak per year in February and one trough around August with a magnitude that differed between years.

- After adjusting for seasonal trends, flow and concentration at the upstream site, flow from the tributary and load from the four WWTPs, the total nitrogen geometric mean concentration:
    - In period 1 before St Marys and Riverstone WWTPs TN upgrade was 1.76 mg/L (1.62 to 1.92 mg/L)
    - In period 2 after St Marys and Riverstone WWTP TN upgrade and before Richmond WWTP TN upgrade was 1.11 mg/L (1.03 to 1.19 mg/L)
    - In period 3 after Richmond WWTP TN upgrade and before St Marys AWTP commissioned and Riverstone WWTPs increased discharge was 0.96 mg/L (0.90 to 1.02 mg/L).
    - In period 4 after St Marys AWTP commissioned and Riverstone WWTP's increased discharge and before Riverstone WWTP TN upgrade was 0.82 mg/L (0.76 to 0.89 mg/L)
    - In period 5 after Riverstone WWTP's TN upgrade was 0.99 mg/L (0.86 to 1.14 mg/L).
- Comparing the total nitrogen concentrations between periods:
    - The geometric mean for the period after the nitrogen upgrades at St Marys and Riverstone WWTPs and before the nitrogen upgrade at Richmond WWTP (period 2) was 63% (56 to 70%) of the period prior to these upgrades (period 1)
    - The geometric mean for the period after the Richmond WWTP nitrogen upgrade and before the commissioning of St Marys AWTP (period 3) was 87% (79 to 94%) of the period after the nitrogen upgrades at St Marys and Riverstone WWTPs and before the nitrogen upgrade at Richmond WWTP (period 2)
    - The geometric mean for the period after commissioning St Marys AWTP and before the nitrogen upgrade at Riverstone WWTP (period 4) was 86% (78 to 95%) of the period after Richmond WWTP nitrogen upgrade and before the commissioning of St Marys AWTP (period 3)
    - The geometric mean for the period after Riverstone WWTPs nitrogen upgrade (period 5) was 120% (103 to 141%) of the geometric mean for the period after commissioning St Marys AWTP (period 4).

4.3.6 Hawkesbury River at Wilberforce (N35) and Freemans Reach (N39) – Total nitrogen concentration (downstream/upstream)

There were no records from 2002 to mid-2008 at the tributary site of NS04A. The analysis models included data from 2008 ie 639 records in total, of which 216 were from N35 (downstream Hawkesbury River) 208 were from NS04A (South Creek tributary), and 215 were from N39 (upstream Hawkesbury River). However, the data prior to this time are plotted for completeness. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included a factor for site identifier for the upstream site, tributary site and downstream site, site by flow interaction term to allow the relationship with flow to differ between sites, a site by period interaction term to allow the site means to differ in each of the three periods defined as before the commissioning of St Marys AWTP and Riverstone WWTP increased capacity (period 3), the period after this point and before Riverstone WWTP phosphorus upgrade (period 4) and the period after the phosphorus upgrade (period 5), interaction terms for site by linear and quadratic trends to allow them to differ within each period and 3-factor interaction terms for site by 1st, 2nd and 3rd order harmonic interaction terms to model the seasonal trends and allow them to differ between sites. Period numbers have been retained as for the analyses of the downstream river sites to avoid confusion.

The model:

Log_{10}(TN concentration) = site (N35, NS04A or N39) + site by flow + site by period + site by linear trend in period 3 + site by linear trend in period 4 + site by linear trend in period 5 + site by quadratic trend in period +3 site by quadratic trend in period 4 + site by quadratic trend in period 5 + site by 1st order sine by year + site by 1st order cosine by year + site by 2nd order sine by year + site by 2nd order cosine by year + site by 3rd order sine by year + site by 3rd order cosine by year

Where:

- site, period and year are categorical factors.
- Flow consists of the flow corresponding to the site identified in the site variable as defined in Volume 2: Appendix E (Table E-5)

Model reduction decisions:

- Remove linear and quadratic trends in Period 5
- Remove site by 1st, 2nd and 3rd order harmonic by year terms
- Include site by 1st order harmonic terms.

Step 2: Fit the final, reduced model

Log_{10}(TN concentration) = site (N35, NS04A or N39) + site by flow + site by period + site by linear trend in period 3 + site by linear trend in period 4 + site by quadratic trend in period 3 + site by quadratic trend in period 4 + site by 1st order sine + site by 1st order cosine

Where:

- site, period and year are categorical factors.
- Flow consists of the flow corresponding to the site identified in the site variable as defined in Volume 2: Appendix E (Table E-5)

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-28.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix H). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table H-11 and Table H-12, respectively. The residual plots for this model are shown in Figure H-6.

The site, site by flow and site by period parameters were retained in the model as they were part of the study design. The p-values corresponding to the Type III SS varied compared with the type I SS. The site by linear and quadratic trends in period 3 have type III SS p-values higher than type I but still <0.15. This suggested that, the site by harmonic interaction terms accounted for some of these trends in the short timespan for this period. The site by flow interaction term was significant for the type III SS (<0.0001) and not for the type I SS (p=0.3). This suggested that, after taking into account differences between the mean concentration of TN at each site and linear, quadratic and seasonal trends within each site, flow assisted in explaining the pattern of TN across the series of data being analysed.

The model fitted the data well (R^2=0.88 and adjusted R^2=0.87) except for those at extremely high concentrations or, to a lesser extent, low concentrations. A few values showed a high leverage (ie terms in the model are included because of their contribution to the variability in the data). The distribution of the residuals was approximately Normal and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

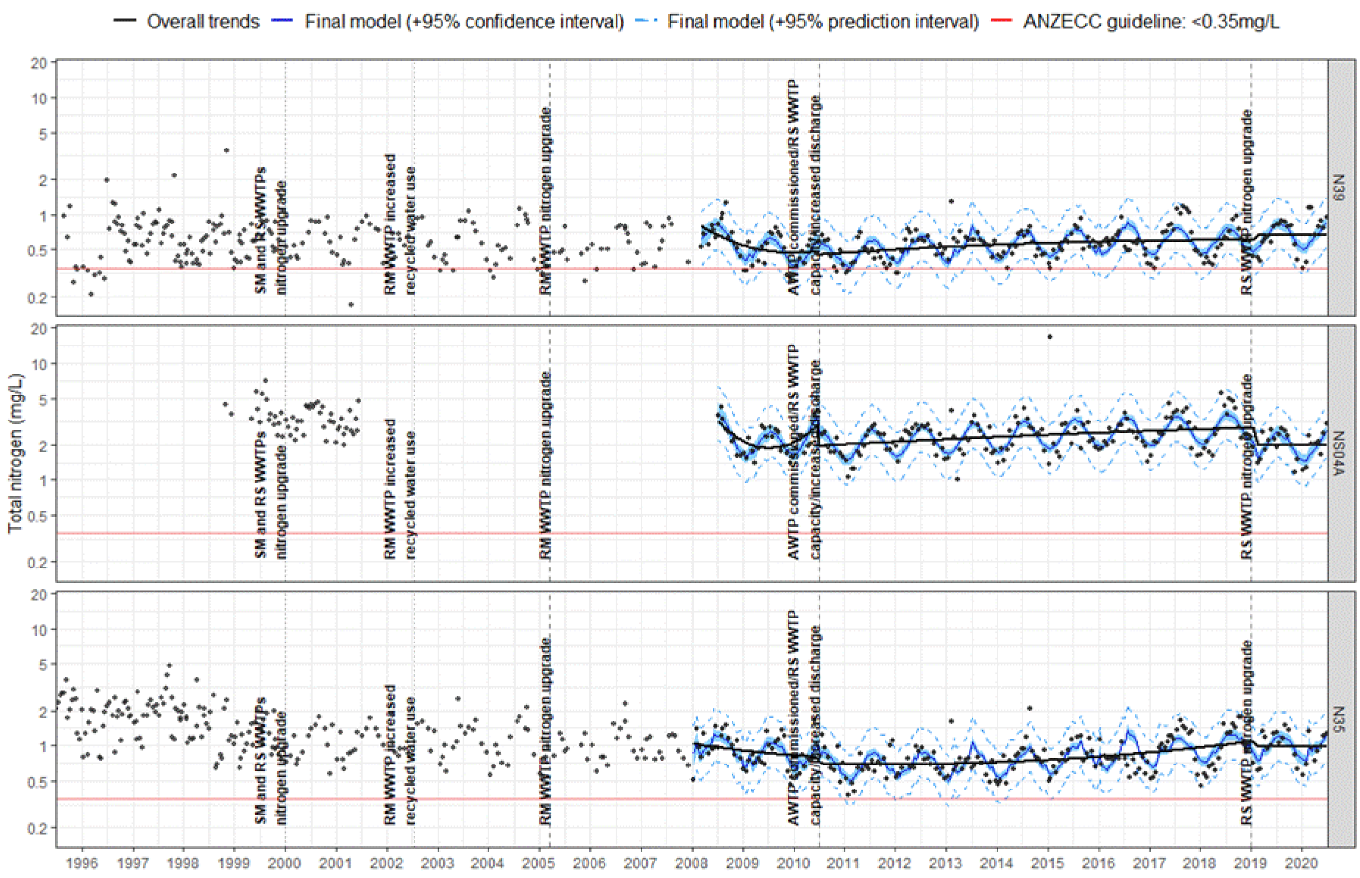

Figure 4-28 Total nitrogen concentrations at Freemans Reach (N39) and Wilberforce (N35), Hawkesbury River and South Creek (NS04A): fitting terms to model site differences and associated flow along with linear and quadratic trends and seasonal trends overlaid with the trends in each period

Key outcomes

- Total nitrogen concentration:
  - TN concentration remained above the ANZG default level of <0.35mg/L for the downstream site of N35, the tributary NS04A and the upstream site of N39.
  - The final reduced model fitted well with R^2=0.87 and adjusted R^2=0.87 . However, the residual plots showed the model did not capture the extremely high or low total nitrogen concentrations.
- Flow:
  - Although the interaction between flow and site was not significant with the type I SS (p=0.3), it was significant after adjusting for all terms in the model (p<0.0001).
  - As flow increased, TN increased at all sites with different levels of significance. Flow increased concentration more significantly at N35 (p<0.0001) than at N39 (p=0.02) and NS04A (p=0.4).
    - when flow at N35 is low eg 1000 ML/day, a 100 ML/day increase in flow decreased the TN concentration at N35 by 2.9%
    - when flow at N35 is moderate eg 1300 ML/day, a 100 ML/day increase in flow increased the concentration at N35 by 2.2%
    - when flow at N35 is high, eg 1600 ML/day, a 100 ML/day increase in flow increased the concentration at N35 by 1.8%.
    - When flow at N39 is low eg 850 ML/day, a 100 ML/day increase in flow increased the TN concentration at N39 by 0.4%
    - when flow at N39 is moderate eg 1150 ML/day, a 100 ML/day increase in flow increased the concentration at N39 by 0.3%
    - when flow at N39 is high, eg 1550 ML/day, a 100 ML/day increase in flow increased the concentration at N39 by 0.25%.
  - There was no relationship evident at NS04A.
- Long term trends:
  - There was a significant interaction between site and linear trends in period 3 (p=0.004), between site and quadratic trend in period 3 (p=0.0007), between site and linear trend in period 4 (p<0.0001), and between site and quadratic trend in period 4 (p=0.02). No interaction terms were required for period 5.
  - There was an overall decrease in total nitrogen concentration at all three sites in the period before commissioning of St Marys (period 3), but the trend slightly differed between sites.
  - After the commissioning of St Marys AWTP and Riverstone WWTP reached capacity/increased discharge (period 4), there was a gradual increase in total nitrogen concentration at all sites.

- After the nitrogen upgrade at Riverstone WWTP (period 5), the trend was stable at all sites.

- Seasonal trends:
  - All site by 1st order sine and cosine terms interactions were included to capture a pattern of one peak per year in February and the trough around July that was the same for each year within a site but differed between sites.
- Site by period geometric mean total nitrogen concentrations:
  - There was a significant interaction between site and period ($p<0.0001$).
  - After adjusting for linear, quadratic and seasonal trends:
    - Prior to commissioning St Marys AWTP and Riverstone WWTP reached capacity/increased discharge (period 1), the geometric mean concentration at N35 was 0.89 mg/L (95% CI = 0.80 to 1.00 mg/L), at NS04A was 2.00 mg/L (95% CI = 1.76 to 2.28 mg/L) and at N39 was 0.51 mg/L (95% CI = 0.46 to 0.57 mg/L).
    - After commissioning of St Marys AWTP and Riverstone WWTP reached capacity/increased discharge (period 2) the geometric mean at N35 was 0.78 mg/L (95% CI = 0.73 to 0.83 mg/L), at NS04A was 2.44 mg/L (95% CI = 2.29 to 2.60 mg/L) and at N39 was 0.59 mg/L (95% CI = 0.55 to 0.63 mg/L).
    - After the nitrogen upgrade at Riverstone WWTP (period 3), the geometric mean at N35 was 1.05 mg/L (95% CI = 0.95 to 1.17 mg/L), at NS04A was 2.00 mg/L (95% CI = 1.80 to 2.23 mg/L) and at N39 was 0.68 mg/L (95% CI = 0.62 to 0.75 mg/L).
  - Comparing the modelled geometric mean total nitrogen concentration between sites within periods:
    - The geometric mean for N35 in the period before commissioning St Marys AWTP and Riverstone WWTP reached capacity/increased discharge (period 3) was 174% (149 to 204%) of the geometric mean for N39 (upstream)
    - The geometric mean for N35 in the period before commissioning St Marys AWTP and Riverstone WWTP reached capacity/increased discharge (period 3) was 45% (38 to 53%) of the geometric mean for NS04A (South Creek tributary)
    - The geometric mean for N35 in the period after commissioning St Marys AWTP and Riverstone WWTP reached capacity/increased discharge period 4) was 132% (121 to 145%) of the geometric mean for N39
    - The geometric mean for N35 in the period after commissioning St Marys AWTP and Riverstone WWTP reached capacity/increased discharge (period 4) was 32% (29 to 35%) of the geometric mean for NS04A
    - The geometric mean for N35 in the period after the nitrogen upgrade at Riverstone WWTP (period 5) was 155% (134 to 179%) of the geometric mean for N39.
    - The geometric mean for N35 in the period after the nitrogen upgrade at Riverstone WWTP (period 5) was 53% (45 to 61%) of the geometric mean for NS04A

- Comparing the modelled geometric mean total nitrogen concentrations between period:
  - To reduce output and to place more emphasis on the recent times, no comparisons were undertaken between periods 4 and 3. Note that the confidence intervals are wide due to the small numbers of records in period 5.
  - The geometric mean for the period after the nitrogen upgrade at Riverstone WWTP (period 5) was 135% (95% CI = 120 to 152%) of the geometric mean for the period prior to the upgrade and after the commissioning of St Marys AWTP and the increased capacity at Riverstone (period 4) at site N35.
  - The geometric mean for the period after the nitrogen upgrade at Riverstone WWTP (period 5) was 82% (95% CI = 73 to 92%) of the geometric mean for the period prior to the upgrade and after the commissioning of St Marys AWTP and the increased capacity at Riverstone (period 4) at site NS04A
  - The geometric mean for the period after the nitrogen upgrade at Riverstone WWTP (period 5) was 116% (95% CI = 103 to 130%) of the geometric mean for the period prior to the upgrade and after the commissioning of St Marys AWTP and Riverstone WWTP reached capacity/ increased discharge (period 4) at site N39
  - The percentage difference between periods 5 and 4 for the geometric mean concentration at N35 was 117% (98 to 139%) of the percentage difference at N39
  - The percentage difference between periods 5 and 4 for the geometric mean concentration at N35 was 165% (138 to 196%) of the percentage difference at NS04A

4.3.7 St Marys WWTP – Dissolved inorganic nitrogen load

There were 1392 dissolved inorganic nitrogen load records in the St Marys WWTP data series. There were 152 records in the period prior to the nitrogen upgrade in 2000 (period 1), 635 records after the nitrogen upgrade and before the commissioning of St Marys AWTP in 2010 (period 2) and 605 records after commissioning St Marys AWTP (period 3). All records are included in the analyses. Key outcomes are summarised at the end of this section.

There were no records from mid-1996 to mid-1998. The analysis models do not fit any terms during this time-period and hence, did not predict any loads during this period.

Step 1: Fit the full model

Fitting the full model included the three periods defined by the nitrogen upgrade at St Marys WWTP and the commissioning of the St Marys AWTP, linear and quadratic trends within each period and 1st, 2nd and 3rd order harmonic interaction terms to model the seasonal trends.

The model:

Log_{10}(DIN load) = period + linear trend in period 1 + linear trend in period 2 + linear trend in period 3 + quadratic trend in period 1 + quadratic trend in period 2 + quadratic trend in period 3 + 1st order sine + 1st order cosine + 2nd order sine + 2nd order cosine + 3rd order sine + 3rd order cosine + 1st order sine by year + 1st order cosine by year

+ 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

period and year are categorical factors.

Model reduction decisions:

- Periods 1, 2 and 3: retain the linear and quadratic trend terms as the p-values for the quadratic terms using the type I SS were <0.15
- Retain all harmonic interaction terms as the p-values for the 3rd order terms from the type I SS were <0.15
- Remove the main effect harmonic terms since they can be included in the harmonic interaction terms.

Step 2: Fit the final, reduced model

Log_{10}(DIN load) = period + linear trend in period 1 + linear trend in period 2 + quadratic trend in period 1 + quadratic trend in period 2 + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

period and year are categorical factors.

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-29. The straight line on the figure purely joins the predicted value for the last data point prior to the missing data period from mid-1996 to mid-1998 and the predicted value for the first data point after this missing data period.

All terms in the final, reduced model had a p-value for the corresponding type I SS <0.15. Each term in the model also had a p value <0.15 after adjusting for all other terms in the model (type III SS) except for the linear and quadratic trends prior to the first nitrogen upgrade (period 1) suggesting that the harmonic interaction terms in period 1 are explaining the trend. The effect of this can be seen in Figure 4-29 where the total nitrogen loads are reducing each year prior to the first nitrogen upgrade.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix H). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table H-13 and Table H-14, respectively. The residual plots for this model are shown in Figure H-7.

The model generally fitted the data well (R^2=0.67 and adjusted R^2=0.63) except for those at extremely high and low loads. Several values showed a high leverage (ie terms in the model are included because of their contribution to the variability in the data). The distribution of the residuals was approximately Normal with two extreme outliers and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

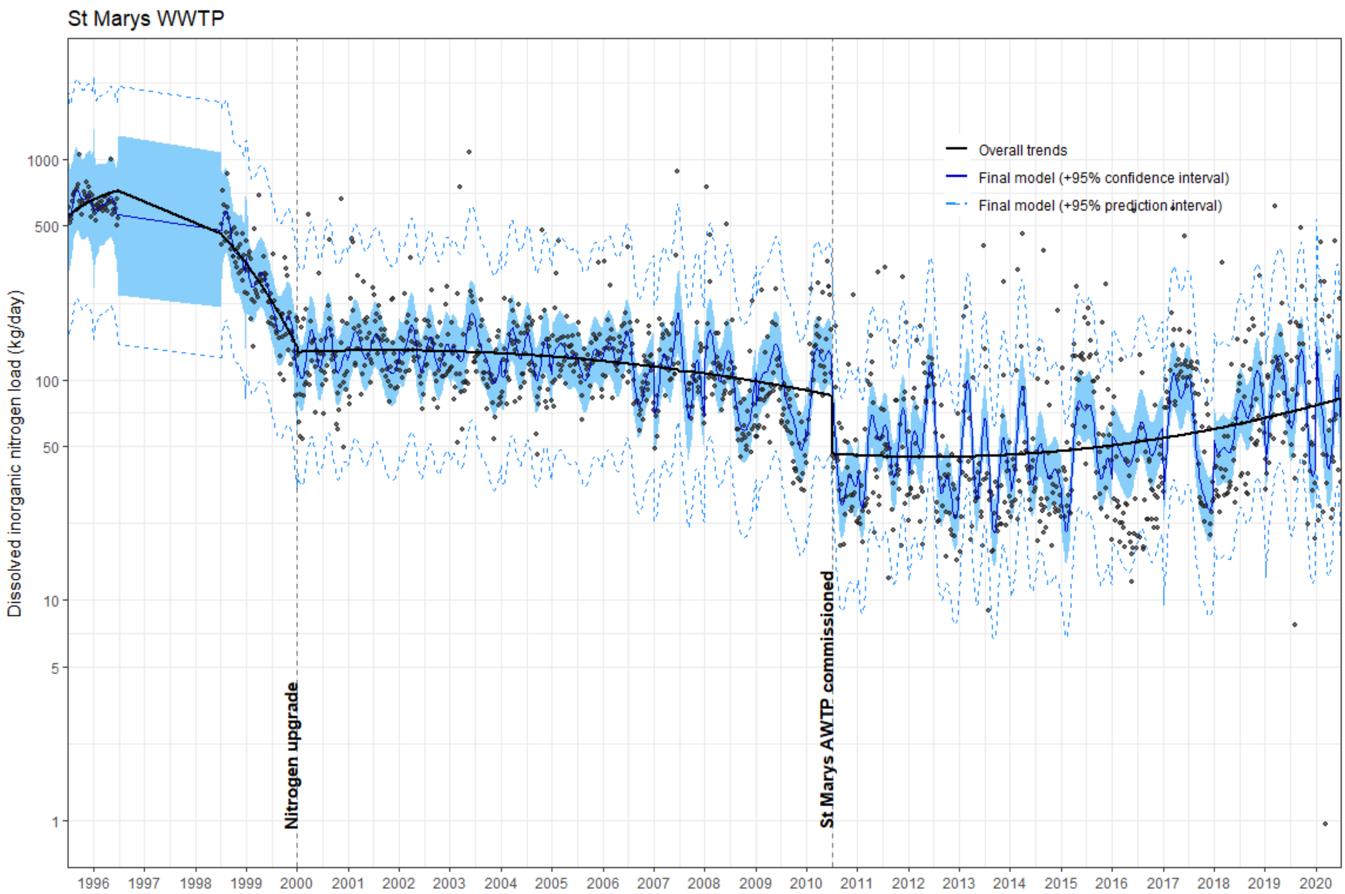

Figure 4-29 St Marys WWTP dissolved inorganic nitrogen load: fitting terms to model interventions, linear and quadratic trends within each period and seasonal trends overlaid with the trends in each period

Key outcomes

- Dissolved inorganic nitrogen load:
  - The final reduced model fitted reasonably well with R^2=0.67 and adjusted R^2=0.63. However, the residual plots showed the model did not capture the extremely high and low dissolved inorganic nitrogen loads.
  - There was no EPL limit for dissolved inorganic nitrogen load
- Long term trends:
  - Significant curvilinear trends were observed in all three periods
    - Prior to the nitrogen upgrade at St Marys WWTP in 2000 (period 1), there was an overall decreasing trend in DIN load. The trend is also explained by the seasonal trends by year.
    - After the nitrogen upgrade at St Marys WWTP (period 2), the DIN load had a slightly increasing trend until around 2014 when load started to slightly decrease.

    - After commissioning of St Marys AWTP (period 3), there was a larger decrease in load, followed by a gradually increasing trend.
    - As of mid-2020, the trend was increasing
- Seasonal trends:
  - First, second and third order sine and cosine terms by year interactions were included to capture a more complex pattern of three peaks per year, capturing the largest one in February and two smaller ones in late May/early June and September. The lowest trough was around late October/early November. The magnitude of the peaks and troughs differed between years.
- After adjusting for seasonal trends, the geometric mean DIN load:
  - Prior to the nitrogen upgrade at St Marys WWTP (period 1) was 955.7 kg/day (95% CI =210.6 to 4332.4.9 kg/day). Note that this estimates the DIN at the middle day of period 1 that happens to be within the missing data period. Not shown on the figure, the curvilinear trend is assuming the trend is increasing during this period, hence the larger estimated geometric mean and also the wide confidence interval.
  - After the nitrogen upgrade and before the commissioning of the St Marys AWTP (period 2) was 128.1 kg/day (95% CI = 120.0 to 136.8 kg/day)
  - After commissioning of the St Marys AWTP (period 3) was 46.8 kg/day (95% CI = 43.8 to 50.1 kg/day)
- Comparing the dissolved inorganic nitrogen loads between periods:
  - The geometric mean for the period between the nitrogen upgrade and commissioning of St Marys AWTP (period 2) was 13% (95% CI = 3 to 61%) of the geometric mean for the period prior to the nitrogen upgrade at St Marys WWTP (period 1). The confidence interval is wide due to the few records and missing data gap in period 1.
  - The geometric mean after the commissioning of St Marys AWTP (period 3) was 37% (95% CI = 33 to 40%) of the geometric mean for the period between the nitrogen upgrade at St Marys WWTP and commissioning of St Marys AWTP (period 2).

4.3.8 Quakers Hill WWTP – Dissolved inorganic nitrogen load

There were 1158 dissolved inorganic nitrogen load records in the Quakers Hill WWTP data series. There were 728 records prior to commissioning of St Marys AWTP in 2010 (period 1) and 430 records after commissioning (period 2). All records are included in the analyses. There were no records from mid-1996 to mid-1998. The analysis models did not fit any terms during this time-period and hence, did not predict any loads during this period. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included the two periods defined by the commissioning of the St Marys AWTP, linear and quadratic trends within each period and 1st, 2nd and 3rd order harmonic interaction terms to model the seasonal trends.

The model:

Log_{10}(DIN load) = period + linear trend in period 1 + linear trend in period 2 + quadratic trend in period 1 + quadratic trend in period 2 + 1st order sine + 1st order cosine + 2nd order sine + 2nd order cosine + 3rd order sine + 3rd order cosine + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

period and year are categorical factors.

Model reduction decisions:

- Period 1 and 2: retain the linear and quadratic trend terms (all p-values from the type I SS were < 0.15)
- Retain all harmonic interaction terms as the p-values for the 3rd order terms from the type I SS were <0.15
- Remove the main effect harmonic terms since they can be included in the harmonic interaction terms.

Step 2: Fit the final, reduced model

Log_{10}(DIN load) = period + linear trend in period 1 + linear trend in period 2 + quadratic trend in period 1 + quadratic trend in period 2 + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

period and year are categorical factors.

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-30. The straight line and shaded areas on the figure purely join the predicted value for the last data point prior to the missing data period from mid-1996 to mid-1998 and the predicted value for the first data point after this missing data period.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix H). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table H-15 and Table H-16, respectively. The residual plots for this model are shown in Figure H-8.

All terms in the final, reduced model had a p-value for the corresponding type I SS <0.15 except for the 3rd order sine by year interaction term. This was included in the model as its partner, the 3rd order cosine by year interaction term had a p-value of <0.15. The linear and quadratic terms for period 1 had p-values after adjusting for all other terms in the model (type III SS) >0.15. This suggested that, the changes in the seasonal trend each year also accounted for the linear and quadratic pattern in period 1.

The model fitted the data well (R^2=0.45 and adjusted R^2=0.38) except for those at extremely high loads and to a lesser extent, those at the extremely low loads. A few values showed a high leverage (ie terms in the model are included because of their contribution to the variability in the data). The distribution of the residuals was approximately Normal with a slightly long tail reflecting the lack of fit at very high loads. Residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

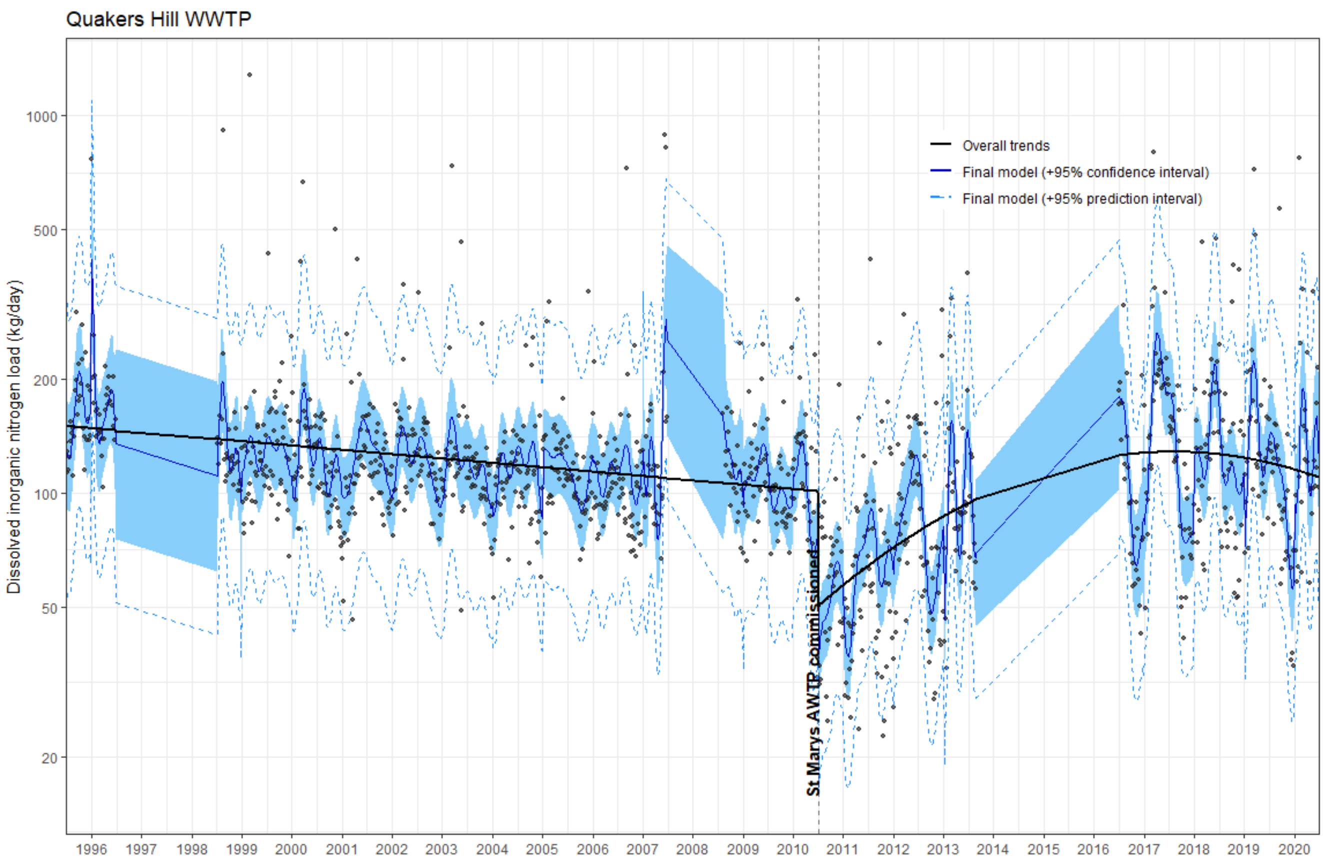

Figure 4-30 Quakers Hill WWTP dissolved inorganic nitrogen load: fitting terms to model interventions, linear and quadratic trends within each period and seasonal trends overlaid with the trends in each period

Key outcomes

- Dissolved inorganic nitrogen load:
  - The final reduced model fitted reasonably well with R^2=0.45 and adjusted R^2=0.38. However, the residual plots showed the model did not capture the extremely high DIN loads, and to a lesser extent, the extremely low loads.

- There was no EPL limit for dissolved inorganic nitrogen load

- Long term trends:
  - Significant curvilinear trends were observed in both periods
    - Prior to commissioning St Marys AWTP, the DIN load had a gradual decreasing trend
    - The commissioning of St Marys AWTP saw an immediate large decrease in DIN load that has been increasing until approximately 2017 when the load started to decrease.
    - As of mid-2020, the trend was decreasing and approaching pre AWTP commissioning levels.
- Seasonal trends:
  - First, second and third order sine and cosine terms by year interactions were included to capture a more complex pattern of three peaks per year, capturing the largest one in February and two smaller ones in late May/ early June and September. The lowest trough was around late October/ early November. The magnitude of the peaks and troughs differed between years.
- After adjusting for seasonal trends, the geometric mean DIN load:
  - Prior to the commissioning of St Marys AWTP (period 1) was 116.6 kg/day (95% CI =111.6 to 121.8 kg/day)
  - After the commissioning of St Marys AWTP (period 2) was 128.4 kg/day (95% CI = 115.2 to 143.2 kg/day).
- Comparing the modelled loads between periods:
  - The geometric mean for the period after commissioning of St Marys AWTP (period 2) was 110% (95% CI = 98 to 124%) of the geometric mean for the period prior to the commissioning (period 1).

4.3.9 Riverstone WWTP – Dissolved inorganic nitrogen load

There were 729 dissolved inorganic nitrogen load records in the Riverstone WWTP data series. There were 152 records prior to the nitrogen upgrade in 2020 (period 1), 457 records between the nitrogen upgrade and Riverstone WWTP reached capacity/increased discharge in 2010 (period 2), 34 records after Riverstone WWTP reached capacity/increased discharge and before the second nitrogen upgrade (period 3), and 86 records after the second upgrade (period 4). All records are included in the analyses. There were no records from mid-1996 to mid-1998 and from mid-2007 to mid-2018. The analysis models did not fit any terms during these time-periods and hence, did not predict any loads during these periods. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included the four periods defined by two nitrogen upgrades and an increase in Riverstone WWTP capacity and discharge, linear and quadratic trends within each period and 1st, 2nd and 3rd order harmonic interaction terms to model the seasonal trends.

The model:

Log_{10}(DIN load) = period + linear trend in period 1 + linear trend in period 2 + linear trend in period 3 + linear trend in period 4 + quadratic trend in period 1 + quadratic trend in period 2 + quadratic trend in period 3 + quadratic trend in period 4 + 1^{st} order sine + 1^{st} order cosine + 2^{nd} order sine + 2^{nd} order cosine + 3^{rd} order sine + 3^{rd} order cosine + 1^{st} order sine by year + 1^{st} order cosine by year + 2^{nd} order sine by year + 2^{nd} order cosine by year + 3^{rd} order sine by year + 3^{rd} order cosine by year

Where:

period and year are categorical factors.

Model reduction decisions:

- Periods 1, 2, 3 and 4: retain the linear and quadratic trend terms as the p-values for the quadratic terms using the type I SS were <0.15
- Retain all harmonic interaction terms as the p-values for the 3^{rd} order terms from the type I SS were <0.15
- Remove the main effect harmonic terms since they can be included in the harmonic interaction terms.

Step 2: Fit the final, reduced model

Log_{10}(DIN load) = period + linear trend in period 1 + linear trend in period 2 + linear trend in period 3 + linear trend in period 4 + quadratic trend in period 1 + quadratic trend in period 2 + quadratic trend in period 3 + quadratic trend in period 4 + 1^{st} order sine by year + 1^{st} order cosine by year + 2^{nd} order sine by year + 2^{nd} order cosine by year + 3^{rd} order sine by year + 3^{rd} order cosine by year

Where:

period and year are categorical factors.

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-31. The straight line on the figure purely joins the predicted value for the last data point prior to the missing data period and the predicted value for the first data point after this missing data period for each missing data period.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix H). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table H-17 and Table H-18, respectively. The residual plots for this model are shown in Figure H-9.

All terms in the final, reduced model had a p-value for the corresponding type I SS <0.15 except for the linear trend in period 1 with a p-value of 0.78. This term was included in the model as the corresponding quadratic term was significant (p=0.0004). The p-values after adjusting for all other terms in the model (type III SS) suggested that the linear and quadratic terms were explained by the different seasonal trends each year.

The model fitted the data well (R^2=0.82 and adjusted R^2=0.79) except for those at extremely high and low loads. The very high R^2 possibly suggests that there were too many terms in the model (ie overfitted). However, all terms meet the criterion to keep them in the model. Several values showed a high leverage (ie terms in the model are included because of their contribution to the variability in the data). The distribution of the residuals was approximately Normal and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

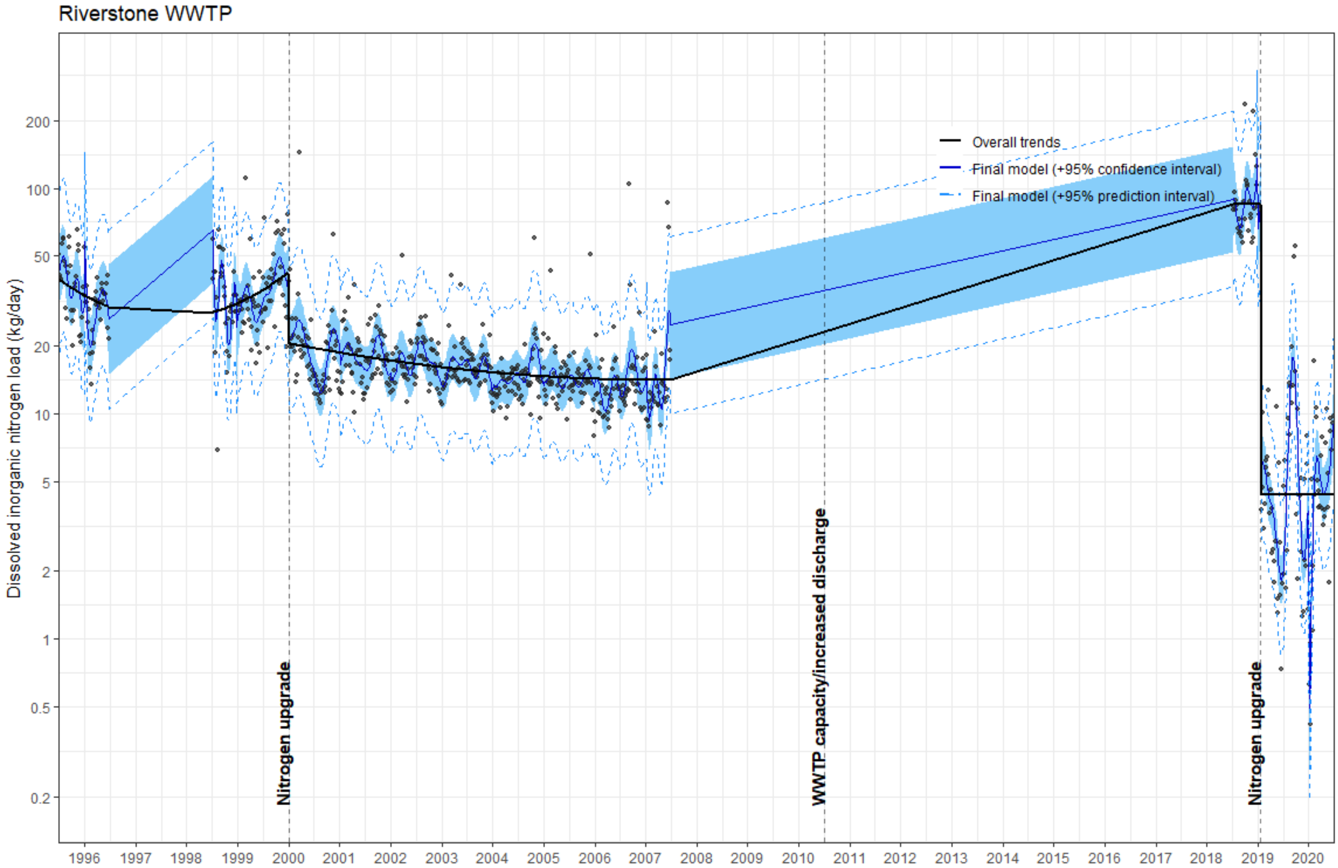

Figure 4-31 Riverstone WWTP dissolved inorganic nitrogen load: fitting terms to model interventions, linear and quadratic trends within each period and seasonal trends overlaid with the trends in each period

Key outcomes

- Dissolved inorganic nitrogen load:
  - The final reduced model fitted well with R^2=0.82 and adjusted R^2=0.79. However, the residual plots showed the model did not capture the extremely high DIN loads. The very high R^2 possibly suggests that there were too many terms in the model (ie overfitted). However, all terms meet the criterion to keep them in the model.
  - There was no EPL limit for dissolved inorganic nitrogen load

- Long term trends:
  - Before the first nitrogen upgrade in 2000, the DIN load was increasing.
  - After the first nitrogen upgrade there was a gradual decrease in DIN load prior to the start of the missing data period.
  - After Riverstone WWTP reached capacity and discharge increased, there were no records until just prior to the second nitrogen upgrade. There was an obvious increase in load from the data collected in period 2.
  - After the second nitrogen upgrade, there was no trend apparent in the series, partly due to the very short time scale.
  - As of mid-2020, the trend in DIN load from Riverstone WWTP was stable.
- Seasonal trends:
  - First, second and third order sine and cosine terms by year interactions were included to capture a more complex pattern of three peaks per year, capturing the largest one in February and two smaller ones in late May/ early June and September. The lowest trough was around late October/ early November. The magnitude of the peaks and troughs differed between years.
- After adjusting for seasonal trends, the geometric mean DIN load:
  - Prior to the first nitrogen upgrade (period 1) was 35.2 kg/day (95% CI =12.7 to 97.8 kg/day). The confidence interval is wide due to the small number of records in the period.
  - After the first nitrogen upgrade (period 2) was 15.7 kg/day (95% CI =14.9 to 16.5 kg/day.
  - After Riverstone WWTP reached capacity/increased discharge (period 3) was 63.0 kg/day (95% CI =12.9 to 308.2 kg/day). The wide confidence interval is due to the small number of records in this period.
  - After the second nitrogen upgrade (period 4) was 5.5 kg/day (95% CI = 3.5 to 8.6 kg/day).
- Comparing the modelled loads between periods:
  - The geometric mean for the period after the first nitrogen upgrade (period 2) was 45% (95% CI = 16 to 124%) of the geometric mean for the period prior to the first nitrogen upgrade (period 1).
  - The geometric mean for the period after Riverstone WWTP reached capacity/increased discharge (period 3) was 402% (95% CI = 82 to 1969%) of the geometric mean for the previous period (period 2). The width of the confidence interval is extremely large due to the small number of records in period 3.
  - The geometric mean for the period after the second nitrogen upgrade period 4) was 9% (95% CI = 1 to 59%) of the geometric mean for the previous period (period 3).

4.3.10 Richmond WWTP – Dissolved inorganic nitrogen load

There were 500 dissolved inorganic nitrogen load records in the Richmond WWTP data series. There were 306 records prior to the increase in recycled water use in mid-2000 (period 1), 22 records after the increase in recycled water use and before the nitrogen upgrade (period 3) and 172 records after the nitrogen upgrade (period 4). There were no records after 2008, hence no analyses of the trends in DIN at Richmond WWTP were undertaken.

The observed data are shown in Figure 4-32.

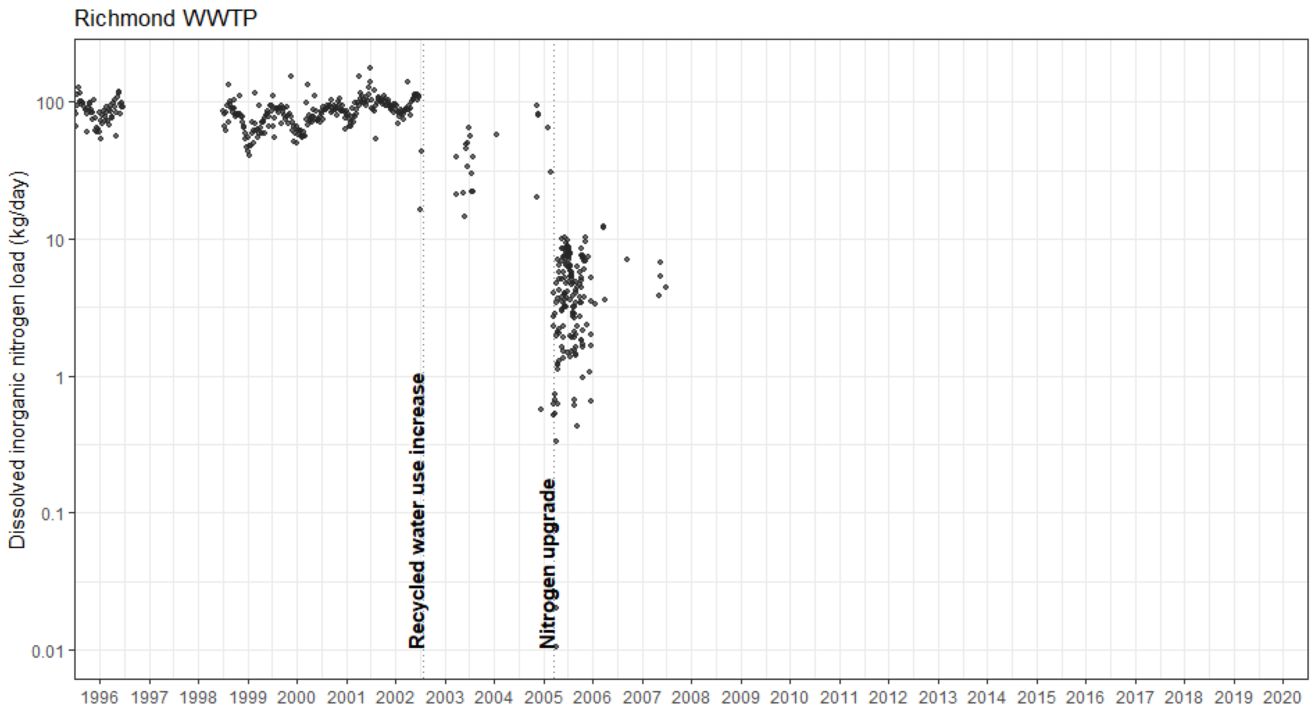

Figure 4-32 Richmond WWTP dissolved inorganic nitrogen load: insufficent data, no model fitted

4.3.11 Hawkesbury River at Wilberforce (N35) – Dissolved inorganic nitrogen concentration

Due to the missing data gaps in the DIN loads from the various WWTPs fitted as covariates in the model, only data from mid-2018 was included in the model ie 33 records at N35.

Step 1: Fit the full model

Fitting the full model included DIN concentration at the upstream site N39, the flow at N39, the flow in South and Eastern Creeks, Riverstone WWTP DIN load, St Marys WWTP DIN load, Quakers Hill WWTP DIN load, the five periods defined by the nitrogen upgrades at St Marys and Riverstone WWTPs, the nitrogen upgrade at Richmond WWTP, commissioning of St Marys AWTP and the nitrogen upgrade at Riverstone WWTP, linear and quadratic trends within each period. Only the 1st order harmonic interaction terms was included to model the seasonal trends given the small number of records. Note: no DIN load for Richmond WWTP was included as a covariate in this model as Richmond has no DIN load estimates after 2008

The model:

Log_{10}(N35 DIN concentration) = log_{10}(N39 DIN concentration) + log_{10}(flow at N39) + log_{10}(Combined flow from South and Eastern Creeks) + log_{10}(lag 1 (Quakers Hill WWTP DIN load)) + log_{10}(lag 1 (St Marys WWTP DIN load)) + log_{10}(lag 1 (Riverstone WWTP DIN load)) + linear trend + quadratic trend + 1st order sine by year + 1st order cosine by year

Where:

- year is categorical factors.
- Flow at N39 is derived as described in Volume 2: Appendix E (Table E-5)
- Lag 1 for the loads from the WWTPs are loads estimated on the day before the sampling dates at N35.

Model reduction decisions:

- Retain linear trend, remove quadratic trend term
- Remove the 1st order main effect harmonic terms.

Step 2: Fit the final, reduced model

Log_{10}(N35 DIN concentration) = log_{10}(N39 DIN concentration) + log_{10}(flow at N39) + log_{10}(Combined flow from South and Eastern Creeks) + log_{10}(lag 1 (Quakers Hill WWTP DIN load)) + log_{10}(lag 1 (St Marys WWTP DIN load)) + log_{10}(lag 1 (Riverstone WWTP DIN load)) + linear trend

Where:

- Flow at N39 is derived as described in Volume 2: Appendix E (Table E-5)
- Lag 1 for the loads from the WWTPs are loads estimated on the day before the sampling dates at N35.

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-33.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix H). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table H-19 and Table H-20, respectively. The residual plots for this model are shown in Figure H-10.

Flow and DIN concentrations corresponding to site N39 and the three WWTPs TN load estimates and period effect were retained in the model as part of the study design. The p-values corresponding to the type III SS were similar to the type I SS.

The model fitted the data well (R^2=0.86 and adjusted R^2=0.82) except for those at extremely high and low concentrations. There were a few very low records that did not fit the model. The distribution of the residuals was approximately Normal and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series except for the extremely small records.

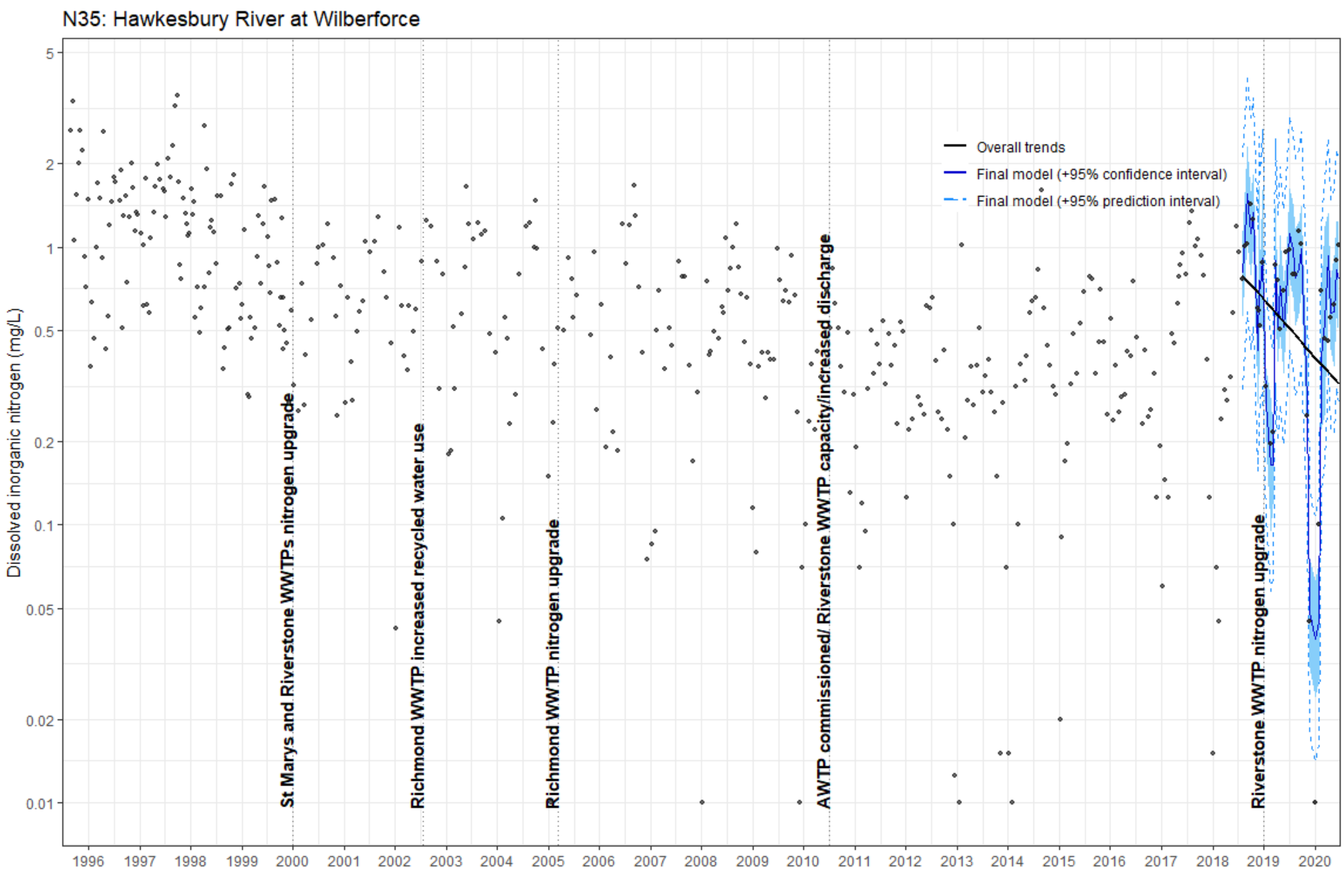

Figure 4-33 Dissolved inorganic nitrogen concentrations at Wilberforce Hawkesbury River (N35): fitting terms to model upstream concentration, upstream river flow, South Creek flow, TN and DIN loads from St Marys, Quakers Hill, Riverstone and Richmond WWTPs, along with linear and quadratic trends and seasonal trends overlaid with the trends in the latest period

Key outcomes

- Dissolved inorganic nitrogen concentration:
  - There was no ANZG default level for dissolved inorganic nitrogen concentration
  - The final reduced model fitted well with R^2=0.86 and adjusted R^2=0.82. However, the residual plots showed the model did not capture the extremely high or low DIN concentrations.
- Impact of upstream catchment and tributary:
  - DIN concentration at N39 (upstream) was significantly correlated to the concentration at N35 (downstream) (p<0.0001).

    - when DIN concentration at N39 is low eg 0.3 mg/L, a 0.005 mg/L increase of DIN concentration increased the concentration at N35 by 1.9%
    - when DIN concentration at N39 is moderate eg 0.5 mg /L, a 0.005 mg /L increase in concentration increased the concentration at N35 by 1.2%
    - when DIN concentration at N39 is high eg 1 mg /L, a 0.005 mg /L increase in concentration increased the concentration at N35 by 0.6%.
  - Flow in the Nepean River at N39 (upstream) was significantly correlated to the concentration of DIN at N35 downstream (p=0.008 after adjusting for concentration at N39 and p=0.02 after adjusting for all terms in the model).
    - when flow at N39 is low eg 850 ML/day, a 100 ML increase in flow increased the concentration at N35 by 4.1%
    - when flow at N39 is moderate eg 1150 ML/day, a 100 ML increase in flow increased the concentration at N35 by 3%
    - when flow at N39 is high eg 1550 ML/day, a 100 ML increase in flow increased the concentration at N35 by 2.3%.
  - Flow in South and Eastern Creeks was not correlated to the concentration of DIN at N35 (p=0.19 after adjusting for the upper catchment variables and p=0.13 after adjusting for all terms in the model)
- Impact of WWTPs:
  - The DIN load from Riverstone WWTP was not significantly correlated to the concentration of DIN at N35 when adjusted only for upstream catchment measures (p=0.19) and was not significantly correlated after adjusting for all variables in the model (p=0.30).
  - The DIN load from St Marys WWTP was significantly correlated to the concentration of DIN at N35 when adjusted only for upstream catchment measures and Riverstone WWTP load, and after adjusting for all variables in the model (p=0.01).
    - when the load from St Marys WWTP is low eg 30 kg/day, a 5 kg/day increase in load increased the concentration at N35 by 3.7%
    - when the load from St Marys WWTP is moderate eg 50 kg/day, a 10 kg/day increase in load increased the concentration at N35 by 2.3%
    - when the load from St Marys WWTP is high eg 100 kg/day, a 10 kg/day increase in load increased the concentration at N35 by 1.2%.
  - The DIN load from Quakers Hill WWTP was not significantly correlated to the concentration of DIN at N35 when adjusted for upstream catchment measures and Riverstone and St Marys WWTP loads (p=0.5) or after adjusting for all variables in the model (p=0.2).
- Long term trends:
  - In period 5, after Riverstone WWTP's nitrogen upgrade the trend is decreasing.

- Seasonal trends:
  - The seasonal trend was explained by the terms in the model. No additional seasonal trend terms needed to be fitted.
- After adjusting for flow and concentration at the upstream site, flow from the tributary and load from the four WWTPs, the dissolved inorganic nitrogen geometric mean concentration:
  - In period 5, after Riverstone WWTP's TN upgrade was 0.94 mg/L (95% CI = 0.73 to 1.20 mg/L).

4.3.12 Hawkesbury River at Wilberforce (N35) and Freemans Reach (N39) – Dissolved inorganic nitrogen concentration (downstream/upstream)

There were no dissolved inorganic nitrogen records from 2002 to mid-2008 at the tributary site of NS04A. The analysis models include data from 2008 ie 639 records in total, 216 from N35, 208 from NS04A and 215 from N39. However, the data prior to this time have been plotted for completeness. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included a factor for site identifier for the upstream site, tributary site and downstream site, site by flow interaction term to allow the relationship with flow to differ between sites, a site by period interaction term to allow the site means to differ in each of the three periods defined as before the commissioning of St Marys AWTP and Riverstone WWTP increased capacity (period 3), the period after this point and before Riverstone WWTP phosphorus upgrade (period 4) and the period after the phosphorus upgrade (period 5), interaction terms for site by linear and quadratic trends to allow them to differ within each period and 3-factor interaction terms for site by 1st, 2nd and 3rd order harmonic interaction terms to model the seasonal trends and allow them to differ between sites. Period numbers have been retained as for the analyses of the downstream river sites to avoid confusion.

The model:

Log_{10}(DIN concentration) = site (N35, NS04A or N39) + site by flow + site by period + site by linear trend in period 3 + site by linear trend in period 4 + site by linear trend in period 5 + site by quadratic trend in period 3 + site by quadratic trend in period 4 + site by quadratic trend in period 5 + site by 1st order sine by year + site by 1st order cosine by year + site by 2nd order sine by year + site by 2nd order cosine by year + site by 3rd order sine by year + site by 3rd order cosine by year

Where:

- site, period and year are categorical factors.
- Flow consists of the flow corresponding to the site identified in the site variable as defined in Volume 2: Appendix E (Table E-5)

Model reduction decisions:

- Remove linear and quadratic trends in period 5

- Remove site by 1st, 2nd and 3rd order harmonic by year terms
- Include site by 1st order harmonic terms.

Step 2: Fit the final, reduced model

Log_{10}(DIN concentration) = site (N35, NS04A or N39) + site by flow + site by period + site by linear trend in period 3 + site by linear trend in period 4 + site by quadratic trend in period 3 + site by quadratic trend in period 4 + site by 1st order sine + site by 1st order cosine

Where:

- site and period are categorical factors.
- Flow consists of the flow corresponding to the site identified in the site variable as defined in Volume 2: Appendix E (Table E-5)

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-34.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix H). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table H-21 and Table H-22, respectively. The residual plots for this model are shown in Figure H-11.

The site, site by flow and site by period parameters were retained in the model as they were part of the study design. The p-values corresponding to the Type III SS varied compared with the type I SS. The site by linear and quadratic trends in period 3 have type III SS p-values higher than type I and >0.15. This suggested that, the site by harmonic interaction terms accounted for the trends in the short timespan for this period. The site by flow interaction term was significant for both type I and type III SS (<0.0001).

The model fitted the data well (R^2=0.78 and adjusted R^2=0.77) except for those at extremely high concentrations or, to a greater extent, low concentrations. A few values showed a high leverage (ie terms in the model are included because of their contribution to the variability in the data). The distribution of the residuals was approximately Normal and residuals plotted against the predicted values showed no remaining pattern in the data series. The Scale-location plot showed that as the predicted value increases the square root of the residual decreases, suggesting that, even with the log transformation, the data were not showing an equal variance, and a different transformation may be more appropriate. No other transformations were investigated as, this approach was reasonable for all other analyses of DIN.

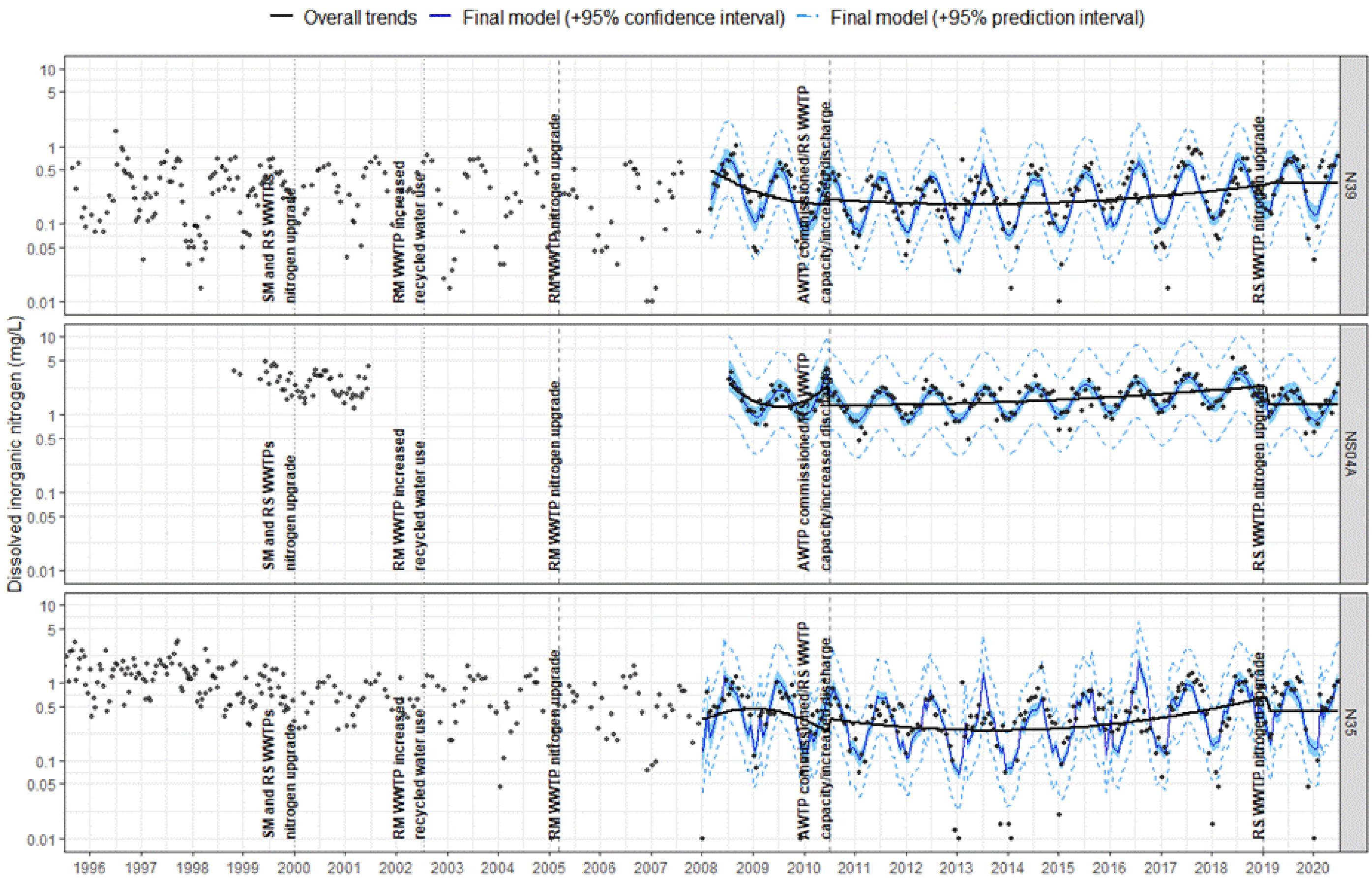

Figure 4-34 Dissolved inorganic nitrogen concentrations at Freemans Reach (N39) and Wilberforce (N35), Hawkesbury River and South Creek (NS04A): fitting terms to model site differences and associated flow along with linear and quadratic trends and seasonal trends overlaid with the trends in each period

Key outcomes

- Dissolved inorganic nitrogen concentration:
  - There was no ANZG default level for dissolved inorganic nitrogen.
  - The final reduced model fitted well with R^2=0.78 and adjusted R^2=0.77. Residual plots showed the model did not capture the extremely high or low DIN concentrations.
- Flow:
  - The interaction between flow and site was significant ($p<0.0001$).
  - As flow increased, DIN increased at N35 ($p<0.0001$) and at N39 ($p=0.01$). However, no evidence of a relationship between flow and DIN was found for NS04A ($p=0.9$).
    - when flow at N35 is low eg 1000 ML/day, a 100 ML/day increase in flow increased the DIN concentration by 2.9%

    - when flow at N35 is moderate eg 1300 ML/day, a 100 ML/day increase in flow increased the concentration at N35 by 2.2%
    - when flow at N35 is high, eg 1600 ML/day, a 100 ML/day increase in flow increased the concentration at N35 by 1.8%.
    - when flow at N39 is low eg 850 ML/day, a 100 ML/day increase in flow increased the DIN concentration by 1.1%
    - when flow at N39 is moderate eg 1150 ML/day, a 100 ML/day increase in flow increased the concentration at N39 by 0.8%
    - when flow at N39 is high, eg 1550 ML/day, a 100 ML/day increase in flow increased the concentration at N39 by 0.6%.
  - There was no relationship evident at NS04A.
- Long term trends:
  - There was a significant interaction between site and linear trends in period 3 (p=0.008), between site and quadratic trend in period 3 (p=0.02), between site and linear and quadratic trends in period 4 (p<0.0001). No interaction terms were required for period 5.
  - There was a curvilinear trend at the three sites seen in the period before commissioning of St Marys AWTP (period 3) that differed between sites.
  - After the commissioning of St Marys AWTP and Riverstone WWTP reached capacity/increased discharge (period 4), there was also a difference between the curvilinear trends at each site, but they all showed a gradual increase in DIN concentration.
  - After the nitrogen upgrade at Riverstone WWTP in 2019 (period 5), the trend was flat at all sites.
- Seasonal trends:
  - All site by 1st order sine and cosine terms interactions were included to capture a pattern of one peak per year in February and the trough around July that was the same for each year within a site and differed between sites.
- Site by period modelled geometric mean dissolved inorganic nitrogen concentrations:
  - There was a significant interaction between site and period (p<0.0001).
  - After adjusting for linear, quadratic and seasonal trends:
    - Prior to commissioning St Marys AWTP and Riverstone WWTP reached capacity/increased discharge (period 3), the geometric mean concentration at N35 was 0.51 mg/L (95% CI = 0.40 to 0.65 mg/L), at NS04A was 1.35 mg/L (95% CI = 1.02 to 1.80 mg/L) and at N39 was 0.25 mg/L (95% CI = 0.19 to 0.32 mg/L).
    - After commissioning of St Marys AWTP and Riverstone WWTP reached capacity/increased discharge (period 4), the geometric mean at N35 was 0.30 mg/L

(95% CI = 0.26 to 0.35 mg/L), at NS04A was 1.51 mg/L (95% CI = 1.31 to 1.74 mg/L) and at N39 was 0.20 mg/L (95% CI = 0.18 to 0.24 mg/L).

    - After the nitrogen upgrade at Riverstone WWTP (period 5), the geometric mean at N35 was 0.53 mg/L (95% CI = 0.42 to 0.67 mg/L), at NS04A was 1.31 mg/L (95% CI = 1.03 to 1.67 mg/L) and at N39 was 0.34 mg/L (95% CI = 0.27 to 0.43 mg/L).
- Comparing the adjusted dissolved inorganic nitrogen concentrations between sites within periods:
    - The geometric mean for N35 in the period before commissioning St Marys AWTP and Riverstone WWTP reached capacity/increased discharge (period 3) was 205% (144 to 293%) of the geometric mean for N39.
    - The geometric mean for N35 in the period before commissioning St Marys AWTP and Riverstone WWTP reached capacity/increased discharge (period 3) was 37% (26 to 55%) of the geometric mean for NS04A.
    - The geometric mean for N35 in the period after commissioning St Marys AWTP and the Riverstone WWTP reached capacity/increased discharge (period 4) was 147% (121 to 180%) of the geometric mean for N39.
    - The geometric mean for N35 in the period after commissioning St Marys AWTP and Riverstone WWTP reached capacity/increased discharge, (period 4) was 20% (16 to 24%) of the geometric mean for NS04A.
    - The geometric mean for N35 in the period after the nitrogen upgrade at Riverstone WWTP (period 5) was 158% (114 to 218%) of the geometric mean for N39.
    - The geometric mean for N35 in the period after the nitrogen upgrade at Riverstone WWTP (period 5) was 40% (29 to 56%) of the geometric mean for NS04A.
- Comparing the adjusted dissolved inorganic nitrogen concentrations between periods:
    - To reduce output and to place more emphasis on the recent times, no comparisons were undertaken between periods 4 and 3. Note that the confidence intervals are wide due to the small numbers of records in period 5.
    - The geometric mean for the period after the nitrogen upgrade at Riverstone WWTP (period 5) was 176% (95% CI = 135 to 229%) of the geometric mean for the period prior to the upgrade (period 4) at site N35.
    - The geometric mean for the period after the nitrogen upgrade at Riverstone WWTP (period 5) was 87% (95% CI = 67 to 113%) of the geometric mean for the period prior to the upgrade (period 4) at site NS04A.
    - The geometric mean for the period after the nitrogen upgrade at Riverstone WWTP (period 5) was 164% (95% CI = 127 to 212%) of the geometric mean for the period prior to the upgrade (period 4) at site N39.
    - The percentage difference between periods 5 and 4 for the geometric mean concentration at N35 was 107% (73 to 157%) of the percentage difference at N39.

- The percentage difference between periods 5 and 4 for the geometric mean concentration at N35 was 202% (137 to 299%) of the percentage difference at NS04A.

4.3.13 St Marys WWTP – Total phosphorus load

There were 1528 total phosphorus load records in the St Marys WWTP data series. Prior to the St Marys WWTP phosphorus upgrade in 2000 there were 274 records (period 1), after the upgrade and prior to commissioning of St Marys AWTP there were 645 records (period 2) and after the commissioning of St Marys AWTP, 609 records (period 3). All records are included in the analyses. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included the three periods defined by the phosphorus upgrade at St Marys WWTP and the commissioning of the St Marys AWTP, linear and quadratic trends within each period and 1st, 2nd and 3rd order harmonic interaction terms to model the seasonal trends.

The model:

Log_{10}(TP load) = period + linear trend in period 1 + linear trend in period 2 + linear trend in period 3 + quadratic trend in period 1 + quadratic trend in period 2 + quadratic trend in period 3 + 1st order sine + 1st order cosine + 2nd order sine + 2nd order cosine + 3rd order sine + 3rd order cosine + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

period and year are categorical factors.

Model reduction decisions:

- Periods 1: remove the quadratic trend in period 1 as the p-value using the type I SS was >0.15
- Period 2: retain the linear and quadratic trend terms as the p-values for the quadratic terms using the type I SS were <0.15
- Period 3: remove the linear and quadratic trends in period 3 as the p-values for both terms using the type I SS were >0.15
- Retain all harmonic interaction terms as the p-values for the 3rd order terms from the type I SS were <0.15
- Remove the main effect harmonic terms since they can be included in the harmonic interaction terms.

Step 2: Fit the final, reduced model

Log_{10}(TP load) = period + linear trend in period 1 + linear trend in period 2 + quadratic trend in period 2 + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

period and year are categorical factors.

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-35.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix H). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table H-23 and Table H-24, respectively. The residual plots for this model are shown in Figure H-12.

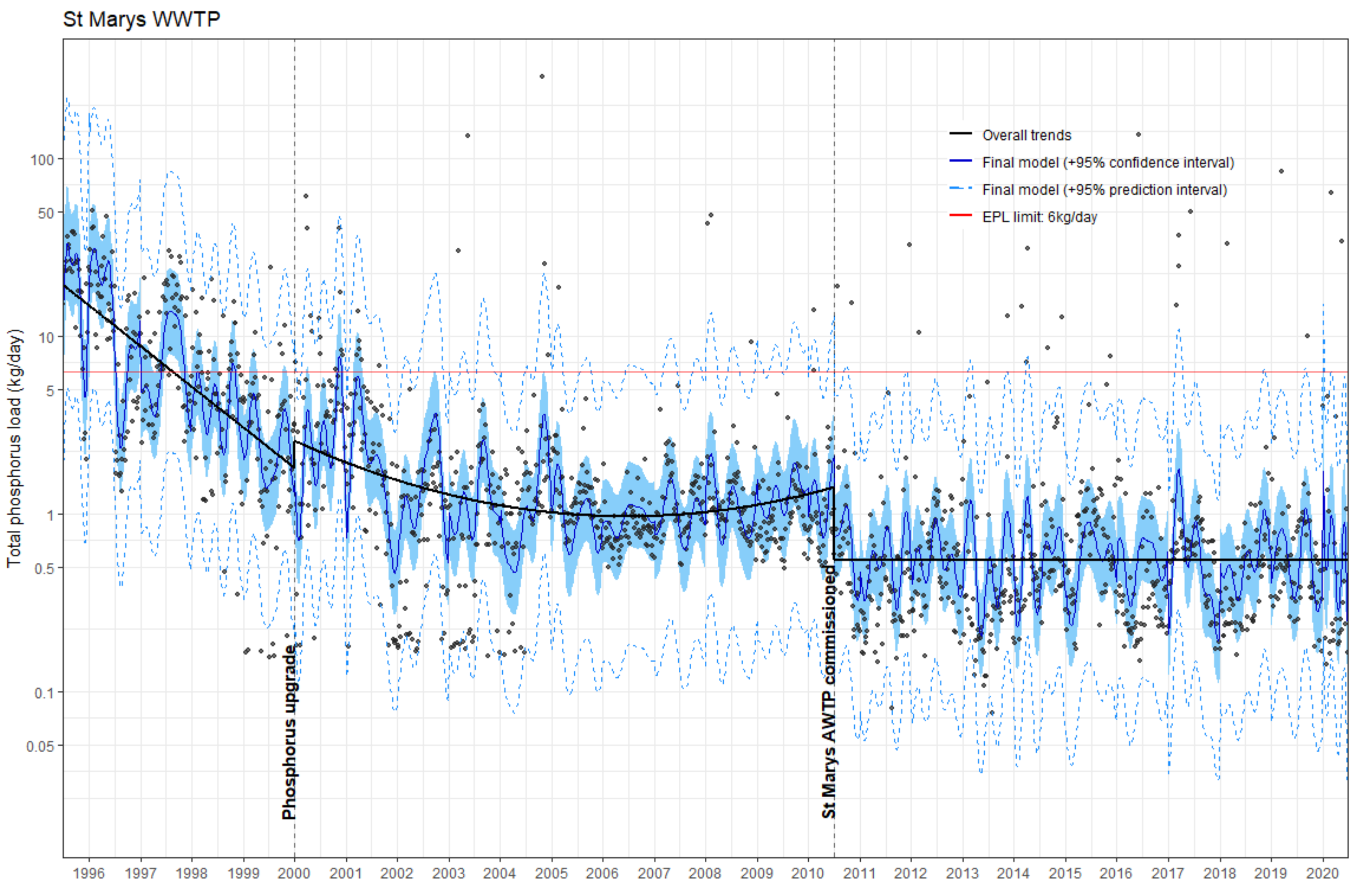

Figure 4-35 St Marys WWTP total phosphorus load: fitting terms to model interventions, linear and quadratic trends within each period and seasonal trends overlaid with the trends in each period

All terms in the final, reduced model had a p-value for the corresponding type I SS <0.15. Each term in the model also had a p value of similar magnitude after adjusting for all other terms in the model (type III SS) supporting the idea that each explanatory variable in the model independently explains some of the variation across the series of data.

The model fitted the data well (R^2=0.60 and adjusted R^2=0.55) except for those at extremely high loads and to a lesser extent, those at extremely low loads. Three values showed a high leverage (ie terms in the model are included because of their contribution to the variability in the data). The distribution of the residuals was approximately Normal with two extreme outliers and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

Key outcomes

- Total phosphorus load:
  - The final reduced model fitted well with R^2=0.60 and adjusted R^2=0.55. The residual plots showed the model did not capture the extremely high and low total phosphorus loads.
  - Since the phosphorus upgrade in 2000, the majority of total phosphorus records were less than the current combined EPL limit of South Creek WWTPs (6.3 kg/day)
- Long term trends:
  - Prior to the phosphorus upgrade at St Marys WWTP (period 1), there was a significant linear decrease in TP load.
  - After the phosphorus upgrade at St Marys WWTP and before the commissioning of St Marys AWTP (period 2), TP load decreased until around 2006-07 before gradually increasing
  - After commissioning of St Marys AWTP (period 3), the total phosphorus load trend was stable
  - As of mid-2020, there was no trend in TP load, with the load varying around its geometric mean level of 0.54 kg/day.
- Seasonal trends:
  - First, second and third order sine and cosine terms by year interactions were included to capture a more complex pattern of three peaks per year, capturing the largest one in February and two smaller ones in late May/ early June and September. The lowest trough was around late October/ early November. The magnitude of the peaks and troughs differed between years.
- After adjusting for seasonal trends, the modelled geometric mean total phosphorus load:
  - Prior to the phosphorus at St Marys WWTP (period 1) was 5.89 kg/day (95% CI = 5.26 to 6.60 kg/day)
  - After the phosphorus upgrade and before the commissioning of the St Marys AWTP (period 2) was 0.96 kg/day (95% CI = 0.87 to 1.07 kg/day)
  - After commissioning of the St Marys AWTP (period 3) was 0.54 kg/day (95% CI = 0.50 to 0.58 kg/day)
- Comparing the modelled geometric mean total phosphorus loads between periods:
  - The geometric mean for the period between the phosphorus upgrade and commissioning of St Marys AWTP (period 2) was 16% (95% CI = 14 to 19%) of the geometric mean for the period prior to the phosphorus upgrade at St Marys WWTP (period 1)

- The geometric mean after the commissioning of St Marys AWTP (period 3) was 56% (95% CI = 50 to 64%) of the geometric mean for the period between the phosphorus upgrade at St Marys WWTP and commissioning of St Marys AWTP (period 2).

4.3.14 Quakers Hill WWTP – Total phosphorus load

There were 1529 total phosphorus load records in the Quakers Hill WWTP data series. There were 214 records prior to the phosphorus upgrade in 1999 (period 1), 706 records after the phosphorus upgrade and before the commissioning of St Marys AWTP in 2010 (period 2) and 609 records after the commissioning of St Marys AWTP (period 3). All records are included in the analyses. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included the three periods defined by the phosphorus upgrade and commissioning of the St Marys AWTP, linear and quadratic trends within each period and 1st, 2nd and 3rd order harmonic interaction terms to model the seasonal trends.

The model:

Log_{10}(TP load) = period + linear trend in period 1 + linear trend in period 2 + linear trend in period 3 + quadratic trend in period 1 + quadratic trend in period 2 + quadratic trend in period 3 + 1st order sine + 1st order cosine + 2nd order sine + 2nd order cosine + 3rd order sine + 3rd order cosine + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

period and year are categorical factors.

Model reduction decisions:

- Period 1 and 3: retain the linear and quadratic trend terms (all p-values from the type I SS were < 0.15)
- Period 2: remove the quadratic trend term (p-value from the type I SS was >0.15)
- Retain all harmonic by year interaction terms as the p-values for the 3rd order terms from the type I SS were <0.15
- Remove the main effect harmonic terms since they can be included in the harmonic interaction terms.

Step 2: Fit the final, reduced model

Log_{10}(TP load) = period + linear trend in period 1 + linear trend in period 2 + linear trend in period 3 + quadratic trend in period 1 + quadratic trend in period 3 + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

period and year are categorical factors.

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-36.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix H). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table H-25 and Table H-26, respectively. The residual plots for this model are shown in Figure H-13.

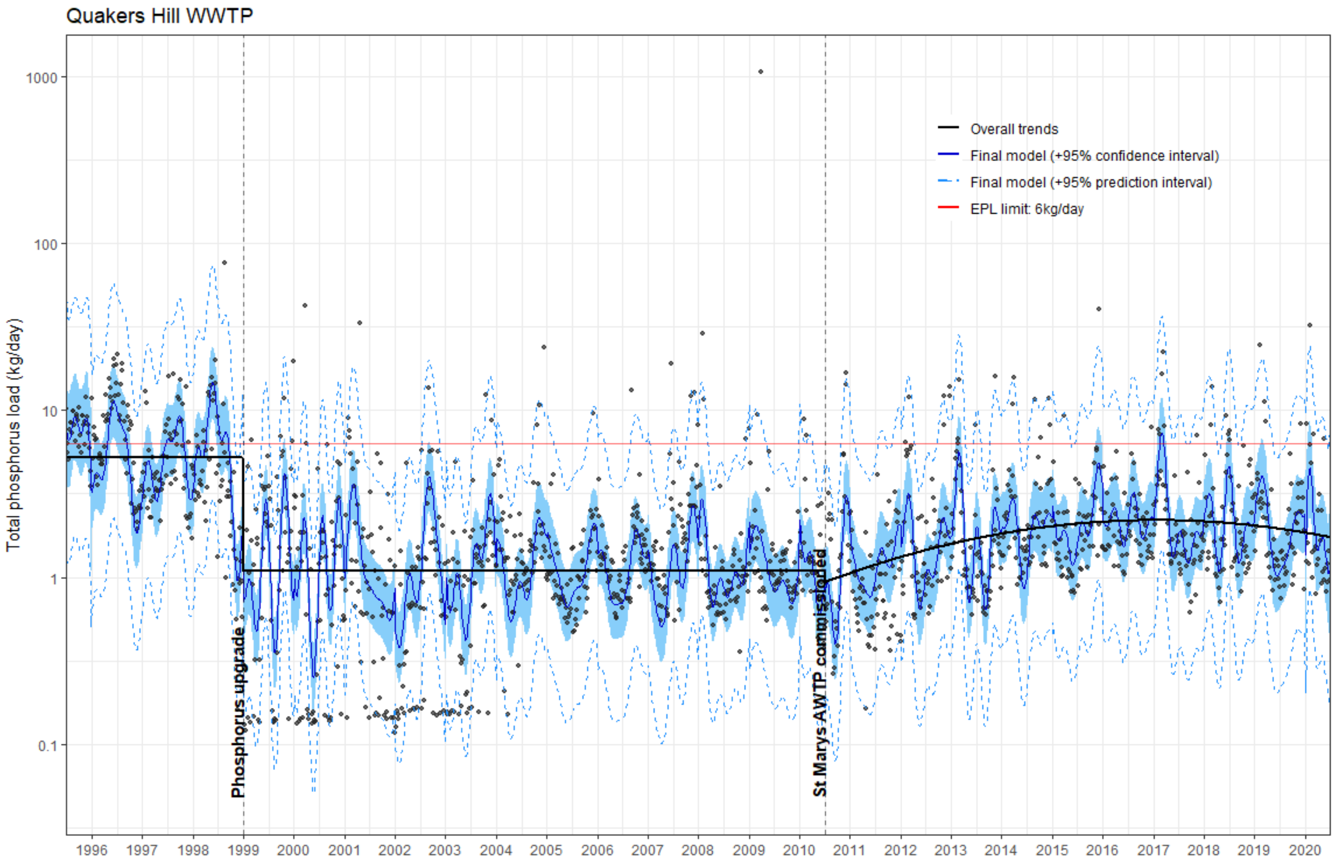

Figure 4-36 Quakers Hill WWTP total phosphorus load: fitting terms to model interventions, linear and quadratic trends within each period and seasonal trends overlaid with the trends in each period

All terms in the final, reduced model had a p-value for the corresponding type I SS <0.15. Each term in the model had a similar p-value after adjusting for all other terms in the model (type III SS). This suggested that, each term in the model was independently explaining some of the variation in the data.

The model fitted the data well (R^2=0.51 and adjusted R^2=0.46) except for those at extremely high loads and to a lesser extent, those at the extremely low loads. Three values showed a high leverage (ie terms in the model are included because of their contribution to the variability in the data). The distribution of the residuals was approximately Normal with a slightly long tail reflecting the very high loads. Plots also showed the pattern for loads at the quantification limit, mainly from 1999 through to 2004. Residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

Key outcomes

- Total phosphorus load:
  - Since the phosphorus upgrade in 2000, the majority of total phosphorus load records were less than the current combined EPL limit of South Creek WWTPs (6.3 kg/day)
  - The final reduced model fitted well with R^2=0.51 and adjusted R^2=0.46. However, the residual plots showed the model did not capture the extremely high total phosphorus loads, and to a lesser extent, the extremely low loads.
- Long term trends:
  - Prior to the phosphorus upgrade (period 1) there was a significant decreasing curvilinear trend. The trend also appears to be explained by the different seasonal trends each year.
  - After the phosphorus upgrade and prior to commissioning St Marys AWTP (period 2), there was an immediate reduction in total phosphorus load before increasing linearly until the end of the period
  - Commissioning of St Marys AWTP saw an immediate decrease in total phosphorus load that was gradually increasing until approximately 2017 when the load is now decreasing
  - As of mid-2020, the total phosphorus load from Quakers Hill WWTP was decreasing but had not reached the levels immediately after commissioning of the AWTP.
- Seasonal trends:
  - First, second and third order sine and cosine terms by year interactions were included to capture a more complex pattern of three peaks per year, capturing the largest one in February and two smaller ones in late May/early June and September. The lowest trough was around late October/early November. The magnitude of the peaks and troughs differed between years.
- After adjusting for seasonal trends, the modelled geometric mean total phosphorus load:
  - Prior to the phosphorus upgrade (period 1) was 5.31 kg/day (4.38 to 6.41 kg/day)
  - After the phosphorus upgrade and prior to commissioning of St Marys AWTP (period 2) was 1.11 kg/day (95% CI =1.05 to 1.17 kg/day)
  - after the commissioning of St Marys AWTP (period 3) was 2.10 kg/day (95% CI = 1.91 to 2.31 kg/day)
- Comparing the modelled geometric mean total phosphorus loads between periods:
  - The geometric mean for the period after the phosphorus upgrade and prior to the commissioning of St Marys AWTP (period 2) was 21% (95% CI = 17 to 25%) of the geometric mean for the period prior to the phosphorus upgrade (period 1).

- The geometric mean for the period after commissioning of St Marys AWTP (period 3) was 189% (95% CI = 170 to 212%) of the geometric mean for the period prior to the commissioning (period 2)

4.3.15 Riverstone WWTP – Total phosphorus load

There were 1524 total phosphorus load records in the Riverstone WWTP data series. There were 275 records prior to the first phosphorus upgrade in 2000 (period 1), 640 after the upgrade and before Riverstone WWTP reached capacity/increased discharge (period 2), 529 after Riverstone WWTP reached capacity/increased discharge and before the second phosphorus upgrade (period 3) and 80 after the second phosphorus upgrade (period 4). All records are included in the analyses. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included the four periods defined by two phosphorus upgrades and Riverstone WWTP reaching design capacity/increasing discharge, linear and quadratic trends within each period and 1st, 2nd and 3rd order harmonic interaction terms to model the seasonal trends.

The model:

Log_{10}(TP load) = period + linear trend in period 1 + linear trend in period 2 + linear trend in period 3 + linear trend in period 4 + quadratic trend in period 1 + quadratic trend in period 2 + quadratic trend in period 3 + quadratic trend in period 4 + 1st order sine + 1st order cosine + 2nd order sine + 2nd order cosine + 3rd order sine + 3rd order cosine + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

period and year are categorical factors.

Model reduction decisions:

- Periods 1, 2 and 3: retain the linear and quadratic trend terms as the p-values for the quadratic terms using the type I SS were <0.15
- Period 4: remove the linear and quadratic trends as both p-values for the type I SS were >0.15
- Retain all harmonic interaction terms as the p-values for the 3rd order terms from the type I SS were <0.15
- Remove the main effect harmonic terms since they can be included in the harmonic interaction terms.

Step 2: Fit the final, reduced model

Log_{10}(TP load) = period + linear trend in period 1 + linear trend in period 2 + linear trend in period 3 + quadratic trend in period 1 + quadratic trend in period 2 + quadratic trend in period 3 + 1st order sine by Year + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

period and year are categorical factors.

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-37.

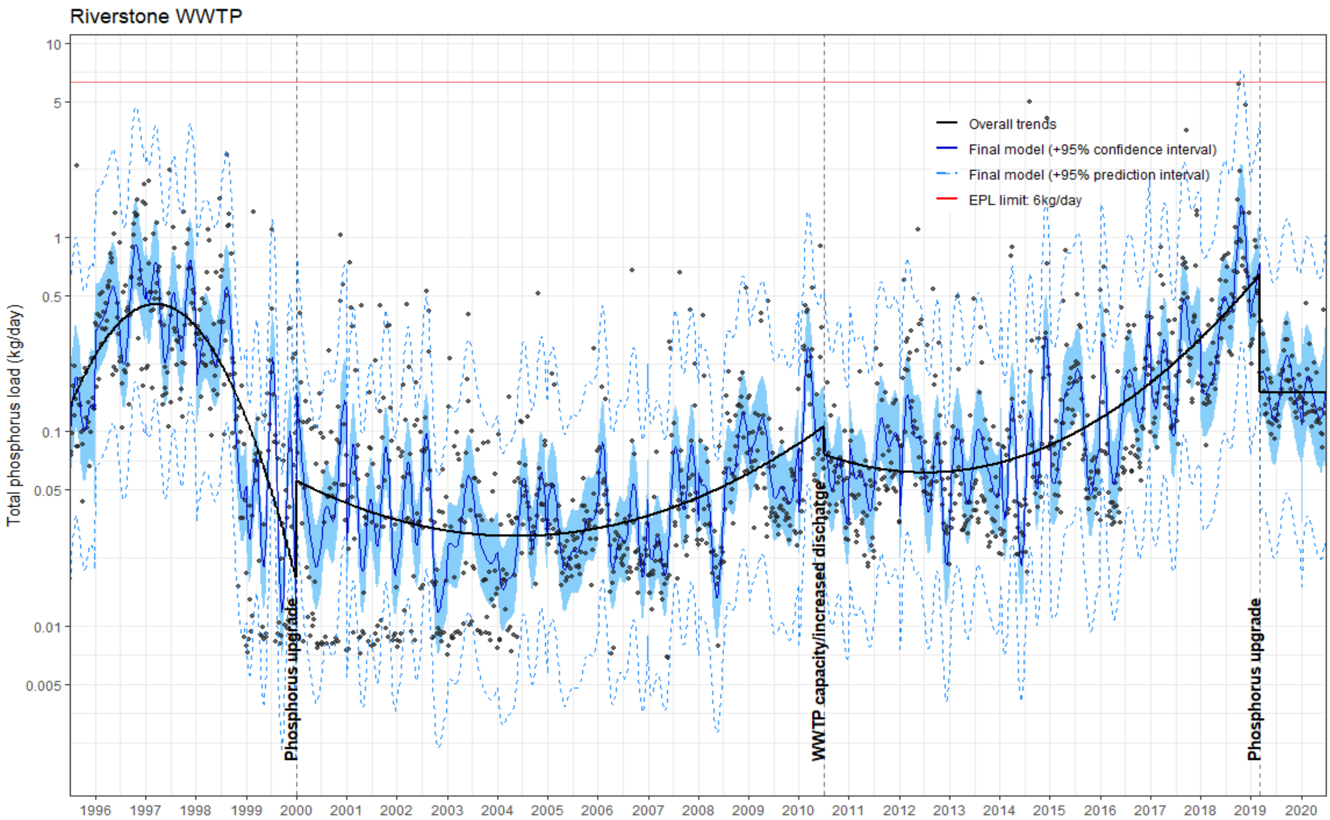

Figure 4-37 Riverstone WWTP total phosphorus load: fitting terms to model interventions, linear and quadratic trends within each period and seasonal trends overlaid with the trends in each period

The detailed statistical outcomes of this model are included in Volume 2 (Appendix H). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table H-27 and Table H-28, respectively. The residual plots for this model are shown in Figure H-14.

All terms in the final, reduced model had a p-value for the corresponding type I SS <0.15. Each term in the model also had a type III SS p-value of similar magnitude except for the linear and quadratic terms in period 3. This suggested that, the linear trend in period 3 was explained by other terms in the model such as the annual increases captured by the harmonic interaction terms.

The model fitted the data well (R^2=0.65 and adjusted R^2=0.60) except for those at extremely high loads. Four values showed a high leverage (ie terms in the model are included because of their contribution to the variability in the data). The distribution of the residuals was approximately Normal and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

Key outcomes

- Total phosphorus load:
    - The final reduced model fitted well with R^2=0.65 and adjusted R^2=0.60. The residual plots showed the model did not capture the extremely high total phosphorus loads.
    - All total phosphorus load records were less than the current combined EPL limit of South Creek WWTPs (6.3 kg/day)
- Long term trends:
    - Different curvilinear trends were observed in the three periods prior to the second phosphorus upgrade at Riverstone WWTP
        - Prior to the first phosphorus upgrade (period 1) the total phosphorus load was increasing up to approximately mid-1997 before decreasing sharply.
        - After the first phosphorus upgrade and prior to Riverstone WWTP reaching capacity/increased discharge (period 2) there was a decreasing trend to approximately 2004-05 before the load started to increase.
        - After Riverstone WWTP reached capacity and increased discharge (period 3), there was a linear increase in total phosphorus load.
        - After the second nitrogen upgrade, (period 4) there was no trend apparent in the series, partly due to the very short time scale.
- Seasonal trends:
    - First, second and third order sine and cosine terms by year interactions were included to capture a more complex pattern of three peaks per year, capturing the largest one in February and two smaller ones in late May/early June and September. The lowest trough was around late October/early November. The magnitude of the peaks and troughs differed between years.
- After adjusting for seasonal trends, the modelled geometric mean total phosphorus load:
    - for period 1 before the phosphorus upgrade was 0.402 kg/day (95% CI = 0.343 to 0.473 kg/day)
    - for period 2 after the phosphorus upgrade was 0.030 kg/day (95% CI = 0.027 to 0.033 kg/day)
    - for period 3 after Riverstone WWTP reached capacity/increased discharge was 0.082 kg/day (95% CI = 0.074 to 0.091 kg/day)
    - for period 4 after the second phosphorus upgrade was 0.164 kg/day (95% CI = 0.129 to 0.208 kg/day).

- Comparing the modelled geometric mean total phosphorus loads between periods:
  - The geometric mean for the period between the first phosphorus upgrade and Riverstone WWTP reached capacity/increased discharge (period 2) was 8% (95% CI = 6 to 9%) of the geometric mean for the period prior to the first phosphorus upgrade (period 1)
  - The geometric mean after the Riverstone WWTP reached capacity/increased discharge and before the second phosphorus upgrade (period 3) was 270% (95% CI = 234 to 331%) of the geometric mean for the period between the first phosphorus upgrade and Riverstone WWTP reached capacity/increased discharge (period 2)
  - The geometric mean after the second phosphorus upgrade (period 4) was 200% (95% CI = 155 to 258%) of the geometric mean for the period after the increased capacity and before the phosphorus upgrade (ie period 3).

4.3.16 Richmond WWTP – Total phosphorus load

There were 1063 total phosphorus load records in the Richmond WWTP data series. There were 428 records prior to the increase in recycled water use in mid-2000 (period 1), 22 records after the increase in recycled water use and before the phosphorus upgrade (period 2), and 613 records after the phosphorus upgrade (period 3). Due to the large differences in the number of load samples, the analysis was restricted to records from 2007 onwards (N=445 records). Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fit the full model to the data from 2007 onwards, linear and quadratic trends and 1st, 2nd and 3rd order harmonic interaction terms to model the seasonal trends.

The model:

Log_{10}(TN load) = linear trend + quadratic trend + 1st order sine + 1st order cosine + 2nd order sine + 2nd order cosine + 3rd order sine + 3rd order cosine + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

year is a categorical factor.

Model reduction decisions:

- Retain the linear and quadratic trend terms as the p-values for the quadratic terms using the type I SS were <0.15
- Retain all harmonic interaction terms as the p-values for the 3rd order terms from the type I SS were <0.15
- Remove the main effect harmonic terms since they can be included in the harmonic interaction terms.

Step 2: Fit the final, reduced model

Log_{10}(TN load) = linear trend + quadratic trend + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

year is a categorical factors.

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-38. All data not fitted in the model are also shown.

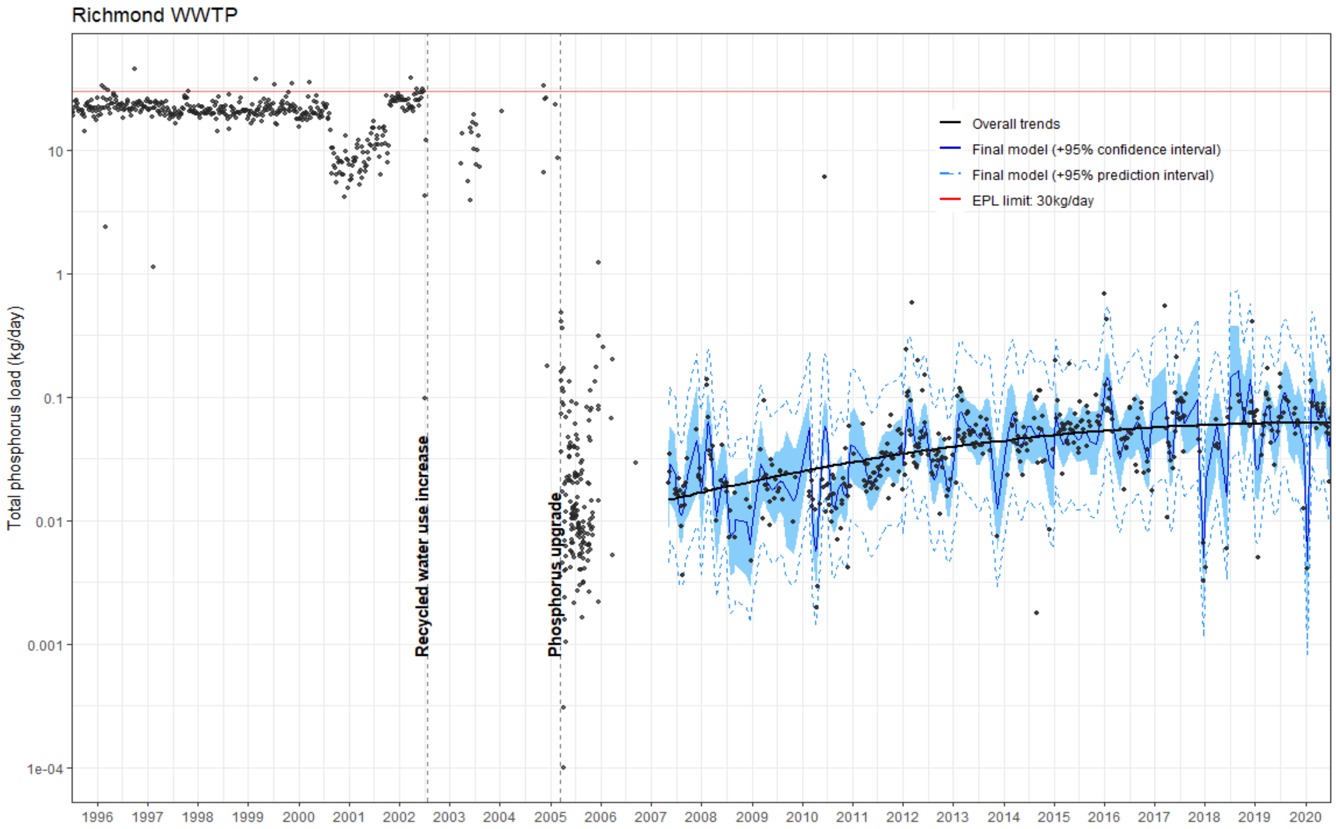

Figure 4-38 Richmond WWTP total phosphorus load: fitting terms to model linear and quadratic trends in the latest period and seasonal trends overlaid with the trends

The detailed statistical outcomes of this model are included in Volume 2 (Appendix H). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table H-29 and Table H-30, respectively. The residual plots for this model are shown in Figure H-15.

All terms in the final, reduced model had a p-value for the corresponding type I SS <0.15. All terms also had p-values <0.15 after adjusting for all other terms in the model (type III SS) suggesting they explained different parts of the variation in the data.

The model fitted the data well (R^2=0.55 and adjusted R^2=0.44) except for those at extremely high and low loads. A few values showed a high leverage (ie terms in the model are included because of their contribution to the variability in the data). The distribution of the residuals was approximately Normal with one extremely low load from 2014 with a very small estimated residual value and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

Key outcomes

- Total phosphorus load:
  - Since 2005, all total phosphorus load records were below the current EPL limit of 29.8 kg/day.
  - The final reduced model fitted well with R^2=0.55 and adjusted R^2=0.44. The Normal Q-Q plot showed the model did not capture the extremely high and low total phosphorus loads. The distribution of residuals was approximately Normal with one extreme value.
- Long term trends:
  - Total phosphorus load gradually increased until around 2016 when load started to plateau and curve downwards slightly
  - As of mid-2020 the trend in total phosphorus load from Richmond WWTP was curving downwards slightly.
- Seasonal trends:
  - First, second and third order sine and cosine terms by year interactions were included to capture a more complex pattern of three peaks per year, capturing the largest one in February and two smaller ones in late May/early June and September. The lowest trough was around late October/early November. The magnitude of the peaks and troughs differed between years.
- After adjusting for seasonal trends, the modelled geometric mean total phosphorus load:
  - The geometric mean total phosphorus load was 0.044 kg/day (95% CI = 0.039 to 0.049 kg/day)

4.3.17 Hawkesbury River at Wilberforce (N35) – Total phosphorus concentration

There were 439 total phosphorus concentration records from the Hawkesbury River at Wilberforce (N35) in the data series. All records are included in the analysis. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included TP concentration at the upstream site N39, the flow at N39, the flow in South and Eastern creeks, Riverstone WWTP TP load, St Marys WWTP TP load, Quakers Hill WWTP TP load, the five periods defined by the phosphorus upgrades at St Marys and Riverstone

WWTPs, the phosphorus upgrade at Richmond WWTP, commissioning of St Marys AWTP and the phosphorus upgrade at Riverstone WWTP, linear and quadratic trends within each period and 1st, 2nd and 3rd order harmonic interaction terms to model the seasonal trends. Note, Richmond WWTP data was excluded from the analysis dataset as there were large gaps in the Richmond WWTP data series.

The model:

Log_{10}(N35 TP concentration) = log_{10}(N39 TP concentration) + log_{10}(flow at N39) + log_{10}(Combined flow from South and Eastern Creeks) + log_{10}(lag 1 (Quakers Hill WWTP TP load)) + log_{10}(lag 1 (St Marys WWTP TP load)) + log_{10}(lag 1 (Riverstone WWTP TP load)) + period + linear trend in period 1 + linear trend in period 2 + linear trend in period 3 + linear trend in period 4 + linear trend in period 5 + quadratic trend in period 1 + quadratic trend in period 2 + quadratic trend in period 3 + quadratic trend in period 4 + quadratic trend in period 5 + 1st order sine + 1st order cosine + 2nd order sine + 2nd order cosine + 3rd order sine + 3rd order cosine + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

- period and year are categorical factors.
- Flow at N39 is derived as described in Volume 2: Appendix E (Table E-5)
- Lag 1 for the loads from the WWTPs are loads estimated on the day before the sampling dates at N35.

Model reduction decisions:

- Remove linear and quadratic trends in periods 2, 3 and 5 as all type I SS had p-values >0.15
- Retain only 1st order harmonic interaction terms. Even though the 2nd and 3rd order harmonic interaction terms were included based on the p-value cut-off, these terms only captured the unusual patterns in 2013, 2014 and 2020. Due to the small number of records and the risk of overfitting, these terms were excluded.
- Remove the main effect harmonic terms since they can be included in the harmonic interaction terms.

Step 2: Fit the final, reduced model

Log_{10}(N35 TP concentration) = log_{10}(N39 TP concentration) + log_{10}(flow at N39) + log_{10}(Combined flow from South and Eastern Creeks) + log_{10}(lag 1 (Quakers Hill WWTP TP load)) + log_{10}(lag 1 (St Marys WWTP TP load)) + log_{10}(lag 1 (Riverstone WWTP TP load)) + period + linear trend in period 1 + linear trend in period 4 + quadratic trend in period 1 + quadratic trend in period 4 + 1st order sine by year + 1st order cosine by year

Where:

- period and year are categorical factors.

- Flow at N39 is derived as described in Volume 2: Appendix E (Table E-5)
- Lag 1 for the loads from the WWTPs are loads estimated on the day before the sampling dates at N35.

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-39.

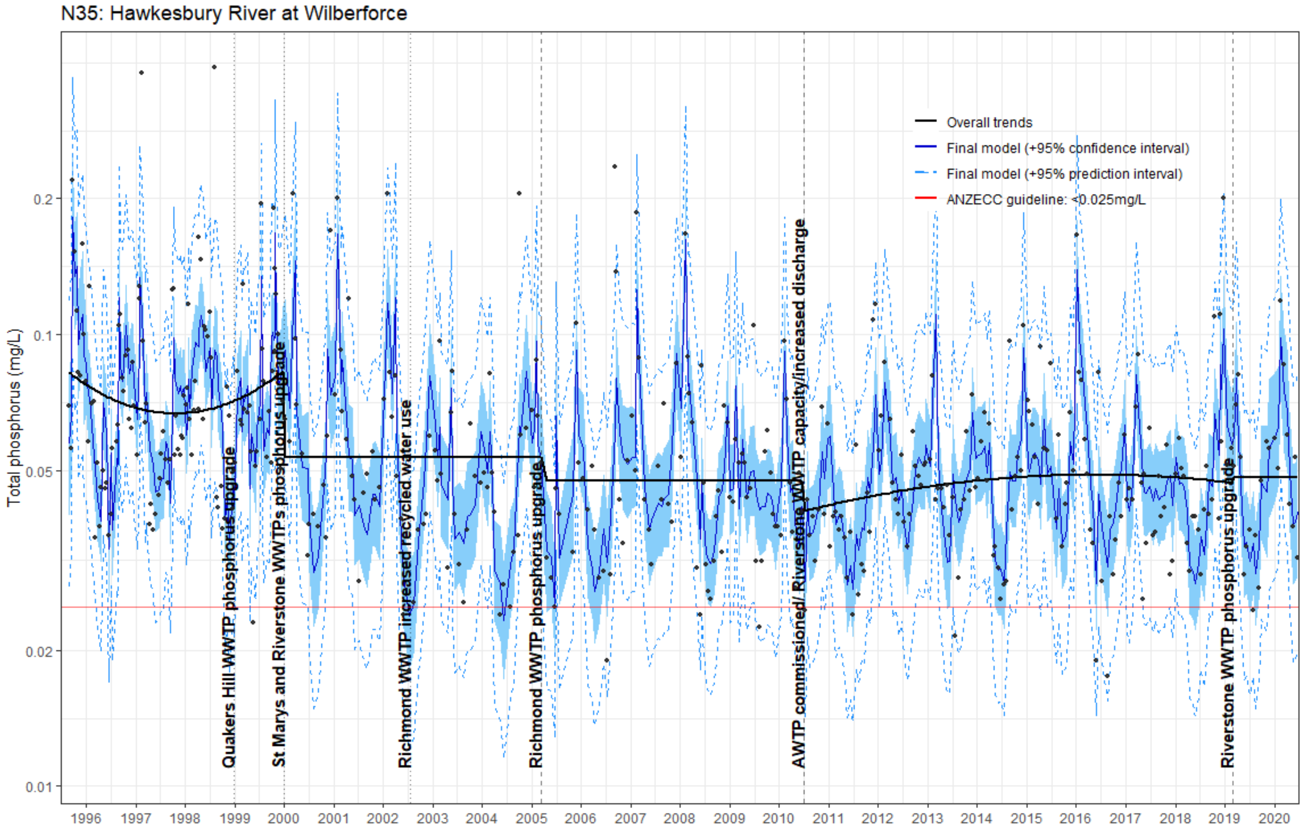

Figure 4-39 Total phosphorus concentrations at Wilberforce Hawkesbury River (N35): fitting terms to model upstream concentration, upstream river flow, South Creek flow, TP loads from St Marys, Quakers Hill, Riverstone and Richmond WWTPs, along with linear and quadratic trends and seasonal trends overlaid with the trends in each period

The detailed statistical outcomes of this model are included in Volume 2 (Appendix H). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table H-31 and Table H-32, respectively. The residual plots for this model are shown in Figure H-16.

The period parameter as well as the upstream concentration at N39, flow corresponding to N39 and the three WWTPs TN load estimates and period effect were retained in the model as part of the study design. The p-values corresponding to the Type III SS varied compared with the type I SS. The quadratic trends in period 4 have type III SS p-values >0.4, suggesting that the harmonic interaction terms accounted for these trends. The TP loads from Riverstone WWTP were significantly correlated to TN concentrations at N35 via the sequential type I SS and were not correlated after adjusting for St Marys and Quakers Hill WWTP loads. Loads from Quakers Hill WWTP are also less significantly correlated to N35 concentrations after adjusting for loads from St Marys WWTP.

The model fitted the data well (R^2=0.63 and adjusted R^2=0.56) except for those at extremely high and low concentrations. There were a few records with high leverage. The distribution of the residuals was approximately Normal and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

Key outcomes

- Total phosphorus concentration:
    - TP concentrations are above the ANZG default level of <0.025 mg/L
    - The final reduced model fitted well with R^2=0.63 and adjusted R^2=0.56. The residual plots showed the model did not capture the extremely high or low total phosphorus concentrations.
- Impact of upstream catchment and tributary:
    - TP concentration at N39 was significantly correlated to the concentration at N35 ($p<0.0001$).
        - when TP concentration at N39 is low eg 0.01 mg/L, a 0.005 mg/L increase of TP concentration increased the concentration at N35 by 8.9%
        - when TP concentration at N39 is moderate eg 0.02 mg/L, a 0.005 mg/L increase in concentration increased the concentration at N35 by 4.8%
        - when TP concentration at N39 is high eg 0.03 mg/L, a 0.005 mg/L increase in concentration increased the concentration at N35 by 3.3%.
    - Flow in the Nepean River at N39 was significantly correlated to the concentration of TP at N35 ($p<0.0001$).
        - when flow at N39 is low eg 850 ML/day, a 100 ML increase in flow increased the concentration at N35 by 1.2%
        - when flow at N39 is moderate eg 1150 ML/day, a 100 ML increase in flow increased the concentration at N35 by 0.9%
        - when flow at N39 is high eg 1550 ML/day, a 100 ML increase in flow increased the concentration at N35 by 0.7%.
    - Flow in South and Eastern creeks was significantly correlated to concentration of TP at N35 ($p=0.003$ after adjusting for the upper catchment variables and $p=0.05$ after adjusting for all terms in the model).
        - when flow in the tributary is low eg 100 ML/day, a 50 ML increase in flow increased the concentration at N35 by 1.2%

- when flow at N39 is moderate eg 250 ML/day, a 50 ML increase in flow increased the concentration at N35 by 0.4%
- when flow at N39 is high eg 400 ML/day, a 50 ML increase in flow increased the concentration at N35 by 0.2%.

- Impact of WWTPs:
  - The TP load from Riverstone WWTP was significantly correlated to the concentration of TP at N35 when adjusted only for upstream catchment measures (p<0.0001) but was not significantly correlated after adjusting for all variables in the model (p=0.1). The load from Riverstone WWTPs had no impact after accounting for the effect of WWTPs with larger discharges.
    - when the load from Riverstone WWTP is low eg 0.15 kg/day, a 0.05 kg/day increase in load increased the concentration at N35 by 1.0%
    - when the load from Riverstone WWTP is moderate eg 0.25 kg/day, a 0.05 kg/day increase in load increased the concentration at N35 by 0.6%
    - when the load from Riverstone WWTP is high eg 0.5 kg/day, a 10 kg/day increase in load increased the concentration at N35 by 0.3%.
  - The TP load from St Marys WWTP was significantly correlated to the concentration of TP at N35 when adjusted only for upstream catchment measures and Riverstone WWTP load (p<0.0001) and was not significantly correlated after adjusting for all variables in the model (p=0.14). This could be due to the TP load from Quakers Hill WWTP. Once this is taken into account, the load from St Marys WWTP does not add to the explanation of the variability in the data.
    - when the load from St Marys WWTP is low eg 0.3 kg/day, a 0.1 kg/day increase in load increased the concentration at N35 by 0.9%
    - when the load from St Marys WWTP is moderate eg0.5 kg/day, a 0.1 kg/day increase in load increased the concentration at N35 by 0.5%
    - when the load from St Marys WWTP is high eg 1 kg/day, a 0.1 kg/day increase in load increased the concentration at N35 by 0.3%.
  - The TP load from Quakers Hill WWTP was significantly correlated to the concentration of TP at N35 when adjusted for upstream catchment measures and Riverstone and St Marys WWTP loads (p=<0.0001) and after adjusting for all variables in the model (p=0.05).
    - when the load from Quakers Hill WWTP is low eg 0.8 kg/day, a 0.1 kg/day increase in load increased the concentration at N35 by 0.5%
    - when the load from Quakers Hill WWTP is moderate eg 2.5 kg/day, a 0.1 kg/day increase in load increased the concentration at N35 by 0.2% and
    - when the load from Quakers Hill WWTP is high eg 8 kg/day, a 0.1 kg/day increase in load increased the concentration at N35 by 0.1%.

- Long term trends:
  - In period 1 before the St Marys and Riverstone WWTPs phosphorus upgrade the trend in total phosphorus concentration decreased until approximately 1998 before increasing to the end of the period
  - In period 2 after St Marys and Riverstone WWTP phosphorus upgrade and before Richmond WWTP phosphorus upgrade there was no trend, only a seasonal trend.
  - In period 3 after Richmond WWTP phosphorus upgrade and before St Marys AWTP commissioned and Riverstone WWTP reached capacity/increased discharge there was no trend.
  - In period 4 after St Marys AWTP commissioned and Riverstone WWTP reached capacity/increased discharge and before Riverstone WWTP phosphorus upgrade the trend in total phosphorus concentration curved upwards to approximately 2015 before flattening out or curved slightly downwards
  - In period 5, after Riverstone WWTP's phosphorus upgrade there was no trend.
- Seasonal trends:
  - First order sine and cosine terms by year interactions were included to capture a pattern of one peak per year in February and one trough around August with a magnitude that differed between years.
- After adjusting for seasonal trends, flow and concentration at the upstream site, flow from the tributary and load from the four WWTPs, the modelled geometric mean total phosphorus concentration:
  - In period 1 before St Marys and Riverstone WWTPs phosphorus upgrade was 0.084 mg/L (95% CI = 0.076 to 0.094 mg/L)
  - In period 2 after St Marys and Riverstone WWTP phosphorus upgrade and before Richmond WWTP phosphorus upgrade was 0.068 mg/L (95% CI = 0.061 to 0.075 mg/L).
  - In period 3 after Richmond WWTP phosphorus upgrade and before St Marys AWTP commissioned and Riverstone WWTP reached capacity/increased discharge was 0.059 mg/L (95% CI = 0.054 to 0.064 mg/L)
  - In period 4 after St Marys AWTP commissioned and Riverstone WWTP reached capacity/increased discharge and before Riverstone WWTP phosphorus upgrade was 0.054 mg/L (95% CI = 0.049 to 0.060 mg/L)
  - In period 5, after Riverstone WWTP's phosphorus upgrade was 0.060 mg/L (95% CI = 0.050 to 0.072 mg/L).
- Comparing the modelled geometric mean total phosphorus concentration between periods:
  - The geometric mean for the period after the phosphorus upgrades at St Marys and Riverstone WWTPs (period 2) was 80% (95% CI = 70 to 92%) of the period prior to these upgrades (period 1)

- The geometric mean for the period after the Richmond WWTP phosphorus upgrade (period 3) was 87% (95% CI = 78 to 97%) of the period before the phosphorus upgrade at Richmond WWTP (period 2)
- The geometric mean for the period after commissioning St Marys (period 4) was 92% (95% CI = 82 to 103%) of the period before the commissioning of St Marys AWTP (period 3)
- The geometric mean for the period after Riverstone WWTPs phosphorus upgrade (period 5) was 112% (95% CI = 91 to 137%) of the geometric mean for the period before the upgrade (period 4)

4.3.18 Hawkesbury River at Wilberforce (N35) and Freemans Reach (N39) – Total phosphorus concentration (downstream/upstream)

There were no total phosphorus concentration records from 2002 to mid-2008 at the tributary site of NS04A. The analysis models include data from 2008 ie 639 records in total, 216 from N35 and 208 from NS04A and 215 from N39. However, the data prior to this time are plotted for completeness. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included a factor for site identifier for the upstream site, tributary site and downstream site, site by flow interaction term to allow the relationship with flow to differ between sites, a site by period interaction term to allow the site means to differ in each of the three periods defined as before the commissioning of St Marys AWTP and Riverstone WWTP increased capacity (period 3), the period after this point and before Riverstone WWTP phosphorus upgrade (period 4) and the period after the phosphorus upgrade (period 5), interaction terms for site by linear and quadratic trends to allow them to differ within each period and 3-factor interaction terms for site by 1st, 2nd and 3rd order harmonic interaction terms to model the seasonal trends and allow them to differ between sites. Period numbers have been retained as for the analyses of the downstream river sites to avoid confusion.

The model:

Log_{10}(TP concentration) = site (N35, NS04A or N39) + site by flow + site by period + site by linear trend in period 3 + site by linear trend in period 4 + site by linear trend in period 5 + site by quadratic trend in period 3 + site by quadratic trend in period 4 + site by quadratic trend in period 5 + site by 1st order sine by year + site by 1st order cosine by year + site by 2nd order sine by year + site by 2nd order cosine by year + site by 3rd order sine by year + site by 3rd order cosine by year

Where:

- site, period and year are categorical factors.
- Flow consists of the flow corresponding to the site identified in the site variable as defined in Volume 2: Appendix E (Table E-5)

Model reduction decisions:

- Remove all site by 1st, 2nd and 3rd order harmonic by year terms
- Remove quadratic term for period 5

Step 2: Fit the final, reduced model

Log_{10}(TP concentration) = site (N35, NS04A or N39) + site by flow + site by period + site by linear trend in period 3 + site by linear trend in period 4 + site by quadratic trend in period 3 + site by quadratic trend in period 4

Where:

- SITE and PERIOD are categorical factors.
- Flow consists of the flow corresponding to the site identified in the site variable as defined in Volume 2: Appendix E (Table E-5)

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-40.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix H). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table H-33 and Table H-34, respectively. The residual plots for this model are shown in Figure H-17.

The site, site by flow and site by period parameters were retained in the model as they were part of the study design. The p-values corresponding to the Type III SS varied compared with the type I SS. The site by linear trends in periods 3 and 4 have been included in the model because the quadratic terms were significant.

The model fitted the data well (R^2=0.84 and adjusted R^2=0.83) except for those at extremely high concentrations or, to a lesser extent, low concentrations. The leverage plot showed a random scatter. The distribution of the residuals was approximately Normal and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

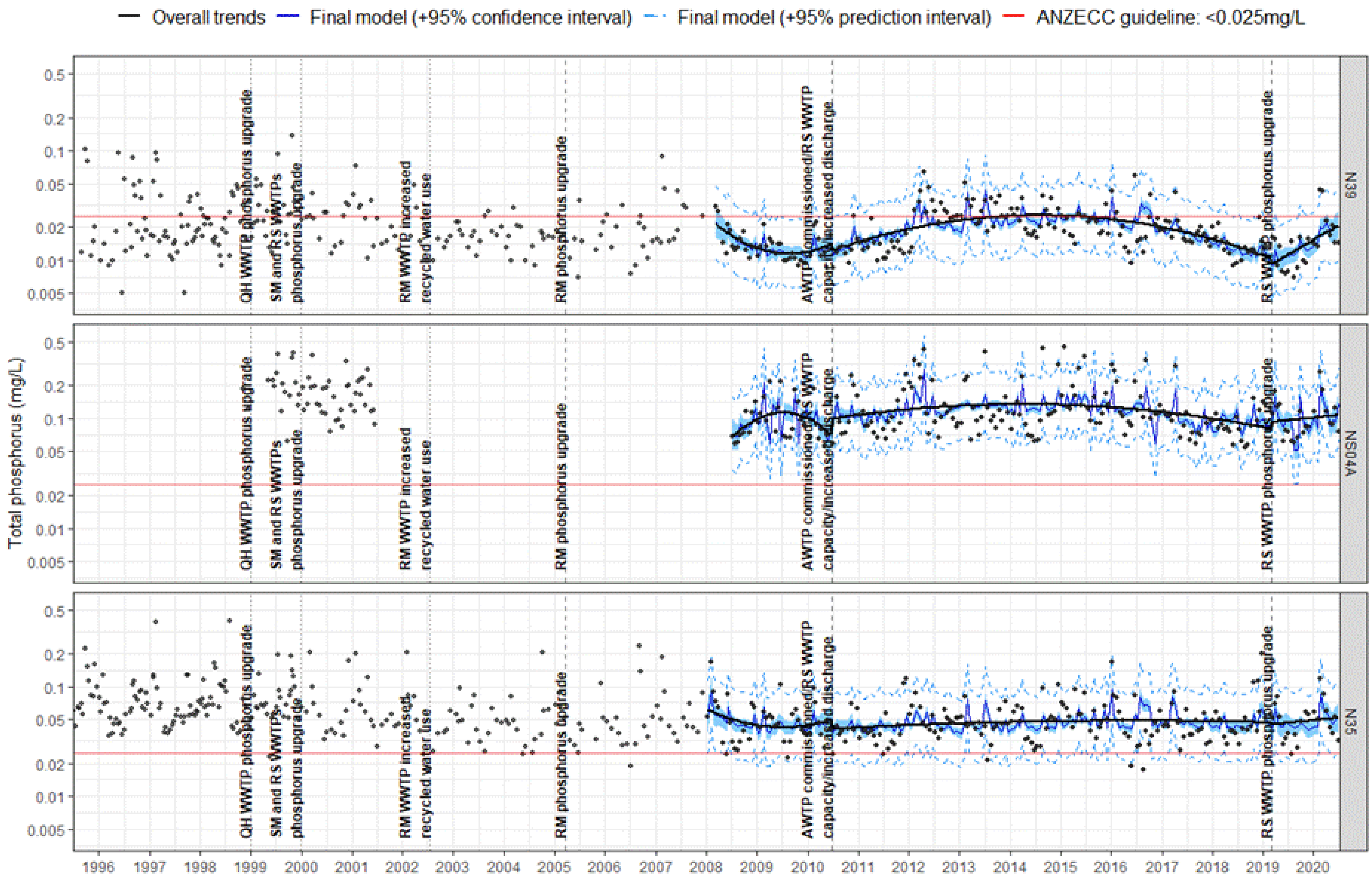

Figure 4-40 Total phosphorus concentrations at Freemans Reach (N39) and Wilberforce (N35), Hawkesbury River and South Creek (NS04A): fitting terms to model site differences and associated flow along with linear and quadratic trends and seasonal trends overlaid with the trends in each period

Key outcomes

- Total phosphorus concentration:
  - The total phosphorus concentration remained above the ANZG default level of <0.025 mg/L for both the downstream site of N35 and the tributary site of NS04A. Most records at the upstream site of N39 were below the guideline.
  - The final reduced model fitted well with R^2=0.84 and adjusted R^2=0.83. The residual plots showed the model did not capture the extremely high total phosphorus concentrations.
- Flow:
  - The interaction between flow and site was significant (p<0.0001).
  - As flow increased, TP increased at all sites (p<0.0001).

    - when flow at N35 is low eg 1000 ML/day, a 100 ML/day increase in flow increased the TP concentration by 1.7%
    - when flow at N35 is moderate eg 1300 ML/day, a 100 ML/day increase in flow increased the concentration at N35 by 1.3%
    - when flow at N35 is high, eg 1600 ML/day, a 100 ML/day increase in flow increased the concentration at N35 by 1.1%.
    - when flow at N39 is low eg 850 ML/day, a 100 ML/day increase in flow increased the TP concentration by 1.8%
    - when flow at N39 is moderate eg 1150 ML/day, a 100 ML/day increase in flow increased the concentration at N39 by 1.3%
    - when flow at N39 is high, eg 1550 ML/day, a 100 ML/day increase in flow increased the concentration at N39 by 1.0%.
    - When flow at NS04A is low eg 100 ML/day, a 10 ML/day increase in flow increased the TP concentration by 1.6%
    - when flow at NS04A is moderate eg 250 ML/day, a 10 ML/day increase in flow increased the concentration at NS04A by 0.7%
    - when flow at NS04A is high, eg 400 ML/day, a 10 ML/day increase in flow increased the concentration at NS04A by 0.4%.
- Long term trends:
  - There was a significant interaction between site and quadratic trends in period 3 (p=0.0009) and between site and quadratic trend in period 4 (p<0.0001). The site by linear terms for period 3 and 4 were included in the model because the quadratic terms were significant. There was an interaction between site and linear trends in period 5 (p=0.08). No interaction term was fitted for quadratic terms in period 5.
  - There was a curvilinear trend at all sites seen in the period before commissioning of St Marys AWTP and Riverstone WWTP reached capacity/increased discharge (period 3) that differed between sites. At the upstream and downstream sites, the total phosphorus concentration decreased until approximately 2009 before increasing. At NS04A, the trend was the opposite with total phosphorus increasing until approximately 2009 before decreasing.
  - After the commissioning of St Marys AWTP and when Riverstone WWTP reached capacity/increased discharge (period 4), there was a slight difference between the curvilinear trends at each site. At the downstream site, the trend in total phosphorus concentration was almost flat, while the tributary and upstream sites showed an increasing trend until approximately 2016 before curving downwards. The trend at the upstream site was more pronounced than the tributary.
  - After the phosphorus upgrade at Riverstone WWTP, the trend at the downstream site and the tributary was relatively flat, but increased at the upstream site.

- As of mid-2020, the trend at the downstream and tributary sites were relatively flat, while the trend at the upstream site was increasing towards the guideline level.

- Seasonal trends:
  - No additional terms were required to assist in capturing any seasonal trends in the data.
- Site by period total phosphorus geometric mean marginal concentrations:
  - There was a significant interaction between site and period ($p<0.0001$).
  - After adjusting for linear and seasonal trends:
    - Prior to commissioning St Marys AWTP and Riverstone WWTP reaching capacity/increasing discharge (period 3), the geometric mean at N35 was 0.047 mg/L (95% CI = 0.040 to 0.056 mg/L), at NS04A was 0.144 mg/L (95% CI = 0.120 to 0.174 mg/L) and at N39 was 0.012 mg/L (95% CI = 0.010 to 0.015 mg/L).
    - After commissioning of St Marys AWTP and Riverstone WWTP reaching capacity/increasing discharge and before the phosphorus upgrade at Riverstone WWTP (period 4), the geometric mean at N35 was 0.052 mg/L (95% CI = 0.048 to 0.057 mg/L) at NS04A was 0.156 mg/L (95% CI = 0.143 to 0.171 mg/L) and at N39 was 0.029 mg/L (95% CI = 0.026 to 0.031 mg/L).
    - After the phosphorus upgrade at Riverstone WWTP (period 5), the geometric mean at N35 was 0.055 mg/L (95% CI = 0.047 to 0.064 mg/L), at NS04A was 0.132 mg/L (95% CI = 0.113 to 0.155 mg/L) and at N39 was 0.014 mg/L (95% CI = 0.013 to 0.017 mg/L).
  - Comparing the modelled geometric mean total phosphorus concentration between sites within periods:
    - The geometric mean for N35 in the period before commissioning St Marys AWTP and Riverstone WWTP reaching capacity/increasing discharge (period 3) was 385% (307 to 484%) of the geometric mean for N39.
    - The geometric mean for N35 in the period before commissioning St Marys AWTP and Riverstone WWTP reaching capacity/increasing discharge (period 3) was 33% (26 to 42%) of the geometric mean for NS04A.
    - The geometric mean for N35 in the period after commissioning St Marys AWTP and Riverstone WWTP reaching capacity/increasing discharge, and the phosphorus at Riverstone WWTP (period 4) was 182% (160 to 206%) of the geometric mean for N39.
    - The geometric mean for N35 in the period after commissioning St Marys AWTP and Riverstone WWTP reaching capacity/increasing discharge, and the phosphorus upgrade at Riverstone WWTP (period 4) was 33% (29 to 38%) of the geometric mean for NS04A.
    - The geometric mean for N35 in the period after the phosphorus upgrade at Riverstone WWTP (period 5) was 380% (308 to 469%) of the geometric mean for N39.
    - The geometric mean for N35 in the period after the phosphorus upgrade at Riverstone WWTP (period 5) was 42% (34 to 52%) of the geometric mean for NS04A.

- Comparing the modelled geometric mean total phosphorus concentration between periods:
  - To reduce output and to place more emphasis on the recent times, no comparisons were undertaken between periods 4 and 3. Note that the confidence intervals are wide due to the small numbers of records in period 5.
  - The geometric mean for the period after the phosphorus upgrade at Riverstone WWTP (period 5) was 106% (95% CI = 89 to 126%) of the geometric mean for the period prior to the upgrade and after the commissioning of St Marys AWTP and Riverstone WWTP reaching capacity/increasing discharge (period 4) at site N35.
  - The geometric mean for the period after the phosphorus upgrade at Riverstone WWTP (period 5) was 85% (95% CI = 71 to 100%) of the geometric mean for the period prior to the upgrade and after the commissioning of St Marys AWTP and Riverstone WWTP reaching capacity/increasing discharge (period 4) at site NS04A.
  - The geometric mean for the period after the phosphorus upgrade at Riverstone WWTP (period 5) was 51% (95% CI = 43 to 60%) of the geometric mean for the period prior to the upgrade and after the commissioning of St Marys AWTP and Riverstone WWTP reaching capacity/increasing discharge (period 4) at site N39.
  - The percentage difference between periods 5 and 4 for the geometric mean concentration at N35 was 209% (95% CI = 164 to 268%) of the percentage difference at N39.
  - The percentage difference between periods 5 and 4 for the geometric mean concentration at N35 was 129% (95% CI = 54 to 305%) of the percentage difference at NS04A.

4.3.19 Hawkesbury River at Wilberforce (N35) – Chlorophyll-*a* concentration

There were 414 Chl-*a* concentration records in the Hawkesbury River at Wilberforce (N35) data series. All records are included in the analyses. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included Chl-*a* concentration at the upstream site N39, the flow at N39, the flow in South and Eastern Creeks, Riverstone WWTP TP and TN loads, St Marys WWTP TP and TN loads, Quakers Hill WWTP TP and TN loads, the five periods defined by the nitrogen and phosphorus upgrades at St Marys and Riverstone WWTPs, the nitrogen and phosphorus upgrade at Richmond WWTP, commissioning of St Marys AWTP and the nitrogen and phosphorus upgrade at Riverstone WWTP, linear and quadratic trends within each period and 1st, 2nd and 3rd order harmonic interaction terms to model the seasonal trends. Note that the aim was to also include TN and TP loads from Richmond WWTP, however, there were large gaps in the Richmond WWTP data series. Hence Richmond WWTP data has been excluded from the analysis dataset.

The model:

Log_{10}(N35 Chl-*a*) = log_{10}(N39 Chl-*a*) + log_{10}(flow at N39) + log_{10}(Combined flow from South and Eastern Creeks) + log_{10}(lag 1 (Quakers Hill WWTP TP load)) + log_{10}(lag 1 (Quakers Hill WWTP TN load)) + log_{10}(lag 1 (St Marys WWTP TP load)) + log_{10}(lag 1 (St Marys WWTP TN load)) + log_{10}(lag 1 (Riverstone WWTP TP load)) + log_{10}(lag 1 (Riverstone WWTP TN load)) + period + linear trend in period 1 + linear trend in period 2 + quadratic trend in period 1 + quadratic trend in period 2 + 1st order sine + 1st order cosine + 2nd order sine + 2nd order cosine + 3rd order sine + 3rd order cosine + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

- period and year are categorical factors.
- Flow at N39 is derived as described in Volume 2: Appendix E (Table E-5)
- Lag 1 for the loads from the WWTPs are loads estimated on the day before the sampling dates at N35.

Model reduction decisions:

- Remove linear and quadratic trends in periods 1 and 2, remove the quadratic trend in period 5 as all type I SS had p-values >0.15
- Retain only 1st order harmonic interaction terms. Even though the 2nd and 3rd order harmonic interaction terms could have been included based on the p-value cut-off, these terms only captured the unusual patterns in 2013, 2014 and 2020. Due to the small number of records and the risk of overfitting, these terms were excluded.
- Remove the main effect harmonic terms since they can be included in the harmonic interaction terms.

Step 2: Fit the final, reduced model

Log_{10}(N35 Chl-*a*) = log_{10}(N39 Chl-*a*) + log_{10}(flow at N39) + log_{10}(Combined flow from South and Eastern Creeks) + log_{10}(lag 1 (Quakers Hill WWTP TP load)) + log_{10}(lag 1 (Quakers Hill WWTP TN load)) + log_{10}(lag 1 (St Marys WWTP TP load)) + log_{10}(lag 1 (St Marys WWTP TN load)) + log_{10}(lag 1 (Riverstone WWTP TP load)) + log_{10}(lag 1 (Riverstone WWTP TN load)) + period + linear trend in period 3 + linear trend in period 4 + linear trend in period 5 + quadratic trend in period 3 + quadratic trend in period 4 + 1st order sine by year + 1st order cosine by year

Where:

- period and year are categorical factors.
- Flow at N39 is derived as described in Volume 2: Appendix E (Table E-5)
- Lag 1 for the loads from the WWTPs are loads estimated on the day before the sampling dates at N35.

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-41.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix H). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table H-35 and Table H-36, respectively. The residual plots for this model are shown in Figure H-18.

The period parameter as well as the upstream concentration at N39, flow corresponding to N39 and the three WWTPs TP and TN load estimates were retained in the model as part of the study design. The p-values corresponding to the Type III SS varied compared with the type I S, that was not unexpected for the TN and TP loads after adjusting for the effect of loads from larger WWTPs on the concentration at N35.

The model fitted the data well (R^2=0.69 and adjusted R^2=0.63) except for those at extremely low concentrations. There were two records with high leverage. The distribution of the residuals was approximately Normal and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

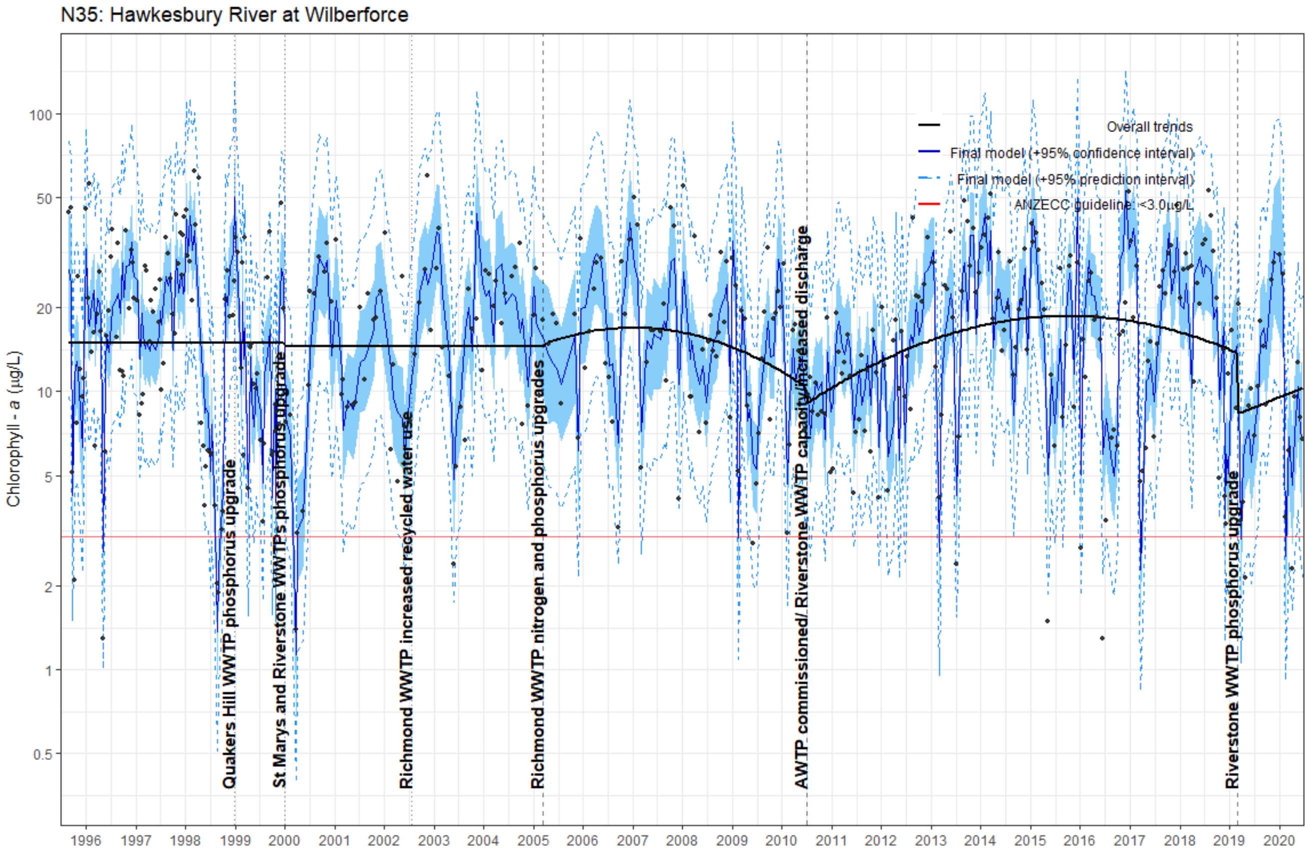

Figure 4-41 Chlorophyll-a concentrations at Wilberforce Hawkesbury River (N35): fitting terms to model upstream concentration, upstream river flow, South Creek flow, TN and TP loads from St Marys, Quakers Hill, Riverstone and Richmond WWTPs, along with linear and quadratic trends and seasonal trends overlaid with the trends in each period

Key outcomes

- Chlorophyll-*a* concentration:
  - Chl-*a* concentrations were above the ANZG default level of <3.0 µg/L
  - The final reduced model fitted well with R^2=0.69 and adjusted R^2=0.63. The residual plots showed the model did not capture the extremely low Chl-*a* concentrations.
- Impact of upstream catchment and tributary:
  - Chl-*a* concentration at N39 was significantly correlated to the concentration at N35 ($p<0.0001$ when fitted on its own and $p=0.02$ after adjusting for all terms in the model).
    - when Chl-*a* concentration at N39 is low eg 3 µg/L, a 0.5 µg/L increase of Chl-*a* concentration increased the concentration at N35 by 1.6%
    - when Chl-*a* concentration at N39 is moderate eg 10 µg/L, a 0.5 µg/L increase in concentration increased the concentration at N35 by 0.5%
    - when Chl-*a* concentration at N39 is high eg 15 µg/L, a 0.5 µg/L increase in concentration increased the concentration at N35 by 0.3%.
  - Flow in the Nepean River at N39 was significantly correlated to the concentration of Chl-*a* at N35 ($p<0.0001$).
    - when flow at N39 is low eg 850 ML/day, a 100 ML increase in flow decreased the concentration at N35 by 5.3%
    - when flow at N39 is moderate eg 1150 ML/day, a 100 ML increase in flow decreased the concentration at N35 by 4%
    - when flow at N39 is high eg 1550 ML/day, a 100 ML increase in flow decreased the concentration at N35 by 3%.
  - Flow in South and Eastern creeks was not significantly correlated to concentration of Chl-*a* at N35 after adjusting for the upper catchment variables ($p=0.1$) but was significant after adjusting for all terms in the model ($p=0.003$). This suggested that, after taking into account TN and TP loads from the WWTPs, any linear and quadratic trends and any seasonal trends, the flow from South and Eastern Creeks provides additional explanation of the variability in Chl-*a* concentration at N35.
    - when flow in the tributary is low eg 100 ML/day, a 10 ML increase in flow decreased the concentration at N35 by 0.6%
    - when flow in the tributary is moderate eg 250 ML/day, a 10 ML increase in flow decreased the concentration at N35 by 0.2%
    - when flow in the tributary is high eg 400 ML/day, a 10 ML increase in flow decreased the concentration at N35 by 0.1%.
- Impact of WWTPs:
  - Riverstone WWTP:

- The TN load from Riverstone WWTP was not correlated to the concentration of Chl-*a* at N35 when adjusted only for upstream catchment measures ($p=0.55$) or after adjusting for all variables in the model ($p=0.11$).
- The TP load from Riverstone WWTP was not correlated to the concentration of Chl-*a* at N35 when adjusted only for upstream catchment measures ($p<0.44$) or after adjusting for all variables in the model ($p=0.32$).

- St Marys WWTP:
  - The TN load from St Marys WWTP was significantly correlated to the concentration of Chl-*a* at N35 when adjusted only for upstream catchment measures and Riverstone WWTP load ($p<0.0001$) but was not significantly correlated after adjusting for all variables in the model ($p=0.9$).
    - when the load from St Marys WWTP is low eg 30 kg/day, a 10 kg/day increase in load increased the concentration at N35 by 0.3%
    - when the load from St Marys WWTP is moderate eg 90 kg/day, a 10 kg/day increase in load increased the concentration at N35 by 0.1%
    - when the load from St Marys WWTP is high eg 200 kg/day, a 10 kg/day increase in load increased the concentration at N35 by 0.1%.
  - The TP load from St Marys WWTP was not correlated to the concentration of Chl-*a* at N35 when adjusted only for upstream catchment measures, Riverstone WWTP TN and TP load ($p=0.12$) and St Marys WWTP TN load or after adjusting for all variables in the model ($p=0.7$)
- Quakers Hill WWTP:
  - The TN load from Quakers Hill WWTP was significantly correlated to the concentration of Chl-*a* at N35 when adjusted for upstream catchment measures and Riverstone and St Marys WWTP loads ($p=0.005$) but not after adjusting for all variables in the model ($p=0.4$). This suggested that, after taking into account any linear and quadratic trends and any seasonal trends, Quakers Hill WWTP TN load did not provide any additional explanation of the variability in Chl-*a* concentration at N35.
    - when the load from Quakers Hill WWTP is low eg 80 kg/day, a 10 kg/day increase in load decreased the concentration at N35 by 0.9%
    - when the load from Quakers Hill WWTP is moderate eg 150 kg/day, a 10 kg/day increase in load decreased the concentration at N35 by 0.5%
    - when the load from Quakers Hill WWTP is high eg 250 kg/day, a 10 kg/day increase in load decreased the concentration at N35 by 0.3%.
  - The TP load from Quakers Hill WWTP was not significantly correlated to the concentration of Chl-*a* at N35 when adjusted for upstream catchment measures and Riverstone and St Marys WWTP loads ($p=0.15$) or after adjusting for all variables in the model ($p=0.8$).

- Long term trends:
  - In period 1 before St Marys and Riverstone WWTPs phosphorus upgrade there was no trend, only a seasonal trend
  - In period 2 after St Marys and Riverstone WWTP phosphorus upgrade and before Richmond WWTP phosphorus upgrade there was no trend, only a seasonal trend.
  - In period 3 after Richmond WWTP nitrogen and phosphorus upgrade and before St Marys AWTP commissioned and Riverstone WWTP reached capacity/increased there was an increasing trend in Chl-*a* concentrations to approximately 2007 before decreasing.
  - In period 4 after St Marys AWTP commissioned and Riverstone WWTP reached capacity/increased discharge and before Riverstone WWTP phosphorus upgrade the Chl-*a* concentration increased to approximately 2015 before decreasing.
  - In period 5 after Riverstone WWTP's nitrogen and phosphorus upgrade, in Chl-a concentration dropped immediately before increasing. However, this could be due to the short time period.
- Seasonal trends:
  - First order sine and cosine terms by year interactions were included to capture a pattern of one peak per year in February and one trough around August with a magnitude that differed between years.
- After adjusting for seasonal trends, flow and concentration at the upstream site, flow from the tributary and load from the four WWTPs, the geometric mean chlorophyll-*a* concentration:
  - In period 1 before St Marys and Riverstone WWTPs TP upgrade was 10.1 µg/L (95% CI = 9.0 to 11.3 µg/L)
  - In period 2 after St Marys and Riverstone WWTP TP upgrade and before Richmond WWTP TP upgrade was 11.7 µg/L (95% CI = 10.1 to 13.7 µg/L)
  - In period 3 after Richmond WWTP TP upgrade and before St Marys AWTP commissioned and Riverstone WWTP reached capacity/increased discharge was 13.7 µg/L (95% CI = 11.5 to 16.4 µg/L)
  - In period 4 after St Marys AWTP commissioned and Riverstone WWTP reached capacity/increased discharge and before Riverstone WWTP TP upgrade was 13.9 µg/L (95% CI = 11.9 to 16.2 µg/L)
  - In period 5 after Riverstone WWTP's TP upgrade was 7.1 µg/L (95% CI = 5.2 to 9.8 µg/L)
- Comparing the modelled geometric mean chlorophyll-*a* concentration between periods:
  - The geometric mean for the period after Riverstone WWTPs phosphorus upgrade (period 5) was 51% (95% CI = 36 to 72%) of the geometric mean for the period before the upgrade (period 4)
  - The geometric mean for the period after commissioning St Marys AWTP and Riverstone WWTP reached capacity/increased discharge (period 4) was 101% (95% CI = 81 to

127%) of the period before the commissioning of St Marys AWTP and Riverstone WWTP reached capacity/increased discharge (period 3)

  - The geometric mean for the period after the Richmond WWTP phosphorus upgrade (period 3) was 117% (95% CI = 94 to 145%) of the period before the phosphorus upgrade at Richmond WWTP (period 2)
  - The geometric mean for the period after the phosphorus upgrades at St Marys and Riverstone WWTPs (period 2) was 117% (95% CI = 99 to 138%) of the period prior to these upgrades (period 1)

4.3.20 Hawkesbury River at Wilberforce (N35) and Freemans Reach (N39) – Chlorophyll-*a* concentration (downstream/upstream)

There were no records from 2002 to mid-2008 at the tributary site of NS04A. The analysis models include data from 2008 ie 634 records in total, 213 from N35, 208 from NS04A and 213 from N39. However, the data prior to this time are plotted for completeness. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included a factor for site identifier for the upstream site, tributary site and downstream site, site by flow interaction term to allow the relationship with flow to differ between sites, a site by period interaction term to allow the site means to differ in each of the three periods defined as before the commissioning of St Marys AWTP and Riverstone WWTP increased capacity (period 3), the period after this point and before Riverstone WWTP phosphorus upgrade (period 4) and the period after the phosphorus upgrade (period 5), interaction terms for site by linear and quadratic trends to allow them to differ within each period and 3-factor interaction terms for site by 1st, 2nd and 3rd order harmonic interaction terms to model the seasonal trends and allow them to differ between sites. Period numbers have been retained as for the analyses of the downstream river sites to avoid confusion.

The model:

Log_{10}(Chl-*a* concentration) = site (N35, NS04A or N39) + site by flow + site by period + site by linear trend in period 3 + site by linear trend in period 4 + site by linear trend in period 5 + site by quadratic trend in period 3 + site by quadratic trend in period 4 + site by quadratic trend in period 5 + site by 1st order sine by year + site by 1st order cosine by year + site by 2nd order sine by year + site by 2nd order cosine by year + site by 3rd order sine by year + site by 3rd order cosine by year

Where:

- site, period and year are categorical factors.
- Flow consists of the flow corresponding to the site identified in the site variable as defined in Volume 2: Appendix E (Table E-5)

Model reduction decisions:

- Remove quadratic term for Period 3

Step 2: Fit the final, reduced model

Log_{10}(Chl-a concentration) = site (N35, NS04A or N39) + site by flow + site by period + site by linear trend in period 3 + site by linear trend in period 4 + site by linear trend in period 5 + site by quadratic trend in period 4 + site by quadratic trend in period 5 + site by 1st order sine by year + site by 1st order cosine by year + site by 2nd order sine by year + site by 2nd order cosine by year + site by 3rd order sine by year + site by 3rd order cosine by year

Where:

- site, period and year are categorical factors.
- Flow consists of the flow corresponding to the site identified in the site variable as defined in Volume 2: Appendix E (Table E-5)

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-42.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix H). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table H-37 and Table H-38, respectively. The residual plots for this model are shown in Figure H-19.

The site, site by flow and site by period parameters were retained in the model as they were part of the study design. The p-values corresponding to the type III SS, although varying slightly compared with the type I SS, were still significant.

The model fitted the data well (R^2=0.78 and adjusted R^2=0.63) except for those at extremely high concentrations or, to a lesser extent, low concentrations. A few values showed a high leverage (ie terms in the model are included because of their contribution to the variability in the data). The distribution of the residuals was approximately Normal and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

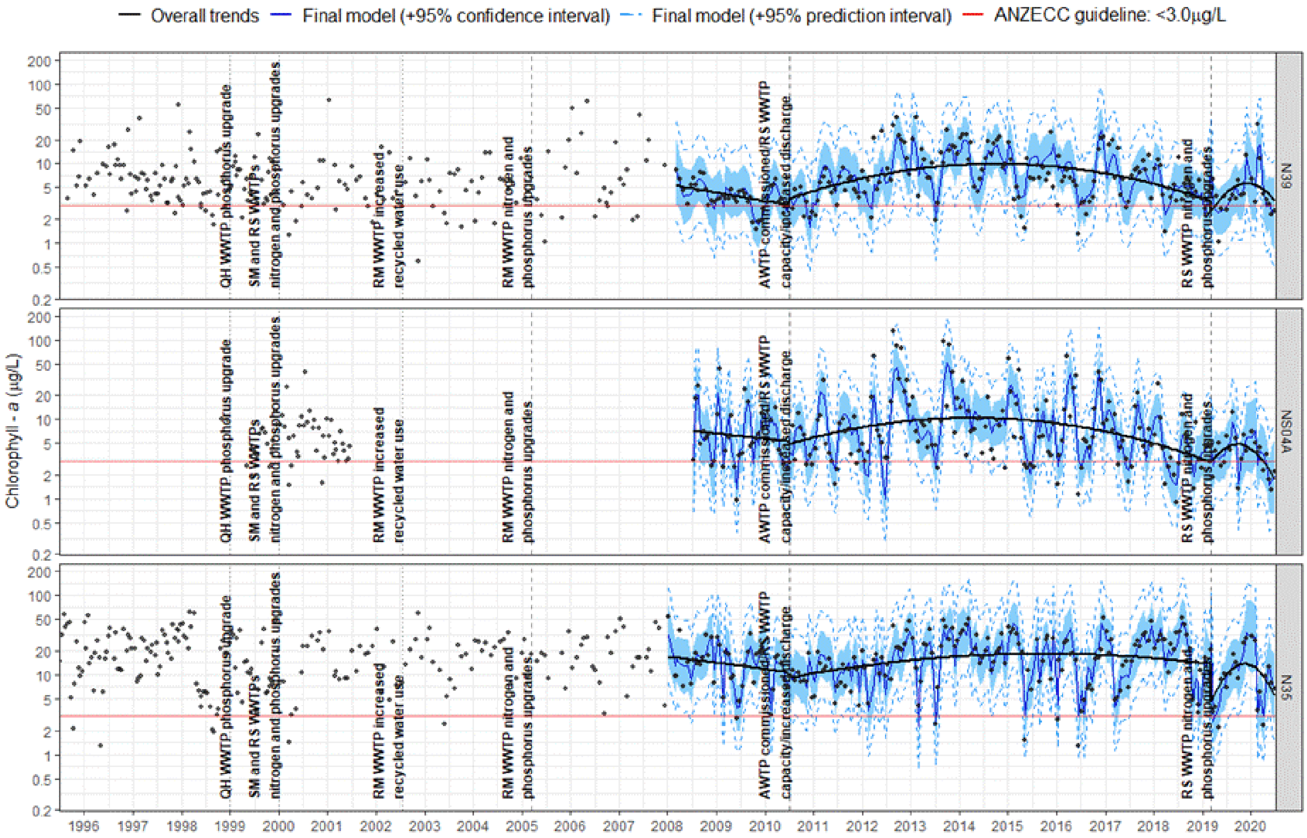

Figure 4-42 Chlorophyll-*a* concentrations at Freemans Reach (N39) and Wilberforce (N35), Hawkesbury River and South Creek (NS04A): fitting terms to model site differences and associated flow along with linear and quadratic trends and seasonal trends overlaid with the trends in each period

Key outcomes

- Chlorophyll-a concentrations:
  - The Chl-*a* concentration was above the ANZG default level of <3.0 µg/L at the downstream site (N35)and was mostly above the guideline at the upstream site (N39). While mostly above the guideline, the Chl-*a* concentration for the tributary site of NS04A decreased to below the guideline in the recent period.
  - The final reduced model fitted well with R^2=0.78 and adjusted R^2=0.63. The residual plots showed the model did not capture the extremely high Chl-*a* concentrations.
- Flow:
  - The interaction between flow and site was significant (p<0.0001).
  - As flow increased, Chl-*a* decreased at N35 (p<0.0001), at N39 (p=0.003) and at NS04A (p<0.0001).

    - when flow at N35 is low eg 1000 ML/day, a 100 ML/day increase in flow decreased the Chl-*a* concentration by 5.6%
    - when flow at N35 is moderate eg 1300 ML/day, a 100 ML/day increase in flow decreased the concentration at N35 by 4.3%
    - when flow at N35 is high, eg 1600 ML/day, a 100 ML/day increase in flow decreased the concentration at N35 by 3.6%.
    - when flow at N39 is low eg 850 ML/day, a 100 ML/day increase in flow decreased the Chl-*a* concentration by 2.2%
    - when flow at N39 is moderate eg 1150 ML/day, a 100 ML/day increase in flow decreased the Chl-*a* concentration at N39 by 1.7%
    - when flow at N39 is high, eg 1550 ML/day, a 100 ML/day increase in flow decreased the concentration at N39 by 1.2%.
    - when flow at NS04A is low eg 100 ML/day, a 10 ML/day increase in flow decreased the Chl-*a* concentration by 1.9%
    - when flow at NS04A is moderate eg 250 ML/day, a 10 ML/day increase in flow decreased the concentration at NS04A by 0.8%
    - when flow at NS04A is high, eg 400 ML/day, a 10 ML/day increase in flow decreased the concentration at NS04A by 0.5%.

- Long term trends:
  - There was a significant interaction between site and linear trends in period 3 (p=0.03). No quadratic trend was fitted for period 3. There was a significant interaction between site and linear and quadratic trends in period 4 (p<0.0001). The site by quadratic term for period 5 was included (p=0.12) and the site by linear term was also included (p=0.11).
  - There was a decreasing linear trend in Chl-*a* concentration at all sites in the period before commissioning of St Marys AWTP (period 3), however at a different mean level.
  - After the commissioning of St Marys AWTP (period 4), all sites showed in increase in Chl-*a* concentration until around 2014-2015. After 2014-2015, the Chl-*a* concentration plateaued at N35, but decreased at the upstream and the tributary sites.
  - After the phosphorus upgrade at Riverstone WWTP, there was a pronounced curvilinear trend in Chl-*a* concentration increasing to late-2019 before decreasing in the first half of 2020.
  - As of mid-2020, the trend at all sites was decreasing.
- Seasonal trends:
  - All site by 1st, 2nd and 3rd order sine and cosine terms by year interactions were included to capture a pattern of three peaks per year, capturing the largest one in February and two smaller ones in late May/early June and September. The lowest trough was around late October/early November. The magnitude of the peaks and troughs differed between years and sites.

- Site by period geometric mean chlorophyll-*a* concentrations:
  - There was a significant interaction between site and period (p<0.0001).
  - After adjusting for linear, quadratic and seasonal trends:
    - Prior to commissioning St Marys AWTP and Riverstone WWTP reaching capacity/increasing discharge (period 3), the geometric mean at N35 was 11.7 µg/L (95% CI = 9.8 to 14.1 µg/L), at NS04A was 4.7 µg/L (95% CI = 3.6 to 6.3 µg/L) and at N39 was 3.5 µg/L (95% CI = 2.9 to 4.3 µg/L)
    - After commissioning of St Marys AWTP and Riverstone WWTP reaching capacity/increasing discharge and before the nitrogen and phosphorus upgrade at Riverstone WWTP (period 4), the geometric mean at N35 was 13.7 µg/L (95% CI = 11.8 to 15.9 µg/L), at NS04A was 8.5 µg/L (95% CI = 7.3 to 9.9 µg/L) and at N39 was 8.5 µg/L (95% CI = 7.3 to 10.0 µg/L)
    - After the nitrogen and phosphorus upgrade at Riverstone WWTP (period 5), the geometric mean at N35 was 4.7 µg/L (95% CI = 0.9 to 24.8 µg/L), at NS04A was 3.3 µg/L (95% CI = 0.7 to 16.1 µg/L) and at N39 was 14.0 µg/L (95% CI = 2.9 to 67.2 µg/L)
  - Comparing the modelled geometric mean chlorophyll-*a* concentration between sites within periods:
    - The geometric mean for N35 in the period before commissioning St Marys AWTP and Riverstone WWTP reaching capacity/increasing discharge (period 3) was 334% (95% CI = 255 to 438%) of the geometric mean for N39.
    - The geometric mean for N35 in the period before commissioning St Marys AWTP and Riverstone WWTP reaching capacity/increasing discharge (period 3) was 249% (95% CI = 178 to 348%) of the geometric mean for NS04A.
    - The geometric mean for N35 in the period after commissioning St Marys AWTP and Riverstone WWTP reaching capacity/increasing discharge, and the nitrogen and phosphorus upgrade at Riverstone WWTP (period 4) was 161% (95% CI = 130 to 200%) of the geometric mean for N39.
    - The geometric mean for N35 in the period after commissioning St Marys AWTP and Riverstone WWTP reaching capacity/increasing discharge, and the nitrogen and phosphorus upgrade at Riverstone WWTP (period 4) was 161% (95% CI = 131 to 199%) of the geometric mean for NS04A.
    - The geometric mean for N35 in the period after the nitrogen and phosphorus upgrade at Riverstone WWTP (period 5) was 33% (95% CI = 3 to 330%) of the geometric mean for N39.
    - The geometric mean for N35 in the period after the nitrogen and phosphorus upgrade at Riverstone WWTP (period 5) was 142% (95% CI = 14 to 1434%) of the geometric mean for NS04A.
  - Comparing the modelled geometric mean chlorophyll-*a* concentration between periods:

- To reduce output and to place more emphasis on the recent times, no comparisons were undertaken between periods 4 and 3. Note that the confidence intervals are wide due to the small numbers of records in period 5.
- The geometric mean for the period after the nitrogen and phosphorus upgrade at Riverstone WWTP (period 5) was 34% (95% CI = 7 to 180%) of the geometric mean for the period prior to the upgrade and after the commissioning of St Marys AWTP and Riverstone WWTP reaching capacity/increasing discharge (period 4) at site N35.
- The geometric mean for the period after the nitrogen upgrade at Riverstone WWTP (period 5) was 39% (95% CI = 8 to 188%) of the geometric mean for the period prior to the upgrade and after the commissioning of St Marys AWTP and Riverstone WWTP reaching capacity/increasing discharge (period 4) at site NS04A.
- The geometric mean for the period after the nitrogen upgrade at Riverstone WWTP (period 5) was 164% (95% CI = 35 to 784%) of the geometric mean for the period prior to the upgrade and after the commissioning of St Marys AWTP and Riverstone WWTP reaching capacity/increasing discharge (period 4) at site N39.
- The percentage difference between periods 5 and 4 for the geometric mean concentration at N35 was 21% (2 to 207%) of the percentage difference at N39.
- The percentage difference between periods 5 and 4 for the geometric mean concentration at N35 was 88% (9 to 889%) of the percentage difference at NS04A.

4.3.21 South Creek WWTPs (St Marys, Quakers Hill and Riverstone) and Richmond WWTP and the Hawkesbury River at Wilberforce (N35) – Summary

Nutrient loads

The approach for analysing the nutrient loads data of South Creek (St Marys, Quakers Hill and Riverstone) and Richmond WWTPs in sub-categories enabled the trends in periods between the interventions to be identified more accurately. The type and period of intervention varied for each of these WWTP. The modelled geometric mean loads from these WWTPs for each period and comparisons between periods are shown in Table 4-15. The trend and percent change in population served by the South Creek (St Marys, Quakers Hill and Riverstone) and Richmond WWTPs in these data category periods are provided in Table 4-16. The results are discussed in the detail in Section 5.1.

A summary of final modelling outcomes on temporal trends in South Creek (St Marys, Quakers Hill and Riverstone) and Richmond WWTP nutrient (TN, DIN and TP) loads by each period of intervention is included in Table 4-17. The models identified both seasonal and non-seasonal variation in nutrient load parameters. The results are discussed in the detail in Section 5.1.

Table 4-15 Geometric mean (95% CI) South Creek WWTPs (St Marys, Quakers Hill and Riverstone) and Richmond WWTP nutrient loads for each period and the comparisons (95% CI) between periods

WWTP	Period	TN (kg/day)	DIN (kg/day)	Period	TP (kg/day)
		Geometric Mean (95% CI)	Geometric Mean (95% CI)		Geometric Mean (95% CI)
St Marys	1	621.7 (563.3, 686.1)	955.1 (210.6, 4332.4)	1	5.89 (5.26, 6.60)
	2	152.8 (147.1, 158.8)	128.1 (120.0, 136.8)	2	0.96 (0.87, 1.07)
	3	64.2 (60.4, 68.3)	46.8 (43.8, 50.1)	3	0.54 (0.50, 0.58)
		% (95% CI)	% (95% CI)		% (95% CI)
	2:1	25% (22%, 27%)	13% (3%, 61%)	2:1	16% (14%, 19%)
	3:2	42% (39%, 45%)	37% (33%, 40%)	3:2	56% (50%, 64%)
Quakers Hill		Geometric Mean (95% CI)	Geometric Mean (95% CI)		Geometric Mean (95% CI)
	1	148.9 (143.5, 154.6)	116.6 (111.6, 121.8)	1	5.3 (4.4, 6.1)
	2	152.4 (145.4, 159.7)	128.4 (115.2, 143.2)	2	1.1 (1.0, 1.2)
				3	2.1 (1.9, 2.3)
		% (95% CI)	% (95% CI)		% (95% CI)
	2:1	102% (96%, 109%)	110% (98%, 124%)	2:1	21% (17%, 25%)
				3:2	189% (170%, 212%)
Riverstone		Geometric Mean (95% CI)	Geometric Mean (95% CI)		Geometric Mean (95% CI)
	1	30.6 (28.7, 32.7)	35.2 (12.7, 97.8)	1	0.402 (0.343, 0.473)
	2	16.9 (16.2, 17.6)	15.7 (14.9, 16.5)	2	0.030 (0.027, 0.033)
	3	14.9 (14.3, 15.6)	63.0 (12.9, 308.2)	3	0.082 (0.074 to 0.091)
	4	11.2 (8.3, 15.2)	5.5 (3.5, 8.6)	4	0.164 (0.129 to 0.208)
		% (95% CI)	% (95% CI)		% (95% CI)
	2:1	55% (51%, 60%)	45% (16%, 124%)	2:1	8% (6%, 9%)
	3:2	89% (84%, 94%)	402% (82%, 1969%)	3:2	270% (234%, 311%
	4:3	75% (55%, 102%)	9% (1%, 59%)	4:3	200% (155%, 258%)
Richmond		Geometric Mean (95% CI)	Geometric Mean (95% CI)		Geometric Mean (95% CI)
	1	13.6 (12.6, 14.8)		1	0.044 (0.039, 0.049)

Table 4-16 St Marys, Quakers Hill, Riverstone and Richmond WWTP catchment population serviced and percent change by period

St Marys WWTP		
Period for TN, DIN and TP	**Average population**	**Percent increase**
Period 1: 1995-1999	131,721	
Period 2: 1999-2010	140,543	
Period 3: 2011-2020	158,484	
Period 2 : Period 1		107%
Period 3 : Period 2		113%
Quakers Hill WWTP		
Period for TN and DIN	**Average population**	**Percent increase**
Period 1: 1995-2010	131,163	
Period 2: 2011-2020	158,484	
Period 2 : Period 1		121%
Period for TP	**Average population**	**Percent increase**
Period 1: 1995-1998	105,563	
Period 2: 1999-2010	138,144	
Period 3: 2011-2020	158,484	
Period 2 : Period 1		131%
Period 3 : Period 2		115%
Riverstone WWTP		
Period for TN, DIN and TP	**Average population**	**Percent increase**
Period 1: 1995-1999	6,362	
Period 2: 2000-2010	7,548	
Period 3: 2011-2018	12,113	
Period 4: 2019-2020	40,900	
Period 2 : Period 1		119%
Period 3 : Period 2		160%
Period 4 : Period 3		338%
Richmond WWTP		
Period for TN, DIN and TP	**Average population**	**Percent increase**
Period 1: 1995-2002	9,370	
Period 2: 2003-2005	9,709	
Period 3: 2006-2020	13,715	
Period 2 : Period 1		104%
Period 3 : Period 2		141%

Data source: 2001-2021: forecast data by the Australian Bureau of Statistics and the Department of Planning, Industry and Environment

1995-2000: Sydney Water's internal estimates based on local government area data, sewer and unsewered areas

Table 4-17 Summary of final models for South Creek (St Marys, Quakers Hill and Riverstone) and Richmond WWTPs with detailed results increasing or decreasing trends, significance levels in each period

WWTP	Parameter	TN	DIN	Parameter	TP
St Marys	Period 1: Linear trend	↗	↗	Period 1: Linear trend	↘
	Period 2: Linear trend	↘	↗	Period 2: Linear trend	↘
	Period 3: Linear trend	↘	↘	Period 3: Linear trend	NA
	Period 1: Quadratic trend	↘	↘	Period 1: Quadratic trend	NA
	Period 2: Quadratic trend	NA	↘	Period 2: Quadratic trend	↗
	Period 3: Quadratic trend	↗	↗	Period 3: Quadratic trend	NA
Quakers Hill	Period 1: Linear trend	↘	↘	Period 1: Linear trend	↘
	Period 2: Linear trend	↗	↗	Period 2: Linear trend	↗
	Period 3: Linear trend	NA	NA	Period 3: Linear trend	↗
	Period 1: Quadratic trend	↗	↗	Period 1: Quadratic trend	↗
	Period 2: Quadratic trend	↘	↘	Period 3: Quadratic trend	↘
Riverstone	Period 1: Linear trend	↘	→	Period 1: Linear trend	↗
	Period 2: Linear trend	↗	↘	Period 2: Linear trend	↘
	Period 3: Linear trend	↗	NA	Period 3: Linear trend	↗
	Period 4: Linear trend	↗	↗		
	Period 1: Quadratic trend	↗	↗	Period 1: Quadratic trend	↘
	Period 2: Quadratic trend	↘	↗	Period 2: Quadratic trend	↗
	Period 3: Quadratic trend	↗	NA	Period 3: Quadratic trend	↗
	Period 4: Quadratic trend	NA	↘		
Richmond	Period 1: Linear trend	↗		Period 1: Linear trend	↗
	Period 1: Quadratic trend	↘		Period 1: Quadratic trend	↘

Legend Keys:

(green)	≤0.0001	(blue)	≤0.001	(yellow)	≤0.01	(grey)	≤0.05	(light blue)	≤0.15

↗	Upward trend	↘	Downward trend	→	no trend, p>0.15

NA	p>0.15, term removed from the model during the model reduction process

Notes: Significance level was based on type I SS p-values and the direction of trend (upward/downward/flat) was determined by the regression coefficient estimates positive, negative or stable)

Receiving water quality

The receiving water quality data of Hawkesbury River at Wilberforce (N35) is analysed with an aim to identify the impact of individual or multiple WWTPs. Following four interventions are considered important to split the receiving water quality data into five categories:

- St Marys and Riverstone WWTPs nitrogen and phosphorus treatment upgrades in December 1999
- Richmond WWTP nitrogen and phosphorus treatment upgrade, March 2005
- St Marys AWTP commissioned in June 2010
- Riverstone nitrogen and phosphorus treatment upgrade in 2019

The modelled geometric mean water quality of Hawkesbury River at Wilberforce (N35) for each period and comparisons between periods are shown in Table 4-18. The results are discussed in the detail in Section 5.2.

Table 4-18 Geometric mean (95% CI) nutrient (TN, DIN, TP and Chl-*a*) concentrations at Hawkesbury River – Wilberforce (N35) for each period and the comparisons (95% CI) between periods

Period	TN (mg/L)	DIN (mg/L)	TP (mg/L)	Chl-*a* (µg/L)
	Geometric Mean (95% CI)	Geometric Mean (95% CI)	Geometric Mean (95% CI)	Geometric Mean (95% CI)
1	1.76 (1.62, 1.92)		0.084 (0.076, 0.094)	10.1 (9.0, 11.3)
2	1.11 (1.03, 1.19)		0.068 (0.061, 0.075)	11.7 (10.1, 13.7)
3	0.96 (0.90, 1.02)		0.059 (0.054, 0.064)	13.7 (11.5, 16.4)
4	0.82 (0.76, 0.89)		0.054 (0.049, 0.060)	13.9 (11.9, 16.2)
5	0.99 (0.86, 1.14)	0.94 (0.73, 1.20)	0.060 (0.050, 0.072)	7.1 (5.2, 9.8)
	% (95% CI)	% (95% CI)	% (95% CI)	% (95% CI)
2:1	63% (56%, 70%)		80% (70%, 92%)	117% (99%, 138%)
3:2	87% (79%, 94%)		87% (78%, 97%)	117% (94%, 145%)
4:3	86% (78%, 95%)		92% (82%, 103%)	101% (81%, 127%)
5:4	120% (103%, 141%)		112% (91%, 137%)	51% (36%, 72%)

A summary of the final model outcomes on temporal trends in the water quality of Hawkesbury River at Wilberforce (N35), and the relationship with upstream flow and concentration, and nutrient loads from South Creek (St Marys, Quakers Hill and Riverstone) WWTPs is included in Table 4-19. The results are discussed in the detail in Section 5.2.

Table 4-19 Overall summary table for the Hawkesbury River at Wilberforce (N35) – final models with detailed results on increasing or decreasing trends, significance levels in each period

Parameter	TN	DIN	TP	Parameter	Chl-a
Upstream N39 concentration (mg/L)	↗	↗	↗	Upstream N39 concentration (µg/L)	↗
Upstream N39 flow (ML/day)	↘	↗	↗	Upstream N39 flow (ML/day)	↘
South/Eastern Creek flow (ML/day)	↗	→	↗	South/Eastern Creek flow (ML/day)	↘
Riverstone load (kg/day)	↗	→	↗	Riverstone TN load (kg/day)	→
St Marys load (kg/day)	↗	↗	↗	Riverstone TP load (kg/day)	→
Quakers Hill load (kg/day)	→	→	↗	St Marys TN load (kg/day)	↗
				St Marys TP load (kg/day)	↘
				Quakers Hill TN load (kg/day)	↘
				Quakers Hill TP load (kg/day)	→
Period 1: Linear trend	↗	↘	→	Period 1: Linear trend	NA
Period 2: Linear trend	NA	NA	NA	Period 2: Linear trend	NA
Period 3: Linear trend	NA	NA	NA	Period 3: Linear trend	↗
Period 4: Linear trend	→	NA	→	Period 4: Linear trend	↗
				Period 5: Linear trend	↗
Period 1: Quadratic trend	↘	NA	↗		
				Period 3: Quadratic trend	↘
Period 4: Quadratic trend	↗	NA	↗	Period 4: Quadratic trend	↘

Legend Keys:

(green)	≤0.0001	(blue)	≤0.001	(yellow)	≤0.01	(grey)	≤0.05	(light blue)	≤0.15

↗	Upward trend or positive correlation	↘	Downward trend or negative correlation	→	no trend, p>0.15

NA	p>0.15, term removed from the model during the model reduction process

(magenta) Not significant after adjusting for all terms in the model

Notes: Significance level was based on type I SS p-values and the direction of trend (upward/downward/flat) was determined by the regression coefficient estimates (positive, negative or stable)

Receiving water quality – downstream and upstream comparison

The modelled geometric mean downstream water quality of Hawkesbury River at Wilberforce (N35) and comparison with the upstream site at Freemans Reach (N39) and South Creek (NS04A) for each period and comparisons between periods are shown in Table 4-20. The results are discussed in the detail in Section 5.2.

Table 4-20 Geometric mean (95% CI) nutrient (TN, DIN, TP and Chl-*a*) concentrations at Hawkesbury River – Wilberforce (N35) and Freemans Reach (N39) and South Creek (NS04A) for each period and the comparisons (95% CI) between periods

TN (mg/L)					
Period	**N35**	**N39**	**NS04A**	**N35/N39**	**N35/NS04A**
3	0.89 (0.80, 1.00)	0.51 (0.46, 0.57)	2.00 (1.76, 2.28)	174% (149%, 204%)	45% (38%, 53%)
4	0.78 (0.73, 0.83)	0.59 (0.55, 0.63)	2.44 (2.29, 2.60)	132% (121%, 145%)	32% (29%, 35%)
5	1.05 (0.95, 1.17)	0.68 (0.62, 0.75)	2.00 (1.80, 2.23)	155% (134%, 179%)	53% (45%, 61%)
5:4	135% (120%, 152%)	116% (103%, 130%)	82% (73%, 92%)	117% (98%, 139%)	165% (138%, 196%)
DIN (mg/L)					
Period	**N35**	**N39**	**NS04A**	**N35/N39**	**N35/NS04A**
3	0.51 (0.40, 0.65)	0.25 (0.19, 0.32)	1.35 (1.02, 1.80)	205% (144%, 293%)	37% (26%, 55%)
4	0.30 (0.26, 0.35)	0.20 (0.18, 0.24)	1.51 (1.31, 1.74)	147% (121%, 180%)	20% (16%, 24%)
5	0.53 (0.42, 0.67)	0.34 (0.27, 0.43)	1.31 (1.03, 1.67)	158% (114%, 218%)	40% (29%, 56%)
5:4	176% (135%, 229%)	164% (127%, 212%)	87% (67%, 113%)	107% (73%, 157%)	202% (137%, 299%)
TP (mg/L)					
Period	**N35**	**N39**	**NS04A**	**N35/N39**	**N35/NS04A**
3	0.047 (0.040, 0.056)	0.012 (0.010, 0.015)	0.144 (0.120, 0.174)	385% (307%, 484%)	33% (26%, 42%)
4	0.052 (0.048, 0.057)	0.029 (0.026, 0.031)	0.156 (0.143, 0.171)	182% (160%, 206%)	33% (29%, 38%)
5	0.055 (0.047, 0.064)	0.014 (0.013, 0.017)	0.132 (0.113, 0.155)	380% (308%, 469%)	42% (34%, 52%)
5:4	106% (89%, 126%)	51% (43%, 60%)	85% (71%, 100%)	209% (164%, 268%)	129% (54%, 305%)
Chl-*a* (μg/L)					
Period	**N35**	**N39**	**NS04A**	**N35/N39**	**N35/NS04A**
3	11.7 (9.8, 14.1)	3.5 (2.9, 4.3)	4.7 (3.6, 6.3)	334% (255%, 438%)	249% (178%, 348%)
4	13.7 (11.8, 15.9)	8.5 (7.3, 10.0)	8.5 (7.3, 9.9)	161% (130%, 200%)	161% (131%, 199%)
5	4.7 (0.9, 24.8)	14.0 (2.9, 67.2)	3.3 (0.7, 16.1)	33% (3%, 330%)	142% (14%, 1434%)
5:4	34% (7%, 180%)	164% (35%, 784%)	39% (8%, 188%)	21% (2%, 207%)	88% (9%, 889%)

A summary of final model outcomes on temporal trends in the water quality of Hawkesbury River at Wilberforce (N35) and comparison with the upstream site of Hawkesbury River at Freemans Reach (N39) is included Table 4-21. The results are discussed in the detail in Section 5.2.

Table 4-21 Summary of final models for the Hawkesbury River at Wilberforce (N35) – upstream/downstream and tributary comparison with detailed results on increasing or decreasing trends, significance levels in each period

Parameter	TN	DIN	Parameter	TP	Parameter	Chl-*a*
Site by Flow			Site by Flow		Site by Flow	
N35	↗	↗	N35	↗	N35	↘
N39	↗	↗	N39	↗	N39	↘
NS04A	→	→	NS04A	↗	NS04A	↘
Site by Period			Site by Period		Site by Period	
Site by P3 Linear trend			Site by P3 Linear trend		Site by P3 Linear trend	
N35	→	→	N35	→	N35	↘
N39	↘	→	N39	↘	N39	↘
NS04A	↘	↘	NS04A	↗	NS04A	→
Site by P4 Linear trend			Site by P4 Linear trend		Site by P4 Linear trend	
N35	→	↘	N35	→	N35	↗
N39	↗	→	N39	↗	N39	↗
NS04A	↗	→	NS04A	↗	NS04A	↗
			Site by P5 Linear trend		Site by P5 Linear trend	
			N35	→	N35	↘
			N39	↗	N39	↘
			NS04A	→	NS04A	→
Site by P3 quadratic trend			Site by P3 quadratic trend		Site by P4 quadratic trend	
N35	→	→	N35	→	N35	↘
N39	→	→	N39	↗	N39	↘
NS04A	↗	↗	NS04A	↘	NS04A	↘
Site by P4 quadratic trend			Site by P4 quadratic trend		Site by P5 quadratic trend	
N35	↗	↗	N35	→	N35	↗
N39	→	↗	N39	↘	N39	↗
NS04A	→	→	NS04A	↘	NS04A	→

Legend Keys:

	≤0.0001		≤0.001		≤0.01		≤0.05		≤0.15

↗	Upward trend or positive correlation	↘	Downward trend or negative correlation	→	no trend, p>0.15

Notes: Significance level was based on type I SS p-values and the direction of trend (upward/downward/flat) was determined by the regression coefficient estimates (positive, negative or stable)

4.4 Hawkesbury River at Cattai SRA (N3001) – Cattai Creek WWTPs (Castle Hill and Rouse Hill)

The following sub-sections present the results of the model building steps, and key outcomes for 14 models fitted on data for the Hawkesbury River at Cattai SRA (N3001) and Cattai Creek (Castle Hill and Rouse Hill) WWTPs. A summary is included to interpret the variability in the outcomes due to explanatory variables fitted or any other supplementary changes eg demography, weather etc.

The detailed results of all statistical models fitted for the Hawkesbury River at Cattai SRA (N3001) and Cattai Creek (Castle Hill and Rouse Hill) WWTPs are included in Volume 2: Appendix I. Estimated regression coefficients, standard errors, p values, type I and type III sum of squares details are provided in Table I-1 to Table I-28. Residual plots on all models are provided in Figure I-1 to Figure I-14. The model and model adjusted R^2 are provided to assess the goodness of fit of the models (Table I-29). Examples of relative changes in water quality concentrations (total nitrogen, dissolved inorganic nitrogen, total phosphorus or chlorophyll-*a*) with respect to prespecified ranges of nutrient load, upstream concentrations and, river and creek flow are included in Table I-30 and Table I-31.

4.4.1 Castle Hill WWTP – Total nitrogen load

There were 1524 total nitrogen load records in Castle Hill WWTP data series. There were 334 records prior to the decommissioning of Round Corner WWTP in 2001 (period 1) and 1190 records after the decommissioning (period 2). All records are included in the analyses. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included the two periods defined by the decommissioning of Round Corner WWTP, linear and quadratic trends within each period and 1st, 2nd and 3rd order harmonic interaction terms to model the seasonal trends.

The model:

Log_{10}(TN load) = period + linear trend in period 1 + linear trend in period 2 + quadratic trend in period 1 + quadratic trend in period 2 + 1st order sine + 1st order cosine + 2nd order sine + 2nd order cosine + 3rd order sine + 3rd order cosine + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

period and year are categorical factors.

Model reduction decisions:

- Periods 1 and 2: retain the linear and quadratic trend terms as the p-values for the quadratic terms using the type I SS were <0.15
- Retain all harmonic by year interaction terms as the p-values for the 3rd order terms from the type I SS were <0.15

- Remove the main effect harmonic terms since they can be included in the harmonic interaction terms.

Step 2: Fit the final, reduced model

Log_{10}(TN load) = period + linear trend in period 1 + linear trend in period 2 + quadratic trend in period 1 + quadratic trend in period 2 + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

period and year are categorical factors.

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-43.

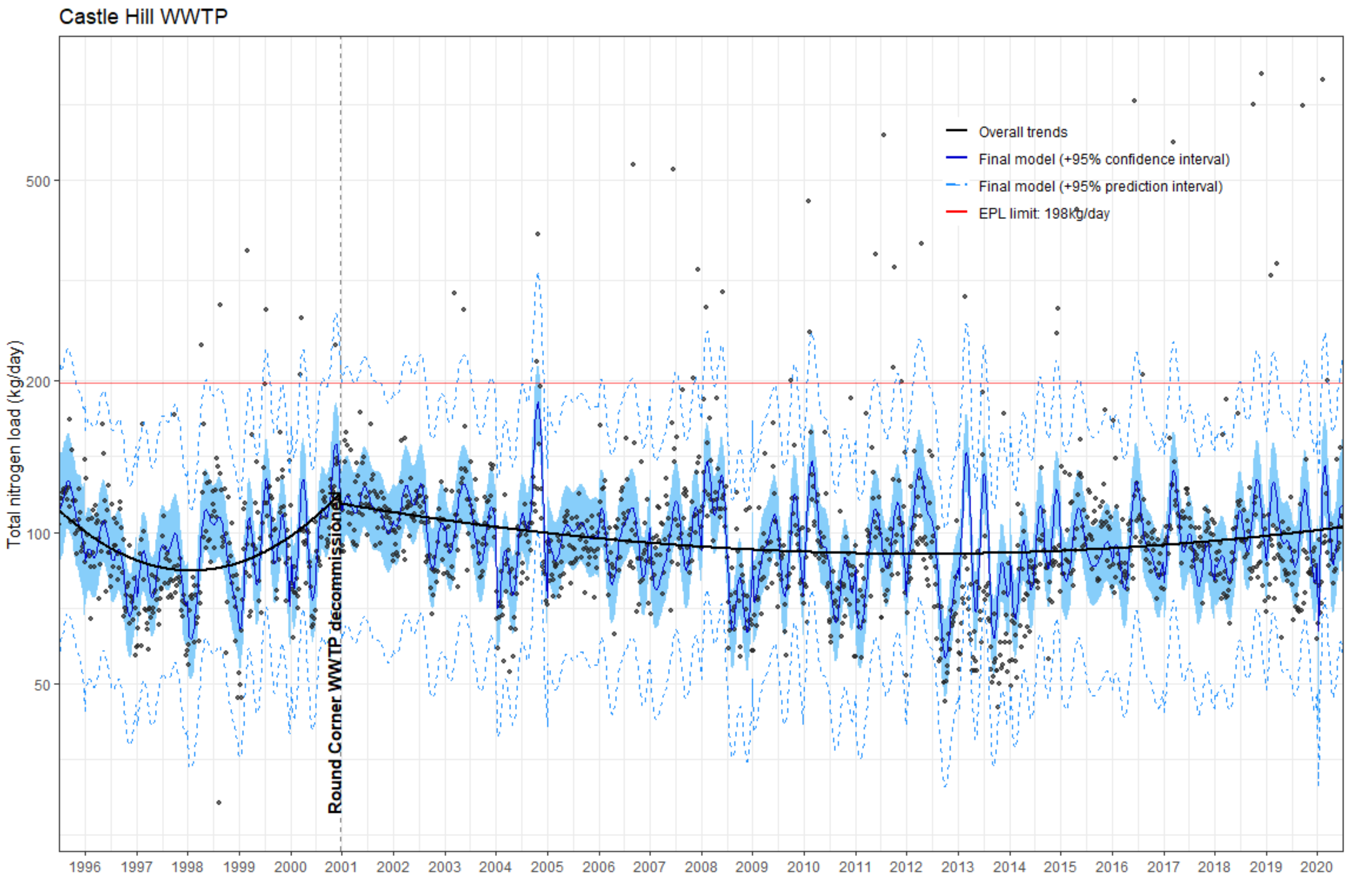

Figure 4-43 Total nitrogen load from Castle Hill WWTP: fitting terms to model interventions, linear and quadratic trends within each period and seasonal trends overlaid with the trends in each period

The detailed statistical outcomes of this model are included in Volume 2 (Appendix I). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table I-1 and Table I-2, respectively. The residual plots for this model are shown in Figure I-1.

All terms in the final, reduced model had a p-value for the corresponding type I SS <0.15 except for the linear trend in period 1 with a p-value of 0.16. This term was included in the model as the corresponding quadratic term was significant (p<0.0001). Each term in the model also had a p-value for the type III SS of a similar magnitude except for the quadratic trend in period 1 (p = 0.02) suggesting that some of the curvature in the trend was accounted for by the change in each year captured by the harmonic by year interaction terms.

The model fitted the data well (R^2=0.31 and adjusted R^2=0.22) except for those at extremely high loads. Four values showed a high leverage (ie terms in the model are included because of their contribution to the variability in the data). The distribution of the residuals was approximately Normal with a low density, long tail capturing the residuals from the high value not being captured by the model. The residuals plotted against the fitted or predicted values showed no remaining pattern in the data series and the scale location plot also supported the lack of fit to the high loads.

Key outcomes

- Total nitrogen load:
  - The majority of records were less than current EPL limit (198 kg/day)
  - The final reduced model fitted well with R^2=0.31 and adjusted R^2=0.22. However, the residual plots showed the model did not capture the extremely high total nitrogen loads.
- Long term trends:
  - Significant curvilinear trends were observed in both periods
    - Prior to decommissioning Round Corner WWTP, the total nitrogen load had a decreasing curvilinear trend until around 1998 when the load started to increase until the end of the period.
    - After decommissioning Round Corner WWTP, there was a slight decreasing curvilinear trend until around 2014 when the total nitrogen load started to increase slightly
    - As of mid-2020, the trend was increasing slightly but was well below the EPL limit.
- Seasonal trends:
  - First, second and third order sine and cosine terms by year interactions were included to capture a more complex pattern of three peaks per year, capturing the largest one in February and two smaller ones in late May/early June and September. The lowest trough was around late October/early November. The magnitude of the peaks and troughs differed between years.
- After adjusting for seasonal trends, the geometric mean total nitrogen load:

- Prior to decommissioning Round Corner WWTP (period 1) was 86.7 kg/day (95% CI = 82.4 to 91.1 kg/day)
- After decommissioning Round Corner WWTP (period 2) was 90.8 kg/day (95% CI = 88.5 to 93.1 kg/day)

- Comparing the modelled geometric mean total nitrogen loads between periods:
  - The geometric mean after decommissioning Round Corner WWTP (period 2) was 105% (95% CI = 99 to 111%) of the geometric mean for the period prior to the decommissioning of Round Corner WWTP (period 1)

4.4.2 Rouse Hill WWTP – Total nitrogen load

There were 1524 total nitrogen load records in the Rouse Hill WWTP data series. There were 884 prior to the nitrogen upgrade in 2010 (period 1) and 640 after the upgrade (period 2). All records are included in the analyses. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included the two periods defined by the nitrogen upgrade at Rouse Hill WWTP, linear and quadratic trends within each period and 1st, 2nd and 3rd order harmonic interaction terms to model the seasonal trends.

The model:

Log_{10}(TN load) = period + linear trend in period 1 + linear trend in period 2 + quadratic trend in period 1 + quadratic trend in period 2 + 1st order sine + 1st order cosine + 2nd order sine + 2nd order cosine + 3rd order sine + 3rd order cosine + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

period and year are categorical factors.

Model reduction decisions:

- Periods 1 and 2: retain the linear and quadratic trend terms as the p-values for the quadratic terms using the type I SS were <0.15
- Retain all harmonic interaction terms as the p-values for the 3rd order terms from the type I SS were <0.15 (ie <0.0004 and 0.0005 for cosine and sine respectively)
- Remove the main effect harmonic terms since they can be included in the harmonic interaction terms.

Step 2: Fit the final, reduced model

Log_{10}(TN load) = period + linear trend in period 1 + linear trend in period 2 + quadratic trend in period 2 + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

period and year are categorical factors.

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-44.

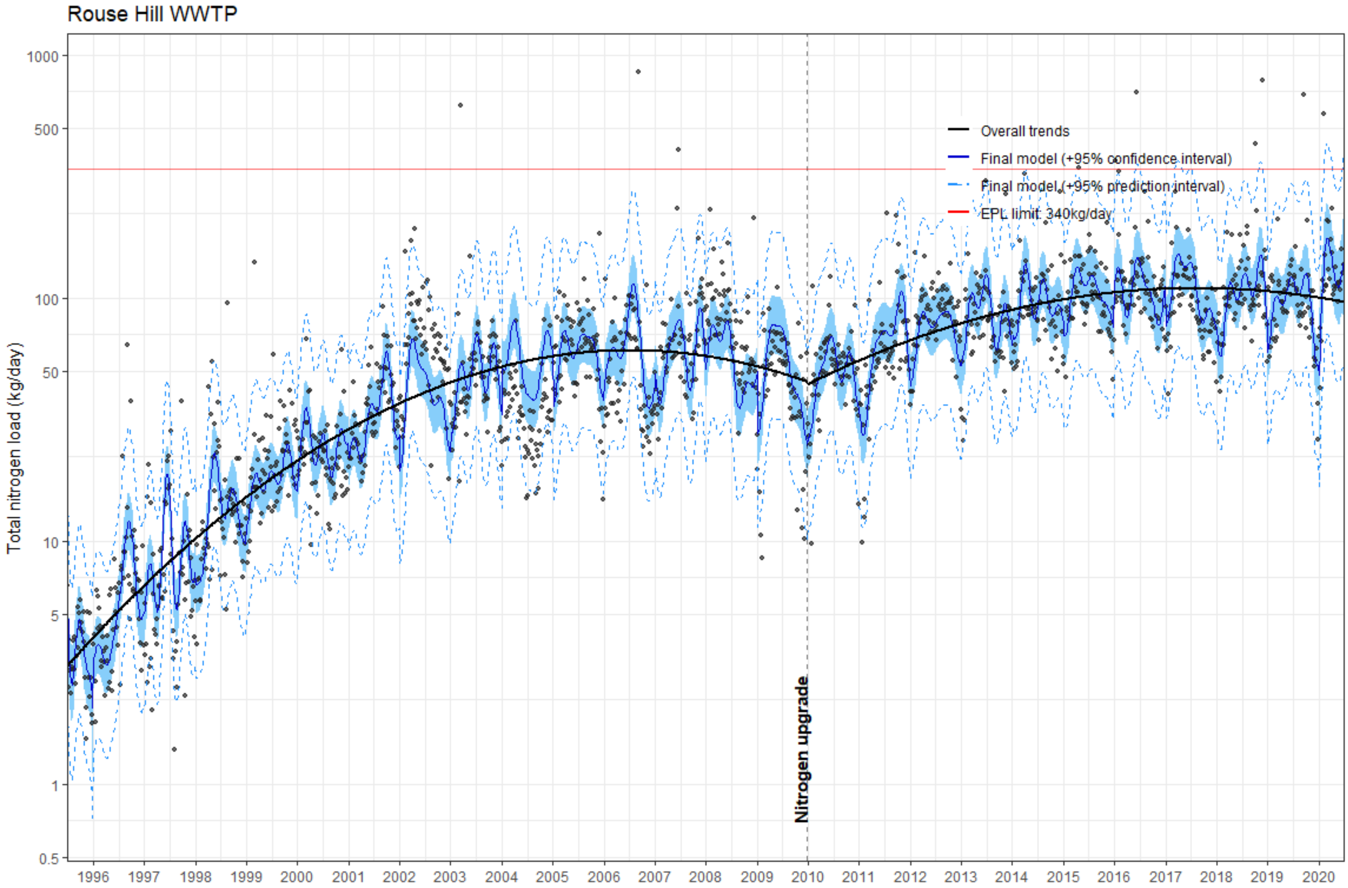

Figure 4-44 Total nitrogen load from Rouse Hill WWTP: fitting terms to model interventions, linear and quadratic trends within each period and seasonal trends overlaid with the trends in each period

The detailed statistical outcomes of this model are included in Volume 2 (Appendix I). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table I-3 and Table I-4, respectively. The residual plots for this model are shown in Figure I-2.

All terms in the final, reduced model had a p-value for the corresponding type I SS <0.15. Each term in the model also had a p-value for the corresponding type III SS of a similar magnitude suggesting that each term explained different types of patterns within the data series.

The model fitted the data well (R^2=0.84 and adjusted R^2=0.82) except for those at extremely high loads, and, to a lesser extent the extremely low loads. The very high R^2 possibly suggests that there were too many terms in the model (ie overfitted). However, all terms meet the criterion to keep them in the model. Four values showed a high leverage (ie terms in the model are included because of their contribution to the variability in the data). The distribution of the residuals was approximately Normal and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

Key outcomes

- Total nitrogen load:
  - The majority of records were less than current EPL limit (340 kg/day)
  - The final reduced model fitted well with R^2=0.84 and adjusted R^2=0.82. However, the residual plots showed the model did not capture the extremely high, and to a lesser extend extremely low total nitrogen loads. The very high R^2 possibly suggests that there were too many terms in the model (ie overfitted). However, all terms meet the criterion to keep them in the model.
- Long term trends:
  - Significant curvilinear trends were observed in both periods:
    - Before the nitrogen upgrade, total nitrogen load had an increasing curvilinear trend until around 2005 when the load started to decrease
    - After the nitrogen upgrade a similar pattern was seen with an increasing curvilinear trend to approximately 2017 when total nitrogen load started to decrease slightly.
    - As of mid-2020, the trend was slightly decreasing.
- Seasonal trends:
  - First, second and third order sine and cosine terms by year interactions were included to capture a more complex pattern of three peaks per year, capturing the largest one in February and two smaller ones in late May/early June and September. The lowest trough was around late October/early November. The magnitude of the peaks and troughs differed between years.
- After adjusting for seasonal trends, the geometric mean total nitrogen load:
  - Prior to the nitrogen upgrade at Rouse Hill WWTP (period 1) was 42.5 kg/day (95% CI = 40.7 to 44.4 kg/day)
  - After the nitrogen upgrade at Rouse Hill WWTP (period 2) was 101.7 kg/day (95% CI = 96.6 to 107.1 kg/day)
- Comparing the modelled geometric mean total nitrogen loads between periods:
  - The geometric mean after the nitrogen upgrade at Rouse Hill WWTP (period 2) was 239% (95% CI = 224 to 256%) of the geometric mean for the period prior to the nitrogen upgrade (period 1)

4.4.3 Hawkesbury River at Cattai SRA (N3001) – Total nitrogen concentration

There were no total nitrogen concentration records from the Hawkesbury River at Cattai SRA (N3001) between mid-2001 to mid-2008. The analysis models include data from 2008 ie 206 records for N3001. However, the data prior to 2001 are plotted for completeness. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fit the full model as one period, TN concentration at the upstream site N39, the flow at N35, the flow in Cattai Creeks Castle Hill WWTP TN load, Rouse Hill WWTP TN load, linear and quadratic trends within the period and 1st, 2nd and 3rd order harmonic interaction terms to model the seasonal trends.

The model:

Log_{10}(N3001 TN concentration) = log_{10}(N35 TN concentration) + log_{10}(flow at N35) + log_{10}(flow from Cattai Creek) + log_{10}(lag 1 (Castle Hill WWTP TN load)) + log_{10}(lag 1 (Rouse Hill WWTP TN load)) + linear trend + quadratic trend + 1st order sine + 1st order cosine + 2nd order sine + 2nd order cosine + 3rd order sine + 3rd order cosine + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

- year is a categorical factor.
- Flow at N35 is derived as described in Volume 2: Appendix E (Table E-5)
- Lag 1 for the loads from the WWTPs are loads estimated on the day before the sampling dates at N3001

Model reduction decisions:

- Remove all harmonic by year interaction terms
- Remove 2nd and 3rd order main effect harmonic terms, retain the 1st order main effect harmonic terms
- Remove the quadratic trend term

Step 2: Fit the final, reduced model

Log_{10}(N3001 TN concentration) = log_{10}(N35 TN concentration) + log_{10}(flow at N35) + log_{10}(flow from Cattai Creek) + log_{10}(lag 1 (Castle Hill WWTP TN load)) + log_{10}(lag 1 (Rouse Hill WWTP TN load)) + linear trend + 1st order sine + 1st order cosine

Where:

- Flow at N35 is derived as described in Volume 2: Appendix E (Table E-5)

- Lag 1 for the loads from the WWTPs are loads estimated on the day before the sampling dates at N3001

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-45.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix I). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table I-5 and Table I-6, respectively. The residual plots for this model are shown in Figure I-3.

The upstream concentration at N39, flow corresponding to N35, flow corresponding to Cattai Creek and the two WWTPs TN load estimates and period effect were retained in the model as part of the study design. The p-values corresponding to the type III SS varied compared with the type I SS that is not unexpected.

The model fitted the data well (R^2=0.79 and adjusted R^2=0.78) except for those at extremely high concentrations or, to a lesser extent, low concentrations. A few values showed a high leverage (ie terms in the model are included because of their contribution to the variability in the data). The distribution of the residuals was approximately Normal with some very low points and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

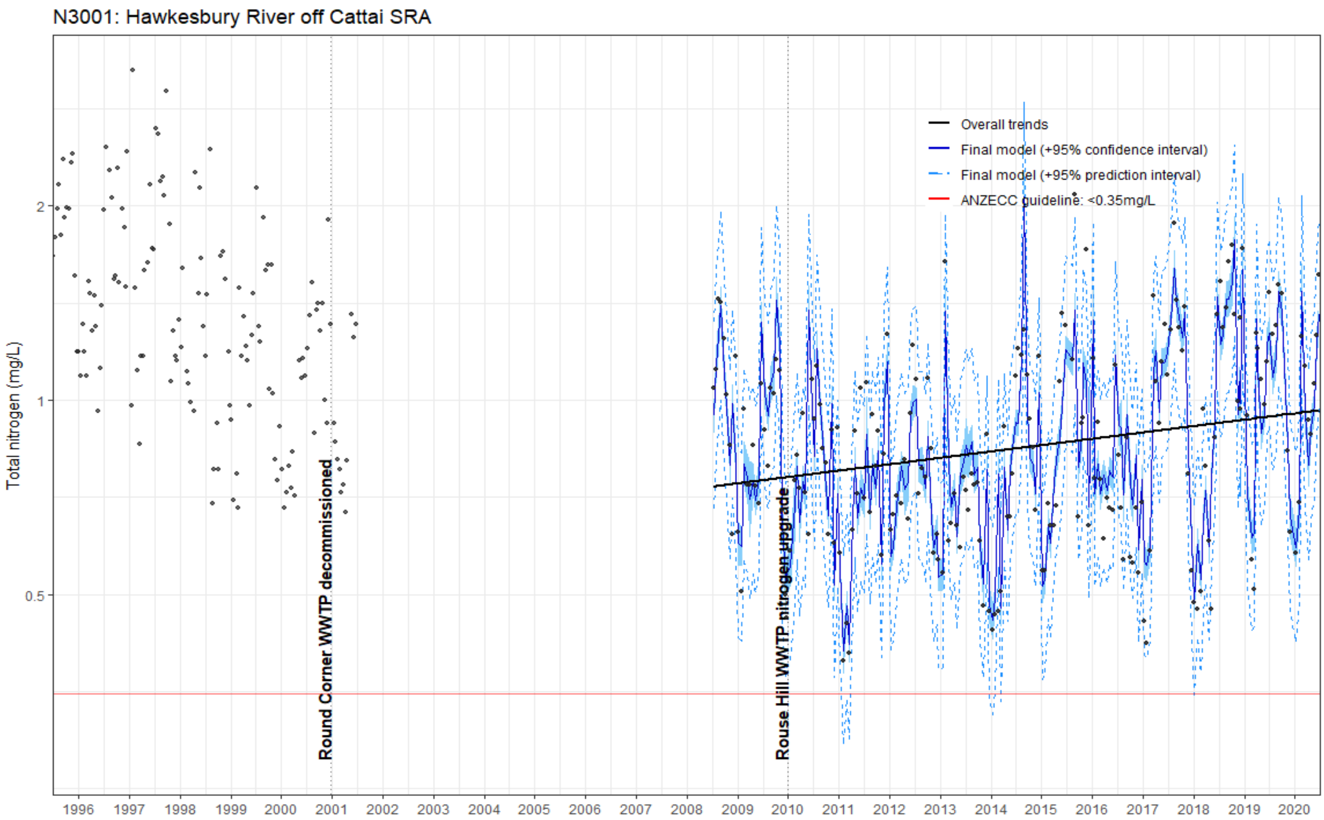

Figure 4-45 Total nitrogen concentrations at Cattai SRA (N3001): fitting terms to model upstream concentration, upstream river flow, Cattai Creek flow, seasonal trends, TN loads from Castle Hill and Rouse Hill WWTPs, along with linear and quadratic trends and seasonal trends overlaid with the trend

Key outcomes

- Total nitrogen concentration:
  - TN concentration remained above the ANZG default level of <0.35mg/L
  - The final reduced model fitted well with R^2=0.79 and adjusted R^2=0.78. However, the residual plots showed the model did not capture the extremely high total nitrogen concentrations.
- Impact of upstream catchment and tributary:
  - TN concentration at N35 was significantly correlated to the concentration at N3001 ($p<0.0001$).
    - when TN concentration at N35 is low eg 0.5 mg/L, a 0.005 mg/L increase of TN concentration increased the concentration at N3001 by 0.5%
    - when TN concentration at N35 is moderate eg 1 mg/L, a 0.005 mg/L increase in concentration increased the concentration at N3001 by 0.4%

        - when TN concentration at N35 is high eg 1.5 mg/L, a 0.005 mg/L increase in concentration increased the concentration at N3001 by 0.3%.
    - Flow in the Nepean River at N35 was significantly correlated to the concentration of TN at N3001 after adjusting for TN concentration at N35 (p<0.0001) and after adjusting for all terms in the model (p=0.001).
        - when flow at N35 is low eg 1000 ML/day, a 100 ML increase in flow decreased the concentration at N3001 by 0.5%
        - when flow at N35 is moderate eg 1300 ML/day, a 100 ML increase in flow decreased the concentration at N3001 by 0.4%
        - when flow at N35 is high eg 1600 ML/day, a 100 ML increase in flow decreased the concentration at N3001 by 0.3%.
    - Flow in Cattai Creek was not significantly correlated to concentration of TN at N3001 (p=0.7 after adjusting for the upper catchment variables and p=0.3 after adjusting for all terms in the model)
- Impact of WWTPs:
    - The TN load from Castle Hill WWTP was not significantly correlated to the concentration of TN at N3001 when adjusted only for upstream catchment measures (p=0.3) and was significantly correlated after adjusting for all variables in the model (p=0.02). This suggested that, after taking into account any linear and quadratic trends and any seasonal trends, Castle Hill WWTP TN load provides an additional explanation of the variability in TN concentration at N3001.
        - when the load from Castle Hill WWTP is low eg 40 kg/day, a 10 kg/day increase in load increased the concentration at N3001 by 1.8%
        - when the load from Castle Hill WWTP is moderate eg 100 kg/day, a 10 kg/day increase in load increased the concentration at N3001 by 0.8%
        - when the load from Castle Hill WWTP is high eg 160 kg/day, a 10 kg/day increase in load increased the concentration at N35 by 0.5%.
    - The TN load from Rouse Hill WWTP was not significantly correlated to the concentration of TN at N3001 when adjusted only for upstream catchment measures and Castle Hill WWTP load (p=0.6) or after adjusting for all variables in the model (p=0.2).
- Long term trends:
    - As of mid-2020, there was an increasing linear trend.
- Seasonal trends:
    - First order sine and cosine terms were included to capture a pattern of one peak per year in February and one trough around August with a magnitude that was the same each year.
- Geometric mean total nitrogen concentration

- After adjusting for seasonal trends, flow and concentration at the upstream site and load from Castle Hill and Rouse Hill WWTPs, the geometric mean at N3001 was 0.93 mg/L (95% CI = 0.90 to 0.96 mg/L).

4.4.4 Hawkesbury River at Cattai SRA (N3001) and Wilberforce (N35) – Total nitrogen concentration (downstream/upstream)

There were no total nitrogen concentration records from 2002 to mid-2008 at the tributary site of NC11A. The analysis models include data from 2008 ie 637 records in total, 206 from N3001, 215 from NC11A and 216 from N35. However, the data prior to this time are plotted for completeness. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included a factor for site identifier for the upstream site, tributary site and downstream site, site by flow interaction term to allow the relationship with flow to differ between sites, interaction terms for site by linear and quadratic trends to allow them to differ and 3-factor interaction terms for site by 1st, 2nd and 3rd order harmonic interaction terms to model the seasonal trends and allow them to differ between sites. Note, no Period term was included as there is only one period.

The model:

$\log_{10}$(TN concentration) = site (N3001, NC11A or N35) + site by flow + site by linear trend + site by quadratic trend + site by 1st order sine by year + site by 1st order cosine by year + site by 2nd order sine by year + site by 2nd order cosine by year + site by 3rd order sine by year + site by 3rd order cosine by year

Where:

- site and year are categorical factors.
- Flow consists of the flow corresponding to the site identified in the site variable as defined in Volume 2: Appendix E (Table E-5)

Model reduction decisions:

- Remove all site by 2nd and 3rd order harmonic by year terms

Step 2: Fit the final, reduced model

$\log_{10}$(TN concentration) = site (N3001, NC11A or N35) + site by flow + site by linear trend + site by quadratic trend + site by 1st order sine by year + site by 1st order cosine by year

Where:

- site and year are categorical factors.
- Flow consists of the flow corresponding to the site identified in the site variable as defined in Volume 2: Appendix E (Table E-5)

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-46.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix I). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table I-7 and Table I-8, respectively. The residual plots for this model are shown in Figure I-4.

The site and site by flow parameters were retained in the model as they formed part of the study design. The p-values corresponding to the type III SS are the same as those with the type I SS.

The model fitted the data well (R^2=0.77 and adjusted R^2=0.73). There were a few exceptionally low values of TN that the model was not fitting. The distribution of the residuals was approximately Normal and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

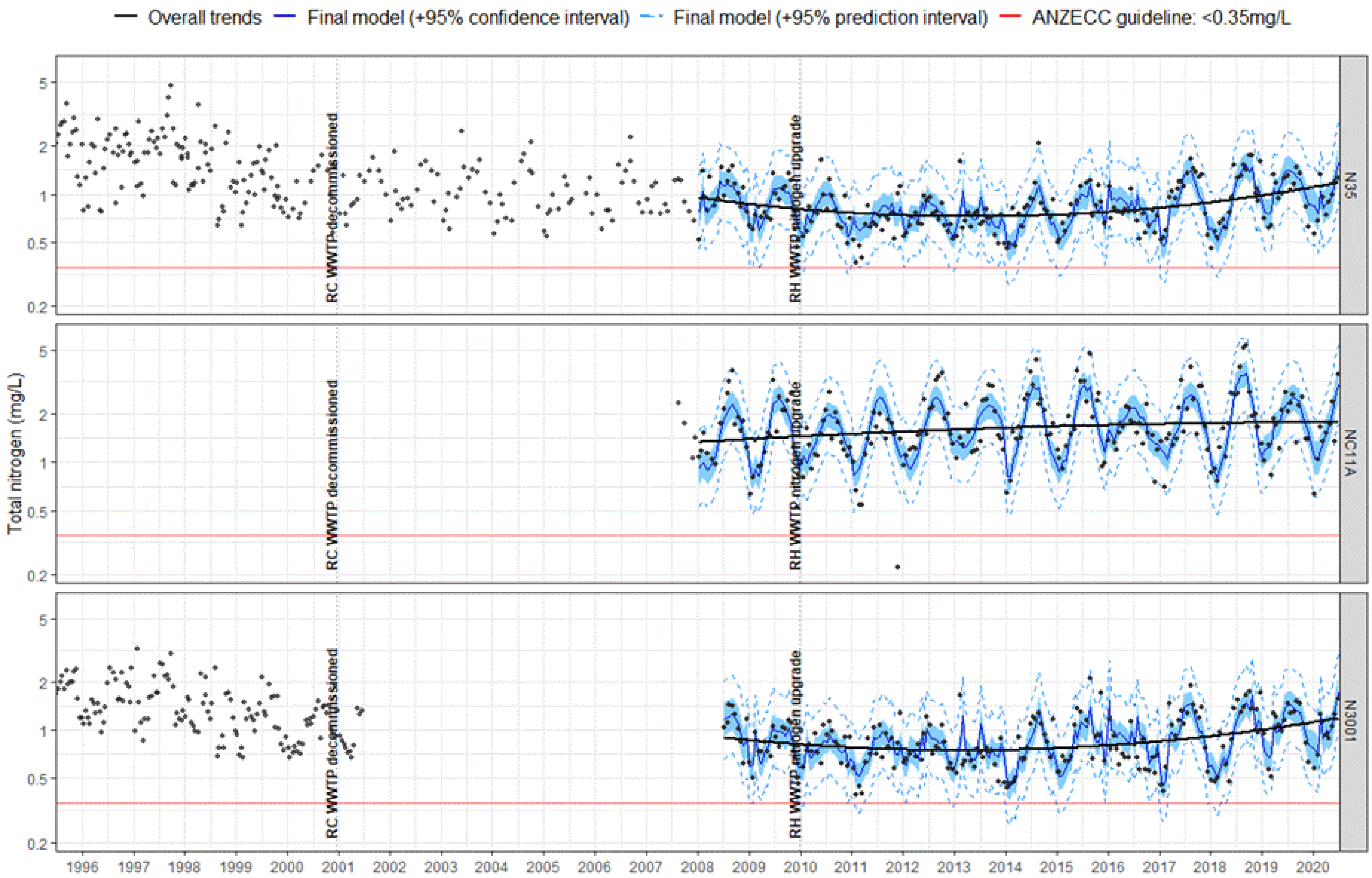

Figure 4-46 Total nitrogen concentrations at Wilberforce (N35) and Off Carrai SRA (N3001), Hawkesbury River and Cattai Creek (NC11A): fitting terms to model site differences and associated flow along with linear and quadratic trends and seasonal trends

Key outcomes

- Total nitrogen concentration:
  - TN concentration remained above the ANZG default level of <0.355 mg/L for all sites.

- The final reduced model fitted well with R^2=0.77 and adjusted R^2=0.73. However, the residual plots showed the model did not capture the three extremely low total nitrogen concentrations.

- Flow:
  - The interaction between flow and site was significant (p=0.0005).
  - As flow increased, TN concentration increased at N3001 (p<0.0001), at N35 (p<0.0001) and at NC11A (p=0.008).
    - when flow at N3001 is low eg 1100 ML/day, a 100 ML/day increase in flow increased the TN concentration by 1.5%
    - when flow at N3001 is moderate eg 1400 ML/day, a 100 ML/day increase in flow increased the concentration at N3001 by 1.2%
    - when flow at N3001 is high, eg 1700 ML/day, a 100 ML/day increase in flow increased the concentration at N3001 by 1.0%.
    - When flow at N35 is low eg 1000 ML/day, a 100 ML/day increase in flow increased the TN concentration by 1.1%
    - when flow at N35 is moderate eg 1300 ML/day, a 100 ML/day increase in flow increased the concentration at N3001 by 0.8%
    - when flow at N35 is high, eg 1600 ML/day, a 100 ML/day increase in flow increased the concentration at N35 by 0.7%.
    - when flow at NC11A is low eg 30 ML/day, a 5 ML/day increase in flow increased the TN concentration by 0.5%
    - when flow at NC11A is moderate eg 55 ML/day, a 5 ML/day increase in flow increased the concentration at NC11A by 0.3%
    - when flow at NC11A is high, eg 100 ML/day, a 5 ML/day increase in flow increased the concentration at NC11A by 0.1%.
- Long term trends:
  - There was a significant interaction between site and linear and quadratic trends (p<0.0001).
  - At the upstream and downstream sites, the total nitrogen concentration trend decreased until approximately 2015 before increasing. Whereas, at the tributary site (NC11A), the total nitrogen concentration showed a slightly increasing linear trend.
  - As of mid-2020, the trend at the downstream and upstream sites was increasing, while the trend at the tributary site was flattening out.
- Seasonal trends:
  - All site by 1st order sine and cosine terms by year interactions were included to capture a pattern of one peak per year in February and a trough around July with an amplitude that differed between years and sites.

- Site geometric mean total nitrogen concentrations:
  - There was only one period of data for the downstream-upstream comparison which showed a significant difference between sites ($p<0.0001$).
  - After adjusting for linear, quadratic and seasonal trends the geometric mean total nitrogen concentration:
    - At N3001 was 0.82 mg/L (95% CI = 0.77 to 0.86 mg/L), at NC11A was 1.73 mg/L (95% CI = 1.61 to 1.85 mg/L) and at N35 was 0.76 mg/L (95% CI = 0.72 to 0.80 mg/L).
  - Comparing the modelled geometric mean total nitrogen concentrations between sites:
    - The geometric mean for N3001 was 107% (95% CI 99 to 117%) of the geometric mean for N35.
    - The geometric mean for N3001 was 47% (95% CI 43 to 52%) of the geometric mean for NC11A.

4.4.5 Castle Hill WWTP – Dissolved inorganic nitrogen load

There were 753 dissolved inorganic nitrogen load records in the Castle Hill WWTP data series. There were 211 records prior to Round Corner WWTP being decommissioned in 2001 (period 1) and 542 records after Round Corner WWTP was decommissioned (period 2). All records are included in the analyses. There were no records from mid-1996 to mid-1998 and from mid-2007 to mid-2016. The analysis models do not fit any terms during these time-periods and hence, do not predict any loads during these periods. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included the two periods defined by the decommissioning of Round Corner WWTP, linear and quadratic trends within each period and 1st, 2nd and 3rd order harmonic interaction terms to model the seasonal trends.

The model:

Log_{10}(DIN load) = period + linear trend in period 1 + linear trend in period 2 + quadratic trend in period 1 + quadratic trend in period 2 + 1st order sine + 1st order cosine + 2nd order sine + 2nd order cosine + 3rd order sine + 3rd order cosine + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

period and year are categorical factors.

Model reduction decisions:

- Periods 1 and 2: retain the linear and quadratic trend terms as the p-values for the quadratic terms using the type I SS were <0.15
- Retain all harmonic interaction terms as the p-values for the 3rd order terms from the type I SS were <0.15

- Remove the main effect harmonic terms since they can be included in the harmonic interaction terms.

Step 2: Fit the final, reduced model

Log_{10}(DIN load) = period + linear trend in period 1 + linear trend in period 2 + quadratic trend in period 1 + quadratic trend in period 2 + 1st order sine by Year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

period and year are categorical factors.

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-47. There were no records from mid-1996 to mid-1998 and from mid-2007 to mid-2016. The analysis model does not fit any terms during these time-periods and hence, does not predict any loads during these periods. The straight line on the figure joins the predicted value for the last data point prior to the missing data period and the predicted value for the first data point after the missing data period for each missing data period.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix I). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table I-9 and Table I-10, respectively. The residual plots for this model are shown in Figure I-5.

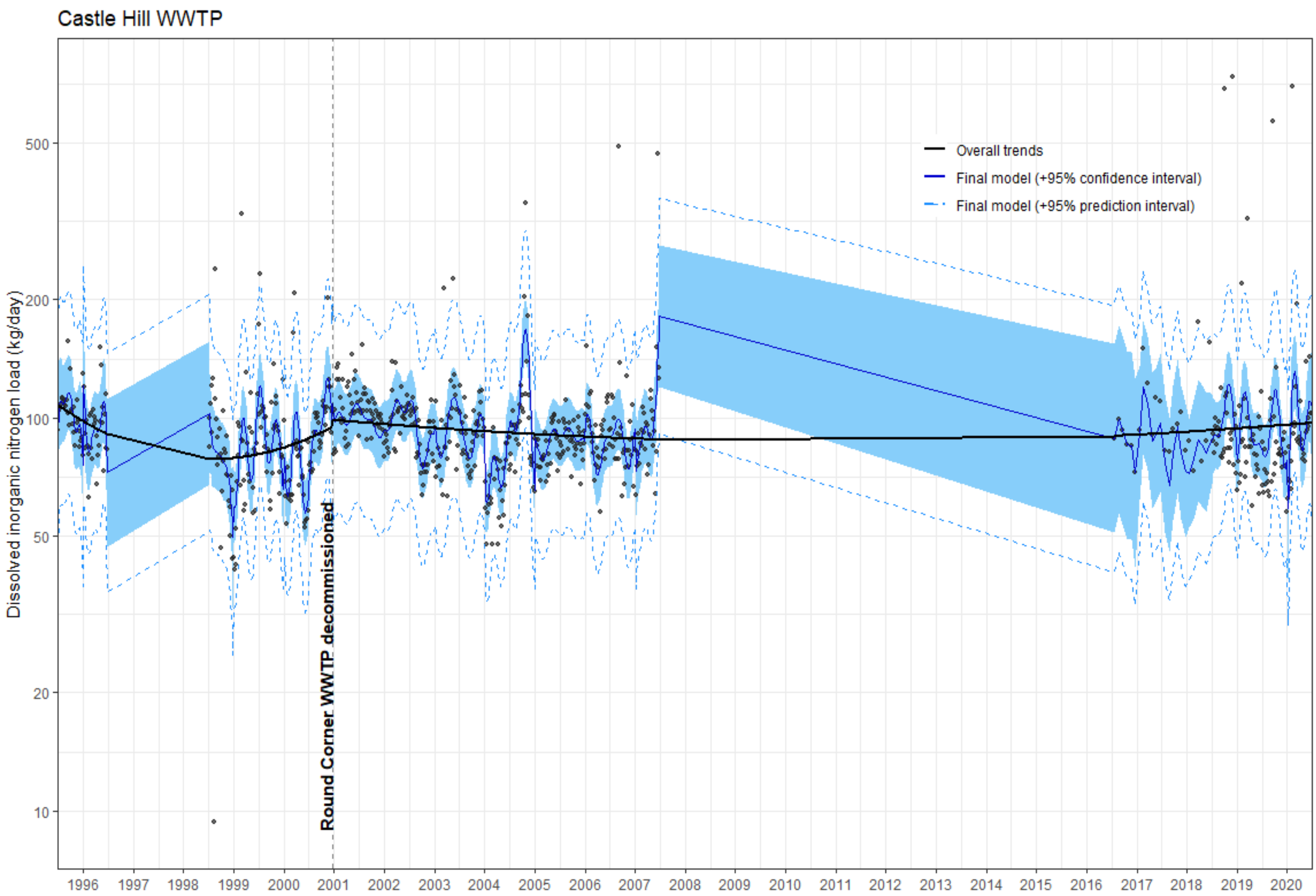

Figure 4-47 Dissolved inorganic nitrogen load from Castle Hill WWTP: fitting terms to model interventions, linear and quadratic trends within each period and seasonal trends overlaid with the trends in each period

All terms in the final, reduced model had a p-value for the corresponding type I SS <0.15 except for the linear trend in period 2 with a p-value of 0.81. This term was included in the model as the corresponding quadratic term was significant (p=0.009). The magnitude and p-values for the type III SS differ compared to the type I SS suggesting that the regression parameters were not necessarily independent. In period 1, some of the curvilinear trend is accounted for by the seasonal trends each year as they dominate this part of the data series. In period 2, with a longer series of data, the linear and quadratic trends were more significant after adjusting for the seasonal trends each year.

The model fitted the data well (R^2=0.30 and adjusted R^2=0.19) except for those at extremely high loads. Six values had a leverage of 1 (ie the model fitted these values exactly). These were the records in the second half of 2016. The distribution of the residuals was approximately Normal with a low density, long tail capturing the residuals from the high value not being captured by the model. The residuals plotted against the fitted or predicted values showed no remaining pattern in the data series and the scale location plot also supports the lack of fit to the high loads.

Key outcomes

- Dissolved inorganic nitrogen load:
  - There was no EPL limit for dissolved inorganic nitrogen load
  - The final reduced model fitted well with R^2=0.30 and adjusted R^2=0.19. However, the residual plots showed the model did not capture the extremely high dissolved inorganic nitrogen loads.
- Long term trends:
  - Significant curvilinear trends were observed in both periods
    - Prior to decommissioning Round Corner WWTP, dissolved inorganic nitrogen load appeared to have a decreasing curvilinear trend until sometime during the missing data period (presumably around 1998 as for TN), when the load started to increase until the end of the period.
    - After decommissioning Round Corner WWTP, there was a slight decreasing curvilinear trend until sometime during the missing data period, again presumably until around 2014 as for TN when total nitrogen load started to curve slightly upwards again.
    - As of mid-2020, the trend was increasing slightly.
- Seasonal trends:
  - First, second and third order sine and cosine terms by year interactions were included to capture a more complex pattern of three peaks per year, capturing the largest one in February and two smaller ones in late May/early June and September. The lowest trough was around late October/early November. The magnitude of the peaks and troughs differed between years.
- After adjusting for seasonal trends, the geometric mean dissolved inorganic nitrogen load:
  - Prior to the decommissioning of Round Corner WWTP (period 1) was 75.3 kg/day (95% CI = 56.6 to 100.1 kg/day). The width of the confidence interval is large due to the small number of records in Period 1.
  - After decommissioning of Round Corner WWTP (period 2) was 84.3 kg/day (95% CI = 79.5 to 89.4 kg/day)
- Comparing the modelled geometric mean dissolved inorganic nitrogen loads between periods:
  - The geometric mean after decommissioning Round Corner WWTP (period 2) was 112% (95% CI = 84 to 150%) of the geometric mean for the period prior to the decommissioning of Round Corner WWTP (period 1). The width of the confidence interval is large due to the smaller number of records in period 1.

4.4.6 Rouse Hill WWTP – Dissolved inorganic nitrogen load

There were 1524 dissolved inorganic nitrogen load records in the Rouse Hill WWTP data series. There were 690 prior to the nitrogen upgrade in 2010 (period 1) and 122 after the upgrade (period 2). All records are included in the analyses. There were no records from mid-1996 to mid-1998, from mid-2007 to mid-2008 and from mid-2009 to mid-2018. The analysis models do not fit any terms during these time-periods and hence, do not predict any loads during these periods. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included the two periods defined by the nitrogen upgrade at Rouse Hill WWTP, linear and quadratic trends within each period and 1st, 2nd and 3rd order harmonic interaction terms to model the seasonal trends.

The model:

Log_{10}(DIN load) = period + linear trend in period 1 + linear trend in period 2 + quadratic trend in period 1 + quadratic trend in period 2 + 1st order sine + 1st order cosine + 2nd order sine + 2nd order cosine + 3rd order sine + 3rd order cosine + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

period and year are categorical factors.

Model reduction decisions:

- Periods 1 and 2: retain the linear and quadratic trend terms as the p-values for the quadratic terms using the type I SS were <0.15
- Retain 1st and 2nd order harmonic by year interaction terms and remove the 3rd order harmonic by year term as the p-values from the type I SS were >0.15 for both terms (ie 0.25 and 0.43 for cosine and sine respectively)
- Remove the main effect harmonic terms since they can be included in the harmonic interaction terms.

Step 2: Fit the final, reduced model

Log_{10}(DIN load) = period + linear trend in period 1 + linear trend in period 2 + quadratic trend in period 2 + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

period and year are categorical factors.

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-48.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix I). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table I-11 and Table I-12, respectively. The residual plots for this model are shown in Figure I-6.

All terms in the final, reduced model had a p-value for the corresponding type I SS <0.15 except for the linear trend in period 2 (p=0.95). This term was included in the model as the quadratic trend for period 2 is <0.15. The magnitude and p-values for the type III SS differ compared to the type I SS for period 2 suggesting that the regression parameters were not necessarily independent. In period 1, while the type III SS p-values were the same as the type I SS p-values, the amount of variation explained by the terms in the model was reduced after adjusting for the seasonal trends by year in a similar fashion as for DIN at Castle Hill WWTP. The seasonal trends by year dominated this part of the data series given its length and the two periods of missing data. In period 2, with a longer time period and a very large gap in the data series, the linear and quadratic trends had p-values of 0.15 and 0.14 respectively after adjusting for the seasonal trends each year. The seasonal trend by year dominates this short series.

The model fitted the data well (R^2=0.82 and adjusted R^2=0.80) except for those at extremely high loads, and, to a lesser extent the extremely low loads. The very high R^2 possibly suggests that there were too many terms in the model (ie overfitted). However, all terms meet the criterion to keep them in the model. Four values showed a high leverage (ie terms in the model are included because of their contribution to the variability in the data). The distribution of the residuals was approximately Normal and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

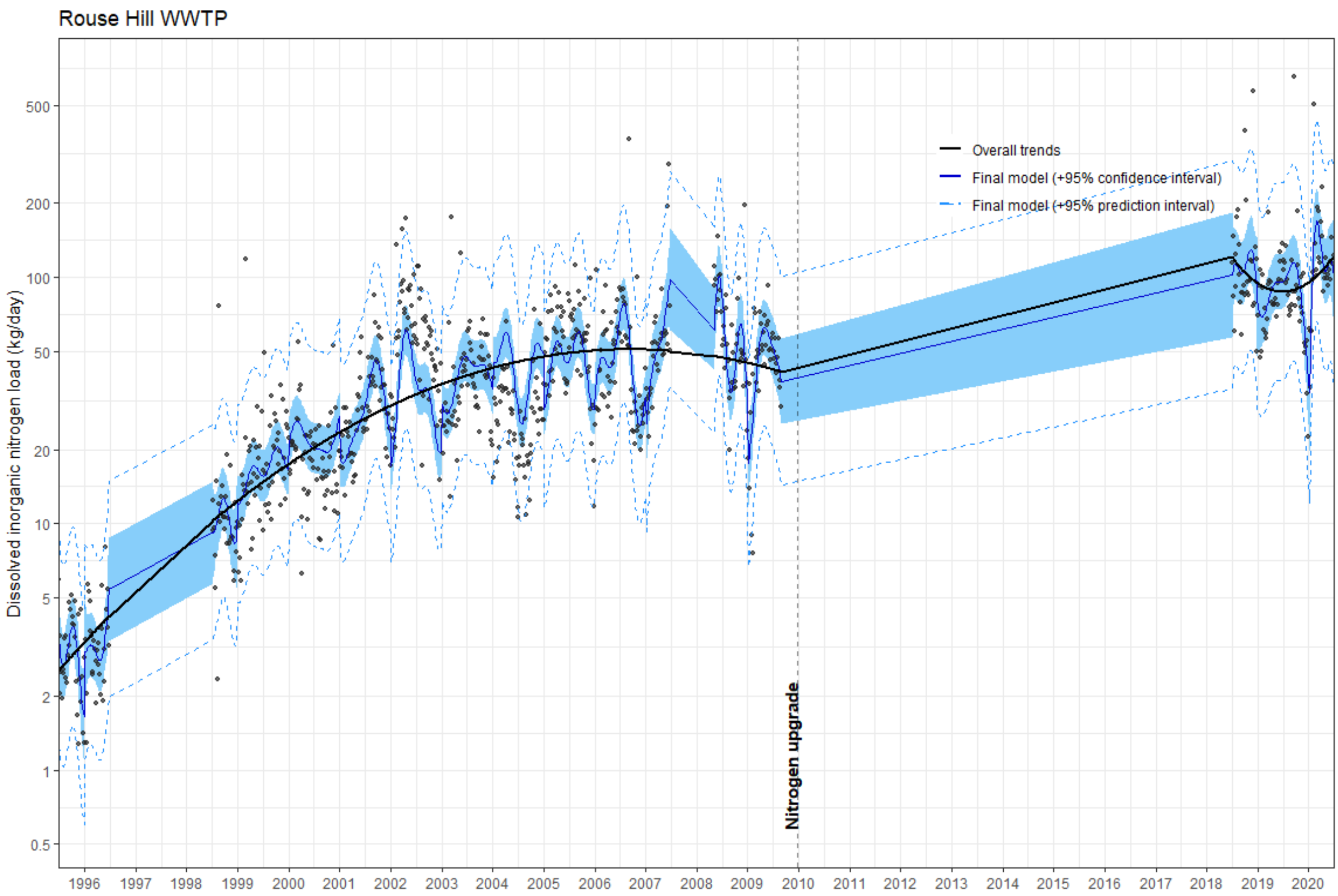

Figure 4-48 Dissolved inorganic nitrogen load from Rouse Hill WWTP: fitting terms to model interventions, linear and quadratic trends within each period and seasonal trends overlaid with the trends in each period

Key outcomes

- Dissolved inorganic nitrogen load:
  - There was no EPL limit for dissolved inorganic nitrogen load
  - The final reduced model fitted well with R^2=0.82 and adjusted R^2=0.80. However, the residual plots showed the model did not capture the extremely high, and to a lesser extend extremely low DIN loads. The very high R^2 possibly suggests that there were too many terms in the model (ie overfitted). However, all terms meet the criterion to keep them in the model.
- Long term trends:
  - Significant curvilinear trends were observed in both periods:

    - Before the nitrogen upgrade (period 1), dissolved inorganic nitrogen load had an increasing curvilinear trend until around 2005 when the load started to decrease to the end of the period
    - After the nitrogen upgrade (period 2), there were no records until 2018, where DIN load was higher than at the end of period 1 (ie before the nitrogen upgrade). From 2018, the DIN load showed a decreasing curvilinear trend to mid-2019 when load started to increase again.
    - As of mid-2020, the trend in DIN load was increasing.
- Seasonal trends:
  - First and, second and third order sine and cosine terms by year interactions were included to capture a more complex pattern of three two peaks per year, capturing the largest one in February and a smaller one around August/September. The magnitude of the peaks and troughs differed between years.
- After adjusting for seasonal trends, the geometric mean dissolved inorganic nitrogen load:
  - Prior to the nitrogen upgrade at Rouse Hill WWTP (period 1) was 37.2 kg/day (95%CI = 35.3 to 39.3 kg/day)
  - After the nitrogen upgrade at Rouse Hill WWTP (period 2) was 96.6 kg/day (95% CI = 78.6 to 118.6 kg/day)
- Comparing the modelled geometric mean dissolved inorganic nitrogen loads between periods:
  - The geometric mean after the nitrogen upgrade at Rouse Hill WWTP (period 2) was 259% (95% CI = 210 to 321%) of the geometric mean for the period prior to the nitrogen upgrade (period 1)

4.4.7 Hawkesbury River at Cattai SRA (N3001) – Dissolved Inorganic nitrogen concentration

Due to the missing data gaps in the DIN loads from the various WWTPs fitted as covariates in the model, only data from mid-2018 was included in the model ie 33 records at N3001. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included DIN concentration at the upstream site N35, the flow at N35, the flow in Cattai Creek, Castle Hill WWTP DIN load, Rouse Hill WWTP DIN load, linear and quadratic trends. Only the 1^{st} order harmonic interaction terms was included to model the seasonal trends given the small number of records.

The model:

Log_{10}(N3001 DIN concentration) = log_{10}(N35 DIN concentration) + log_{10}(flow at N35) + log_{10}(flow at Cattai Creek) + log_{10}(lag 1 (Castle Hill WWTP DIN load)) + log_{10}(lag 1 (Rouse Hill

WWTP DIN load)) + linear trend + quadratic trend + 1st order sine by year + 1st order cosine by year

Where:

- year is categorical factors.
- Flow at N35 is derived as described in Volume 2: Appendix E (Table E-5)
- Lag 1 for the loads from the WWTPs are loads estimated on the day before the sampling dates at N39.

Model reduction decisions:

- remove linear and quadratic trend terms
- Remove the 1st order harmonic by year interaction terms.

Step 2: Fit the final, reduced model

Log_{10}(N3001 DIN concentration) = log_{10}(N35 DIN concentration) + log_{10}(flow at N35) + log_{10}(flow at Cattai Creek) + log_{10}(lag 1 (Castle Hill WWTP DIN load)) + log_{10}(lag 1 (Rouse Hill WWTP DIN load)) + linear trend

Where:

- Flow at N35 is derived as described in Volume 2: Appendix E (Table E-5)
- Lag 1 for the loads from the WWTPs are loads estimated on the day before the sampling dates at N39.

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-49.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix I). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table I-13 and Table I-14, respectively. The residual plots for this model are shown in Figure I-7.

Flow corresponding to N35 and the three WWTPs TN load estimates were retained in the model as part of the study design. The p-values corresponding to the Type III SS varied are similar to the type I SS p-values.

The model fitted the data well (R^2=0.84 and adjusted R^2=0.81) except for those at extremely high and low concentrations as shown on the Q-Q plot. The high R^2 also reflected the model with six terms to explain 33 records was possibly overfitted. However, the terms in the model, while not statistically significant, were included to answer various hypotheses. This lack of fit was also shown by the pattern in the residuals vs fitted plot, scale location plot and distribution of the residuals.

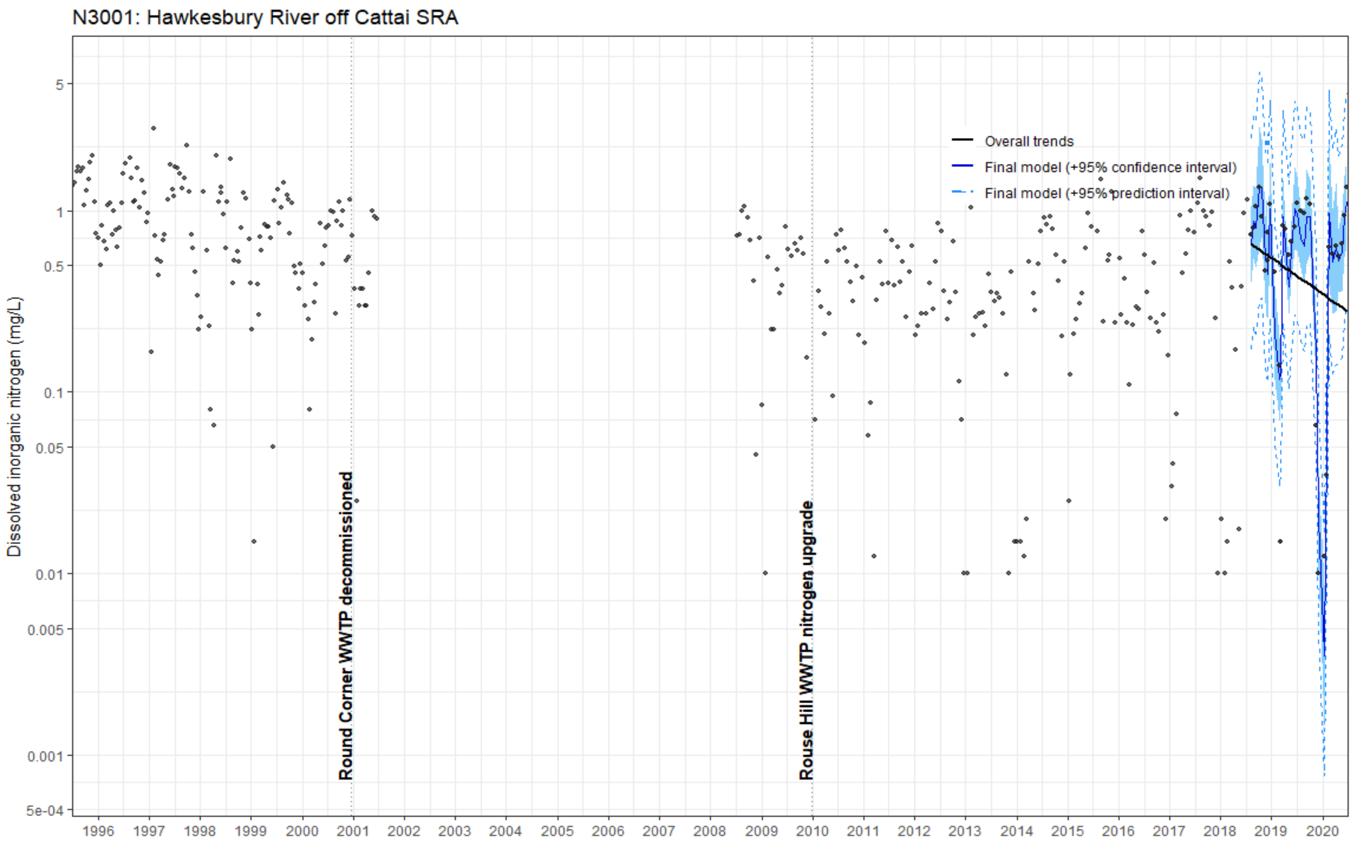

Figure 4-49 Dissolved inorganic nitrogen concentrations at Cattai SRA (N3001): fitting terms to model upstream concentration, upstream river flow, Cattai Creek flow, seasonal trends, TN and DIN loads from Castle Hill and Rouse Hill WWTPs, along with linear and quadratic trends and seasonal trends overlaid with the trend

Key outcomes

- Dissolved inorganic nitrogen concentration:
  - There was no ANZG default level for DIN
  - The final reduced model fitted well with R^2=0.84 and adjusted R^2=0.81. However, the residual plots showed the model did not capture the extremely high or low dissolved inorganic nitrogen concentrations.
- Impact of upstream catchment and tributary:
  - DIN concentration at N35 was significantly correlated to the concentration at N3001 ($p<0.0001$).
    - when DIN concentration at N35 is low eg 0.1 mg/L, a 0.005 mg/L increase of DIN concentration increased the concentration at N3001 by 5.8%
    - when DIN concentration at N35 is moderate eg 0.5 mg/L, a 0.005 mg/L increase in concentration increased the concentration at N3001 by 1.2%

- when DIN concentration at N35 is high eg 1 mg/L, a 0.005 mg/L increase in concentration increased the concentration at N3001 by 0.6%.
  - Flow in the Nepean River at N35 was not correlated to the concentration of DIN at N3001 when adjusted for concentration at N35 (p=0.2) or after adjusting for all terms in the model (p=0.4).
  - Flow in Cattai Creek was not correlated to the concentration of TN at N3001 after adjusting for the upper catchment variables (p=0.9) or after adjusting for all terms in the model (p=0.8).
- Impact of WWTPs:
  - DIN load from Castle Hill WWTP was not significantly correlated to the concentration of DIN at N3001 when adjusted only for upstream catchment measures (p=0.9) or after adjusting for all variables in the model (p=0.8).
  - DIN load from Rouse Hill WWTP was not significantly correlated to the concentration of TN at N3001 when adjusted only for upstream catchment measures and Castle Hill WWTP load (p=0.4) or after adjusting for all variables in the model (p=0.4).
- Long term trends:
  - There was no trend in DIN concentration at N3001. The overlayed trend on the figure was influenced by the extremely low number of records.
- Seasonal trends:
  - No additional seasonal trends needed to be accounted for.
- After adjusting for flow and concentration at the upstream site, flow from the tributary and load from Castle Hill and Rouse Hill WWTPs, the geometric mean DIN concentration
  - In period 3, after Rouse Hill WWTP nitrogen upgrade was 0.64 mg/L (95% CI 0.46 to 0.89 mg/L).

4.4.8 Hawkesbury River at Cattai SRA (N3001) and Wilberforce (N35) – Dissolved Inorganic nitrogen concentration (downstream/upstream)

There were no dissolved Inorganic nitrogen concentration records from 2002 to mid-2008 at the tributary site of NC11A. The analysis models included data from 2008 ie 637 records in total, 206 from N3001, 215 from NC11A and 216 from N35. However, the data prior to this time are plotted for completeness. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included a factor for site identifier for the upstream site, tributary site and downstream site, site by flow interaction term to allow the relationship with flow to differ between sites, interaction terms for site by linear and quadratic trends to allow them to differ within each period and 3-factor interaction terms for site by 1st, 2nd and 3rd order harmonic interaction terms to model the seasonal trends and allow them to differ between sites. Note, no Period term was included as there was only one period.

The model:

Log_{10}(DIN concentration) = site (N3001, NC11A or N35) + site by flow + site by linear trend + site by quadratic trend + site by 1st order sine by year + site by 1st order cosine by year + site by 2nd order sine by year + site by 2nd order cosine by year + site by 3rd order sine by year + site by 3rd order cosine by year

Where:

- SITE and YEAR are categorical factors.
- Flow consists of the flow corresponding to the site identified in the site variable as defined in Volume 2: Appendix E (Table E-5)

Model reduction decisions:

- No model reduction is undertaken

Step 2: Fit the final, reduced model

Log_{10}(DIN concentration) = site (N3001, NC11A or N35) + site by flow + site by linear trend + site by quadratic trend + site by 1st order sine by year + site by 1st order cosine by year + site by 2nd order sine by year + site by 2nd order cosine by year + site by 3rd order sine by year + site by 3rd order cosine by year

Where:

- site and year are categorical factors.
- Flow consists of the flow corresponding to the site identified in the site variable as defined in Volume 2: Appendix E (Table E-5)

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-50.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix I). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table I-15 and Table I-16, respectively. The residual plots for this model are shown in Figure I-8.

The site and site by flow parameters were retained in the model as they formed part of the study design. The p-values corresponding to the type III SS are similar those with the type I SS.

The model fitted the data well (R^2=0.82 and adjusted R^2=0.71). The distribution of the residuals was approximately Normal and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series. The Q-Q plot shows the model did not capture the extremely low and to a lesser extent, the high dissolved inorganic nitrogen loads.

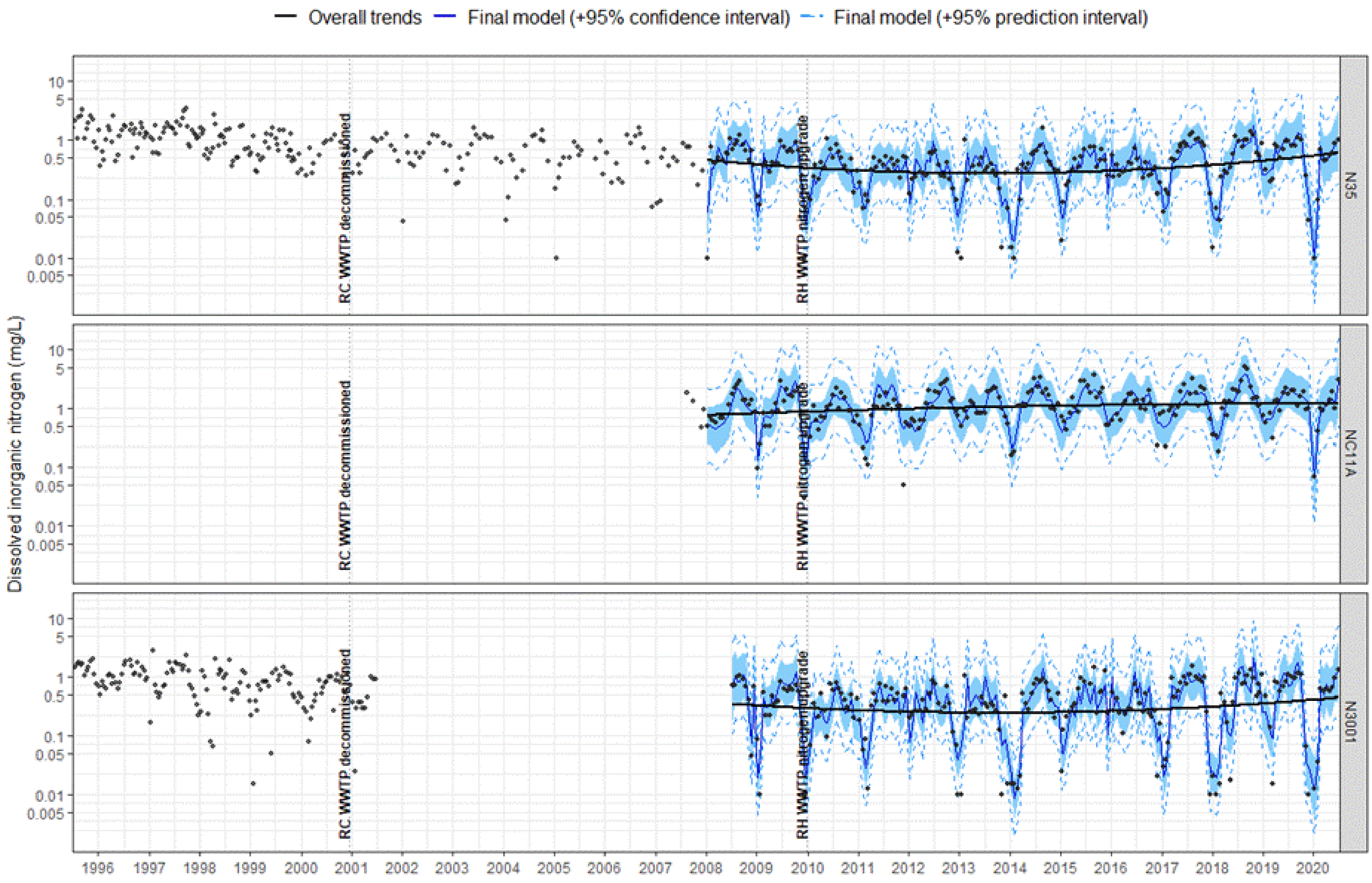

Figure 4-50 Dissolved inorganic nitrogen concentrations at Wilberforce (N35) and Off Carrai SRA (N3001), Hawkesbury River and Cattai Creek (NC11A): fitting terms to model site differences and associated flow along with linear and quadratic trends and seasonal trends

Key outcomes

- Dissolved inorganic nitrogen concentration:
  - There was no ANZG default level for DIN.
  - The final reduced model fitted well with R^2=0.82 and adjusted R^2=0.71. However, the residual plots showed the model did not capture the extremely low and to a lesser extent, the high dissolved inorganic nitrogen concentrations.
- Flow:
  - The interaction between flow and site was significant ($p<0.0001$).
  - As flow increased, DIN concentration increased at N3001 and N35 ($p<0.0001$). There was no evidence of any relationship at NC11A ($p=0.3$).

        - when flow at N3001 is low eg 1100 ML/day, a 100 ML/day increase in flow increased the DIN concentration by 4.4%
        - when flow at N3001 is moderate eg 1400 ML/day, a 100 ML/day increase in flow increased the concentration at N3001 by 3.5%
        - when flow at N3001 is high, eg 1700 ML/day, a 100 ML/day increase in flow increased the concentration at N3001 by 2.9%.
        - when flow at N35 is low eg 1000 ML/day, a 100 ML/day increase in flow increased the DIN concentration by 3.4%
        - when flow at N35 is moderate eg 1300 ML/day, a 100 ML/day increase in flow increased the concentration at N3001 by 2.6%
        - when flow at N35 is high, eg 1600 ML/day, a 100 ML/day increase in flow increased the concentration at N35 by 2.1%.
- Long term trends:
    - There was a significant interaction between site and linear and quadratic trends ($p<0.01$)
    - There was a curvilinear trend that differed between sites. At the upstream and downstream sites, the DIN concentration trended downwards until approximately 2015 before slightly increasing. Whereas, at NC11A, the trend was reasonably flat.
    - As of mid-2020, the trend at the downstream and upstream sites was increasing and the trend at the tributary site was flat.
- Seasonal trends:
    - All site by 1st order sine and cosine terms by year interactions were included to capture a pattern of one peak per year in February and a trough around July with an amplitude that differed between years and sites.
- Site geometric mean dissolved inorganic nitrogen concentrations:
    - There was only one period of data for the downstream-upstream comparison. There was a significant difference between sites ($p<0.0001$).
    - After adjusting for linear, quadratic and seasonal trends:
        - the geometric mean at N3001 was 0.31 mg/L (95% CI = 0.27 to 0.36 mg/L), at NC11A was 1.13 mg/L (95% CI = 0.94 to 1.35 mg/L) and at N35 was 0.31 mg/L (95% CI = 0.27 to 0.36 mg/L).
    - Comparing the modelled geometric mean dissolved inorganic nitrogen concentrations between sites:
        - The geometric mean for N3001 was 101% (82 to 124%) of the geometric mean for N35.
        - The geometric mean for N3001 was 28% (22 to 35%) of the geometric mean for NC11A.

4.4.9 Castle Hill WWTP – Total phosphorus load

There were 1524 total phosphorus load records in the Castle Hill WWTP data series. There were 334 records prior to Round Corner WWTP being decommissioned in 2001 (period 1) and 1190 records after the decommissioning (period 2). All records are included in the analyses. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included the two periods defined by the decommissioning of Round Corner WWTP, linear and quadratic trends within each period and 1st, 2nd and 3rd order harmonic interaction terms to model the seasonal trends.

The model:

Log_{10}(TP load) = period + linear trend in period 1 + linear trend in period 2 + quadratic trend in period 1 + quadratic trend in period 2 + 1st order sine + 1st order cosine + 2nd order sine + 2nd order cosine + 3rd order sine + 3rd order cosine + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

period and year are categorical factors.

Model reduction decisions:

- Periods 1: remove the quadratic trend term as the p-value is >0.15
- Period 2: retain the linear and quadratic trend terms as the p-values for the quadratic term using the type I SS were <0.15
- Retain all harmonic interaction terms as the p-values for the 3rd order terms from the type I SS were <0.15 (ie <0.0001 and 0.03 for cosine and sine respectively)
- Remove the main effect harmonic terms since they can be included in the harmonic interaction terms.

Step 2: Fit the final, reduced model

Log_{10}(TP load) = period + linear trend in period 1 + linear trend in period 2 + quadratic trend in period 2 + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

period and year are categorical factors.

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-51.

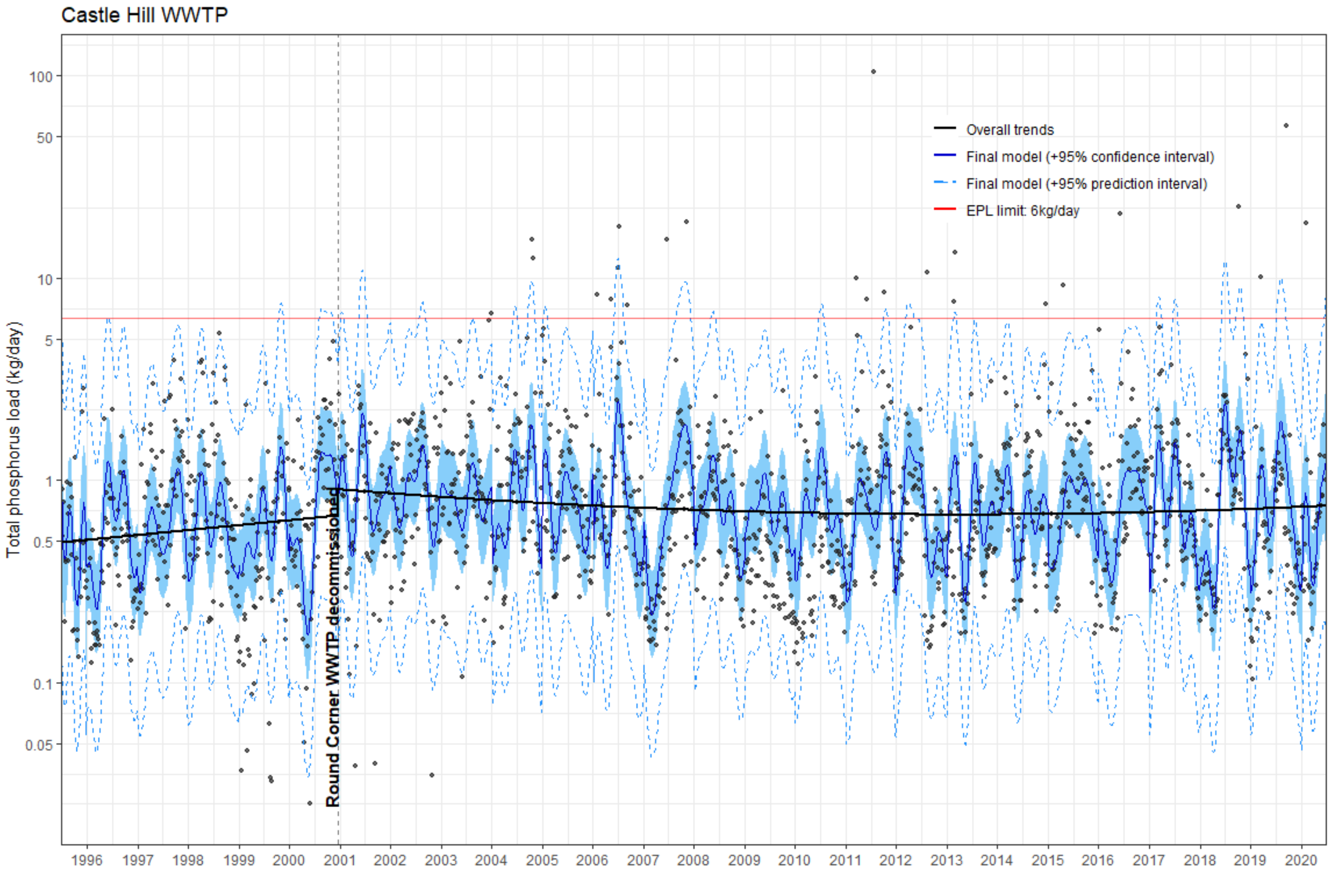

Figure 4-51 Total phosphorus load from Castle Hill WWTP: fitting terms to model interventions, linear and quadratic trends within each period and seasonal trends overlaid with the trends in each period

The detailed statistical outcomes of this model are included in Volume 2 (Appendix I). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table I-17 and Table I-18, respectively. The residual plots for this model are shown in Figure I-9.

All terms in the final, reduced model had a p-value for the corresponding type I SS <0.15. Each term in the model also had a p-value of similar magnitude after adjusting for all other terms in the model (type III SS) except for the linear trends in periods 1 and 2. The linear trend in period 1 had type III SS p-value of 0.44 suggesting that the seasonal trend across the years was also accounted for the linear trend. In period 2, the linear trend was more significant (type III SS p-value= 0.002) suggesting that even after accounting for the seasonal trends across years, there was an underlying quadratic trend.

The model fitted the data well (R^2=0.30 and adjusted R^2=0.21) except for those at extremely high loads, and to a lesser extent, those at extremely low loads. Four values showed a high leverage (ie terms in the model are included because of their contribution to the variability in the data). The distribution of the residuals was approximately Normal and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

Key outcomes

- Total phosphorus load:
  - The majority of records were less than current EPL limit (6.3 kg/day)
  - The final reduced model fitted well with R^2=0.30 and adjusted R^2=0.21. However, the residual plots showed the model did not capture the extremely high, and to a lesser extent, the extremely low total phosphorus loads.
- Long term trends:
  - Before the decommissioning of Round Corner WWTP, total phosphorus load had an increasing linear trend that was accounted for by the seasonal trends each year
  - After decommissioning Round Corner WWTP, there was a very slight (almost linear) curvilinear trend.
  - As of mid-2020, the trend was slightly increasing but the majority of observed TP loads were less than the EPL limit.
- Seasonal trends:
  - First, second and third order sine and cosine terms by year interactions were included to capture a more complex pattern of three peaks per year, capturing the largest one in February and two smaller ones in late May/ early June and September. The lowest trough was around late October/ early November. The magnitude of the peaks and troughs differed between years.
- After adjusting for seasonal trends, the modelled geometric mean total phosphorus load:
  - Prior to the decommissioning of Round Corner WWTP (period 1) was 0.58 kg/day (95% CI = 0.53 to 0.63 kg/day)
  - After the decommissioning of Round Corner WWTP (period 2) was 0.68 kg/day (95% CI = 0.64 to 0.73 kg/day)
- Comparing the modelled geometric mean total phosphorus loads between periods:
  - The geometric mean after decommissioning Round Corner WWTP (period 2) was 117% (95% CI = 105 to 132) of the geometric mean for the period prior to the decommissioning (period 1).

4.4.10 Rouse Hill WWTP – Total phosphorus load

There were 1524 total phosphorus load records in the Rouse Hill WWTP data series. There were 669 records prior to the phosphorus upgrade in 2006 (period 1) and 855 after the upgrade (period 2). All records are included in the analyses. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included the two periods defined by the phosphorus upgrade at Rouse Hill WWTP, linear and quadratic trends within each period and 1st, 2nd and 3rd order harmonic interaction terms to model the seasonal trends.

The model:

Log_{10}(TP load) = period + linear trend in period 1 + linear trend in period 2 + quadratic trend in period 1 + quadratic trend in period 2 + 1st order sine + 1st order cosine + 2nd order sine + 2nd order cosine + 3rd order sine + 3rd order cosine + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

period and year are categorical factors.

Model reduction decisions:

- Period 1: retain the linear and quadratic trend terms as the p-values for the quadratic terms using the type I SS were <0.15
- Period 2: Remove the quadratic trend term as the p-value is >0.15
- Retain all harmonic interaction terms as at least one the p-values for the pair of 3rd order terms from the type I SS were <0.15 (ie 0.68 and 0.009 for cosine and sine respectively)
- Remove the main effect harmonic terms since they can be included in the harmonic interaction terms.

Step 2: Fit the final, reduced model

Log_{10}(TP load) = period + linear trend in period 1 + linear trend in period 2 + quadratic trend in period 1 + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

period and year are categorical factors.

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-52.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix I). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table I-19 and Table I-20, respectively. The residual plots for this model are shown in Figure I-10.

All terms in the final, reduced model had a p-value for the corresponding type I SS <0.15 except for the 3rd order cosine by year term. This was included in the model as its partner term, 3rd order sine by year interaction term had a p value <0.15. Each term in the model also had a p-value for the corresponding type III SS of a similar magnitude except for the quadratic term in period 1 and the 2nd order cosine by year term, although both still had p<0.15. This suggested that, the seasonal trend over the years accounted for some of the curvature in the trend in period 1 ie possible multicollinearity.

The model fitted the data well (R^2=0.46 and adjusted R^2=0.39) except for those at extremely high loads, and, to a lesser extent the extremely low loads. Four values showed a high leverage (ie terms in the model are included because of their contribution to the variability in the data). The distribution of the residuals was approximately Normal and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

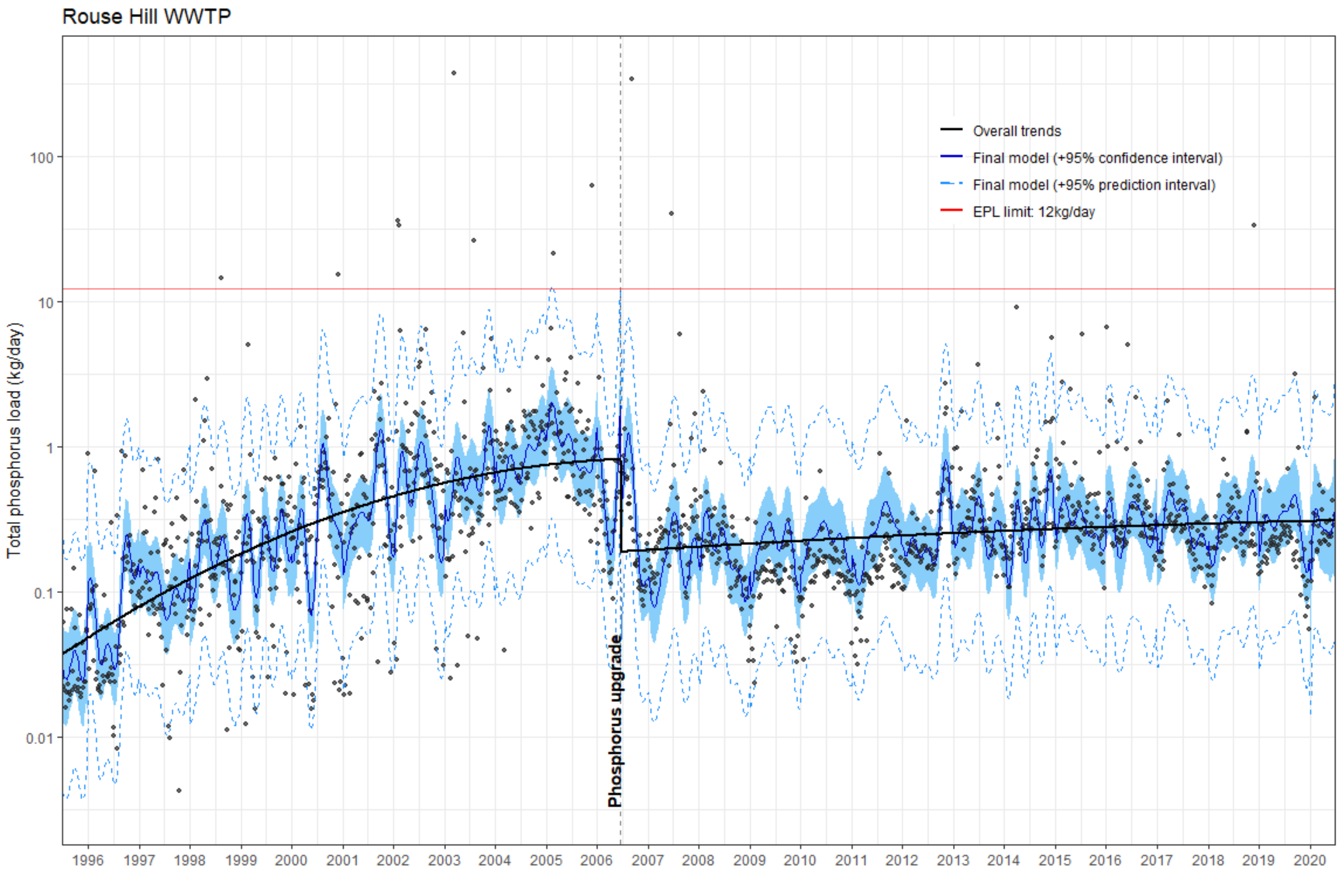

Figure 4-52 Total phosphorus load from Rouse Hill WWTP: fitting terms to model interventions, linear and quadratic trends within each period and seasonal trends overlaid with the trends in each period

Key outcomes

- Total phosphorus load:
  - The majority of records were less than current EPL limit (12.2 kg/day)
  - The final reduced model fitted well with R^2=0.46 and adjusted R^2=0.39. However, the residual plots showed the model did not capture the extremely high, and to a lesser extend extremely low total phosphorus loads.

- Long term trends:
  - Before the phosphorus upgrade, total phosphorus load had an increasing curvilinear trend until around 2005 when the load plateaued to the end of the period
  - After the phosphorus upgrade there was a significantly increasing linear trend.
  - As of mid-2020, the trend was slightly increasing.
- Seasonal trends:
  - First, second and third order sine and cosine terms by year interactions were included to capture a more complex pattern of three peaks per year, capturing the largest one in February and two smaller ones in late May/early June and September. The lowest trough was around late October/early November. The magnitude of the peaks and troughs differed between years.
- After adjusting for seasonal trends, the modelled geometric mean total phosphorus load:
  - Prior to the phosphorus upgrade at Rouse Hill WWTP (period 1) was 0.322 kg/day (95% CI = 0.289 to 0.358 kg/day)
  - After the phosphorus upgrade at Rouse Hill WWTP (period 2) was 0.246 kg/day (95% CI = 0.231 to 0.262 kg/day)
- Comparing the modelled geometric mean total phosphorus loads between periods:
  - The geometric mean after the phosphorus upgrade at Rouse Hill WWTP (period 2) was 76% (95% CI = 68 to 86%) of the geometric mean for the period prior to the phosphorus upgrade (period 1)

4.4.11 Hawkesbury River at Cattai SRA (N3001) – Total phosphorus concentration

There were no total phosphorus concentration records from mid-2001 to mid-2008. The analysis models include data from 2008 ie206 records at N3001. However, the data prior to 2001 are plotted for completeness. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fit the full model as one period, TP concentration at the upstream site N39, the flow at N35, the flow in Cattai Creek, Castle Hill WWTP TP load, Rouse Hill WWTP TP load, linear and quadratic trends within the period and 1st, 2nd and 3rd order harmonic interaction terms to model the seasonal trends.

The model:

Log_{10}(N3001 TP concentration) = $\log_{10}$(N35 TP concentration) + $\log_{10}$(flow at N35) + $\log_{10}$(flow from Cattai Creek) + $\log_{10}$(lag 1 (Castle Hill WWTP TP load)) + $\log_{10}$(lag 1 (Rouse Hill WWTP TP load)) + linear trend + quadratic trend + 1st order sine + 1st order cosine + 2nd order sine + 2nd order cosine + 3rd order sine + 3rd order cosine + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

- year is a categorical factor.
- Flow at N35 is derived as described in Volume 2: Appendix E (Table E-5)
- Lag 1 for the loads from the WWTPs are loads estimated on the day before the sampling dates at N3001

Model reduction decisions:

- Remove all harmonic by year interaction terms
- Remove 2nd and 3rd order main effect harmonic terms, retain the 1st order main effect harmonic terms
- Remove the quadratic trend term

Step 2: Fit the final, reduced model

Log_{10}(N3001 TP concentration) = log_{10}(N35 TP concentration) + log_{10}(flow at N35) + log_{10}(flow from Cattai Creek) + log_{10}(lag 1 (Castle Hill WWTP TP load)) + log_{10}(lag 1 (Rouse Hill WWTP TP load)) + linear trend + 1st order sine + 1st order cosine

Where:

- Flow at N35 is derived as described in Volume 2: Appendix E (Table E-5)
- Lag 1 for the loads from the WWTPs are loads estimated on the day before the sampling dates at N3001

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-53.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix I). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table I-21 and Table I-22, respectively. The residual plots for this model are shown in Figure I-11.

The upstream concentration at N35, flow corresponding to N35, flow corresponding to Cattai Creek and the two WWTPs TP load estimates and period effect were retained in the model as part of the study design. The p-values corresponding to the type III SS varied compared with the type I SS that is not unexpected - the TP loads after adjusting for the effect of loads from the other WWTP or the upstream concentration and so on

The model fitted the data well (R^2=0.79 and adjusted R^2=0.78) except for those at extremely high concentrations or, to a lesser extent, low concentrations. A few values showed a high leverage (ie terms in the model are included because of their contribution to the variability in the data). The distribution of the residuals was approximately Normal with some very low points and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

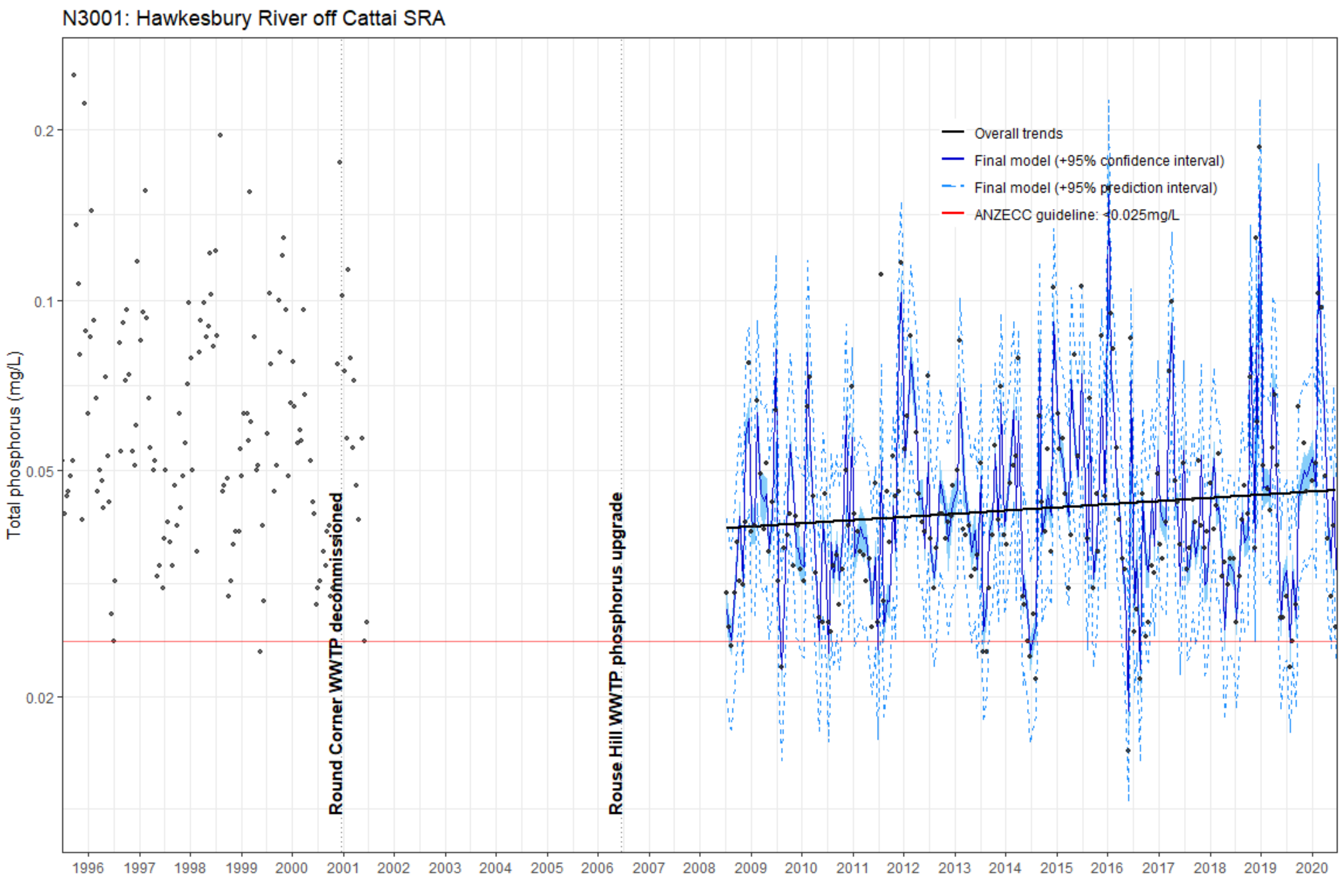

Figure 4-53 Total phosphorus concentrations at Cattai SRA (N3001): fitting terms to model upstream concentration, upstream river flow, Cattai Creek flow, loads from Castle Hill and Rouse Hill WWTPs, along with linear and quadratic trends and seasonal trends overlaid with the trends

Key outcomes

- Total phosphorus concentration:
  - TP concentration remained above the ANZG default level of <0.025 mg/L
  - The final reduced model fitted well with R^2=0.79 and adjusted R^2=0.78. However, the residual plots showed the model did not capture the extremely high or low total phosphorus concentration.
- Impact of upstream catchment and tributary:
  - TP concentration at N35 was significantly correlated to the concentration at N3001 (p<0.0001).
    - when TP concentration at N35 is low eg 0.03 mg/L, a 0.0005 mg/L increase of TP concentration increased the concentration at N3001 by 1.3%

    - when TP concentration at N35 is moderate eg 0.05 mg/L, a 0.0005 mg/L increase in concentration increased the concentration at N3001 by 0.8%
    - when TP concentration at N35 is high eg 0.08 mg/L, a 0.0005 mg/L increase in concentration increased the concentration at N3001 by 0.5%.
  - Flow in the Nepean River at N35 was significantly correlated to the concentration of TP at N3001 ($p<0.0001$).
    - when flow at N35 is low eg 1000 ML/day, a 100 ML increase in flow decreased the concentration at N3001 by 0.7%
    - when flow at N35 is moderate eg 1300 ML/day, a 100 ML increase in flow decreased the concentration at N3001 by 0.5%
    - when flow at N35 is high eg 1600 ML/day, a 100 ML increase in flow decreased the concentration at N3001 by 0.4%.
  - Flow in Cattai Creek was not significantly correlated to concentration of TP at N3001 after adjusting for the upper catchment variables ($p=0.2$) or after adjusting for all terms in the model ($p=0.1$).
- Impact of WWTPs:
  - The TP load from Castle Hill WWTP was not significantly correlated to the concentration of TP at N3001 when adjusted only for upstream catchment measures ($p=0.6$) or after adjusting for all variables in the model ($p=0.12$).
  - The TP load from Rouse Hill WWTP was not significantly correlated to the concentration of TP at N3001 when adjusted only for upstream catchment measures and Castle Hill WWTP load ($p=0.1$) or after adjusting for all variables in the model ($p=0.07$).
- Long term trends:
  - As of mid-2020, there was an increasing linear trend.
- Seasonal trends
  - First order sine and cosine terms were included to capture a pattern of one peak per year in February and one trough around August with a magnitude that was the same each year.
- After adjusting for seasonal trends, flow and concentration at the upstream site and load from Castle Hill and Rouse Hill WWTPs, the geometric mean TP concentration was 0.049 mg/L (95% CI = 0.047 to 0.051 mg/L).

4.4.12 Hawkesbury River at Cattai SRA (N3001) and Wilberforce (N35) – Total phosphorus concentration (downstream/upstream)

There were no total phosphorus concentration records from 2002 to mid-2008 at the tributary site of NC11A. The analysis models include data from 2008 ie 637 records in total, 206 from N3001, 215 from NC11A and 216 from N35. However, the data prior to this time are plotted for completeness. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included a factor for site identifier for the upstream site, tributary site and downstream site, site by flow interaction term to allow the relationship with flow to differ between sites, interaction terms for site by linear and quadratic trends to allow them to differ within each period and 3-factor interaction terms for site by 1st, 2nd and 3rd order harmonic interaction terms to model the seasonal trends and allow them to differ between sites. Note, no Period term was included as there was only one period.

The model:

Log_{10}(TP concentration) = site (N3001, NC11A or N35) + site by flow + site by linear trend + site by quadratic trend + site by 1st order sine by year + site by 1st order cosine by year + site by 2nd order sine by year + site by 2nd order cosine by year + site by 3rd order sine by year + site by 3rd order cosine by year

Where:

- site and year are categorical factors.
- Flow consists of the flow corresponding to the site identified in the site variable as defined in Volume 2: Appendix E (Table E-5)

Model reduction decisions:

- Remove all site by 2nd and 3rd order harmonic by year terms

Step 2: Fit the final, reduced model

Log_{10}(TP concentration) = site (N3001, NC11A or N35) + site by flow + site by linear trend + site by quadratic trend + site by 1st order sine by year + site by 1st order cosine by year

Where:

- SITE and YEAR are categorical factors.
- Flow consists of the flow corresponding to the site identified in the site variable as defined in Volume 2: Appendix E (Table E-5)

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-54.

The detailed statistical outcomes of this model are included in Volume 2 (Appendix I). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table I-23 and Table I-24, respectively. The residual plots for this model are shown in Figure I-12.

The site, site by flow and site by period parameters were retained in the model as they were part of the study design. The p-values corresponding to the type III SS were similar to those with the type I SS.

The model fitted the data well (R^2=0.52 and adjusted R^2=0.44). The distribution of the residuals was approximately Normal and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

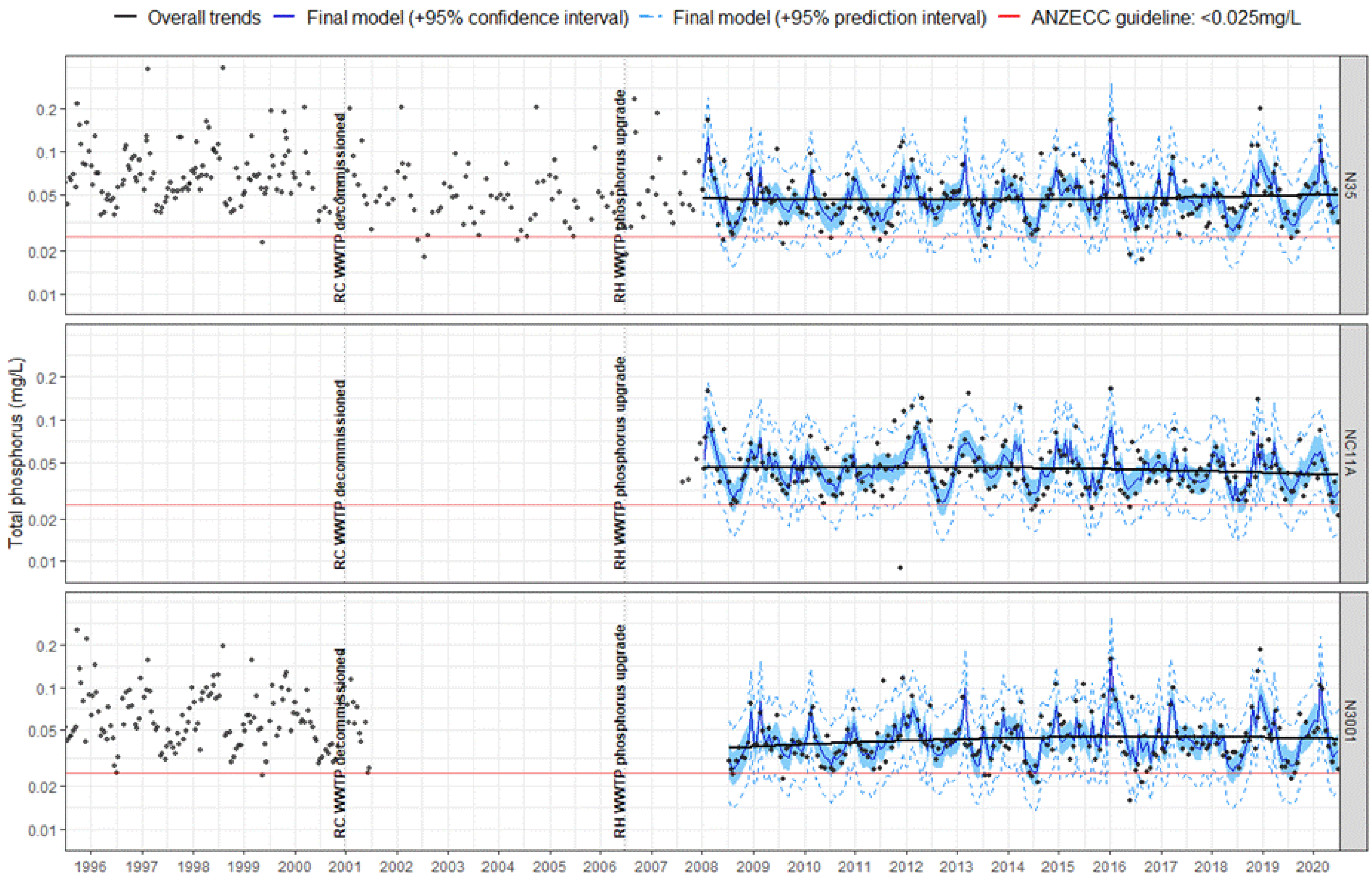

Figure 4-54 Total phosphorus concentrations at Wilberforce (N35) and Off Cattai SRA (N3001), Hawkesbury River and Cattai Creek (NC11A): fitting terms to model site differences and associated flow along with linear and quadratic trends and seasonal trends

Key outcomes

- Total phosphorus concentration:
  - TP concentration remained above the ANZG default level of <0.025 mg/L for all sites.
  - The final reduced model fitted well with R^2=0.52 and adjusted R^2=0.44. However, the residual plots showed the model did not capture the extremely high total phosphorus concentrations.
- Flow:
  - The interaction between flow and site was significant (p<0.0001).
  - As flow increased, TP concentration increased at all sites (p<0.0001).
    - when flow at N3001 is low eg 1100 ML/day, a 100 ML/day increase in flow increased the TP concentration by 1.8%

        - when flow at N3001 is moderate eg 1400 ML/day, a 100 ML/day increase in flow increased the concentration at N3001 by 1.4%
        - when flow at N3001 is high, eg 1700 ML/day, a 100 ML/day increase in flow increased the concentration at N3001 by 1.2%.
        - when flow at N35 is low eg 1000 ML/day, a 100 ML/day increase in flow increased the TP concentration by 1.8%
        - when flow at N35 is moderate eg 1300 ML/day, a 100 ML/day increase in flow increased the concentration at N3001 by 1.4%
        - when flow at N35 is high, eg 1600 ML/day, a 100 ML/day increase in flow increased the concentration at N35 by 1.2%.
        - when flow at NC11A is low eg 30 ML/day, a 5 ML/day increase in flow increased the TP concentration by 1.2%
        - when flow at NC11A is moderate eg 55 ML/day, a 5 ML/day increase in flow increased the concentration at NC11A by 0.7%
        - when flow at NC11A is high, eg 100 ML/day, a 5 ML/day increase in flow increased the concentration at NC11A by 0.4%.

- Long term trends:
    - There was a significant interaction between site and linear trends (p=0.03) and quadratic trends (p=0.05).
    - There was a slight curvilinear trend that differed between sites. N35 had a more curving trend compared to the other two sites where the trend was approximately flat.
    - As of mid-2020, the trend at the downstream and tributary sites was approximately flat and the trend at the upstream site was curving upwards slightly.
- Seasonal trends:
    - All site by 1st order sine and cosine terms by year interactions were included to capture a pattern of one peak per year in February and a trough around July with an amplitude that differed between years and sites.
- Site geometric mean total phosphorus concentrations:
    - There was only one period of data for the downstream-upstream comparison that showed a significant difference between sites (p=0.009).
    - After adjusting for linear, quadratic and seasonal trends the modelled geometric mean total phosphorus concentration:
        - At N3001 was 0.048 mg/L (95% CI = 0.045 to 0.051 mg/L), at NC11A was 0.053 mg/L (95% CI = 0.049 to 0.057 mg/L) and at N35 was 0.050 mg/L (95% CI = 0.047 to 0.053 mg/L).
    - Comparing the modelled geometric mean total phosphorus concentration between sites:

- The geometric mean for N3001 was 95% (87 to 105%) of the geometric mean for N35.
- The geometric mean for N3001 was 90% (81 to 100%) of the geometric mean for NC11A.

4.4.13 Hawkesbury River at Cattai SRA (N3001) – Chlorophyll-*a* concentration

There were no chlorophyll-*a* concentration records from mid-2001 to mid-2008. The analysis models include data from 2008 ie206 records at N3001. However, the data prior to 2001 are plotted for completeness. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fit the full model as one period, Chl-*a* concentration at the upstream site N35, the flow at N35, the flow in Cattai Creeks Castle Hill WWTP TN and TP load, Rouse Hill WWTP TN and TP load, linear and quadratic trends within the period and 1st, 2nd and 3rd order harmonic interaction terms to model the seasonal trends.

The model:

Log_{10}(Chl-*a*) = log_{10}(N35 Chl-*a*) + log_{10}(flow at N35) + log_{10}(flow from Cattai Creek) + log_{10}(lag 1 (Castle Hill WWTP TP load)) + log_{10}(lag 1 (Castle Hill WWTP TN load)) + log_{10}(lag 1 (Rouse Hill WWTP TP load)) + log_{10}(lag 1 (Rouse Hill WWTP TN load)) + linear trend + quadratic trend + 1st order sine + 1st order cosine + 2nd order sine + 2nd order cosine + 3rd order sine + 3rd order cosine + 1st order sine by year + 1st order cosine by year + 2nd order sine by year + 2nd order cosine by year + 3rd order sine by year + 3rd order cosine by year

Where:

- year is a categorical factor.
- Flow at N35 is derived as described in Volume 2: Appendix E (Table E-5)
- Lag 1 for the loads from the WWTPs are loads estimated on the day before the sampling dates at N3001

Model reduction decisions:

- Remove all harmonic by year interaction terms
- Remove all main effect harmonic terms

Step 2: Fit the final, reduced model

Log_{10}(Chl-*a*) = log_{10}(N35 Chl-*a*) + log_{10}(flow at N35) + log_{10}(flow from Cattai Creek) + log_{10}(lag 1 (Castle Hill WWTP TP load)) + log_{10}(lag 1 (Castle Hill WWTP TN load)) + log_{10}(lag 1 (Rouse Hill WWTP TP load)) + log_{10}(lag 1 (Rouse Hill WWTP TN load)) + linear trend + quadratic trend

Where:

- Flow at N35 is derived as described in Volume 2: Appendix E (Table E-5)

- Lag 1 for the loads from the WWTPs are loads estimated on the day before the sampling dates at N3001

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-55.

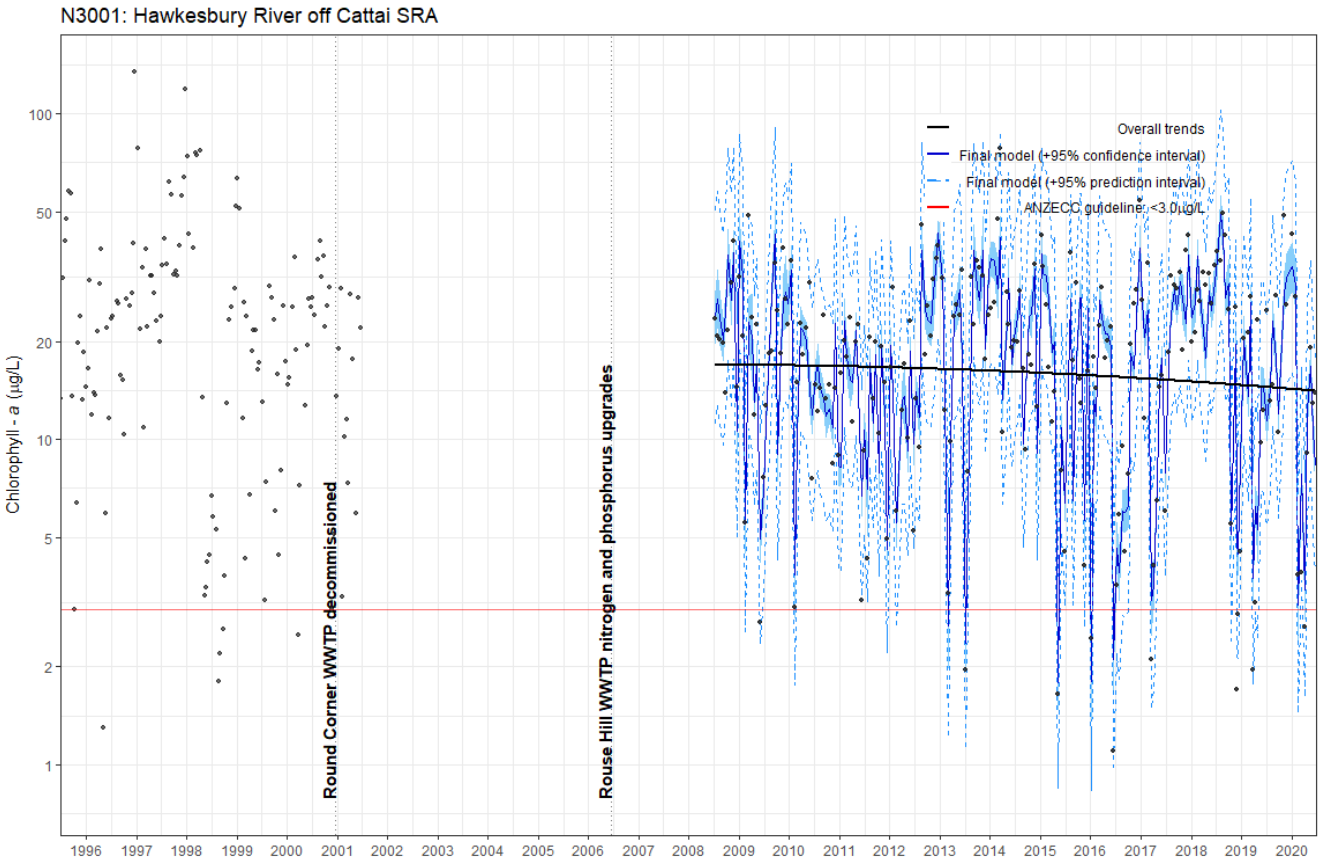

Figure 4-55 Chlorophyll-a concentrations at Cattai SRA (N3001): fitting terms to model upstream concentration, upstream river flow, Cattai Creek flow, TN, and TP loads from Castle Hill and Rouse Hill WWTPs, along with linear and quadratic trends and seasonal trends overlaid with the trend

The detailed statistical outcomes of this model are included in Volume 2 (Appendix I). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table I-25 and Table I-26, respectively. The residual plots for this model are shown in Figure I-13.

The upstream concentration at N35, flow corresponding to N35, flow corresponding to Cattai Creek and the two WWTPs TP load estimates were retained in the model as part of the study design. The p-values corresponding to the Type III SS varied compared with the type I SS that is not unexpected - the effect of the TP loads is after adjusting for the effect of loads from the other WWTP or the upstream concentration and so on.

The model fitted the data well (R^2=0.79 and adjusted R^2=0.78) except for those at extremely high concentrations or, to a lesser extent, low concentrations. A few values showed a high leverage (ie terms in the model are included because of their contribution to the variability in the data). The distribution of the residuals was approximately Normal with some very high points and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

Key outcomes

- Chlorophyll-*a* concentration:
    - Chl-*a* concentration remained above the ANZG default level of <3.0 µg/L
    - The final reduced model fitted well with R^2=0.79 and adjusted R^2=0.78. However, the residual plots showed the model did not capture the extremely high or low Chl-*a* concentration.
- Impact of upstream catchment and tributary:
    - Chl-*a* concentration at N35 was significantly correlated to the concentration at N3001 ($p<0.0001$).
        - when Chl-*a* concentration at N35 is low eg 10 µg/L, a 1 µg/L increase of Chl-*a* concentration increased the concentration at N3001 by 7.0%
        - when Chl-*a* concentration at N35 is moderate eg 20 µg/L, a 1 µg/L increase in concentration increased the concentration at N3001 by 3.5%
        - when Chl-*a* concentration at N35 is high eg 30 µg/L, a 1 µg/L increase in concentration increased the concentration at N3001 by 2.4%.
    - Flow in the Nepean River at N35 was significantly correlated to the concentration of Chl-*a* at N3001 ($p<0.0001$).
        - when flow at N35 is low eg 1000 ML/day, a 100 ML increase in flow decreased the concentration at N3001 by 1.5%
        - when flow at N35 is moderate eg 1300 ML/day, a 100 ML increase in flow decreased the concentration at N3001 by 1.2%
        - when flow at N35 is high eg 1600 ML/day, a 100 ML increase in flow decreased the concentration at N3001 by 1%.
    - Flow in Cattai Creek was not significantly correlated to concentration of Chl-*a* at N3001 after adjusting for the upper catchment variables ($p=0.1$) and was significantly correlated after adjusting for all terms in the model ($p=0.008$). This suggested that, after taking into account any linear and quadratic trends and any seasonal trends, Cattai Creek flow provides additional explanation of the variability in Chl-*a* concentration at N3001.
- Impact of WWTPs:
    - Castle Hill WWTP:

- The TN load from Castle Hill WWTP was significantly correlated to the concentration of Chl-*a* at N3001 when adjusted only for upstream catchment measures (p=0.005) and after adjusting for all variables in the model (p=0.02).
  - when the load from Castle Hill WWTP is low eg 40 kg/day, a 10 kg/day increase in load decreased the concentration at N3001 by 4.6%
  - when the load from Castle Hill WWTP is moderate eg 100 kg/day, a 10 kg/day increase in load decreased the concentration at N3001 by 2%
  - when the load from Castle Hill WWTP is high eg 160 kg/day, a 10 kg/day increase in load decreased the concentration at N35 by 1.3%.
- The TP load from Castle Hill WWTP was not correlated to the concentration of Chl-*a* at N3001 when adjusted only for upstream catchment measures (p=0.6) or after adjusting for all variables in the model (p=0.7).

- Rouse Hill WWTP:
  - The TN load from Rouse Hill WWTP was not significantly correlated to the concentration of Chl-*a* at N3001 when adjusted only for upstream catchment measures and Castle Hill WWTP load (p=0.1) or after adjusting for all variables in the model (p=0.9).
  - The TP load from Rouse Hill WWTP was not significantly correlated to the concentration of Chl-*a* at N3001 when adjusted only for upstream catchment measures and Castle Hill WWTP load (p=0.9) or after adjusting for all variables in the model (p=0.6).

- Long term trends:
  - Currently there is a small but significant decreasing curvilinear trend.
- Seasonal trends:
  - No additional terms were required for the model to help explain any seasonal trends in the data
  - After adjusting for flow and concentration at the upstream site and load from Castle Hill and Rouse Hill WWTPs, the geometric mean Chl-*a* was 13.9 µg/L (95% CI = 12.5 to 15.5 µg/L)

4.4.14 Hawkesbury River at Cattai SRA (N3001) and Wilberforce (N35) – Chlorophyll-*a* concentration (downstream/upstream)

There were no chlorophyll-*a* concentration records from 2002 to mid-2008 at the tributary site of NC11A. The analysis models include data from 2008 ie 634 records in total, 206 from N3001, 215 from NC11A and 213 from N35. However, the data prior to this time are plotted for completeness. Key outcomes are summarised at the end of this section.

Step 1: Fit the full model

Fitting the full model included a factor for site identifier for the upstream site, tributary site and downstream site, site by flow interaction term to allow the relationship with flow to differ between sites, interaction terms for site by linear and quadratic trends to allow them to differ within each period and 3-factor interaction terms for site by 1st, 2nd and 3rd order harmonic interaction terms to model the seasonal trends and allow them to differ between sites. Note, no Period term was included as there was only one period.

The model:

Log_{10}(Chl-*a* concentration) = site (N3001, NC11A or N35) + site by flow + site by linear trend + site by quadratic trend + site by 1st order sine by year + site by 1st order cosine by year + site by 2nd order sine by year + site by 2nd order cosine by year + site by 3rd order sine by year + site by 3rd order cosine by year

Where:

- site and year are categorical factors.
- Flow consists of the flow corresponding to the site identified in the site variable as defined in Volume 2: Appendix E (Table E-5)

Model reduction decisions:

- No model reduction is undertaken

Step 2: Fit the final, reduced model

Log_{10}(Chl-*a* concentration) = site (N3001, NC11A or N35) + site by flow + site by linear trend + site by quadratic trend + site by 1st order sine by year + site by 1st order cosine by year + site by 2nd order sine by year + site by 2nd order cosine by year + site by 3rd order sine by year + site by 3rd order cosine by year

Where:

- SITE and YEAR are categorical factors.
- Flow consists of the flow corresponding to the site identified in the site variable as defined in Volume 2: Appendix E (Table E-5)

The observed data, fitted model with 95% confidence interval, 95% prediction interval and long term trends are shown in Figure 4-56.

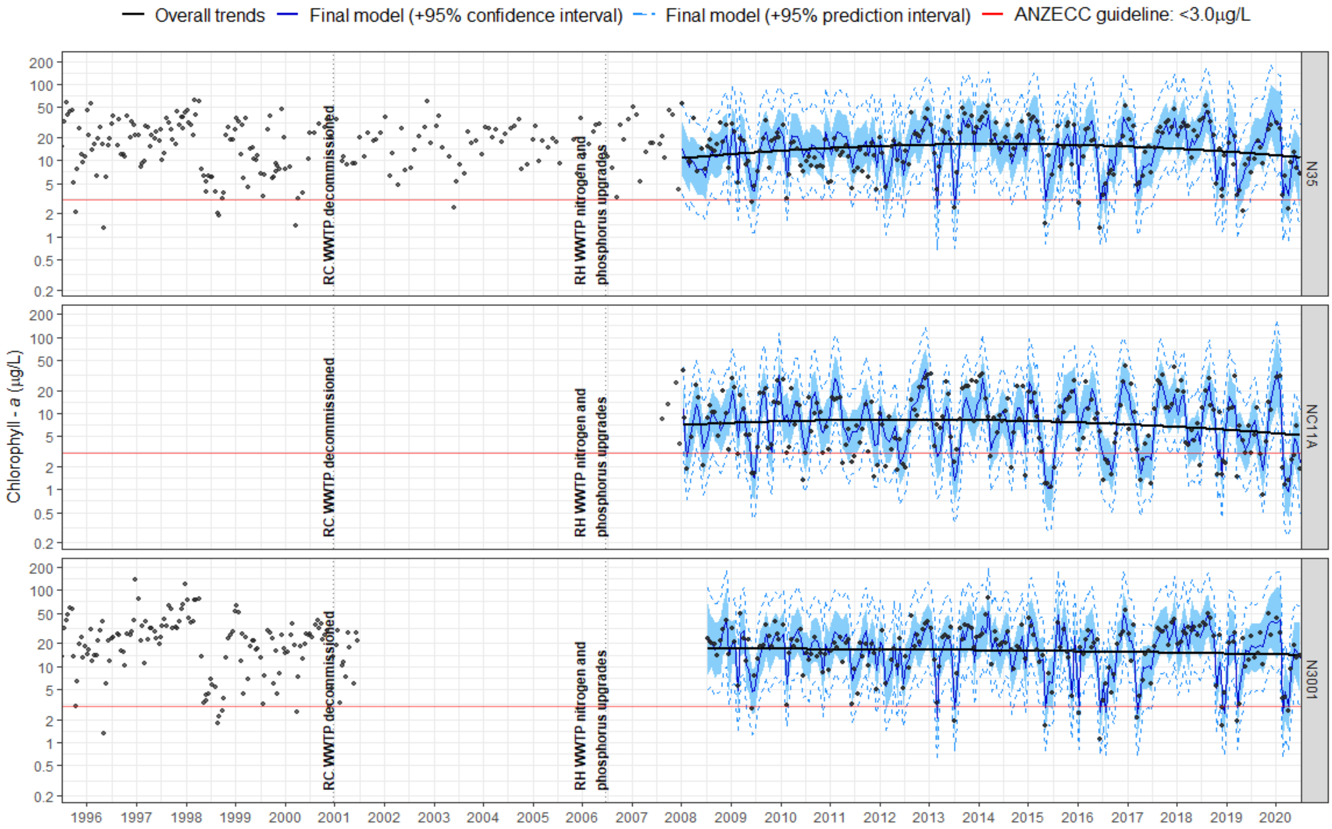

Figure 4-56 Chlorophyll-*a* concentrations at Wilberforce (N35) and Off Cattai SRA (N3001), Hawkesbury River and Cattai Creek (NC11A): fitting terms to model site differences and associated flow along with linear and quadratic trends and seasonal trends

The detailed statistical outcomes of this model are included in Volume 2 (Appendix I). The estimated coefficients for the non-harmonic parameters, the type I and type III sums of squares for each term in the final model along with corresponding p value are shown in Table I-27 and Table I-28, respectively. The residual plots for this model are shown in Figure I-14.

The site, site by flow and site by period parameters were retained in the model as they were part of the study design. The p-values corresponding to the type III SS are similar to those with the type I SS.

The model fitted the data well (R^2=0.77 and adjusted R^2=0.62). The distribution of the residuals was approximately Normal and residuals plotted against the fitted or predicted values showed no remaining pattern in the data series.

Key outcomes

- Chlorophyll-*a* concentration:
  - Chl-a was generally above the ANZG default level of <3.0 µg/L.

- The final reduced model fitted well with R^2=0.77 and adjusted R^2=0.62. However, the residual plots showed the model did not capture the extremely high, and to a lesser extent the extremely low Chl-*a* concentrations.

- Flow:
  - The interaction between flow and site was significant ($p<0.0001$).
  - As flow increased, Chl-*a* concentration decreased at all sites ($p<0.0001$).
    - when flow at N3001 is low eg 1100 ML/day, a 100 ML/day increase in flow decreased the Chl-*a* concentration by 5.9%
    - when flow at N3001 is moderate eg 1400 ML/day, a 100 ML/day increase in flow decreased the Chl-*a* concentration at N3001 by 4.7%
    - when flow at N3001 is high, eg 1700 ML/day, a 100 ML/day increase in flow decreased the Chl-*a* concentration at N3001 by 3.9%.
    - when flow at N35 is low eg 1000 ML/day, a 100 ML/day increase in flow decreased the Chl-*a* concentration by 4.7%
    - when flow at N35 is moderate eg 1300 ML/day, a 100 ML/day increase in flow decreased the Chl-*a* concentration at N3001 by 3.6%
    - when flow at N35 is high, eg 1600 ML/day, a 100 ML/day increase in flow decreased the Chl-*a* concentration at N35 by 3%.
    - when flow at NC11A is low eg 30 ML/day, a 5 ML/day increase in flow decreased the Chl-*a* concentration by 2.1%
    - when flow at NC11A is moderate eg 55 ML/day, a 5 ML/day increase in flow decreased the Chl-*a* concentration at NC11A by 1.2%
    - when flow at NC11A is high, eg 100 ML/day, a 5 ML/day increase in flow decreased the Chl-*a* concentration at NC11A by 0.7%.

- Long term trends:
  - There was a significant interaction between site and linear trends ($p=0.0009$) and quadratic trends ($p<0.0001$).
  - There was a curvilinear trend that differed slightly between sites. At the tributary site (NC11A) the trend was approximately flat, while at the upstream and downstream sites, the Chl-*a* concentration increased slightly until approximately 2015 before decreasing.
  - As of mid-2020, the trend at the downstream and upstream sites was decreasing slightly and the trend at the tributary site was approximately flat.

- Seasonal trends:
  - All site by 1st, 2nd and 3rd order sine and cosine terms by year interactions were included to capture a pattern of three peaks per year, capturing the largest one in February and two smaller ones around late May/early June and September. The lowest trough was around

late October/early November. The magnitude of the peaks and troughs differed between years and sites.

- Site geometric mean chlorophyll-*a* concentrations:
  - There was only one period of data for the downstream-upstream comparison. There was a significant difference between sites ($p<0.0001$).
  - After adjusting for linear, quadratic and seasonal trends and the geometric mean chlorophyll-*a* concentration:
    - At N3001 was 12.6 µg/L (95% CI = 11.0 to 14.3 µg/L), at NC11A was 5.6 µg/L (95% CI = 5.0 to 6.8 µg/L) and at N35 was 13.1 µg/L (95% CI = 11.5 to 14.8 µg/L)
  - Comparing the modelled geometric mean chlorophyll-*a* concentrations between sites, the geometric mean for:
    - N3001 was 96% (80 to 115%) of the geometric mean for N35.
    - N3001 was 215% (175 to 263%) of the geometric mean for NC11A.

4.4.15 Cattai Creek (Castle Hill and Rouse Hill) WWTPs and the Hawkesbury River off Cattai SRA (N3001) – Summary

Nutrient loads

The approach for analysing the nutrient loads data of Cattai Creek (Castle Hill and Rouse Hill) WWTPs into sub-categories enabled the trends in periods between the interventions to be identified more accurately. The type and period of intervention varied for each of these WWTPs. The modelled geometric mean loads for each period and comparisons between periods are shown in Table 4-22. The trend and percent change in population served by the Cattai Creek (Castle Hill and Rouse Hill) WWTPs in these data category periods are provided in Table 4-16. The results are discussed in the detail in Section 5.1.

A summary of final modelling outcomes on temporal trends in Cattai Creek (Castle Hill and Rouse Hill) WWTP nutrient (TN, DIN and TP) loads by each period of intervention is included in Table 4-24. The models identified both seasonal and non-seasonal variation in nutrient load parameters. The results are discussed in the detail in Section 5.1.

Table 4-22 Geometric mean (95% CI) Cattai Creek (Castle Hill and Rouse Hill) WWTP nutrient loads for each period and the comparisons (95% CI) between periods

WWTP	Period	Total nitrogen (kg/day)	Dissolved inorganic nitrogen (kg/day)	Period	Total phosphorus (kg/day)
		Geometric Mean (95% CI)	Geometric Mean (95% CI)		Geometric Mean (95% CI)
Castle Hill	1	86.7 (82.4, 91.1)	75.3 (56.7, 100.1)	1	0.58 (0.53, 0.63)
	2	90.8 (88.5, 93.0)	84.3 (79.5, 89.4)	2	0.68 (0.64, 0.73)
		% (95% CI)	% (95% CI)		% (95% CI)
	2:1	105% (99%, 111%)	112% (84%, 150%)	2:1	117% (105%, 132%)
Rouse Hill		Geometric Mean (95% CI)	Geometric Mean (95% CI)		Geometric Mean (95% CI)
	1	42.5 (40.7, 44.4)	37.2 (35.3, 39.3)	1	0.322 (0.289, 0.358)
	2	101.7 (96.6, 107.1)	96.6 (78.6, 118.6)	2	0.246 (0.231, 0.262)
		% (95% CI)	% (95% CI)		% (95% CI)
	2:1	239% (224%, 256%)	259% (210%, 321%)	2:1	76% (68%, 86%)

Table 4-23 Castle Hill and Rouse Hill WWTP catchment population serviced and percent change by period

Castle Hill WWTPs		
Period for TN, DIN and TP	**Average population**	**Percent increase**
Period 1: 1995-2000	22,182	
Period 2: 2001-2020	27,317	
Period 2 : Period 1		123%
Rouse Hill WWTP		
Period for TN and DIN	**Average population**	**Percent increase**
Period 1: 1995-2009	38,885	
Period 2: 2010-2020	90,937	
Period 2 : Period 1		234%
Period for TP	**Average population**	**Percent increase**
Period 1: 1995-2006	31,571	
Period 2: 2007-2020	85,007	
Period 2 : Period 1		269%

Data source: 2001-2021: forecast data by the Australian Bureau of Statistics and the Department of Planning, Industry and Environment
1995-2000: Sydney Water's internal estimates based on local government area data, sewer and unsewered areas

Table 4-24 Summary of final models for Cattai Creek (Castle Hill and Rouse Hill) WWTPs

WWTP	Parameter	TN	DIN	Parameter	TP
Castle Hill	Period 1: Linear trend	→	↗	Period 1: Linear trend	↗
	Period 2: Linear trend	↘	→	Period 2: Linear trend	↘
	Period 1: Quadratic trend	↗	↘	Period 1: Quadratic trend	NA
	Period 2: Quadratic trend	↗	↗	Period 2: Quadratic trend	↗
Rouse Hill	Period 1: Linear trend	↗	↗	Period 1: Linear trend	↗
	Period 2: Linear trend	↗	→	Period 2: Linear trend	↗
	Period 1: Quadratic trend	↘	↘	Period 1: Quadratic trend	↘
	Period 2: Quadratic trend	↘	↘	Period 2: Quadratic trend	NA

Legend Keys:

	≤0.0001		≤0.001		≤0.01		≤0.05		≤0.15

↗	Upward trend	↘	Downward trend	→	no trend, p>0.15

NA	p>0.15, term removed from the model during the model reduction process

Notes: Significance level was based on type I SS p-values and the direction of trend (upward/downward/flat) was determined by the regression coefficient estimates (positive, negative or stable)

Receiving water quality

The analysis on receiving water quality for this site was limited to the period from 2008 onwards because of a long data missing period (2001-08). No intervention used in splitting this N3001 data set. The modelled geometric mean water quality of Hawkesbury River off Cattai SRA (N3001) is shown in Table 4-25. The results are discussed in the detail in Section 5.2.

Table 4-25 Geometric mean (95% CI) nutrient (TN, DIN, TP and Chl-*a*) concentrations off Cattai SRA (N3001)

TN (mg/L)	DIN (mg/L)	TP (mg/L)	Chl-*a* (µg/L)
0.93 (0.90, 0.96)	0.64 (0.46, 0.89)	0.049 (0.047, 0.051)	13.9 (12.5, 15.5)

A summary of the final model outcomes on temporal trends in the water quality of Hawkesbury River off Cattai SRA (N3001), and the relationship with upstream river and concentration, and nutrient loads from Cattai Creek (Castle Hill and Rouse Hill) WWTPs is included in Table 4-26. The results are discussed in the detail in Section 5.2.

Table 4-26 Overall summary table for the Hawkesbury River off Cattai SRA (N3001) – final models with detailed results on each variable, increasing or decreasing trends, significance levels

Parameter	TN	DIN	TP	Parameter	Chl-a
Upstream N35 TN concentration (mg/L)	↗	↗	↗	Upstream N35 TN concentration (µg/L)	↗
Upstream N35 flow (ML/day)	↗	→	↗	Upstream N35 flow (ML/day)	↘
Cattai Creek flow (ML/day)	→	→	→	Cattai Creek flow (ML/day)	↘
Castle Hill load (kg/day)	→	→	→*	Castle Hill TN load (kg/day)	↘
Rouse Hill load (kg/day)	→	→	↘	Castle Hill TP load (kg/day)	→
				Rouse Hill TN load (kg/day)	↘
				Rouse Hill TP load (kg/day)	→
Period 1: Linear trend	↗	NA	↗	Period 1: Linear trend	↘
				Period 1: Quadratic trend	↗

Legend Keys:

(green)	≤0.0001	(blue)	≤0.001	(yellow)	≤0.01	(grey)	≤0.05	(light blue)	≤0.15

↗	Upward trend or positive correlation	↘	Downward trend or negative correlation	→	no trend, p>0.15

NA	p>0.15, term removed from the model during the model reduction process

(magenta) Not significant after adjusting to all other terms in the model

Notes: Significance level was based on type I SS p-values and the direction of trend (upward/downward/flat) was determined by the regression coefficient estimates (positive, negative or stable)

*significant after adjusting all the terms in the model

Receiving water quality – downstream and upstream comparison

The modelled geometric mean of downstream water quality of Hawkesbury River off Cattai SRA (N3001) and comparison with the upstream site at Wilberforce (N35) and Cattai Creek (NC11A) are shown in Table 4-27. The results are discussed in the detail in Section 5.2.

Table 4-27 Geometric mean (95% CI) nutrient (TN, DIN, TP and Chl-*a*) concentrations at Hawkesbury River off Cattai SRA (N3001) and Wilberforce (N35) and Cattai Creek (NC11A) for each period and the comparisons (95% CI) between periods

Variable	N3001	N35	NC11A	N3001/N35	N3001/NC11A
TN (mg/L)	0.82 (0.77, 0.86)	0.76 (0.72, 0.80)	1.73 (1.61, 1.85)	107% (99%, 117%)	47% (43%, 52%)
DIN (mg/L)	0.31 (0.27, 0.36)	0.31 (0.27, 0.36)	1.13 (0.94, 1.35)	101% (82%, 124%)	28% (22%, 35%)
TP (mg/L)	0.048 (0.045, 0.051)	0.050 (0.047, 0.053)	0.053 (0.049, 0.057)	95% (87%, 105%)	90% (81%, 100%)
Chl-*a* (µg/L)	12.6 (11.0, 14.3)	13.1 (11.5, 14.8)	5.6 (5.0, 6.8)	96% (80%, 115%)	215% (175%, 263%)

A summary of final modelling outcomes on temporal trends in water quality of Hawkesbury River off Cattai SRA (N3001) and comparison with the upstream site of Hawkesbury River at Wilberforce (N35) is included in Table 4-28. The results are discussed in the detail in Section 5.2.

Table 4-28 Summary of final models for the Hawkesbury River off Cattai SRA (N3001) – upstream/downstream and tributary comparison with detailed results on each variable, increasing or decreasing trends, significance levels

Parameter	TN	DIN	TP	Chl-*a*
Site by Flow	(≤0.001)	(≤0.0001)	(≤0.0001)	(≤0.0001)
N3001	↗ (≤0.0001)	↗ (≤0.0001)	↗ (≤0.0001)	↘ (≤0.0001)
N35	↗ (≤0.0001)	↗ (≤0.0001)	↗ (≤0.0001)	↘ (≤0.0001)
NC11A	↗ (≤0.01)	→	↗ (≤0.0001)	↘ (≤0.0001)
Site by linear trend	(≤0.0001)	(≤0.01)	(≤0.05)	(≤0.001)
N3001	↘ (≤0.0001)	↘ (≤0.001)	→	↗ (≤0.01)
N35	↘ (≤0.0001)	↘ (≤0.0001)	↘ (≤0.05)	↗ (≤0.0001)
NC11A	→	→	→	→
Site by quadratic trends	(≤0.0001)	(≤0.0001)		(≤0.0001)
N3001	↗ (≤0.0001)	↗ (≤0.001)	↗ (≤0.15)	↘ (≤0.001)
N35	↗ (≤0.0001)	↗ (≤0.0001)	↗ (≤0.05)	↘ (≤0.0001)
NC11A	→	→	→	→

Legend Keys:

Green	≤0.0001
Blue	≤0.001
Yellow	≤0.01
Grey	≤0.05
Light blue	≤0.15

↗	Upward trend or positive correlation	↘	Downward trend or negative correlation	→	no trend, p>0.15

Notes: Significance level was based on type I SS p-values and the direction of trend (upward/downward/flat) was determined by the regression coefficient estimates (positive, negative or stable)

5 Discussion

5.1 WWTP nutrient loads

West Camden WWTP

- The modelled geometric mean total nitrogen load discharged from West Camden WWTP decreased sharply after the treatment upgrade in 2008, but increased to pre-upgrade level by mid-2020 due to population growth and nitrogen treatment deterioration in 2015
- The geometric mean total phosphorus load increased after the phosphorus treatment upgrade in 2009 due to rapid population growth ie comparing1995-2008 with 2008-2020
- As of mid-2020, total nitrogen and dissolved inorganic nitrogen loads from West Camden WWTP were increasing, while total phosphorus loads were decreasing
- Discharge nutrient concentrations and loads were within the EPL specified limits in recent years.

The interventions used to split the West Camden WWTP nitrogen load data into three categories and phosphorus load data into two categories were:

- nitrogen treatment upgrade completed by October 2008
- phosphorus treatment upgrade completed by February 2009
- process deterioration on nitrogen treatment in January 2015

The nitrogen treatment upgrade in 2008 resulted a sharp drop (32% of pre-upgrade load ie comparing 2008-2015 with 1995-2008) in modelled geometric mean total nitrogen load despite an increase (169%) in catchment population served by the West Camden WWTP. However, ongoing population growth (139%), the return of wetter climate conditions and a nitrogen treatment process deterioration resulted in the modelled geometric mean total nitrogen load to Matahil Creek increasing by 269% of the pre-2015 level in the recent period. The treatment deterioration in 2015 was linked with a structural failure of the Intermittently Decanted Aerated Lagoon (IDAL).

Dissolved inorganic nitrogen data for West Camden WWTP was not available in the period after the nitrogen treatment upgrade in 2008 and partly available for the latest period after the process deterioration. The dissolved inorganic nitrogen load in the latest period was slightly less than the pre-upgrade load.

Phosphorus loads from West Camden WWTP dropped sharply after the upgrade in 2009. However, the average population served by the WWTP almost doubled (198%) in the period after the upgrade, overshadowing the benefit of the upgrade. The total phosphorus modelled geometric mean load increased to 185% of the pre-upgrade level (ie comparing the geometric load from 1995-2009 with 2009-2020).

Total nitrogen and total phosphorus loads from the West Camden WWTP showed highly statistically significant temporal trends (linear or curvilinear) within each period modelled. A significant upward curvilinear trend in total nitrogen and dissolved inorganic loads in the latest period (2015-2020) identified increasing loads from around 2018. This was also reflected in the 2020 STSIMP data report (Sydney Water 2020b) which flagged significantly higher total nitrogen concentrations in the discharge in 2019-2020 compared to the previous nine year's data.

A highly significant downward curvilinear trend in total phosphorus load was detected for the latest period (2009-2020). This was also consistent with Sydney Water report (2020b) where the 2019-2020 total phosphorus concentrations in the discharge were significantly lower compared to the previous nine year's data.

The West Camden WWTP discharge nutrient concentrations and loads were within the EPL specified limits in recent years. A capital project to amplify West Camden WWTP to accommodate population growth, and to upgrade the treatment process to reduce nutrients is currently underway. The expected completion is December 2023.

Winmalee WWTP

- The modelled geometric mean nutrient (nitrogen and phosphorus) loads from Winmalee WWTP dropped sharply after the transfer of North Katoomba and Wentworth Falls WWTPs in 1996 and phosphorus treatment upgrade in 1999
- After the transfer of Blackheath WWTP in 2008, the modelled geometric mean total nitrogen and dissolved inorganic loads from Winmalee WWTP decreased compared to pre-transfer loads. But the modelled geometric mean total phosphorus load increased compared to pre-transfer load.
- Total nitrogen and dissolved inorganic nitrogen loads in the discharge from Winmalee WWTP in the most recent period (2010-2020), showed an increasing trend from around 2016, while the total phosphorus loads showed a significantly decreasing trend from around 2013
- Winmalee WWTP discharge nutrient concentrations and loads were within the EPL specified limits in recent years.

The interventions used to split the Winmalee WWTP nitrogen load data into three categories and phosphorus load data into four categories were:

- North Katoomba and Wentworth Falls WWTPs decommissioning in June 1996
- Winmalee phosphorus treatment upgrade in December 1999
- Blackheath WWTP decommissioned in June 2008

No significant temporal trend in nutrient loads was detected for the one-year period before the decommissioning of North Katoomba and Wentworth Falls WWTPs (1995-1996).

After the transfer of two poor performing Blue Mountains WWTPs (North Katoomba and Wentworth Falls) to Winmalee WWTP in 1996, the nitrogen load sharply increased before improving (84% of pre-transfer load ie comparing the geometric load from 1995-1996 with 1997-2008), while the phosphorus load sharply decreased before increasing, but still remained below the pre-transfer load (68% of pre transfer load). These overall load reductions were despite accommodating additional inflows from an increased catchment population (152%). The phosphorus upgrade in 1999 resulted in a further decrease in the modelled geometric mean total phosphorus load (20% of pre-upgrade level ie comparing the geometric load from 1997-1999 with 2000-2008). There was only a minor increase in catchment population served after the upgrade in comparison to pre-upgrade level (104%).

After the transfer of Blackheath WWTP in 2008, there was a significant decrease in modelled geometric mean total nitrogen and dissolved inorganic nitrogen loads (75% and 77% of pre-transfer load, respectively, ie comparing the geometric load from 1995–2008 with 2008-2020). However, there was a significant increase in the geometric mean total phosphorus load (189% of pre-commissioning load since the phosphorus upgrade in 2000 ie comparing the geometric load from 2000–2008 with 2009-2020). The increase in the total phosphorus load was due to critical structural repairs and connection of additional residential areas from Hawkesbury Heights and Yellow Rocks in the earlier years after the transfer (2011-2013).

A highly significant curvilinear trend in total nitrogen and dissolved inorganic nitrogen loads in the discharge from Winmalee WWTP between 2008 and 2020 showed the load decreased until around 2016 before starting to increase. This is consistent with Sydney Water 2020b that reported ammonia nitrogen and total nitrogen concentrations in the discharge in 2019-2020 were significantly higher compared with to previous nine year's data (Sydney Water 2020b).

The trend in total phosphorus load between 2008 and 2020 was also significantly curvilinear with a slightly increasing trend till around 2012 before decreasing. This is consistent with Sydney Water report 2020b that confirmed total phosphorus concentrations in the discharge were significantly lower in 2019-2020 in comparison to previous nine year's data.

Winmalee WWTP discharge nutrient concentrations and loads were within the EPL specified limits in recent years. A capital project to upgrade the nutrient removal capability and reduce overall nutrient loads from Winmalee WWTP is currently underway. The expected completion date is March 2022.

St Marys WWTP

- The modelled geometric mean nutrient (nitrogen and phosphorus) loads from St Marys WWTP decreased after the nutrient treatment upgrade in 1999 and again after the commissioning of St Marys AWTP in 2010
- After the commissioning of St Marys AWTP, total nitrogen and dissolved inorganic loads from St Marys WWTP have been increasing significantly, although no such significant trend was detected for total phosphorus loads
- Nutrient concentrations and loads were within the EPL specified limits in recent years. However, the combined total phosphorus load from three South Creek WWTPs (St Marys, Quakers Hill and Riverstone) exceeded the total EPL limit in 2019-2020.

The interventions used to split the St Marys WWTP nitrogen and phosphorus load data into three categories were:

- nitrogen and phosphorus treatment upgrade in December 1999
- commissioning of St Marys AWTP in June 2010 (and transfer of a portion of St Marys wastewater for high level treatment and discharge via Boundary Creek at Penrith)

Both nitrogen and phosphorus concentrations in the St Marys WWTP discharge decreased considerably after the nutrient treatment upgrade in 1999, resulting in decreased modelled geometric mean total nitrogen, dissolved inorganic nitrogen and total phosphorus loads (25%, 13% and 16% of pre-upgrade load respectively ie comparing the geometric mean loads from 1995-1999 with 2000-2010). The St Marys WWTP catchment population had little influence on the overall benefit as it only increased marginally after this upgrade (107%).

After the commissioning of St Marys AWTP in 2010, a large proportion of wastewater from St Marys WWTP was transferred to St Marys AWTP for advance level of treatment and discharged to the Nepean River via Boundary Creek at Penrith. This contributed to the decreased nutrient (total nitrogen, dissolved inorganic nitrogen and total phosphorus) loads discharged to South Creek as observed by a sharp drop in modelled geometric mean nutrient loads from St Marys WWTP (42%, 37% and 56% of pre-commissioning loads, respectively ie comparing the geometric loads from 2000-2010 with 2010-2020). The catchment population increased only slightly (113% of pre-commissioning level) in the latest period (ie after the St Marys AWTP commissioning).

There was an overall increasing trend in total nitrogen and dissolved inorganic nitrogen loads from St Marys WWTP (2010-2020), after the initial sharp drop in response to the commissioning of the St Marys AWTP. The total phosphorus load trend was stable in this period (2010-2020). These findings are consistent with STSIMP 2020 data report (Sydney Water 2020b) that identified a significant increasing trend in ammonia nitrogen and total nitrogen concentrations in the St Marys WWTP discharge in 2019-2020 compared to the previous nine years. Although no significant changes in phosphorus concentrations were observed in the discharge.

Nutrient concentrations from the St Marys WWTP were within the EPL specified limits in recent years. However, the combined total phosphorus load from the three South Creek WWTPs (St Marys, Quakers Hill and Riverstone) exceeded the total EPL limit in 2019-2020. The cause of this exceedance was possibly related to the significant rain event in early February 2020, which resulted in increased inflow, and in turn, loads discharged. All process and chemical dosing units were operating according to the unit process default levels at the time of the rain event for all three WWTPs.

A capital project to improve treatment reliability and service growth is currently underway. The upgrade will also improve the nitrogen removal performance. The expected completion date is April 2022.

Quakers Hill WWTP

- The phosphorus upgrade in 1999 resulted in a sharp drop in the modelled geometric mean total phosphorus load discharged from Quakers Hill WWTP but increased later after the commissioning of St Marys AWTP
- After the commissioning of St Marys AWTP in 2010, there was a marginal increase in the modelled geometric mean nitrogen load (total nitrogen and dissolved inorganic nitrogen)
- The trend in nutrient loads (both nitrogen and phosphorus) in the discharge from Quakers Hill WWTP for the most recent period (2010-2020) showed decreasing loads from around 2017

- Nutrient concentrations and loads from Quakers Hill WWTP were within the EPL limits during recent years. However, the combined total phosphorus load from three South Creek WWTPs (St Marys, Quakers Hill and Riverstone) exceeded the total EPL limit in 2019-2020.

The interventions used to split the Quakers Hill WWTP nitrogen and phosphorus load data into categories were:

- Phosphorus upgrade in December 1998
- commissioning of St Marys AWTP in June 2010 (and transfer of a portion of Quakers Hill wastewater for high level treatment and discharge via Boundary Creek at Penrith)

After the phosphorus treatment upgrade (late 1998), total phosphorus concentrations in Quakers Hill WWTP discharge decreased considerably resulting a drop in modelled geometric mean phosphorus loads (21% of pre-upgrade load ie comparing the geometric mean load from 1995-1998 with 1999-2010) despite a moderate increase in catchment population (131%).

After the commissioning of St Marys AWTP in 2010 a portion of wastewater from Quakers Hill WWTP was transferred to the AWTP for high level treatment and discharge to the Nepean River via Boundary Creek at Penrith. However, despite the initial sharp drop in total nitrogen and dissolved inorganic nitrogen loads, the loads gradually increased until around 2017 to be slightly above pre commissioning levels (102% and 110% of the pre commissioning load, respectively). This increase coincided with a marginal increase in catchment population (121%). The total phosphorus load from Quakers Hill WWTP almost doubled to 189% of pre-commissioning level. A different period for the pre-AWTP commissioning is considered for total phosphorus load that excluded pre-1999 data (1999-2010). Quakers Hill WWTP nutrient loads (total nitrogen, dissolved inorganic nitrogen and total phosphorus) showed a decreasing trend from around 2017.
Nutrient concentrations from Quakers Hill WWTP were within the EPL specified limits during recent years. However, the combined total phosphorus load from three South Creek WWTPs (St Marys, Quakers Hill and Riverstone) exceeded the total EPL limit in 2019-2020. The cause of this exceedance was mostly due to a significant rain event in early February 2020, which had a considerable impact on increased flows and loads recorded by these WWTPs. All process and chemical dosing units of these plants were operating according to the unit process default levels at the time of the rain event for all these WWTPs.

A capital project to improve treatment reliability and service growth is currently underway. The upgrade will also improve the nitrogen removal performance. The expected completion date is April 2022.

Riverstone WWTP

- The modelled geometric mean nutrient loads from Riverstone WWTP dropped after the treatment process upgrade in 1999
- After reaching design capacity and increasing discharge in 2010, the modelled geometric mean total nitrogen loads from Riverstone WWTP significantly decreased (ie comparing the total geometric mean loads between periods). However, the modelled geometric mean phosphorus load was higher than the previous period

- After the latest upgrade in 2019 the modelled geometric mean total nitrogen and dissolved inorganic loads showed an immediate and significant reduction. However, the modelled geometric mean phosphorus load was higher than the previous period ie 2010-2019 compared to 2019-20)
- No significant trends in nutrient loads were found in the short period after the latest upgrade in 2019 but an increasing trend was identified prior to upgrade
- Nutrient concentrations and loads from Riverstone WWTP were within the EPL limits during recent years. However, the combined total phosphorus load from three South Creek WWTPs (St Marys, Quakers Hill and Riverstone) exceeded the total EPL limit in 2019-2020.

The interventions used to split the Riverstone WWTP nutrient load data into four categories were:

- treatment upgrade to reduce nitrogen and phosphorus in December 1999
- WWTP reaching the design capacity, June 2010
- treatment upgrade to reduce the nutrient load in 2019

After the treatment upgrade in late 1999, both nitrogen and phosphorus concentrations in the Riverstone WWTP discharge decreased considerably. The benefit of this upgrade was reflected in the decrease in modelled geometric mean nutrient (total nitrogen, dissolved inorganic nitrogen and total phosphorus) loads (55%, 45% and 8% of pre-upgrade loads, respectively ie comparing the geometric mean load from 1995-1999 with 2000-2010). This was achieved despite a marginal increase in catchment population (119%).

The Riverstone WWTP was originally designed to treat wastewater up to 2 ML/day. This design capacity was exceeded in 2010, reducing the nutrient removal performance of the WWTP. The impact of this led to an increase in modelled geometric mean total phosphorus load (270% of the pre-design capacity loads ie comparing the geometric load from 2000-2010 with 2010-2019, while the modelled geometric mean total nitrogen load decreased (89% of pre-design load). The Riverstone WWTP catchment population increased by 160% between these periods.

The most recent upgrade in 2019 improved wastewater treatment and increased the capacity of the plant. The limited 18 months dataset (2019-2020) indicated both total nitrogen and dissolved inorganic nitrogen loads discharged to Eastern Creek decreased to 75% and 9% of pre-upgrade loads, respectively, but total phosphorus load showed an overall increase between the two periods (200% of pre-upgrade load), despite an initial reduction. Riverstone is a rapidly growing sub-catchment. The population increased over three times (338%) after the upgrade. The total nitrogen findings are consistent with Sydney Water report 2020b which identified significantly decreased total nitrogen concentrations in Riverstone WWTP discharges compared to last nine year's data due to the 2019 upgrade or amplification, however the report also identified as significant decrease in total phosphorus concentrations.

Statistical analysis on the limited nutrient load data available after the latest nutrient treatment upgrade at Riverstone WWTP (2019-2020) did not show any significant trends, but an increasing trend was identified in the previous period (2010-2019).

Nutrient concentrations and loads from Riverstone WWTP were within the EPL specified limits during recent years. However, the combined total phosphorus load from three South Creek WWTPs (St Marys, Quakers Hill and Riverstone) exceeded the total EPL limit in 2019-2020. The cause of this exceedance was mostly related to the significant rain event in early February 2020, which had a considerable impact on increased flows and loads recorded by these WWTPs. All process and chemical dosing units of these plants were operating according to the unit process guidelines at the time of the rain event for all these WWTPs.

After the recent treatment upgrade and amplification of Riverstone WWTP in 2019, planning is underway to transfer wastewater from Rouse Hill WWTP to Riverstone WWTP for treatment and discharge. While this may see a localised increase in nutrient loads discharged to South Creek, it will result in an overall reduction in loads discharged to the Hawkesbury-Nepean River system due to the higher level of treatment. The expected completion is December 2022.

Richmond WWTP

- Insufficient nutrient load data for Richmond WWTP in the period before the treatment process upgrade in 2005 meant a comparison of modelled geometric mean loads was not possible
- The trend in nitrogen and phosphorus loads plateaued and/ or started to decrease by mid-2020
- Nutrient concentrations and loads from Richmond WWTP were within EPL limits during recent years.

The interventions used to split the Richmond WWTP nutrient load data into two categories were:

- Increased recycling water use in 2002
- nitrogen and phosphorus upgrade in 2005

The majority of the wastewater from Richmond WWTP is recycled resulting in minimal discharge to the receiving waterway (< 2 ML/day from 2005).

There was an increasing trend in total nitrogen and total phosphorus load from Richmond WWTP between 2007 and 2020, although the load plateaued/started to decrease in recent years. The population in the catchment increased to 141% of pre-upgrade level. No data on dissolved inorganic nitrogen is available. The STSIMP yearly report (Sydney Water 2020b) identified a significant increase in total phosphorus concentrations in Richmond WWTP discharge in 2019-2020 compared to the last nine year's data. But no such significant increase or decrease in total nitrogen concentration in discharges was found in 2019-2020 (Sydney Water 2020b).

Nutrient concentrations and loads from Richmond WWTP were within the EPL specified limits during recent years.

Planning is underway to decommission North Richmond WWTP and transfer the flow to Richmond WWTP. This will enhance the nutrient removal capability to meet the revised licence discharge limits which will come into effect in 2024. Expected completion is October 2024

Castle Hill WWTP

- The modelled geometric mean nutrient (nitrogen and phosphorus) loads discharged from Castle Hill WWTP increased slightly after the transfer of Round Corner WWTP in 2000
- Nutrient loads discharged from Castle Hill WWTP have been gradually increasing since around 2013
- Castle Hill WWTP discharge nutrient concentrations and loads were within the EPL limits in recent years.

The only intervention used to split the Castle Hill WWTP nutrient load data into two categories was:

- Round Corner WWTP decommissioned and transferred to Castle Hill WWTP in December 2000

The transfer of wastewater from the poor performing Round Corner WWTP to Castle Hill WWTP in 2000 resulted in an increase in modelled geometric mean total nitrogen, dissolved inorganic nitrogen, total phosphorus loads (105%, 112% and 117% of pre-transfer loads, respectively ie comparing the geometric mean load from 1995-2001 with 2001-2020). This coincided with an increase in catchment population (123%).

The long-term trend in nutrient loads (total nitrogen, dissolved inorganic nitrogen and total phosphorus) after the transfer of Round Corner WWTP (2001-2020), was significantly curvilinear initially, slightly decreasing and then increasing in the last few years. The annual data report (Sydney Water 2020b) flagged a significant increase in total nitrogen concentrations in Castle Hill WWTP discharges compared to the last nine year's data. No such change was seen in total phosphorus concentration.

Castle Hill WWTP nutrient concentrations and loads were within the EPL specified limits in recent years.

A capital project to upgrade nutrient treatment processes and improve nutrient removal performance at Castle Hill WWTP is currently underway. The expected completion is June 2024

Rouse Hill WWTP

- The modelled geometric mean total nitrogen and dissolved inorganic nitrogen concentrations in the Rouse Hill WWTP discharge increased after the nitrogen treatment upgrade in 2009, while the total phosphorus load decreased after the phosphorus treatment upgrade in 2006
- The trend in the total nitrogen load started to decrease from around 2018, while the total phosphorus load increased significantly from 2006
- Rouse Hill WWTP discharge nutrient concentrations and loads were within the EPL limits in recent years.

The interventions used to split the Rouse Hill WWTP nitrogen and phosphorus load data into two categories were:

- nitrogen treatment upgrade in December 2009
- phosphorus treatment upgrade in June 2006

The modelled geometric mean total phosphorus load from Rouse Hill WWTP decreased to 76% of the pre-upgrade load after the phosphorus treatment upgrade in 2006. This was achieved despite a large increase in catchment population after the upgrade (269% of pre-upgrade population). However, the benefit of the nitrogen treatment upgrade in 2009 was not similarly realised, and the modelled geometric mean total nitrogen and dissolved inorganic nitrogen load increased by 239% and 259%, respectively (ie comparing the geometric mean load from 1995-2009 with 2010-2020). It is likely that the benefit of upgrade was overshadowed by the large increase in catchment population (increased by 234% of pre-upgrade population). The Rouse Hill WWTP sub-catchment is a rapidly growing urban development area.

The trend in the Rouse Hill WWTP total nitrogen loads increased initially after the nutrient treatment upgrade (2010-2020) but started to decrease from around 2018. The trend in total phosphorus load showed a gradual increase for the entire period after the upgrade (2006-2020).

A capital project to transfer wastewater from Rouse Hill WWTP to Riverstone WWTP to reduce the overall nutrient loads to Cattai Creek sub-catchment is in the planning phase. This will facilitate servicing growth and allow planning and delivery for future amplification of Rouse Hill WWTP. The transfer is expected to be complete by December 2022. Riverstone WWTP was upgraded and amplified in 2019 providing opportunity for improved treatment of the Rouse Hill wastewater.

5.2 Receiving water quality

As of mid-2020, key nutrients and chlorophyll-*a* concentrations in the Hawkesbury-Nepean River mostly exceeded the respective ANZG 2018 default levels, the exception being the upper Nepean River at Sharpes Weir, where the modelled geometric mean total phosphorus concentration (2009-2020) was within the default level. The modelled geometric mean total nitrogen and chlorophyll-*a* concentrations were also comparatively lower at this site, although still higher than the respective default levels.

Water quality deteriorated with increased distance downstream where the river widens and receives nutrient rich runoff from urbanised catchments and discharges from multiple WWTPs. The water quality of the lower Hawkesbury River downstream of South and Cattai creeks was comparatively poorer, with high concentrations of nutrients and chlorophyll-*a*. Nutrient concentrations were generally higher in South Creek, followed by Cattai Creek, due to being smaller waterways located closer to the WWTP discharges and other catchment run-off, enabling less opportunity for dilution and assimilation. However, algal growth, as represented by chlorophyll-*a*, was much lower than the mainstream river.

The key outcomes and recent trends (as of mid-2020) after the latest interventions at each site along with the factors influencing the water quality are summarised below.

5.2.1 Receiving water response to WWTP upgrades/changed treatment processes

The benefit of decommissioning the poorer performing WWTPs and treatment upgrades/amplification, was evident with reduced nutrient concentrations at the downstream receiving water sites. A similar reduction in chlorophyll-*a* concentration was not found at most sites.

- Nutrient treatment upgrades at upstream WWTPs contributed to the reduced nutrient concentrations at most downstream sites after upgrades (between 92% to 42% of pre-upgrade level)
- The nitrogen process deterioration at West Camden WWTP in 2015 resulted in increased total nitrogen concentrations at the downstream Nepean River at Sharpes Weir (128% of pre-process deterioration)
- The Riverstone WWTP upgrade in 2019 resulted in reduced total nitrogen loads (9% of pre-upgrade nitrogen). The total phosphorus load showed an immediate reduction in response to the upgrade but was still higher than the geometric mean load from the previous period (200% of pre-upgrade load). A nutrient reduction benefit was not recognised at the downstream Hawkesbury River site (Wilberforce) due to extreme wet weather. The chlorophyll-*a* concentration decreased to 51% of pre-upgrade level due to algal washout
- Decreased total phosphorus loads from upstream WWTPs had minimal to no benefit on downstream chlorophyll-*a* concentrations, with the exception of West Camden WWTP (chlorophyll-*a* 91% of pre-total phosphorus upgrade concentration)

The benefit of nutrient load reductions from West Camden WWTP in response to upgrades in 2008-09 was reflected in lower nutrient concentrations downstream in the Nepean River at Sharpes Weir (N75). The modelled geometric mean total nitrogen and total phosphorus dropped to approximately half the pre-upgrade concentrations (43% and 53% respectively ie comparing the geometric mean concentration from 1995-2008 with 2008-2020). In contrast, after the nitrogen treatment process deterioration at West Camden WWTP in 2015 the modelled geometric mean total nitrogen concentration at N75 increased to 128% of the concentration prior to the issue. The change chlorophyll-*a* concentration was minimal in response to the phosphorus treatment upgrade, with the modelled geometric mean chlorophyll-*a* concentration dropping to 91% of pre-upgrade concentration.

No estimates on the effect of load on dissolved inorganic nitrogen concentrations at the downstream site were determined due to the large period with missing dissolved inorganic nitrogen load data.

There was an apparent benefit in total nitrogen and dissolved inorganic nitrogen concentrations in the Nepean River at Yarramundi Bridge (N44) after the commissioning of St Marys AWTP with the modelled geometric mean concentrations decreasing to 68% and 42% of the pre-commissioning levels respectively ie comparing the geometric mean concentration from 2008-2010 with 2010-2020. However, the changes in total phosphorus and chlorophyll-*a* concentrations were the opposite, with both increasing after the commissioning (123% and 170% respectively). Despite showing an overall increase in geometric mean concentration between the two periods, both total phosphorus and chlorophyll-*a* concentrations decreased from around 2014 to be comparable to, or lower, than the pre AWTP concentrations by 2020. This is consistent with Sydney Water 2013 that identified a statistically significant reduction in nutrient concentrations (both nitrogen and phosphorus) in the Nepean River at Penrith immediately downstream of the discharges after the commissioning of St Marys AWTP. The benefit to total nitrogen concentrations were seen as far downstream as the Hawkesbury River at North Richmond (Sydney Water 2013).

The benefit of WWTP nutrient load reductions in response to the nutrient treatment upgrades at St Marys and Quaker Hill WWTPs in 1999, Richmond WWTP upgrade in 2005 and St Marys AWTP commissioning in 2010, was reflected in lower modelled geometric mean nitrogen and phosphorus concentrations the downstream Hawkesbury River at Wilberforce at Hawkesbury River at Wilberforce (N35) (63% to 92% of pre-upgrade or pre-commissioning levels respectively). However, such a benefit was not identified in modelled geometric mean chlorophyll-*a* concentrations, that increased to 117% of pre-upgrade levels after the first two interventions. After the commissioning of St Marys AWTP, the chlorophyll-*a* concentration at N35 was stable (101% of pre-commissioning level).

The limited available data following the Riverstone WWTP upgrade intervention in 2019 indicated an increase in modelled geometric mean total nitrogen and total phosphorus concentrations (120% and 112% respectively) and a decrease in chlorophyll-*a* concentration (51%) at the downstream Hawkesbury River at Wilberforce site (N35). The increase in total nitrogen concentration was unexpected as the total nitrogen load discharged from Riverstone WWTP decreased to 75% of the pre-upgrade load. These findings may indicate that, volume from Riverstone WWTP discharges has an overall low impact on the downstream site compared to St Marys and Quakers Hill WWTPs. An extreme wet weather event in early 2020 was possibly linked with the increasing nutrient loads due to runoff from the surrounding catchment. The decreased chlorophyll-*a* concentration was not unexpected as algal washout commonly occurs after wet weather events.

The data set for the Hawkesbury River site off Cattai SRA (N3001) was limited (2008 to 2020 only) period. No comparison was made on modelled geometric mean nutrient and chlorophyll-*a* concentrations to identify the benefit of only intervention or WWTP total nitrogen treatment upgrade in 2009.

5.2.2 Trends

Total nitrogen and dissolved inorganic nitrogen concentrations at the majority of receiving water sites were increasing in the most recent period. However, trends in total phosphorus and chlorophyll-*a* concentrations were mixed:

- Total nitrogen and dissolved inorganic nitrogen concentrations at three of the four receiving water sites increased significantly after the latest interventions at upstream WWTPs. The Hawkesbury River at Wilberforce, downstream of South Creek was an exception with no trend detected in a short period after the Riverstone WWTP upgrade in 2019, but there was an increasing trend detected in the earlier period (2010-2019).
- The trend in total phosphorus concentrations were mixed after the latest intervention: decreased in the Nepean River at Sharpes Weir and Yarramundi (since West Camden WWTP upgrade in 2009 and commissioning of St Marys AWTP in 2010, respectively); and increased in the Hawkesbury River off Cattai SRA, downstream of Cattai Creek (2008-2020). The total phosphorus trend was stable

between 2019-2020 in the Hawkesbury River at Wilberforce downstream of South Creek, but decreased in the earlier period (2010-2019).

- Chlorophyll-*a* concentration remained steady in the Nepean River at Sharpes Weir, and decreased in the Nepean River at Yarramundi Bridge and Hawkesbury River Off Cattai SRA, Chlorophyll-*a* significantly increased in the short period from 2019 in the Hawkesbury River at Wilberforce, downstream of South Creek but significantly decreased in the earlier period (2010-2019).

The modelled geometric mean total nitrogen, total phosphorus and chlorophyll-*a* concentrations were above the respective ANZG default levels during most periods at all eight downstream, upstream and tributary sites. The exceptions were the upper Nepean at Sharpes Weir and Macquarie Grove Road in recent years, and the lower Nepean River at Yarramundi and Smith Road before 2010 where the modelled geometric mean total phosphorus concentration was less than the guideline.

Nepean River – West Camden

The total phosphorus concentration in the Nepean River at Sharpes Weir (N75) decreased significantly after the phosphorus treatment upgrade (2009-2020). During this period, there was a nitrogen treatment process deterioration at West Camden WWTP (2015), which resulted in a significant increase in total nitrogen concentration at the downstream N75 site. However, no trend (increasing or decreasing) was identified in the chlorophyll-*a* concentration at this site (2009-2020). A similar trend was reported in 2019-2020, where nitrogen concentrations (ammonia nitrogen, oxidised nitrogen and total nitrogen) had increased significantly compared to the previous nine years concentrations (Sydney Water 2020b). The 2019-2020 total phosphorus concentration was steady and chlorophyll-*a* concentration significantly decreased compared to the previous nine years data (Sydney Water 2020b).

It was not possible to determine the temporal trends for the Nepean River upstream of Matahil Creek (N78) site or West Camden WWTP for a longer period because of insufficient data. A paired downstream upstream comparison on a short term dry weather dominated dataset (2018-2019) indicated an increasing trend in nitrogen concentrations at both sites, although the rate of change was higher at the upstream site of Nepean River at Macquarie Grove road (N78). The trend in phosphorus concentration for the same period was also significantly increasing at the upstream site (N78) but decreasing at the downstream site (N75). At both sites the trend in chlorophyll-*a* concentration was increasing in 2018 but decreasing in 2019.

The temporal trends in nutrients and chlorophyll-*a* concentration confirmed a clear signal on increasing nutrients concentrations in this section of the upper Nepean River while chlorophyll-*a* concentrations were steady or decreasing.

The modelled geometric mean total nitrogen and chlorophyll-*a* concentrations at N75 and N78 for all periods were above the respective ANZG default levels since 1995. However, the modelled geometric mean total phosphorus concentration was higher than the guideline in the earlier period but improved to be less than the guideline limit in the latest period at both sites (N75: 2009-2020 or N78: 2018-2019). The modelled geometric mean nutrient concentrations in 2018-2019 were significantly higher at the downstream site (N75) than the upstream site (N78) confirming nutrient enrichment from West Camden WWTP discharges via Matahil Creek in the dry weather. The modelled geometric mean chlorophyll-*a* concentration was lower at the downstream site indicating no direct influence of the WWTP discharge on algal abundance at this site.

Although, chlorophyll-*a* concentrations were higher than the guideline limit in the upper Nepean River site downstream of West Camden WWTP (N75), a significant downward trends was identified in the latest year (Sydney Water 2020b) indicating an improved water quality with respect to algal abundances.

Nepean River – Yarramundi

After the commissioning of St Marys AWTP in 2010, total nitrogen and dissolved inorganic nitrogen concentrations from the Nepean River at Yarramundi Bridge (N44) showed an overall significantly increasing trend, after an initial sharp decline. Total phosphorus and chlorophyll-*a* concentrations showed the opposite trend, increasing until around 2015 before decreasing. These findings are consistent with Sydney Water 2020b where ammonia nitrogen, oxidised nitrogen and total nitrogen concentrations in 2019-2020 were significantly higher than the previous nine years concentrations. Total phosphorus and chlorophyll-*a* concentrations were steady compared to the previous nine years data (Sydney Water 2020b).

Total nitrogen and dissolved inorganic nitrogen concentrations also increased significantly at the site upstream of Winmalee WWTP (N48A) after the commissioning of St Marys AWTP. The trend in total phosphorus and chlorophyll-*a* concentration at the upstream site (N48A) was similar to the downstream site (N44), increasing until around 2015 before decreasing although the increase was less pronounced at the upstream site during the first part of the period.

The modelled geometric mean total nitrogen and chlorophyll-*a* concentrations were above the respective ANZG default levels before and after the commissioning of St Marys AWTP (2010-2020) at both the upstream (N48A) and downstream (N44) sites. The modelled geometric mean total phosphorus concentration was below the guideline before the commissioning of the AWTP (2008-2010) at both sites. After commissioning, (2010-2020), the total phosphorus concentration was within ANZG default level at the upstream site (N48A) but above the guideline downstream (N44).

Hawkesbury River – South Creek

In the recent 15-17 months period after the Riverstone WWTP nutrient treatment upgrade (2019-2020), no significant temporal trend was identified in nutrient concentrations (total nitrogen, dissolved inorganic nitrogen and total phosphorus) in the Hawkesbury River at Wilberforce (N35), downstream of South Creek. The trend in chlorophyll-*a* concentration was significantly increasing in this short period (2019-2020).

In the previous period (2010-2019) after Riverstone WWTP reached design capacity and increased discharge, there was an initial sharp decrease in total nitrogen at N35, followed by an increasing trend. Total phosphorus and chlorophyll-*a* concentrations at N35 gradually increased until around 2016 when concentrations plateaued (total phosphorus) or decreased (chlorophyll-*a*) by 2019.

This is consistent with Sydney Water 2020b where total nitrogen and total phosphorus concentrations at N35 in 2019-2020 were significantly higher than the previous nine years concentrations. Chlorophyll-*a* concentration was steady compared to the previous nine years data (Sydney Water 2020b).

The trend in total nitrogen and dissolved inorganic nitrogen concentrations at the downstream, upstream river and tributary sites (N39, N35 and NS04A respectively) was flat or insignificant after the recent upgrade of Riverstone WWTP (2019-2020). Total phosphorus concentration increased significantly, particularly at the upstream river site (N39). Chlorophyll-*a* increased initially, before recently decreasing at both the upstream (N39) and downstream (N35) river sites.

The geometric mean total nitrogen, total phosphorus and chlorophyll-*a* concentrations in the Hawkesbury River at Wilberforce (N35) exceeded the respective ANZG default levels in all five periods (1995-2020). At the upstream site (N39), the modelled geometric mean total phosphorus concentration was below the guideline limit in two periods including the latest (2019-2020). Modelled geometric mean total nitrogen and chlorophyll-*a* concentrations at this site were above the respective guideline limits. Modelled geometric mean total nitrogen and total phosphorus concentrations in lower South Creek (NS04A) were higher than the mainstream river sites and exceeded the guideline. However the modelled geometric mean chlorophyll-*a* was lower at this site and only marginally exceeded the guideline in latest period.

Hawkesbury River – Cattai Creek

There were significantly increasing long-term (2008-2020) trends in total nitrogen and total phosphorus concentrations in the Hawkesbury River off Cattai SRA (N3001), downstream of Cattai Creek. There was a small but significant decreasing trend in chlorophyll-*a*. This is consistent with Sydney Water 2020b where total nitrogen and total phosphorus concentrations at N3001 in 2019-2020 were significantly higher than the previous nine years concentrations and the chlorophyll-*a* concentration was steady.

The long-term (2008-2020) trend in nutrients and chlorophyll-*a* concentrations differed between the upstream (N35), downstream river (N3001) and tributary (NC11A) sites. Nutrient concentrations at downstream and upstream river sites decreased slightly before gradually increasing from around 2016. The trend in chlorophyll-*a* concentration at these sites was the opposite and increased slightly before decreasing from around 2016 quadratically. No such trends were identified in nutrient and chlorophyll-*a* concentrations at the tributary site (NC11A).

The water quality of the Hawkesbury River off Cattai SRA (N3001) and the Cattai Creek tributary (NC11A) had modelled geometric mean total nitrogen, total phosphorus and chlorophyll-*a* concentrations exceeding the respective ANZG default levels.

5.2.3 Comparison with upstream river and tributary site

- Nutrient and chlorophyll-*a* concentrations were generally higher at the downstream compared to upstream river water sites confirming possible impact of upstream WWTPs or tributary catchment influences
- Concentrations of nutrients (nitrogen and phosphorus) were lower and chlorophyll-*a* were higher at two downstream Hawkesbury River sites compared to their respective upstream tributaries (South Creek or Cattai Creek).

Modelled geometric mean nutrient concentrations were higher in the Nepean River at Sharpes Weir (N75) downstream of West Camden WWTP and Matahil Creek compared to the upstream site at Macquarie Grove Road (N78), confirming nutrient enrichment via Matahil Creek. The geometric mean total nitrogen concentration at N75 was 289% higher than the concentration at upstream site (N78), while the difference in dissolved inorganic nitrogen was even higher at 1679%, indicating Matahil Creek and West Camden WWTP were the prime source of dissolved inorganic nitrogen during dry weather. Total phosphorus was also significantly higher at the downstream site (123%). This data was collected in the 18 month dry weather period of 2018-2019. The consistent high nutrient concentrations at the downstream site did not influence the chlorophyll-*a* concentrations with the modelled geometric mean chlorophyll-*a* concentration lower at the downstream site (75%). This indicates no direct influence of elevated nutrients from the WWTP discharge on algal growth at this site. The modelled geometric mean total nitrogen and chlorophyll-*a* concentrations at both the upstream (N78) and downstream (N75) sites were all above the respective ANZG default levels (2018-2019). However, the total phosphorus concentration was less than the guideline limit at both sites.

Nutrients (total nitrogen, dissolved inorganic nitrogen and total phosphorus) and chlorophyll-*a* concentrations were significantly lower at the upstream site on the Nepean River at Smith Road (N48A) compared to the downstream concentrations at Yarramundi Bridge (N44), with a more pronounced difference in the period before the commissioning of St Marys AWTP. This indicates a consistent impact of nutrient discharges from Winmalee WWTP and the benefit of commissioning the AWTP. The largest difference is noted for total and dissolved inorganic nitrogen concentrations before the commissioning of St Marys AWTP. The modelled geometric mean total nitrogen and dissolved inorganic nitrogen concentrations in the period before the commissioning of St Marys AWTP at downstream site (N44) were 177% and 377% higher than the upstream concentrations, respectively. The difference between the two sites for all other variables ranged between 109% and 129% higher concentration at the downstream site.

After commissioning the AWTP, the modelled geometric mean total nitrogen and dissolved inorganic nitrogen concentration at N44 dropped to 73% and 50% of pre-upgrade concentrations respectively. The geometric mean total phosphorus increased in this same period to 123% of pre-commissioning concentrations.

At the upstream site (N48A), there was an overall increase in modelled geometric mean concentrations. The post-commissioning total nitrogen, dissolved inorganic nitrogen, total phosphorus and chlorophyll-*a* concentrations were 119%, 168%, 132% and 251% of pre-commissioning concentrations, respectively.

The modelled geometric mean total nitrogen, total phosphorus and chlorophyll-*a* concentrations at downstream site were all above the respective ANZG default levels in the latest period (2010-2020). At upstream site (N48A) the geometric mean total phosphorus concentration was equal to ANZG default level of 0.025 mg/L (2010-2020), however total nitrogen and chlorophyll-*a* concentrations were above the respective guideline limits.

Nutrients and chlorophyll-*a* concentrations were significantly lower at the upstream site on the Hawkesbury River at Freemans Reach (N39) compared to downstream concentrations at Wilberforce (N35), with the largest differences identified in phosphorus (161% to 385% higher at downstream site in all three periods) and chlorophyll-*a* concentrations (385% and 182% higher concentration at downstream site in the first two periods). This was not unexpected given the addition of nutrient rich inflows via South Creek, and the wider tidal river being a more conducive environment for algal growth. The exception was in the final period (2019-2020) which was wet weather dominated, and the difference in modelled geometric mean chlorophyll-*a* was the opposite, ie the downstream concentration was only 33% of upstream concentrations indicating algal washout at the downstream site. The modelled geometric mean total nitrogen and dissolved inorganic nitrogen concentrations at the downstream site (N35) were 132% and 205% higher than the upstream concentrations (N39).

Downstream river nutrient concentrations in the Hawkesbury River at Wilberforce (N35) were much lower than concentrations in the upstream tributary (South Creek), ranging from 20% to 53% of tributary concentration. After South Creek enters the Hawkesbury River, nutrients are lost from the water column due to sedimentation, assimilation, uptake by photosynthetic organisms and dilution with lower nutrient water from the upstream river. Chlorophyll-*a* concentrations were 142% to 249% higher at the downstream river site compared to levels in lower South Creek. This was not unexpected as the river is a more suitable environment for algal growth due to low water retention time, tidal influence, availability of light with low suspended particles/turbidity, as well as other morphological features such as being wider and deeper.

The geometric mean total nitrogen, total phosphorus and chlorophyll-*a* concentrations from the downstream Hawkesbury River at Wilberforce (N35) exceeded the ANZG default levels in all five periods (1995-2020). At the upstream site (N39), the geometric mean total phosphorus concentration was less than the guideline limit in two periods including the latest (2019-2020). The modelled geometric mean total nitrogen and chlorophyll-*a* concentrations at this site were above the respective guideline limits. The geometric mean total nitrogen and total phosphorus concentrations in South Creek (NS04A) were much higher than the mainstream river sites and exceeded the guidelines. But the geometric mean chlorophyll-a was lower at this site, and only marginally exceeded the guideline in latest period.

The nutrient and chlorophyll-*a* concentrations differed only slightly between the Hawkesbury River off Cattai SRA (N3001) downstream of Cattai Creek, with the concentrations from the upstream site in the Hawkesbury River at Wilberforce (N35). The difference was more pronounced when comparing the downstream river site (N3001) with the tributary site (NC11A). The highest difference was for dissolved inorganic nitrogen and total nitrogen, with both less than half of tributary concentrations (47% and 28% of upstream tributary (Cattai Creek) concentrations respectively). For chlorophyll-*a* it was the opposite, with the river concentration more than two times the creek concentration (215%).

5.2.4 Factors contributing to high nutrients and chlorophyll-*a*

Upstream catchment factors

Nutrient and chlorophyll-*a* concentration was significantly correlated with the respective upstream concentrations at three of the four downstream receiving water sites (where data was available). This indicates upstream catchment also influenced the nutrient and chlorophyll-*a* concentrations in addition to the influence of tributary or WWTP discharges downstream.

The statistical model for the downstream site on the Nepean River at Sharpes Weir (N75) did not fit the limited upstream nutrient and chlorophyll-*a* concentration data to determine an influence of catchment factors. Hence no analysis was carried out to determine the relationship between the upstream site nutrient and chlorophyll-*a* concentrations with the downstream concentrations.

The influence of the nutrient load from West Camden WWTP on the receiving water quality of N75 (total nitrogen and total phosphorus concentrations) was confirmed by a highly significant relationship between these variables after taking into account the effect of upstream river/creek flow and also after adjusting all other terms in the model. The increase in the concentration of nutrients at Sharpes Weir (N75) in response to the increase in WWTP nutrient load discharge was not unexpected given the short distance between the WWTP and the Nepean River, providing with limited time for system loss or assimilation and sedimentation.

The dissolved inorganic nitrogen load from West Camden WWTP was not significantly correlated with the downstream N75 dissolved inorganic nitrogen concentrations after adjusting for all other terms in the model.

The total nitrogen and total phosphorus loads from West Camden WWTP were not significantly correlated to the chlorophyll-*a* concentration at N75 after taking into account the effect of flow from Camden Weir and Matahil Creek. This indicates that, although nutrient concentrations increased in the Nepean River at Sharpes Weir (N75) in recent years due to increased WWTP nutrient loads, this had no detectable influence on the chlorophyll-*a* concentrations at this site.

The upstream Camden Weir flow was found to be significantly and inversely correlated with the total nitrogen and dissolved inorganic nitrogen concentrations at the downstream river site (N75). This confirmed that the upstream site transported lower nitrogen water during higher flow and helped to dilute the elevated nitrogen from Matahil Creek. In contrast, Camden Weir flow was significantly and positively correlated with the total phosphorus concentrations at N75 ie upstream Nepean River contributed more phosphorus than from Matahil Creek/WWTP discharges.

The relationship between Matahil Creek flow, dissolved inorganic nitrogen and total phosphorus concentrations at N75 was significant and positive ie increasing flow from Matahil Creek increased the nutrient concentrations at the downstream river site. This indicates that in wet weather, high flows from the upstream Matahil Creek catchment transport more nutrients to downstream site than from the WWTP.

The impact of both Camden Weir and Matahil Creek flow was significant and negatively correlated with the river chlorophyll-*a* concentrations. This was not unexpected given that flow is the key driver to displace algal blooms further downstream (Sydney Water 2018).

Nutrients (total nitrogen, dissolved inorganic nitrogen and total phosphorus) and chlorophyll-*a* concentrations at the downstream site on the Nepean River at Yarramundi Bridge (N44) were significantly and positively correlated with the upstream concentrations in the Nepean River at Smith Road (N48A). The impact of total phosphorus loads from Winmalee WWTP on chlorophyll-*a* concentrations at the downstream river site (N44) was significantly positive ie chlorophyll-*a* increased with an increase in total phosphorus load. A significant positive relationship between upstream and downstream chlorophyll-*a* concentrations was also found. Altogether this indicates that chlorophyll-*a* concentrations at N44 are influenced by total phosphorus load from the Winmalee WWTP, and other upstream factors including the upstream chlorophyll-*a* concentrations.

The analysis identified a significant negative impact of upstream river flow on total nitrogen, dissolved inorganic nitrogen and chlorophyll-*a* concentrations at the downstream river site (N44). No such significant relationship was found between the upstream flow and total phosphorus concentrations. This indicated that the upstream site transported lower nitrogen water during higher flow, diluting the concentrations at the site downstream site.

Nutrients (total nitrogen, dissolved inorganic nitrogen and total phosphorus) and chlorophyll-*a* concentrations at the downstream site on the Hawkesbury River at Wilberforce (N35) were significantly and positively correlated with the upstream concentrations in the Hawkesbury River at Freemans Reach (N39). Site-specific river flow at downstream and upstream river sites was also positively correlated with the concentrations of all three nutrient variables (total nitrogen, dissolved inorganic nitrogen and total phosphorus). South Creek (NS04A) flow was positively correlated with total phosphorus, confirming phosphorus enrichment in lower South Creek in wet weather.

The impact river flow on chlorophyll-*a* concentration at the downstream, upstream and tributary sites was evident with significantly decreasing concentrations with higher flow or wet weather ie algal washout with fresh rain input and run-offs.

Nutrients (total nitrogen, dissolved inorganic nitrogen and total phosphorus) and chlorophyll-*a* concentrations at the downstream site on the Hawkesbury River off Cattai SRA (N3001) were significantly and positively correlated with the upstream concentrations at Wilberforce (N35)

The analysis confirmed that in addition to WWTP discharges and major tributaries, upstream river catchment factors also influenced the nutrient and chlorophyll-*a* concentrations at three of the four downstream receiving water sites (the exception was the upper Nepean River where no long-term data was available for the upstream site to make a comparison).

WWTP Nutrient loads

There were significant positive correlations between the site-specific WWTP nitrogen and phosphorus loads, and the respective downstream concentrations in three zones of the river. No such relationship was found in the Hawkesbury River downstream of Cattai Creek. A positive relationship between the site-specific total nitrogen load or total phosphorus load with the downstream chlorophyll-*a* concentration was rarely found and sometimes gave a negative relationship.

- West Camden WWTP total nitrogen and total phosphorus loads were positively correlated with the respective concentrations downstream at Nepean River at Sharpes Weir

- Winmalee WWTP total nitrogen and total phosphorus load were positively with the respective concentrations downstream at Nepean River at Yarramundi Bridge
- Winmalee WWTP total phosphorus load was positively correlated with the chlorophyll-*a* concentrations downstream at Nepean River at Yarramundi Bridge
- St Marys and Riverstone WWTP total nitrogen and total phosphorus loads were positively correlated with the respective concentrations the downstream Hawkesbury River at Wilberforce
- Castle Hill WWTP total nitrogen loads were positively correlated with the respective concentrations downstream at Hawkesbury River of Cattai SRA
- Quakers Hill WWTP total phosphorus load was positively correlated with the total phosphorus concentrations downstream at Hawkesbury River at Wilberforce
- St Marys WWTP total nitrogen load was positively correlated with the chlorophyll-*a* concentrations downstream at Hawkesbury River at Wilberforce
- St Marys WWTP total phosphorus load and Quakers Hill WWTP total nitrogen load was negatively correlated with the chlorophyll-*a* concentrations downstream at Hawkesbury River at Wilberforce
- Castle Hill and Rouse Hill WWTP total nitrogen loads were negatively correlated with the chlorophyll-*a* concentrations downstream at Hawkesbury River off Cattai SRA.

West Camden WWTP total nitrogen and total phosphorus loads were significantly and positively correlated with the total nitrogen and total phosphorus concentrations in the Nepean River at Sharpes Weir (N75) downstream of Matahil Creek, indicating a direct impact of wastewater discharge on nutrient enrichment. However, neither the total nitrogen nor total phosphorus load from West Camden WWTP was significantly correlated to the chlorophyll-*a* concentrations at N75. This indicates that, although nutrient concentrations increased at the river site in recent years due to increased nutrient loads, there was no detectable influence on chlorophyll-*a* concentrations.

Winmalee WWTP nutrient loads (both nitrogen and phosphorus) were significantly correlated with the nutrient concentrations at the downstream receiving water site. Chlorophyll-*a* was only correlated with the total phosphorus load (not total nitrogen load).

Total phosphorus loads from all three individual South Creek catchment WWTPs (St Marys, Quakers Hill and Riverstone) were significantly and positively correlated with the total phosphorus concentration at the downstream receiving water site N35. Such a significant positive relationship was also identified for the St Marys and Riverstone WWTP total nitrogen load with the downstream receiving water concentration at N35, and St Marys WWTP dissolved inorganic nitrogen load with the dissolved inorganic nitrogen concentration at N35. However, the relationship between individual WWTP nutrient loads with the chlorophyll-*a* concentrations was mixed: increased with St Marys WWTP total nitrogen loads; decreased with St Marys WWTP total phosphorus loads and decreased with Quakers Hill total nitrogen load; or, had no relationship. This indicates there is complex relationship between nutrients and algal dynamics in the river that is not only governed by WWTPs.

The relationship between nutrient loads discharged from the Cattai Creek catchment WWTPs (Castle Hill and Rouse Hill) with total respective nutrient concentrations in the downstream Hawkesbury River (N3001) was mostly insignificant. The only exception was the total nitrogen load from the Castle Hill WWTP which was significantly and positively correlated with the total nitrogen concentrations at N3001, after taking into account the effect of upstream river flow and also after adjusting all other terms in the model. That is, a further increase in total nitrogen load would increase the total nitrogen concentration at the receiving water site. Total nitrogen load from Rouse Hill WWTP was not significantly correlated with the total nitrogen concentrations at N3001. Similarly, neither Castle Hill nor Rouse Hill WWTP total phosphorus loads were significantly correlated with the total phosphorus concentrations at N3001.

The total nitrogen load from Castle Hill WWTP was significantly and inversely correlated to the concentration of chlorophyll-*a* at N3001. That is, chlorophyll-*a* concentration decreased with an increase in total nitrogen load from Castle Hill WWTP. This reinforces the complexity of nutrient algal dynamics in the river.

The relationship between nutrient loads from wastewater discharges and nutrient concentrations in downstream receiving water is complex and may depend on the distance between the actual discharge point and the receiving water site, river morphology, flow rate and other loss processes. An earlier desktop study on the Wallacia WWTP found that loss processes are expected to remove a significant fraction of nutrients entering the river system within a very short distance. The actual concentrations were about 84% less for total nitrogen and 96% less for total phosphorus, compared to those predicted by mass balance (Hawkins *et al* 2004). Statistical analysis on a shorter term data set (2011-2017) identified no significant correlations between the site-specific WWTP nitrogen loads and downstream nitrogen concentrations at most sites (seven out of ten sites, Sydney Water 2018). However, WWTP phosphorus loads correlated with instream phosphorus concentrations (six out of ten sites), despite contributing a small proportion compared to loads from other catchment source (Sydney Water 2018).

River and Creek flow

A significant positive correlation was found between the site-specific flow (upstream river/creek flow, WWTP discharges) with the downstream nutrient concentrations confirming elevation during wet weather. The relationship between the downstream nutrient concentration with the upstream river flow and tributary flow separately revealed their relative contribution to nutrient elevation. The significantly negative relationship of river/creek flow with chlorophyll-*a* confirmed algal washout during wet weather and reduced retention time with increased flow.

- Site-specific flow was significantly and positively correlated with nutrient (nitrogen and phosphorus) concentrations at all four upstream sites in the four zones of the river, confirming upstream wet weather diffuse nutrient sources
- Site-specific flow was significantly and positively correlated with the phosphorus concentrations at three downstream river sites, indicating wet weather phosphorus contribution from both upstream catchment, tributaries, WWTP discharges and other diffuse sources.
- Flow and nutrient concentrations from Camden Weir and Matahil Creek were found to be significantly and positively correlated with phosphorus in the Nepean River at Sharpes Weir, indicating phosphorus elevation from both sources during wet weather. However, in wet weather Camden Weir flow was negatively correlated to total nitrogen and dissolved inorganic nitrogen with the downstream nitrogen concentrations ie increased flow diluted nitrogen concentrations downstream

- Upstream river flow was significantly and negatively correlated with the total nitrogen and/or dissolved inorganic nitrogen concentrations at three downstream sites (except downstream of Cattai Creek) indicating flow from the upstream river catchment is diluting the concentration downstream in wet weather and elevating nutrients via tributary/WWTP discharges in dry weather
- Upstream river site flow was also significantly and positively correlated with the total nitrogen (Cattai Creek), dissolved inorganic nitrogen (South Creek) or total phosphorus (Cattai Creek) concentrations at some downstream sites indicating the upstream river catchment influenced elevated nutrient concentration downstream and the upstream tributary catchment was better than the upstream river catchment in wet weather
- Tributary flow was significantly and positively correlated with the nutrient concentrations at two of the three downstream sites indicating nutrient contribution from the creeks in wet weather; total nitrogen, total inorganic nitrogen and total phosphorus at Matahil Creek and total nitrogen and total phosphorus at South Creek
- Site specific flow, upstream river flow or creek flow of all eight sites were negatively correlated with the chlorophyll-*a* concentrations demonstrating algal wash-out and reduced retention time during high flow conditions and algal growth leading to high chlorophyll-*a* during static low flow conditions.

Nutrients

In the uppermost zone of the river, statistical data analysis confirmed the relationship between upstream river (Camden Weir) or creek (Matahil) flow was significantly positively correlated with the downstream total phosphorus concentration. This indicates that, in wet weather the upstream catchment (both Nepean River and Matahil Creek) contribute to phosphorus enrichment in the river downstream at Sharpes Weir Nepean River (N75). Upstream river (Camden Weir) flow was significantly and negatively correlated to total nitrogen and dissolved inorganic nitrogen with increasing flow effectively diluting nitrogen concentrations downstream. However, the Matahil Creek catchment contributed to the downstream receiving water in terms of dissolved inorganic nitrogen, as confirmed by the positive significant relationship between Matahil Creek flow and dissolved inorganic nitrogen concentrations.

Comparative statistical analysis on the short-term dataset (2018-2019) of Camden Weir flow and river nutrient concentrations indicated that, in wet weather increased river flow impacted the upstream site (N78) with nitrogen (total nitrogen and dissolved inorganic nitrogen) enrichment. However, at downstream site (N75), high river/creek flow was beneficial, reducing the nitrogen (total nitrogen and dissolved inorganic nitrogen) concentrations significantly. Flow was significantly and inversely correlated with the chlorophyll-*a* concentration at this site indicating algal washout during wet weather and lower retention time for algal growth.

In the mid-zone near Penrith, a significant negative correlation between upstream river flow on total nitrogen, dissolved inorganic nitrogen and chlorophyll-*a* concentrations was evident at the downstream river site (N44). No such significant relationship was found between the upstream flow and total phosphorus concentrations. This indicated that the upstream site transported lower nitrogen concentrations downstream of Winmalee WWTP discharge during higher flow as a result of dilution. There was a general dry weather nitrogen and chlorophyll-*a* enrichment at the downstream site.

The relationship between South Creek (NS04A) flow on total nitrogen and total phosphorus concentrations at the downstream Hawkesbury River site (N35) was significantly positive with increasing flow nutrient concentrations increased at the downstream river site. This indicates in wet weather with high flows, the upstream tributary catchment is transporting these nutrients to downstream river site. In contrast, South Creek flow was negatively correlated with the chlorophyll-*a* concentration at N35 confirming a wet weather algal washout contributed by the creek flows.

Comparative statistical analysis between upstream river flow and nutrient (total nitrogen or dissolved inorganic nitrogen or total phosphorus) concentrations at the upstream (N39) and downstream (N35) sites indicated a positive correlation at both upstream and downstream river site. The only positive correlation of South Creek flow and nutrient concentration (NS04A) was evident in total phosphorus level confirming phosphorus enrichment in wet weather.

In the furthermost downstream zone near Cattai Creek, upstream river flow influenced the total nitrogen and total phosphorus concentrations at the downstream river site (N3001), but no such influence was identified with the Cattai Creek flow. This indicates nutrient concentrations at N3001 are more influenced by upstream (N35) concentrations than the water transported by Cattai Creek.

Comparative statistical analysis between upstream river flow and nutrient concentrations at the upstream (N35) and downstream (N3001) sites indicated a positive influence at both upstream and downstream river sites. The influence of flow on Cattai Creek nutrient was evident in both total nitrogen and total phosphorus levels confirming elevation in wet weather.

Chlorophyll-*a*

Both Camden Weir and Matahil Creek flow was significantly and inversely correlated with chlorophyll-*a* concentration in the Nepean River at Sharpes Weir (N75). The limited dataset (2018-2019) for the upstream site on the Nepean River at Macquarie Grove Road (N78) did not show a significant relationship with Camden Weir flow and chlorophyll-*a* concentrations.

Upstream river flow from the Nepean River at Smith Road(N48A) significantly negatively correlated with chlorophyll-*a* concentrations at the downstream Nepean River site (N44). Site-specific river flow was also significantly and inversely correlated with the chlorophyll-*a* concentrations at N48A and N44 ie increased flow at N48A was correlated to decreased chlorophyll-*a* at N48A.

Site-specific river/creek flow was significantly and negatively correlated with the chlorophyll-*a* concentration in the Hawkesbury River both upstream (N39) and downstream (N35) of South Creek, and at South Creek (NS04A).

Site-specific river/creek flow was significantly and negatively correlated with the chlorophyll-*a* concentration at the downstream Hawkesbury River site (N3001) and Cattai Creek (NC11A). A negative relationship between high flow and chlorophyll-*a* was expected due to algal washout in response to high flow/ runoff events.

6 Conclusion and way forward

The fitted statistical models provided estimates of trends in nutrient loads discharged from Sydney Water‘s WWTPs to four prioritised zones of the Hawkesbury-Nepean River and tributaries, and receiving water quality at eight monitoring sites. Key factors associated with changes to nutrients and chlorophyll-*a* concentrations at four downstream sites were also investigated.

Key findings

- Decommissioning the poorer performing WWTPs, treatment upgrades/amplification and diverting wastewater flow for advanced treatment generally resulted in decreased nutrient loads discharged to the downstream receiving water. However, the benefit was often lost or reduced due to increased population in the catchment (eg Rouse Hill WWTP) or a treatment process deterioration (West Camden WWTP).
- The temporal trends after the latest upgrade or intervention at these WWTPs were mixed and varied by WWTPs or zone of the river:
    - As of mid-2020, total nitrogen and dissolved inorganic nitrogen loads were increasing at most WWTPs or zones of the river. The exceptions were no trend for Riverstone WWTP total nitrogen and dissolved inorganic nitrogen loads, and a decreasing trend for Quakers Hill and Rouse Hill WWTP total nitrogen loads
    - The trend in total phosphorus loads was mixed, decreasing at West Camden, Winmalee, Quakers Hill, and Richmond WWTPs, stable at St Marys and Riverstone WWTPs and, increasing marginally at Castle Hill and Rouse Hill WWTPs.
- The benefit of decommissioning the poorer performing WWTPs and WWTP treatment upgrades /amplification was mostly evident with reduced nutrient concentrations at the downstream receiving water sites but a similar reduction in chlorophyll-*a* concentration was not found
    - Modelled geometric mean nutrient concentrations at the downstream river sites generally decreased in response to an upgrade at the closest upstream WWTP. Three exceptions where the modelled geometric mean nutrient concentrations in the most recent period were:
        - total nitrogen concentration in the Nepean River at Sharpes Weir after the nitrogen treatment deterioration at the upstream West Camden WWTP
        - total phosphorus concentrations in the Nepean River at Yarramundi after the commissioning of St Marys AWTP, despite decreasing total phosphorus loads from the upstream Winmalee WWTP
        - total nitrogen and total phosphorus concentrations in the Hawkesbury River at Wilberforce, after the Riverstone WWTP upgrade in 2019. This was likely due to an extreme wet weather event in early 2020 which dominated the relatively small data set
    - A change in modelled geometric mean chlorophyll-*a* concentrations in response to decreased total phosphorus loads from upstream WWTPs was marginal or increased at some sites. Chlorophyll-*a* concentrations:

- decreased in the Nepean River at Sharpes Weir, after the phosphorus treatment process upgrade at the upstream West Camden WWTP in 2009
- increased in the Nepean River at Yarramundi, after the commissioning of St Marys AWTP
- increased marginally in the Hawkesbury River at Wilberforce, after the St Marys and Riverstone WWTP upgrade in 1999, Richmond WWTP nitrogen and phosphorus treatment upgrade in March 2005, and St Marys AWTP commissioning in June 2010
- decreased in the Hawkesbury River at Wilberforce, after the Riverstone WWTP upgrade in 2019, likely due to wet weather washout

- Significantly increasing trends were detected in total nitrogen and/or dissolved inorganic nitrogen at the majority of receiving water sites in mid-2020 after the latest upgrades or interventions at upstream WWTPs. However, trends in total phosphorus were mostly decreasing and chlorophyll-*a* concentrations remained steady or increasing
    - By the mid-2020 there were increasing trends detected in total nitrogen and/or dissolved inorganic nitrogen concentrations at three of the four key receiving water sites:
        - The exception was the Hawkesbury River at Wilberforce downstream of the South Creek inflow where no trend was detected in for total nitrogen and/or dissolved inorganic nitrogen concentrations in the short period after Riverstone WWTP nutrient upgrade in 2019, but an increasing trend was detected in the earlier period (2010-2019)
    - The trends in total phosphorus concentration for the most recent period were:
        - decreasing concentrations at two Nepean River sites ((Sharpes Weir and Yarramundi)
        - increasing concentrations in the Hawkesbury River downstream of Cattai Creek catchment WWTPs
        - stable concentrations since 2019 in Hawkesbury River downstream of the South Creek inflow but decreased in the previous period (2010-2019).
    - The recent trend for chlorophyll-*a* concentration were:
        - steady in the upper Nepean River, downstream of West Camden WWTP
        - decreasing in the Nepean River downstream of Winmalee WWTP and Hawkesbury River, downstream of the Cattai Creek inflow (Castle Hill and Rouse Hill WWTPs).
        - increasing in the short period from 2019 in the Hawkesbury River at Wilberforce, downstream of South Creek, but significantly decreased in the previous period (2010-2019).
- Nutrient and chlorophyll-*a* concentrations were mostly higher at all downstream river sites compared to the upstream concentrations, confirming an impact of upstream WWTPs or tributary catchment as a potential source of nutrients
- Nutrient concentrations were lower and chlorophyll-*a* concentrations were higher at the two downstream Hawkesbury River water sites compared to concentrations in the respective upstream tributaries (South Creek and Cattai Creek)

- Nutrient and chlorophyll-*a* concentration in the downstream river sites were significantly correlated with the respective concentrations at the upstream sites ie upstream catchment factors influenced the nutrient and chlorophyll-*a* concentrations at all three downstream receiving water sites tested:
    - no such analysis was carried out for the downstream Nepean River at Sharpes Weir due to limited data available for the upstream Macquarie Grove Road site.
- There were significant positive correlations between the site-specific WWTP nitrogen and/or phosphorus loads and respective downstream nutrient concentrations at three sites, but no such relationship was found in the Hawkesbury River below Cattai Creek:
    - West Camden WWTP total nitrogen and total phosphorus loads were significantly correlated with respective concentrations in the Nepean River at Sharpes Weir
    - Winmalee WWTP total nitrogen and total phosphorus loads were significantly correlated with respective concentrations in the Nepean River at Yarramundi Bridge
    - St Marys and Riverstone WWTP total nitrogen and total phosphorus loads were significantly correlated with respective concentrations in the Hawkesbury River at Wilberforce
    - Quakers Hill WWTP total phosphorus load was significantly correlated to total phosphorus concentrations in the Hawkesbury River at Wilberforce.
    - Castle Hill WWTP total nitrogen loads were positively correlated with the respective concentrations in the Hawkesbury River off Cattai SRA
- A significantly positive correlation between the total nitrogen load or total phosphorus load with the downstream chlorophyll-*a* concentration was rarely found. Sometimes a negative relationship was found flagging the complexity of nutrient and algal dynamics in the river:
    - St Marys WWTP total nitrogen load was positively correlated with the chlorophyll-*a* concentrations in the Hawkesbury River at Wilberforce
    - St Marys total phosphorus load and Quakers Hill total nitrogen load was negatively correlated with the chlorophyll-*a* concentrations in the Hawkesbury River at Wilberforce
    - Castle Hill and Rouse Hill WWTP total nitrogen loads were negatively correlated with the chlorophyll-*a* concentrations at the downstream Hawkesbury River site off Cattai SRA
- Flow, or wet weather, was an important factor driving the nutrients and chlorophyll-*a* concentrations in the river
    - A significant positive correlation was found between the flow and nutrient concentrations confirming increased nutrients during wet weather:
        - at all four upstream sites indicating nutrient sources from the upstream river catchment in wet weather
        - at three of the four downstream sites indicating wet weather phosphorus sources from both upstream catchment, tributaries and WWTP discharges

- The relationship between the downstream nutrient concentration with the upstream river flow and tributary flow separately, revealed the following relationship between flow and nutrients
  - Upstream river flow was significantly and negatively correlated with the total nitrogen and/or dissolved inorganic nitrogen concentrations at three downstream sites ie flow from the upstream river catchment helped to dilute the concentration downstream in wet weather, indicating nutrient elevation via tributary/WWTP discharges in dry weather
  - Upstream river flow was also significantly and positively correlated with the total nitrogen or dissolved inorganic nitrogen or total phosphorus concentrations at the downstream sites ie upstream river catchment contributed to increased nutrient concentrations downstream and the upstream tributary catchment was better than the upstream river catchment in wet weather (eg South Creek dissolved inorganic nitrogen, Cattai Creek total nitrogen or total phosphorus)
  - Tributary flow was significantly and positively correlated with the nutrient concentrations at two of the three downstream sites indicating nutrient contribution from the tributaries in wet weather (Matahil Creek for dissolved inorganic nitrogen and total phosphorus, South Creek total nitrogen and total phosphorus)
- Site specific flow or upstream river flow or creek flow at all eight sites was negatively correlated with the chlorophyll-*a* concentrations demonstrating algal wash-out and reduced retention time during high flow conditions, and algal growth during static low flow conditions

Way forward

Sydney Water has consistently complied with the vast majority of EPL conditions for wastewater discharge volumes, nutrient concentrations and overall loads to the Hawkesbury-Nepean catchment. The exception was a recent non-compliance for the combined total phosphorus load from the South Creek WWTPs (St Marys, Quakers Hill and Riverstone) in the 2019-2020 year. This was mostly due to an extreme weather condition in 2020 when the WWTPs were unable to treat excessive wastewater to same standard temporarily.

Since the last two major upgrades (St Marys AWTP commissioning and Riverstone WWTP), population growth in the catchment has been rapid especially in selective pockets of the Hawkesbury-Nepean River catchment eg upper Nepean River and Cattai Creek. Population pressure and changing weather patterns has triggered an increasing trend in nutrient loads, especially nitrogen at a number of WWTPs. The rapid population growth forecast for the catchment over the next 30 years means that these pressures, and nutrient loads, are likely to increase further. To address this, wastewater treatment process upgrades are underway or planned for the majority of the Hawkesbury-Nepean River WWTPs:

- Picton WWTP – tertiary denitrification upgrade to enhance the nutrient removal capability is in the planning phase. Expected completion is June 2023. Planning is also underway to augment the effluent management capability to service population growth. Various options are being considered including enhanced treatment and reuse.
- West Camden WWTP – amplification and treatment upgrade is currently underway to accommodate population growth and enhance the level of treatment to comply with the new

nutrient licence limits which will come into effect in 2024. Expected completion is December 2023

- Penrith WWTP – planning is underway for the renewal of the bioreactors. This will improve the aeration system performance and therefore ammonia removal. Expected completion is March 2024
- Winmalee WWTP – treatment upgrade is currently underway to improve the nutrient removal capability to comply with the new nutrient licence limits which will come into effect in 2024. Expected completion is March 2022
- Richmond WWTP and North Richmond WWTP – the decommissioning of North Richmond WWTP and transfer of flow to Richmond WWTP is in the planning phase. This will enhance the nutrient removal capability to meet the revised licence discharge limits which will come into effect in 2024. Expected completion is October 2024
- St Marys WWTP – treatment upgrade to improve reliability and service growth is currently underway. The upgrade will also improve the nitrogen removal performance. Expected completion is April 2022
- Quakers Hill WWTP - treatment upgrade to improve reliability and service growth is currently underway. The upgrade will also improve the nitrogen removal performance. Expected completion April is 2022
- Riverstone WWTP – the treatment upgrade and amplification in 2019 improved the treatment level and capacity of Riverstone WWTP. Flow from Rouse Hill WWTP is planned to be transferred to Riverstone WWTP for treatment and discharge. While this will increase the load discharged to South Creek, it will result in an overall load reduction in the Hawkesbury-Nepean system due to the higher level of treatment. Expected completion is December 2022
- Upper South Creek Advanced Water Recycling Centre (AWRC) – new treatment plant to service growth in the South Creek catchment is in the planning phase. The AWRC will have advanced treatment for dry weather discharge. Expected completion is April 2026
- Castle Hill WWTP – treatment upgrade to facilitate growth and improve nutrient removal performance is currently underway. Expected completion is June 2024
- Rouse Hill WWTP – investigating the interim transfer of flow from Rouse Hill WWTP to Riverstone WWTP to facilitate servicing growth (Stage 1) and allow planning and delivery for future amplification (Stage 2). Stage 1 expected completion is December 2022
- No major treatment upgrades are planned for Wallacia, West Hornsby, Hornsby Heights or Brooklyn WWTPs in the near future.

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8 Glossary and References

8.1 Glossary

Acronyms/ Abbreviations	Full meanings
ANZG	Australian and New Zealand Guidelines
APHA	American Public Health Association
ANCOVA	Analysis of covariance
ARIMA	Auto Regressive Integrated Moving Average
AWRC	Upper South Creek Advanced Water Recycling Centre
St Marys AWTP	St Marys Advanced Water Treatment Plant, St Marys
Chl-*a*	Chlorophyll-*a*
CI	Confidence Intervals
DF	Degrees of freedom
DIN	Dissolved inorganic nitrogen, (ammonia plus oxidised nitrogen)
EIMP	Environmental Indicators Monitoring Program
EIS	Environmental Impact Statement
EMM	Estimated marginal means
DO Sat	Dissolved Oxygen Saturation (%)
d/s	downstream
EOP	Emergency Operation Protocol
EPA	Environment Protection Authority
EPL	Environment Protection Licence
GAM	Generalised Additive Model
GLM	General Linear Model
HRC	Healthy River Commission
IDAL	Intermittently Decanted Aerated Lagoon
kg	Kilogram
kg/day	Kilogram/day
KL/day	Kilolitre/day
km	kilometre(s)
L	litre(s)
M	Million
median	Median or 50th percentile value
mg/L	milligrams per litre
mL	Millilitre

Acronyms/ Abbreviations	Full meanings
ML	Megalitre
ML/day	Megalitre/day
NA	Not Applicable
NATA	National Association of Testing Authorities
NE	Not estimated
NOx	Oxidised nitrogen
NSW	New South Wales
NTU	Nephelometric Turbidity unit
OEH	Office of Environment and Heritage, New South Wales
PRP	Pollution Reduction Program
p value	The value which determines the level of significance (<0.0001, <0.05 etc.)
R^2	A statistical measure of fit that indicates how much variation of a dependent variable is explained by the independent variable(s) in a regression model
REML	Restricted Maximum Likelihood
SRA	State Recreation Area
SRP	Soluble reactive phosphorus
SS	Sum of squares
STSIMP	Sewage Treatment System Impact Monitoring Program
TKN	Total Kjeldahl Nitrogen
TN	Total nitrogen
TP	Total phosphorus
u/s	upstream
VIC	Victoria
WWTP	Wastewater Treatment Plant
WRP	Water Recycling Plant
µS/cm	micro Siemens per centimetre (unit of conductivity)
µg/L	micrograms per litre

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