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Gippsland Lakes and Catchments Task Force

Importance of catchment-sourced nitrogen loads as a factor in determining the health of the Gippsland Lakes

Dr Anthony Ladson
Moroka Pty Ltd
PO Box 1245
Fitzroy North Vic 3070

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Summary

Reducing nutrient loads to the Gippsland Lakes has long been seen as critical if the frequency of algal blooms is to be reduced. However, works targeting phosphorus loads have generally been given a higher priority than those focusing on nitrogen. The importance of nitrogen now requires a reassessment, following research that shows high nitrogen loads in winter and spring may facilitate phosphorus release from sediments and so prime the Lakes for a blue-green algal bloom in the following summer.

This report describes the importance of nitrogen in influencing the health of the Gippsland Lakes and then provides an assessment of the main sources, sinks and pathways of nitrogen. The key findings are:

- Average annual load of nitrogen to the Gippsland Lakes is around 2000 t per year, or about 1 kg/ha/yr from the catchment.
- Catchment loadings are moderate by Australian and international standards.
- Since European settlement, total loads have increased by a factor of about 1.5 because of land use change but it is likely that the load of bioavailable nitrogen has increased by a greater factor.
- Annual nitrogen loads are highly variable, with the volume of flow entering the Gippsland Lakes in any particular year being a major factor in determining the nitrogen load.
- Once the effect of flow is removed, there is no evidence that nitrogen loads have changed since 1978 (the earliest date that records are available). That is, there is no upward or downward trend in nitrogen loads.
- Nitrogen loads following the extensive bushfires and flooding in 2007 were exceptionally large. Together, in one year, these events supplied an extra 4000 t of nitrogen to the Gippsland Lakes (i.e. the equivalent of 2 years of average load).
- In normal years, much of the nitrogen load comes from forested areas with high rainfall and is likely natural in origin and not able to be changed through management action. This nitrogen is likely to be associated with humic material so will be relatively biologically unavailable.
- Atmospheric deposition of nitrogen is likely to be increasing, consistent with world trends; however it currently represents only about 3% of the average annual nitrogen load to the Lakes.

It is clear that reducing nitrogen loads would benefit lake health, but it is also challenging to find ways to achieve significant reductions. Priority should be given to reducing the load of

bioavailable nitrogen. A preliminary assessment of opportunities to mitigate loads has been undertaken and is summarised as follows.

- Overall, reductions in nitrogen loads of 25% are likely to be feasible.
- Nitrogen sources from hillslopes (and to a lesser extent, gully and bank erosion) may be feasible to mitigate. Hotspots of these sources have been identified by others and this could inform the development of management strategies. These sources are also likely to be most significant in wet years when reductions are particularly important.
- Bushfires can release large amounts of nitrogen to the Lakes. The Task Force has previously reviewed options to mitigate bushfire impacts on water quality.
- There is probably further scope to reduce loads from point sources.
- The Macalister Irrigation District (MID) is an important source of nitrogen so activities to reduce nitrogen from the MID should continue but activities in other areas are also necessary.

Specific actions related to further investigation of nitrogen loads, and planning to reduce loads, are provided at the end of this report.

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1. Introduction

Reducing nutrient loads has long been seen as important to maintain and improve the health of the Gippsland Lakes. However, works targeting phosphorus loads have generally been given a higher priority than those focusing on nitrogen. The reason is that management objectives have emphasised the need to reduce the frequency and severity of blooms of blue-green algae, and in particular potentially toxic *Nodularia*. *Nodularia* can fix nitrogen from the air so do not require catchment inputs of nitrogen to grow. In fact, they may be favoured by low nitrogen inputs as their comparative advantage over other more benign algae increases if nitrogen is limiting. There has been concern that reducing nitrogen inputs could favour the algae we want to discourage. The importance of nitrogen now requires a reassessment, following research that shows high nitrogen loads in winter or spring may facilitate phosphorus release from sediments and so prime the Lakes for a blue-green algal bloom in the following summer (Cook and Holland, 2011).

In addition to this research, there has been recent work to quantify nitrogen loads from rivers and a 32-year time series of loads has been developed (Cook et al., 2008; Cook and Holland, 2011). There has also been recent work to identify the sources of nitrogen to the Lakes based on sediment tracing and modelling (Hancock et al., 2007). Valuable information on nitrogen was also documented as part of the environmental audit and modelling undertaken by CSIRO from 1998 to 2001 (Harris et al., 1998; Webster et al., 2001).

This report brings together this work and aims to inform the Gippsland Lakes and Catchment Task Force about the importance of catchment-sourced nitrogen. Section 2 summarises the role of nitrogen in influencing the health of the Gippsland Lakes. Section 3 discusses the loads of nitrogen supplied by rivers. Section 4 lists the main catchment sources of nitrogen to the Lakes. Measurements of nitrogen concentrations in the Lakes are provided in Section 5, while Section 6 summarises potential feasible options to reduce loads. Section 7 comments on research needs and possible management actions.

This report is intended to summarise and bring together available data to provide background for further analysis, research and policy development. In particular, the discussion of feasible options to reduce loads is brief and preliminary. Further work similar to that done by Cottingham et al. (2006) and Cottingham (2008) would be required to develop strategies for implementation.

2. Nitrogen and the health of the Gippsland Lakes

The role of nitrogen in the health of the Gippsland Lakes has been the subject of recent research which has resulted in a detailed hypothesis on the interactions between nitrogen loads and *Nodularia* blooms (Cook et al., 2008; Holland et al., 2010; Cook and Holland, 2011). There was also substantial work on nitrogen behaviour as part of earlier work undertaken by CSIRO (Harris et al., 1998; Webster et al., 2001). The importance of nitrogen is briefly summarised below.

Every year, a large amount of nitrogen enters the Lakes. It is washed in from the catchments via rivers and deposited from the atmosphere. The Gippsland Lakes system is a nitrogen concentrator because 20,000 km^2 of catchment collects nitrogen and supplies it to 400 km^2 of lake. However, nitrogen doesn't build up in the Lakes because most is rapidly lost by denitrification i.e. it is converted into nitrogen gas and escapes from the system. High denitrification efficiency is a sign of a healthy estuary (Harris et al., 1998). Nitrogen can also be flushed into the ocean or buried in lake sediments. It is also an important nutrient so is incorporated into plant and animal tissue. Generally, people prefer the Gippsland Lakes to be infertile (have low nitrogen concentration), because that leads to clear, blue water that is usually considered healthy. Typically, there is not sufficient nitrogen in the Lakes for them to grow enough plants or algae to appear green.

Nitrogen loads to the Gippsland Lakes are highly variable, and the ecosystem is adapted to this. If there is a pulse of nitrogen, too much to be denitrified immediately, then nitrogen concentrations in lake water increases until denitrification can catch up. For example, the pulse of nitrogen introduced following the 2007 fires and floods initially overwhelmed the denitrification processes and nitrogen levels in the Lakes increased. It took 466 days for this excess nitrogen to be removed from the system and for nitrogen concentrations to return to background levels (Holland et al., 2010).

A pulse of nitrogen will have short term effects and the Lakes can recover, but if loads are too high for too long, there is a pattern of effects that can emerge. As nitrogen loads to an estuary increase, algal blooms are stimulated and sea grass is lost largely due to shading (Harris, 2009). At the same time, increased internal loading of available phosphorus, from sediment release, is likely. Systems may change from having clear water with large beds of seagrasses or macrophytes to become algal dominated so the water is green. A process like this has already occurred at Lake Wellington (Harris, 2009).

In Lake Victoria and Lake King, there is an important interaction between nitrogen loads from catchments and blooms of *Nodularia*. When nitrogen loads to these lakes increase, because of high riverine inflows which usually occur in winter and spring, growth in the lakes also increases. Usually this will occur as blooms of diatoms (a type of algae) and dinoflagellates - which are also primary producers.

These blooms can interact with lake sediments, supplying carbon and causing anoxia. These conditions in turn lead to release of available phosphorus from sediment into the water column. At the same time, nitrogen concentrations are decreasing as denitrifiers continue to process the earlier pulse of nitrogen. By the time we get to summer there can be low nitrogen and high phosphorus concentrations in the water column, conditions that favour nitrogen fixing blue-green algae such as *Nodularia,* and therefore causing a nuisance algal bloom. Under conditions of a *Nodularia* bloom the Lakes are phosphorus limited. On the other hand nitrogen is not limited because the *Nodularia* can source it from the atmosphere.

Management actions have generally been designed to limit phosphorus inputs to the Gippsland Lakes to decrease blooms of blue-green algae. Recent work has shown that it is internal sources of phosphorus (P from sediment, rather than P from the catchment), that are particularly important in years when there is a *Nodularia* bloom (Cook and Holland, 2011). It seems that high nitrogen inputs cause a series of chemical and biological processes that assist the release of phosphorus from lake sediments and so lead to a bloom. This is not to disparage efforts to reduce phosphorus loads from the catchment since this is still required to decrease phosphorus in lake sediments in the long term.

The timing of nitrogen loads to the Lakes is also important. High winter/spring inflows of nitrogen can prime the system for an algal bloom in the following summer and autumn. However, if nitrogen loads are high in summer and autumn, this reduces the competitive advantage of nitrogen fixing *Nodularia* and may lead to other algae blooming e.g. *Synocochoccus* or green algae, which are more benign.

Reducing catchment nitrogen loads and lake nitrogen concentrations in winter and spring would help avoid algal blooms. However, reducing nitrogen concentrations in summer/autumn is likely to exacerbate *Nodularia* blooms because the comparative advantage of this nitrogen fixer is increased. This scenario showed up in CSIRO modelling (Webster et al., 2001 p50), where nitrogen load reductions were shown to have the potential to increase *Nodularia* blooms.

There is also a spatial component to nitrogen loads and the response of the Lakes. In general, there is more phytoplankton[1] in Lake Wellington because nitrogen loads are higher from the western rivers. This shows up in the data collected by the EPA as high levels of chlorophyll a[2]. However, *Nodularia* blooms are mostly absent from Lake Wellington because: (1) salinity is too low; (2) there is continuing nitrogen input over summer (N delivered over winter promotes *Nodularia* but will inhibit blooms over summer), and (3) there is less stratification because Lake Wellington is shallower.

The simple message is that large inputs of nitrogen in wet years are likely to cause a *Nodularia* bloom in Lake Victoria and Lake King and it would be appropriate to mitigate these inputs if possible. However, as we discuss later, this is a rather challenging task.

[1] Phytoplankton is the collective term for microscopic floating plants that includes diatoms, algae and blue-green algae e.g. *Nodularia.*

[2] Chlorophyll a is a green pigment found in plants and is essential for photosynthesis.

3. Nitrogen supply to the Lakes

This section looks at how much nitrogen is supplied to the Gippsland Lakes. Loads can be estimated from the major rivers and there have been estimates of average annual loads under both current and natural (pre-European) conditions.

Annual loads of nitrogen to the Gippsland Lakes have been estimated from 1978 to the present by analysing measured inflows and concentration of total nitrogen at gauging stations on the main tributaries (Cook et al., 2008; Cook and Holland, 2011) (Figure 1). Approximately 80% of loads are from gauged catchments (Grayson et al., 2001) so these underestimate the total load by around 20%. Loads are highly variable and load in 2007 stands out (Figure 2). There is also significant uncertainty in load estimates especially in years when loads are high (Figure 3). This means it is challenging to assess any change in load with time.

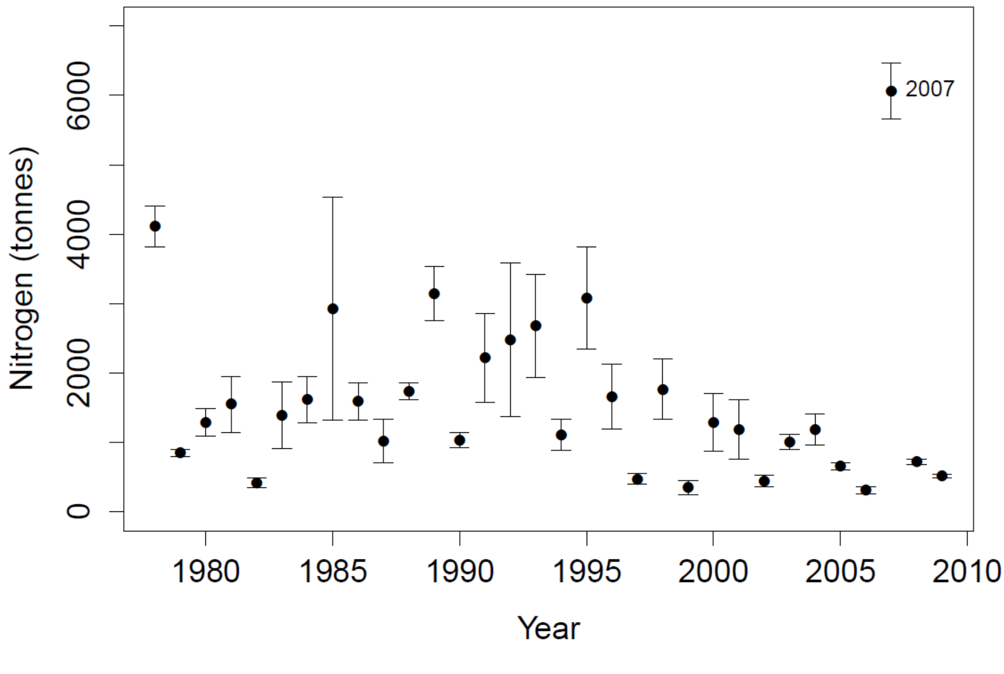

Figure 1: Annual nitrogen loads to the Gippsland Lakes from tributaries (1978-2009). Error bands show +/- 1 standard error.

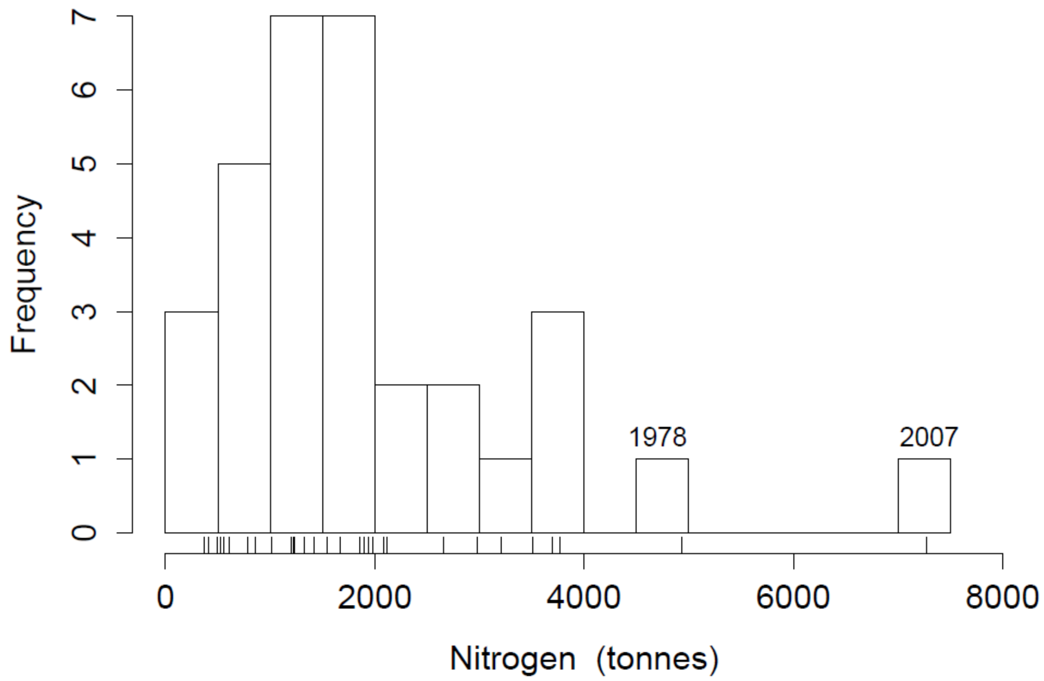

Figure 2: Annual nitrogen loads to the Gippsland Lakes. These have been increased by 20% from Figure 1 to allow for ungauged inflows.

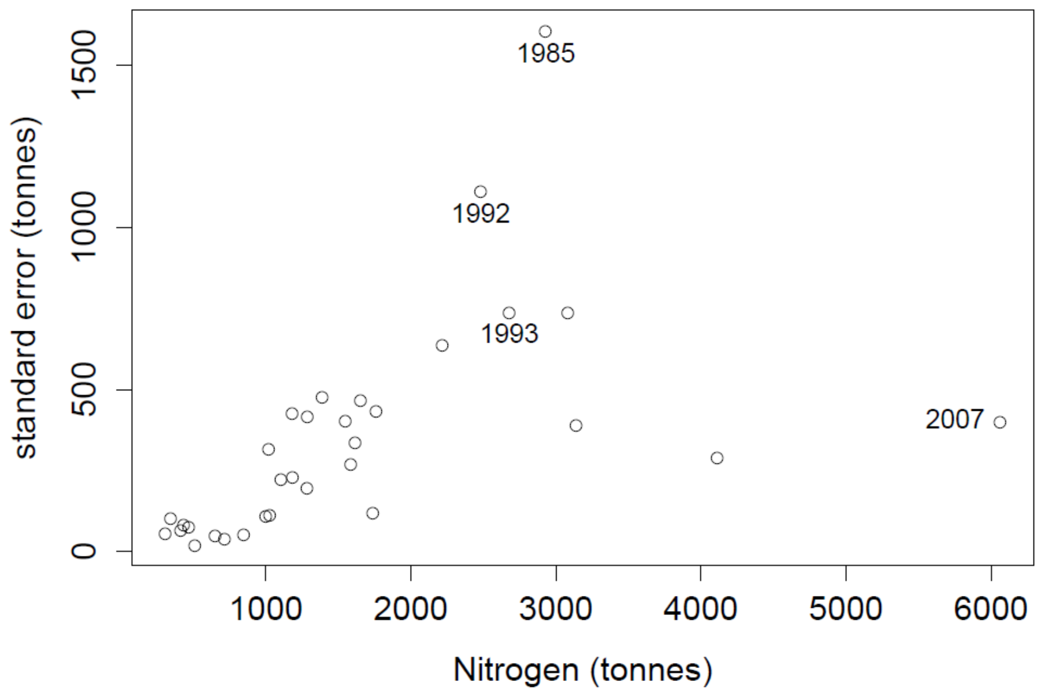

Figure 3: Uncertainty in annual load estimate (standard error), as a function of annual nitrogen load. Significant values are highlighted.

3.1 Average annual nitrogen load

There are a number of ways of estimating the average annual nitrogen load from the measured data (Table 1). The mean of all values (when they have been increased by 20% to take account of ungauged inflows) is 1940 t/year. The mean of 'normal' years, i.e. those not affected by large fires and floods, can be estimated by removing the 2007 value. In this case, the mean reduces to 1770 t/year. The EPA reports average annual nitrogen loads of 2040 t with a large standard error of 1170 t (EPA, 2009a). Using an approach based on sediment tracing and analysis, Hancock et al. (2007) estimated an average annual load of 2400 t/year, while Grayson et al. (2001) used nitrogen generation rates from different land uses to estimate loads of 2800 t/yr. There is a range of values but we have adopted 2000 t per year as an annual average.

The average annual load can be used to estimate the loading rate from the catchment. The catchment area is about 20,000 km^2; so for an annual load of 2000 t, the load per area is 1 kg/ha/yr. This value can help identify nitrogen hot spots; areas where the loading rates associated with a land use in the catchment is significantly above 1 kg/ha/yr. The rate of nitrogen deposition from the atmosphere is also of the order of about 1 kg/ha/yr (discussed later).

The average annual nitrogen load can also be expressed in terms of the area of the Lakes. A 20,000 km^2 catchment provides 2000 t of nitrogen to a 400 km^2 lake so the loading is 50 kg/ha/yr. This value can be compared to other estuaries. Bowen et al. (2007) report values of 14 to 600 kg/ha/yr for 13 international estuaries (including Moreton Bay). Scanes et al. (1998) and Harris (2009) list loadings for estuaries from south east Australia. Gippsland Lakes falls in the bottom half of these values (Figure 4) and, using the rating system proposed by Scanes et al. (1998) would be at moderate risk of degradation because of nitrogen inputs (Table 2). There was a claim in an early CSIRO report (Harris et al., 1998 p23), that nitrogen loadings to the Gippsland Lakes were very high by international standards but this does not seem correct.

Table 1: Average annual nitrogen load

Statistic	Value (t/year)	Uncertainty
Mean (Cook et al. 2008, Cook pers. comm.)	1940	1410-2470 (95% confidence interval)
Mean without 2007	1770	1360-2180 (95% confidence interval)
EPA estimate (EPA, 2009a)	2040	1170 (standard error)
CSIRO (Hancock et al., 2007)	2400	(not provided)
Grayson et al. (2001)	2800	(not provided)

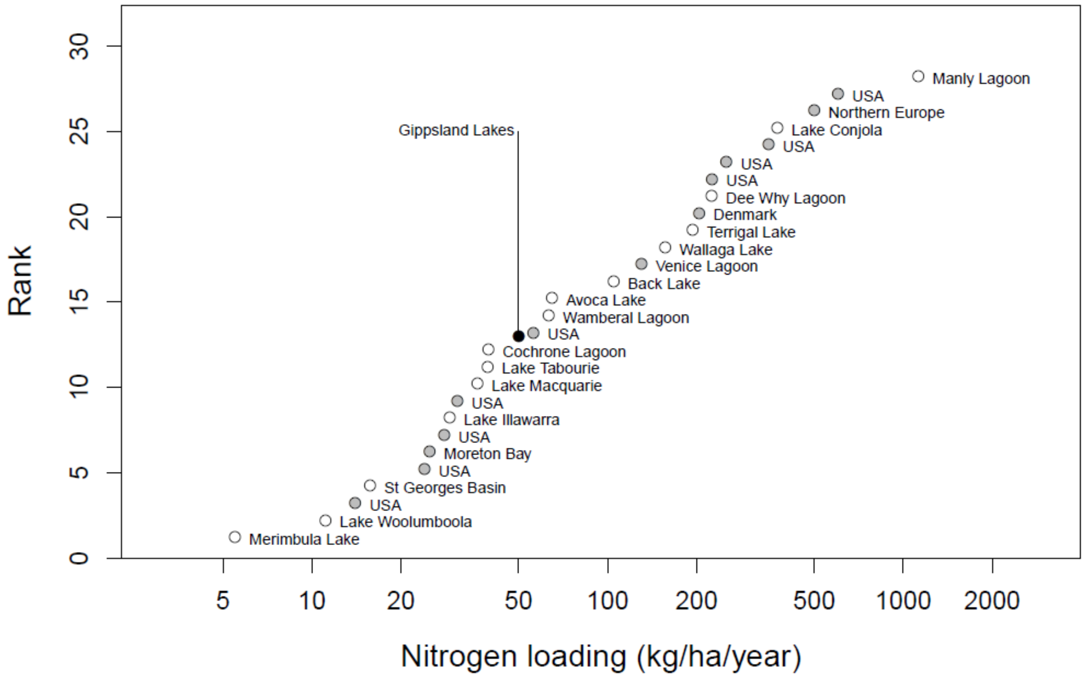

Figure 4: Comparison of nitrogen loads to the Gippsland Lakes with values from the literature (Scanes et al., 1998, Bowen et al. 2007)

Table 2: Risk of estuarine degradation association with nitrogen load (Scanes et al., 1998)

Risk category	Nitrogen load (kg N/ha/yr)
Low	<20
Moderate	20-100
High	>100

3.2 Influence of flow on annual loads

The previous section discussed the average annual load of nitrogen to the Gippsland Lakes. In fact, loads vary substantially between years as shown in Figure 1. There is a strong relationship between annual nitrogen load and annual flow as shown in Figure 5. Flow explains over 90% of the variance in loads. Nitrogen load can be related to gauged flow as follows:

$$L = -43.2 + 0.695F \qquad (1)$$

Where:

L = Annual nitrogen load (tonnes)

F = Annual flow (GL)

Statistical justification of this relationship is provided in Appendix A.

Cook et al. (2008) identified that there had never been a *Nodularia* bloom where the annual inflow was less than 1600 GL. Based on equation 1, this equates to a load of 1000 t of nitrogen. That is, provided nitrogen loads can be kept below 1000 t per year, the risk of a bloom is low. Ten of the 32 years since 1978 have had loads below 1000 t (Figure 1).

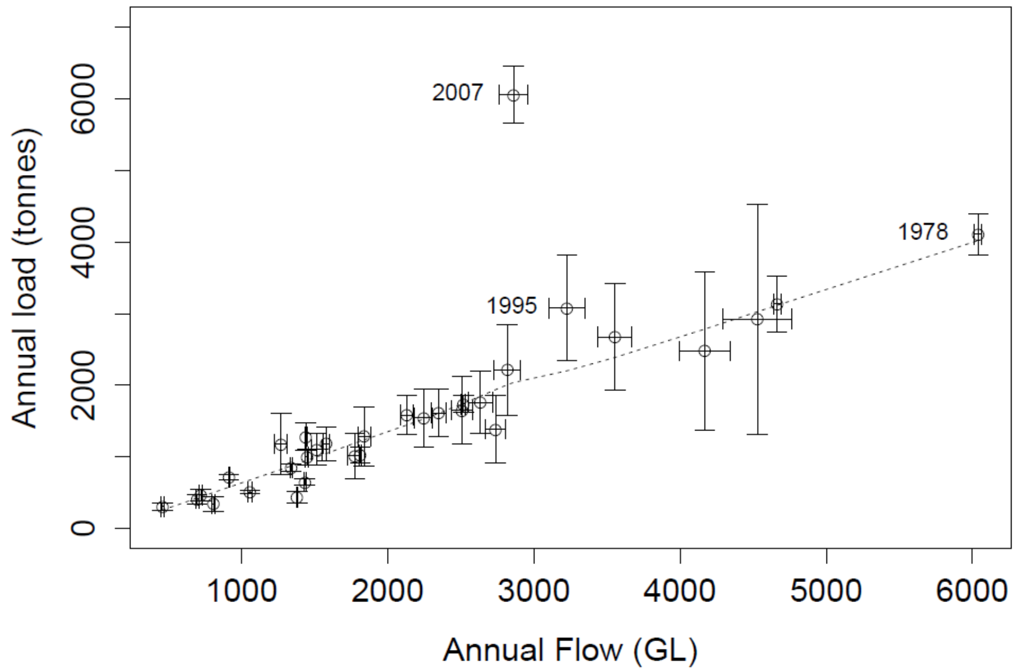

Figure 5: Relationship between annual nitrogen load to the Gippsland Lakes and annual flow. Notable years are highlighted.

3.2.1 Loads during 2007

The relationship between flow and load (equation 1) provides a good description of historical data, for all years except 2007, which was an exceptional year with a very high load. What makes it outstanding is that the load was much higher than would be expected based on the reasonably modest inflow volumes. The annual load was estimated as 6060 tonnes, the highest value between 1978 and 2009 (Figure 5). The annual inflow this year was about 2860 GL. We can estimate the load that would be expected from an inflow of this volume using equation 1. The estimate is 1945 tonnes of N (95% prediction interval 1390 – 2503 tonnes) (see Appendix A). This suggests that an additional 4,000 tonnes of N was supplied to the Lakes during 2007 than would reasonably be expected given the inflow volume. This extra nitrogen has been attributed to the fact that flood followed a severe fire in the catchment (Cook and Holland, 2011).

3.3 Change in loads with time

3.3.1 Change since 1978

The time series of annual loads (Figure 1) can be used to determine if loads have increased or decreased since 1978, independently of changes in flow. It is possible to statistically remove the effect of flow from these data and then check for a trend. This analysis is described in detail in Appendix A, but the conclusion is that since 1978 there is no trend. Loads have not changed. There is no evidence of either a decrease or an increase.

3.3.2 Change in loads over the last 250 years

There is no trend in loads since 1978 but what about in the longer term? Grayson et al. (2001) estimated current and pre-European nitrogen loads. They suggest that loads from the eastern rivers (Mitchell, Nicholson, Tambo) have increased by a factor of 1.1, while loads from the western rivers (Latrobe, Thomson, Macalister, Avon) have increased by a factor of 1.8. Overall loads have increased by a factor of 1.5 since pre-European settlement (Figure 6).

Grayson et al. (2001) derive this change in loads from changes in land use since 1750. The change in land use since 1978 has been relatively modest so it is reasonable that there should be no trend in more recent times.

Although there is little data, it is likely that bioavailable forms of nitrogen have increased by a greater proportion than overall nitrogen loads. Much of the material from forested areas, which would have covered a larger proportion of the catchment historically, has low bioavailability, whereas nitrogen from point sources and some sources associated with agriculture has much higher bioavailability.

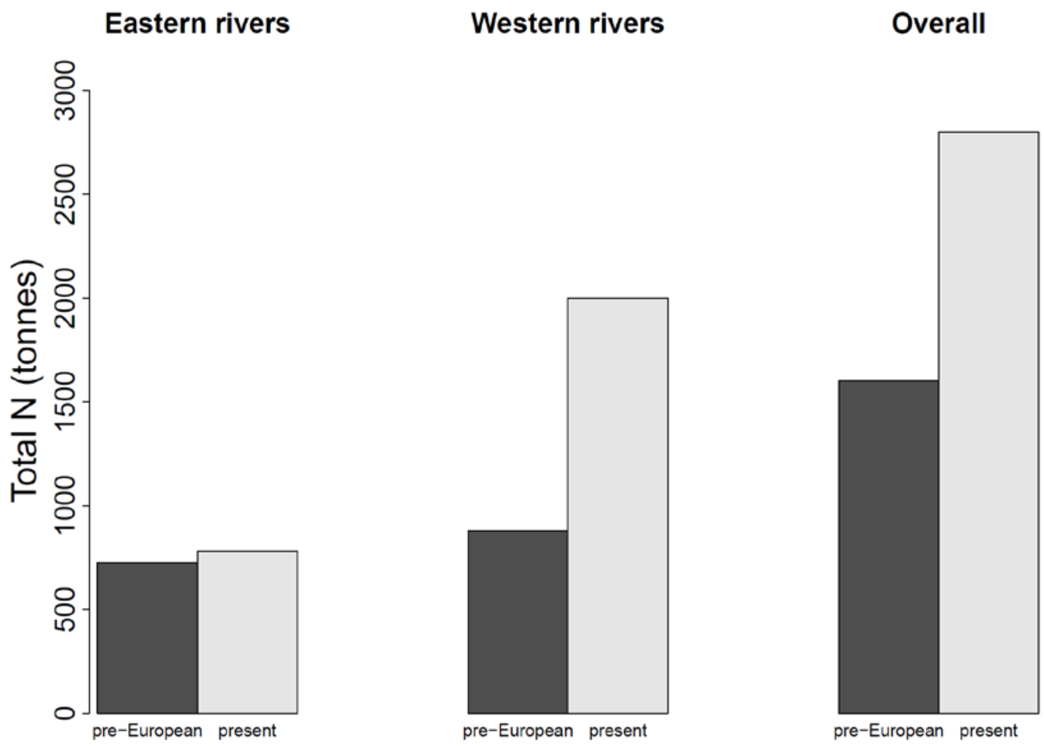

Figure 6: Comparison of pre-European and present average annual loads to the Gippsland Lakes (Source: Grayson et al., 2001)

4. Nitrogen sources

4.1 Catchment sources of nitrogen

Work by CSIRO (Hancock et al., 2007) estimated nitrogen budgets for the Gippsland Lakes. Total nitrogen load was estimated for 18 catchments and nitrogen was partitioned into dissolved form and that associated with hillslope, gully and bank erosion. Results are summarised in Table 3.

This work was based on catchment modelling (SedNet) and sediment tracing. Results in most cases are similar to previous estimates (Grayson et al., 2001; Grayson 2006). One important difference in results and method, is that Grayson used direct measurements of nutrient runoff from the Macalister Irrigation District (MID) to estimate nitrogen loads while in the SedNet modelling, these loads were based on estimated nutrient generation rates from the land uses in the MID. This explains why CSIRO load estimates for the Latrobe and Thomson catchments are lower than those in Grayson (2006). Total average annual loads for all catchments are estimated as 2,400 t/yr (excluding atmospheric deposition on the Lakes); 2,500 t/yr including atmospheric deposition.

We have adopted the values from Hancock et al. (2007) in the analysis that follows i.e. we have not attempted to correct the MID loads as was done by Grayson (2006).

Table 3: Catchment contributions of nitrogen to the Gippsland Lakes (adapted from Hancock et al., 2007)

Catchment	Area (km^2)	Length (km)	Active length (km)	Dissolved (t/yr)	Hillslope erosion (t/yr)	Gully erosion (t/yr)	Bank erosion (t/yr)	Total (t/yr)
West								
Latrobe Upper	761	154	31	106	11	0	16	134
Tanjil	507	135	24	62	2	0	5	69
Moe	638	104	65	92	22	0	10	124
Morwell	665	146	71	82	9	0	8	98
Traralgon	185	44	22	17	3	0	3	23
Latrobe Lower	1,916	445	254	118	31	9	47	205
Thomson Upper	477	74	23	81	0	0	0	81
Macalister Upper	1897	433	35	170	4	0	7	182
Thomson Macalister	3,685	926	250	91	12	1	77	181
Avon	2,089	485	126	68	31	2	24	125
Perry + other[a]	1,404	246	171	33	14	1	1	49
West total	**11,850**	**2,685**	**1,013**	**919**	**141**	**12**	**198**	**1,270**
East								
Wonnangatta	2,097	462	16	197	85	0	42	324
Dargo	708	144	7	60	43	0	13	117
Mitchell	1,865	459	82	73	93	21	75	262
Nicholson	557	124	11	19	22	2	8	51
Tambo Upper	1,602	312	40	67	129	12	25	232
Tambo Lower	1,264	276	30	52	47	3	8	110
Toms + other[b]	520	110	78	31	24	2	0	57
East total	**8,612**	**1,887**	**265**	**499**	**442**	**40**	**171**	**1,153**
Point sources								**87**
Overall total	**20,462**	**4572**	**1,278**	**1418**	**583**	**52**	**369**	**2,510**

a – Perry + other includes the catchment of the Perry River and other areas adjacent to the western lakes

b – Toms + other includes the catchment of Toms Creek and other areas adjacent to the eastern lakes.

The CSIRO results (Hancock et al., 2007) are summarised in a series of graphs below. When catchments are grouped as ‘east’ or ‘west’, the total nitrogen load is about the same from each group (Table 3). Loads per catchment are shown in order in Figure 7 for east catchments and Figure 8 for west catchments. Overall, the highest loads are from the Wonnangatta, Mitchell and Upper Tambo Catchments.

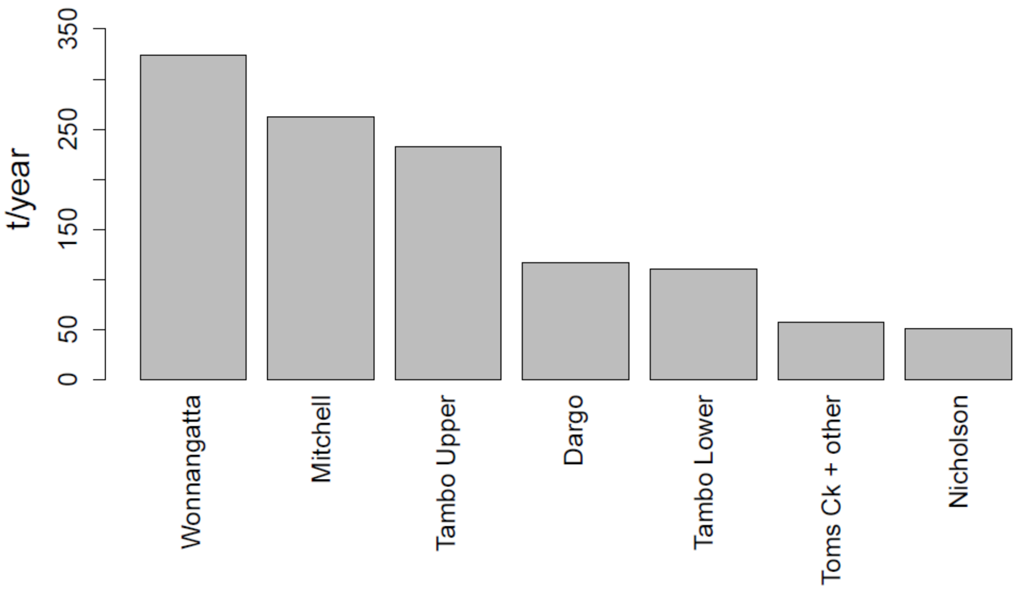

Figure 7: Total nitrogen load for each catchment – east catchments

Loads per ha are shown in Figure 9 for east, and Figure 10 for west catchments. All catchments are presented in sorted order in Figure 11. The Moe Catchment is shown to contribute the highest nitrogen load per unit area, about 2 kg/ha/yr.

Nitrogen loads from catchments were partitioned into dissolved form or forms associated with hillslope, gully or bank erosion (Table 3). Dissolved forms of nitrogen are likely to be nitrate (NO_3-N) and organic nitrogen while nitrogen from erosion will be associated with particulate matter.

Most nitrogen is delivered to the Lakes in dissolved forms (Figure 12). Figure 13 shows that most of the nitrogen in the west is in dissolved forms; most of the nitrogen in the east is associated with erosion. Results are further broken down by catchment in Figure 14 for the east catchments and in Figure 15 for the west catchments.

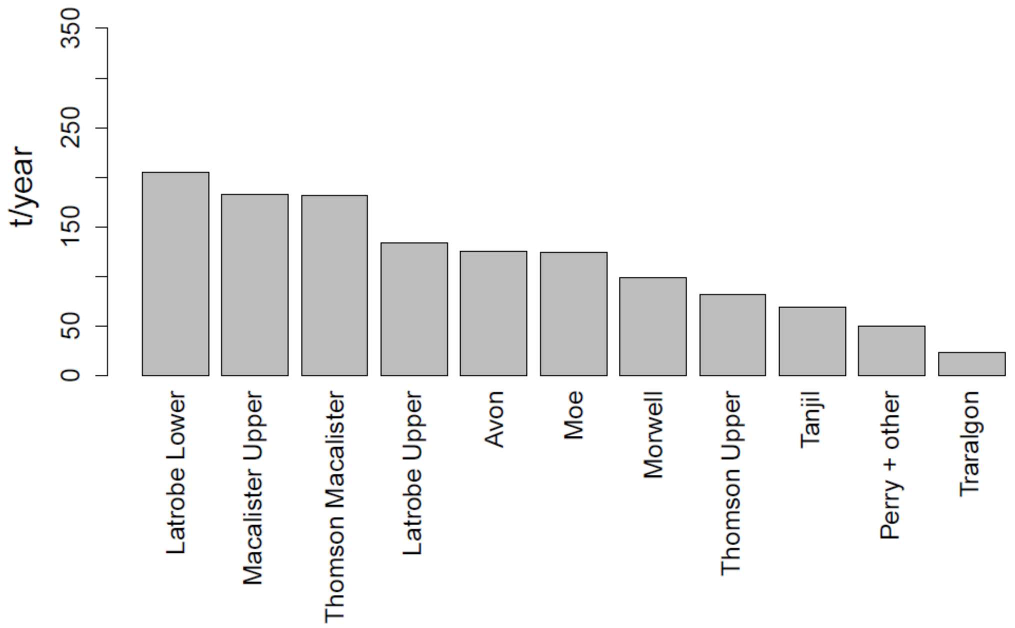

Figure 8: Total nitrogen load for each catchment – west catchments

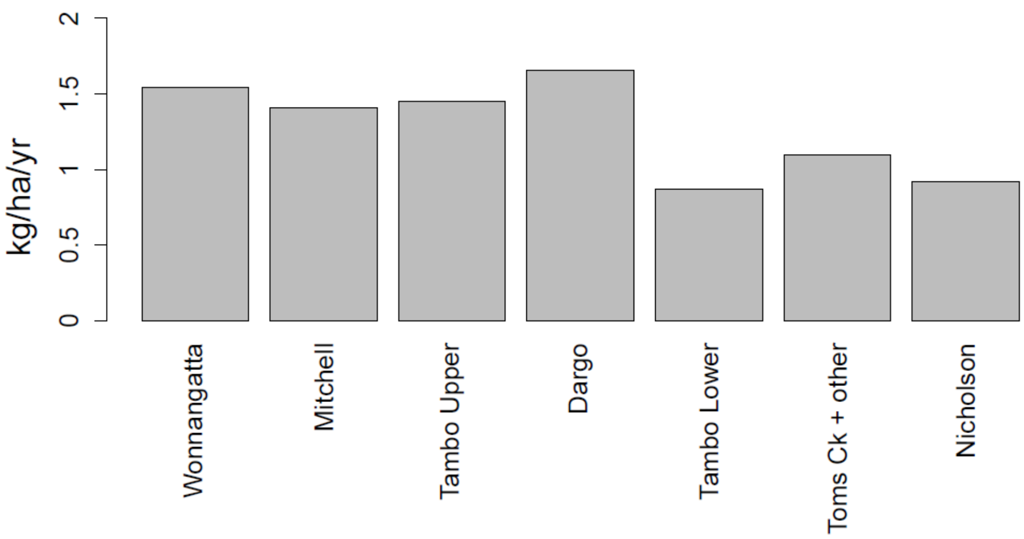

Figure 9: Total nitrogen load per ha for each catchment – east catchments

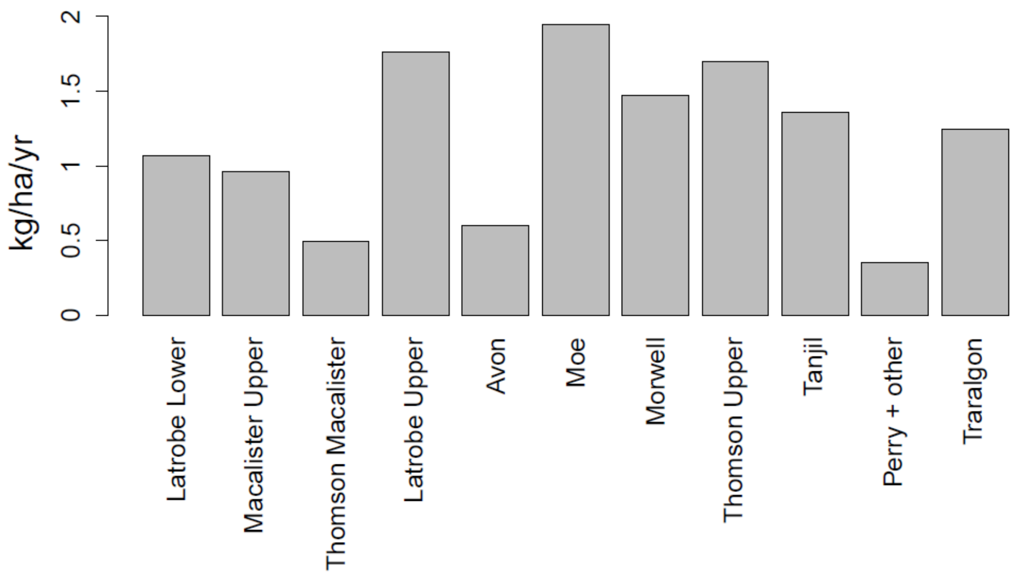

Figure 10: Total nitrogen load per ha for each catchment – west catchments

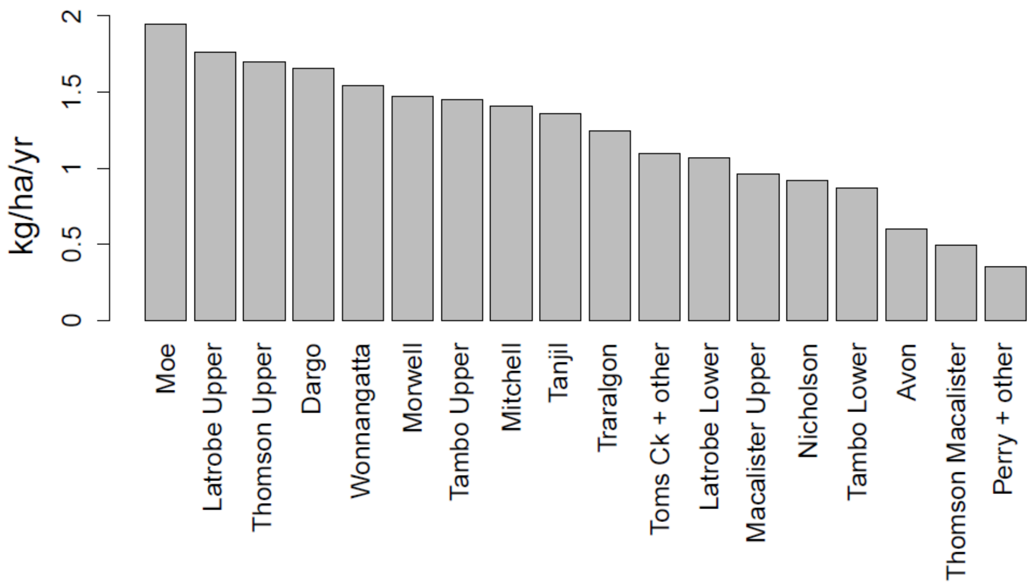

Figure 11: Total nitrogen load per ha for all catchments, sorted from highest to lowest

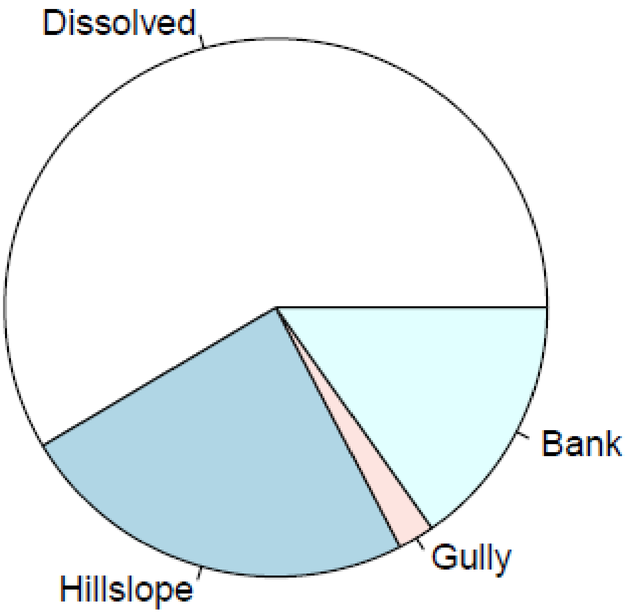

Figure 12: Source of nitrogen (dissolved, bank, gully or hillslope) for the Gippsland Lakes

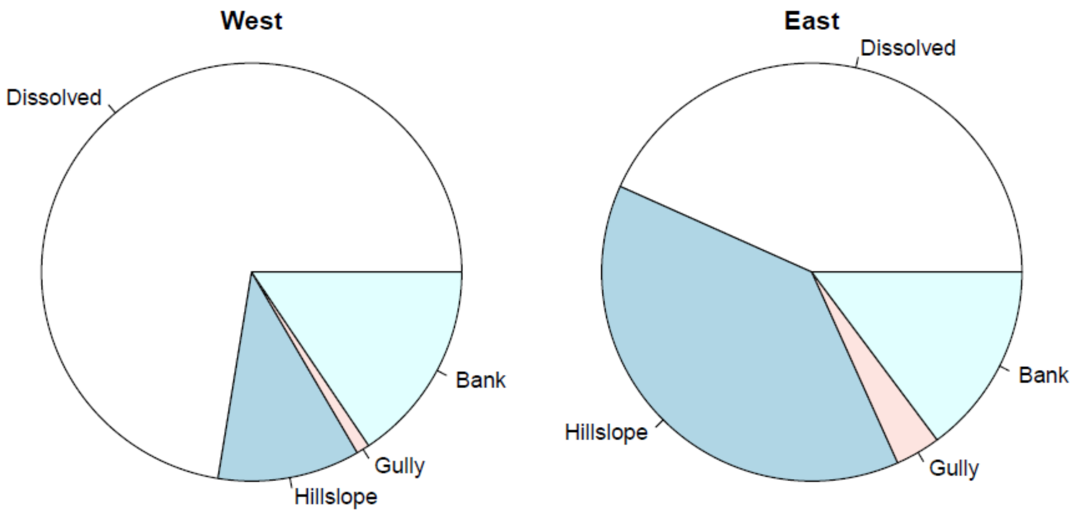

Figure 13: Source of nitrogen (dissolved, bank, gully or hillslope) for the east and west catchments of the Gippsland Lakes

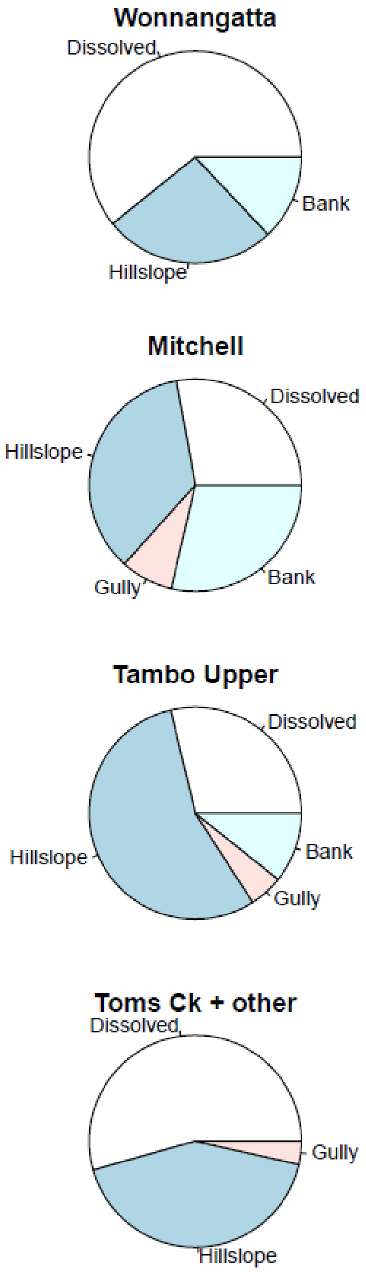

Figure 14: Source of nitrogen (dissolved, bank, gully or hillslope) for each catchment – east catchments

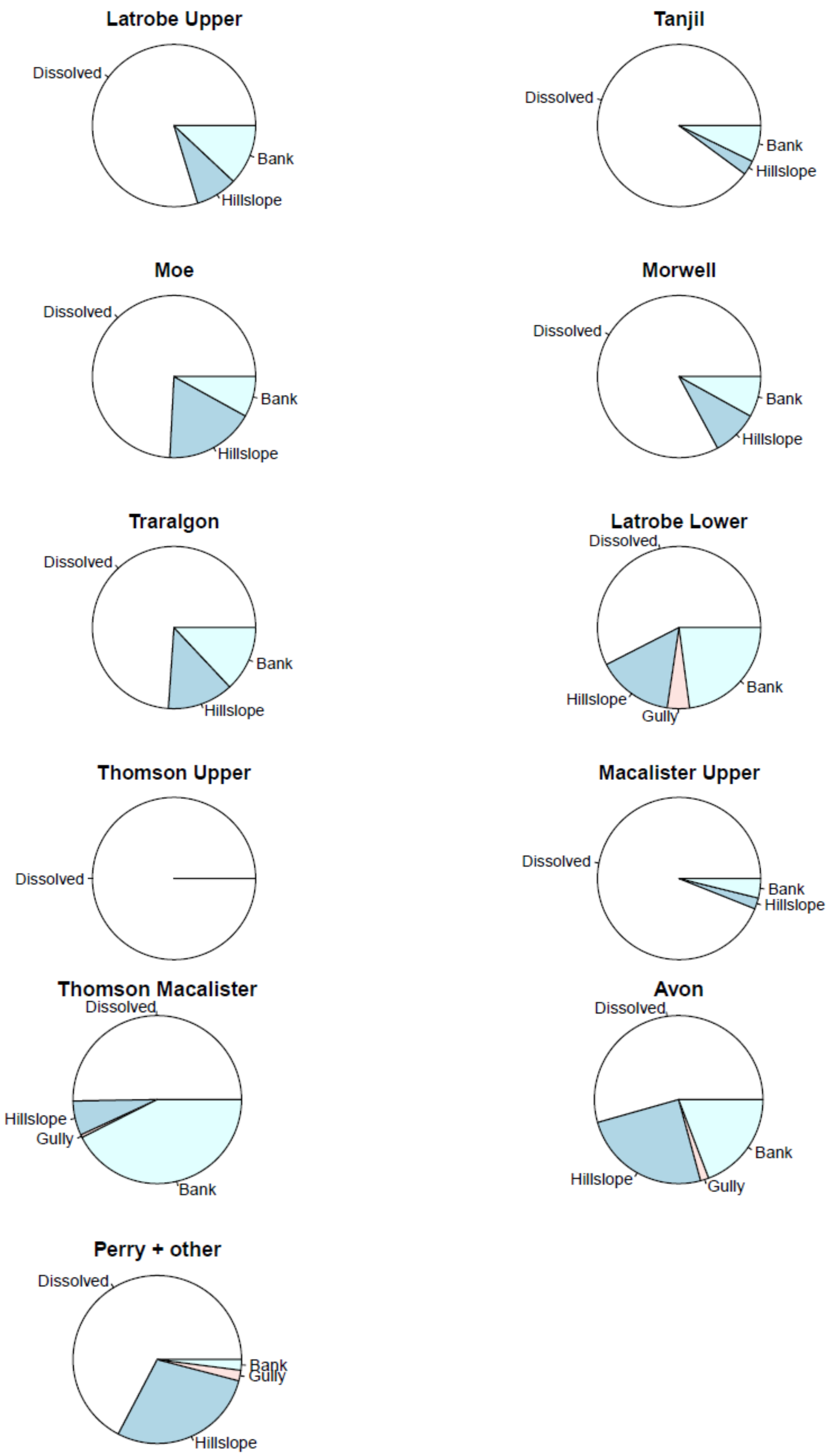

Figure 15: Source of nitrogen (dissolved, bank, gully or hillslope) for each catchment – west catchments

4.2 Dissolved sources of nitrogen

Dissolved nitrogen is the most important source of nitrogen to the Gippsland Lakes making up 58% of the total load. Eastern catchments contribute 20% while 38% is from the west.

Largest total loads come from the Wonnangatta and Mitchell catchments in the east (Figure 16) and the Upper Macalister and Lower Latrobe in the west (Figure 17). Highest loads per ha are from the Wonnangatta and Dargo in the east (Figure 18) and the Upper Thomson and Moe in the west (Figure 19). Most of the dissolved N comes from high rainfall forest areas (Figure 20). This suggests that this source of nitrogen is not likely to have been influenced by human induced changes, nor is there any obvious way to mitigate loads from this source. The actual load to the Lakes from the Upper Thomson catchment will depend on the amount of water released from the dam to the Gippsland Lakes.

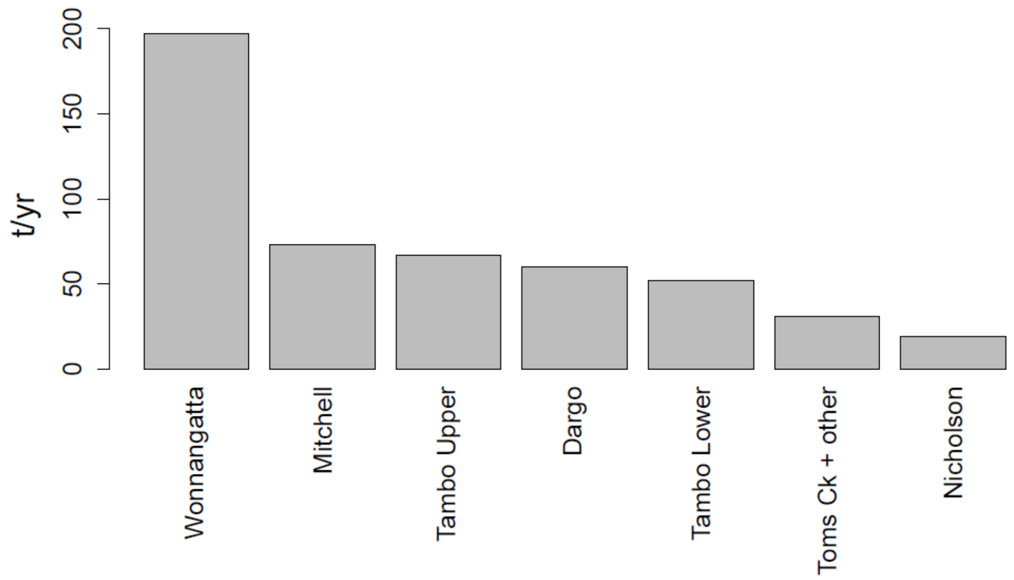

Figure 16: Dissolved nitrogen loads to the Gippsland Lakes – east catchments

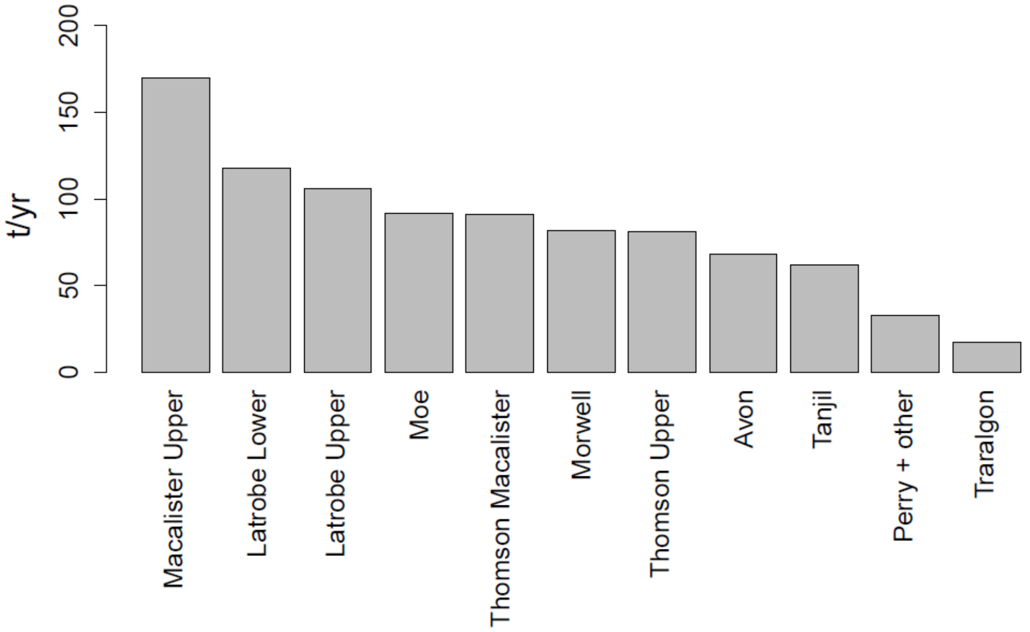

Figure 17: Dissolved nitrogen loads to the Gippsland Lakes – west catchments

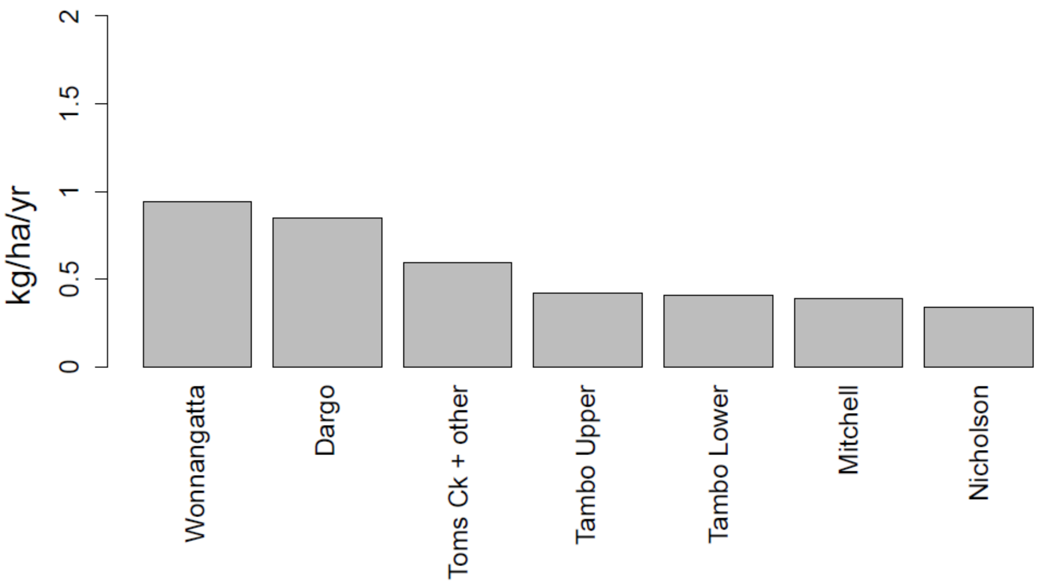

Figure 18: Dissolved nitrogen loads to the Gippsland Lakes per ha – east catchments

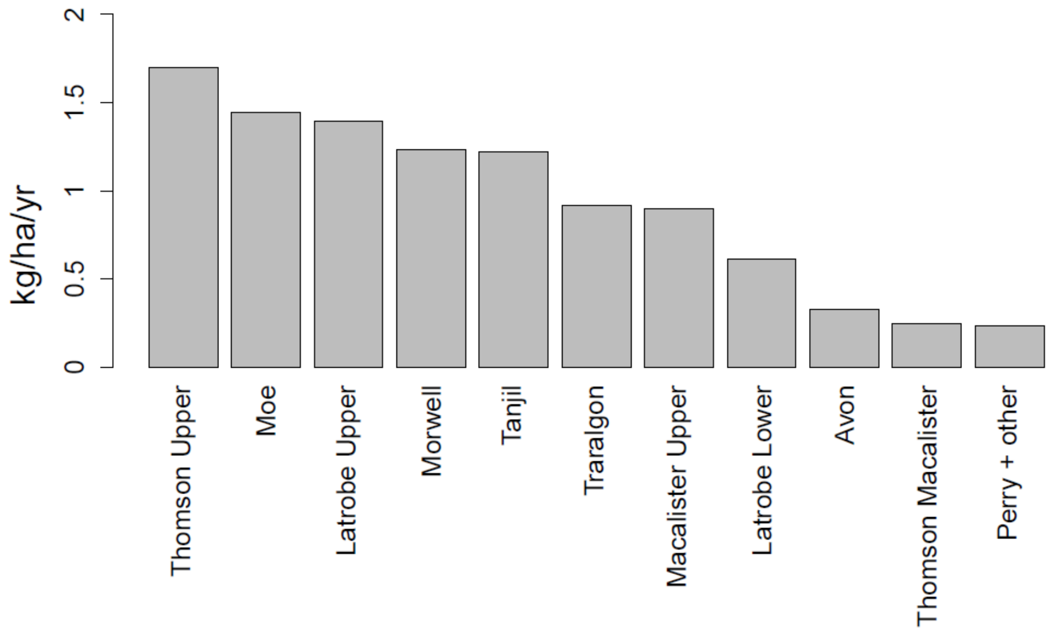

Figure 19: Dissolved nitrogen loads to the Gippsland Lakes per ha – west catchments

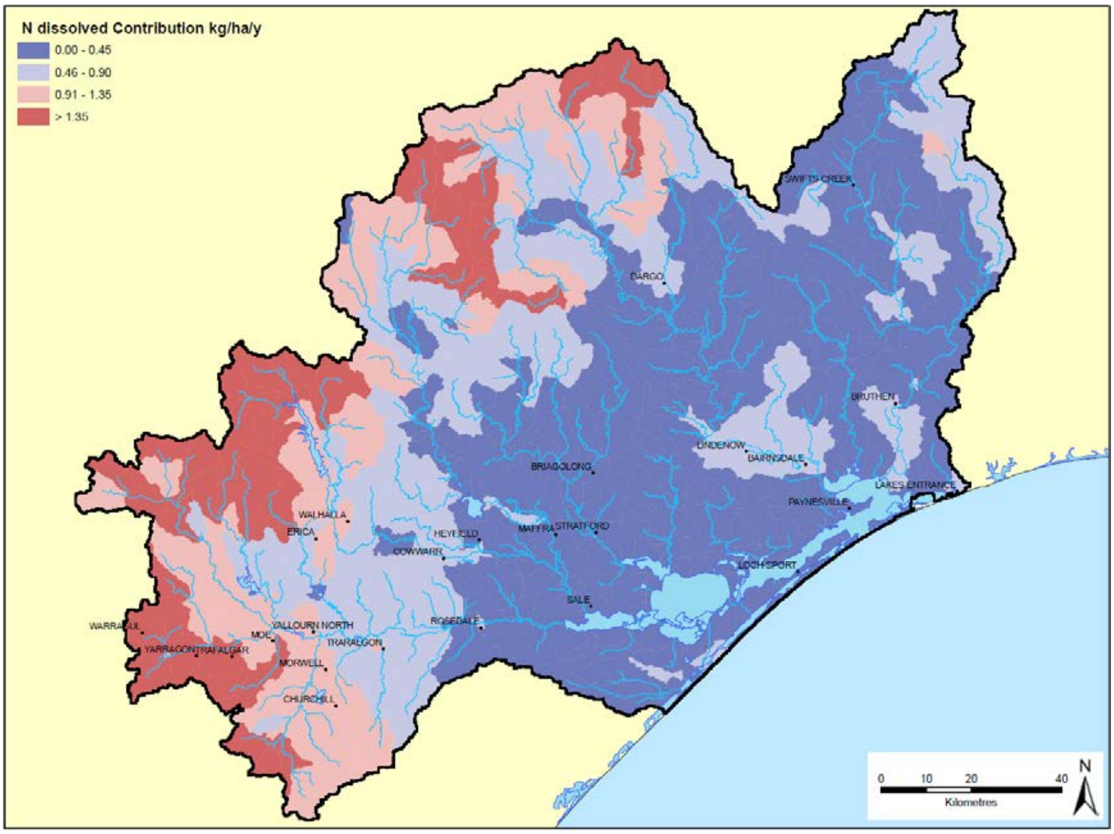

Figure 20: Contribution of nitrogen to Gippsland Lakes from dissolved runoff (Hancock et al., 2007)

4.3 Hillslope sources of nitrogen

The use of the term 'hillslope erosion' by Hancock et al. (2007) differs from the terminology used in soil erosion management planning by the CMAs (WGCMA, 2008) where hillslope erosion is differentiated into sheet and rill erosion and mass movement. These types or erosion are all lumped together in CSIRO reporting.

Nitrogen associated with hillslope erosion is the second most important source of nitrogen to the Gippsland Lakes making up 24% of the total load. Eastern catchments contribute 18% while 6% is from the west.

Largest total loads come from the Upper Tambo and Mitchell catchments in the east (Figure 21), while none of the western catchments contribute much nitrogen in this form (Figure 22). Analysis by CSIRO (Hancock et al., 1997) suggests that hillslope nitrogen comes from a few local areas in the Avon, Mitchell, and Tambo catchments as shown in Figure 23. Management actions to mitigate these sources may be feasible.

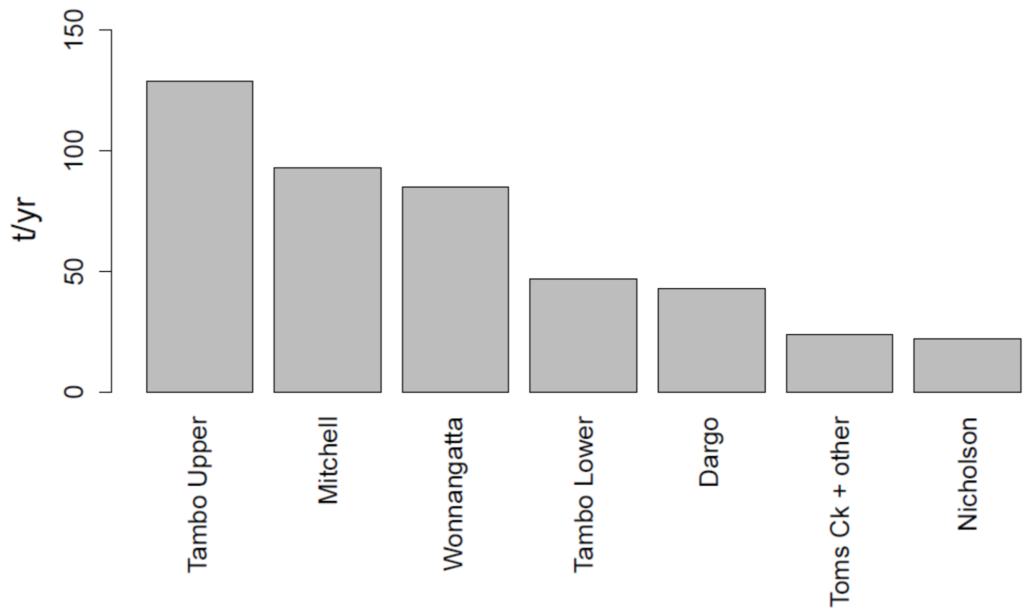

Figure 21: Hillslope nitrogen loads to the Gippsland Lakes – east catchments

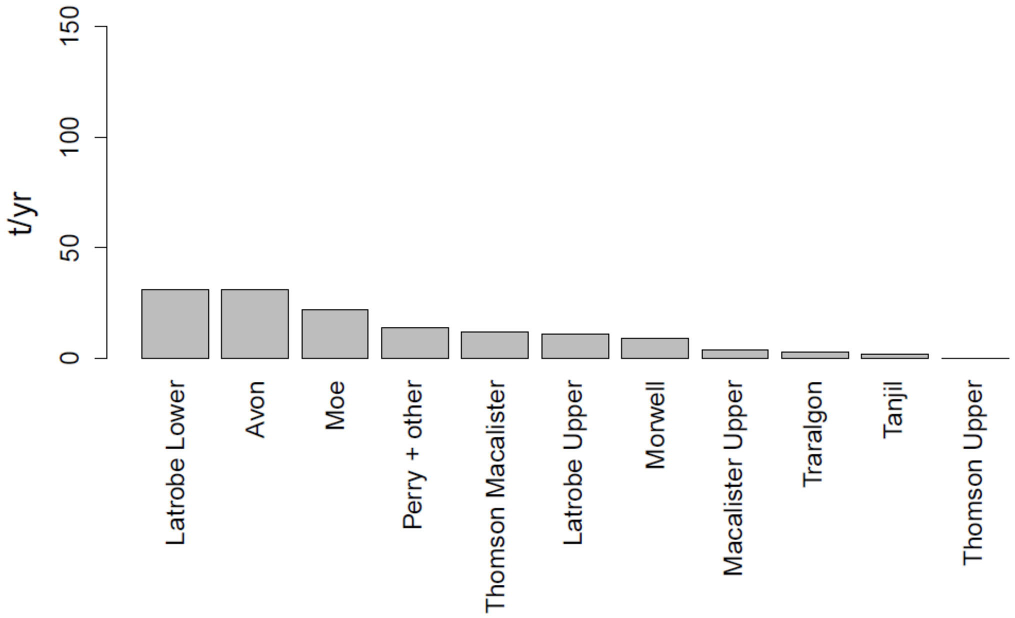

Figure 22: Hillslope nitrogen loads to the Gippsland Lakes – west catchments

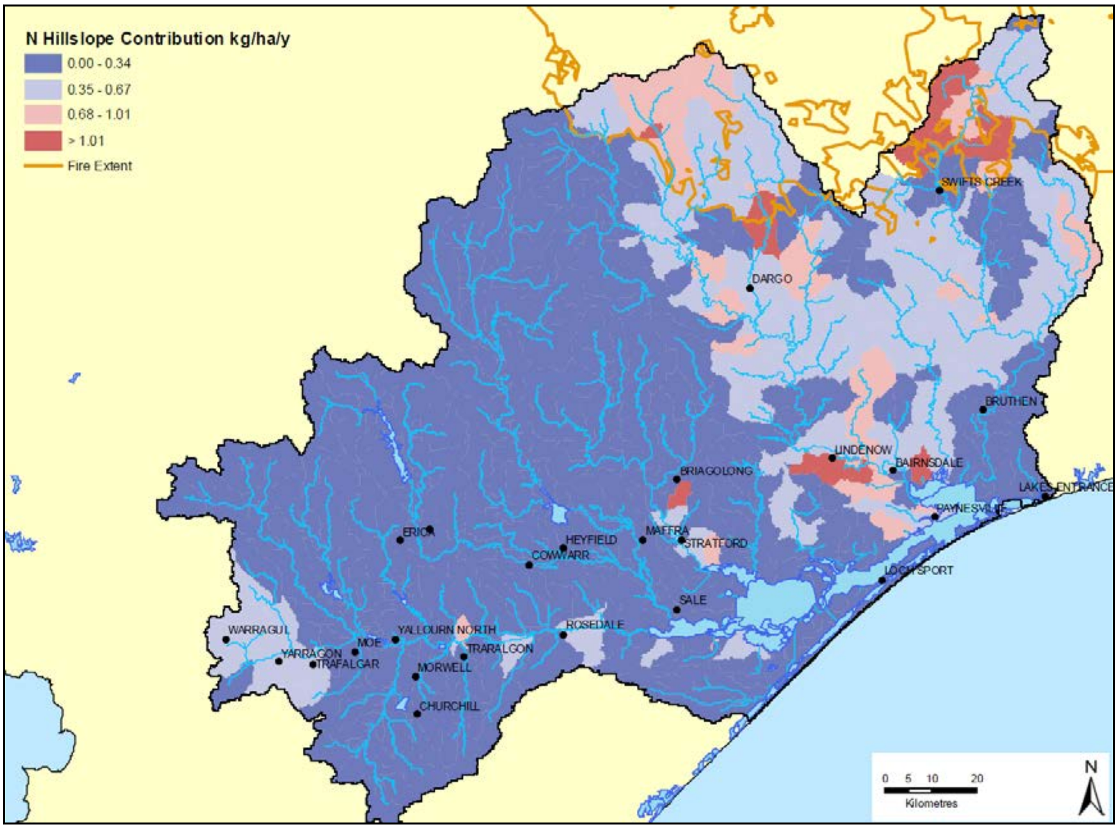

Figure 23: Contribution of nitrogen to the Gippsland Lakes from hillslope erosion (Hancock et al., 2007)

4.4 Bank erosion as a source of nitrogen

Bank erosion is the third most important source of nitrogen representing about 15% of the total nitrogen load to the Lakes; 8% from the east and 7% from the west. The nitrogen load from bank erosion for each catchment is shown in Figure 24 for east catchments and Figure 25 for west catchments. The absolute size of the bank erosion source is similar in each grouping with the Mitchell, Wonnangatta and Upper Tambo being the most important sources in the east and the Thomson/Macalister and Lower Latrobe being the most important in the west.

Nitrogen loads per unit length of stream that is actively eroding in each catchment are shown in Figure 26 for east catchments and Figure 27 for west catchments. There are hot spots of bank erosion in the Mitchell catchment including the Wonnangatta and Dargo Rivers where nitrogen production per km of eroding bank is around 2000 kg per year. The spatial distribution of nitrogen from bank erosion is shown in Figure 28. Bank erosion is a localised source of nitrogen in some cases and may be able to be mitigated by management interventions.

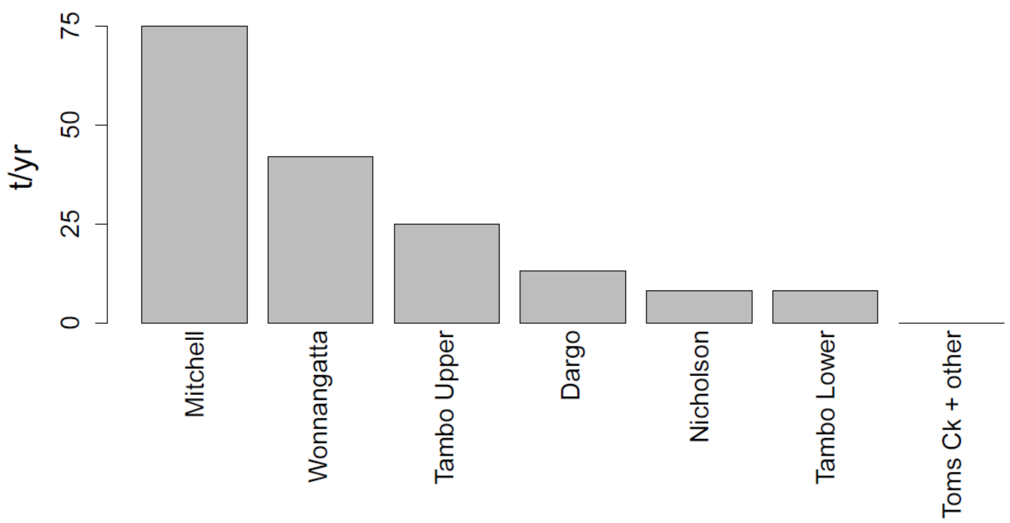

Figure 24: Nitrogen loads to the Gippsland Lakes from bank erosion – east catchments

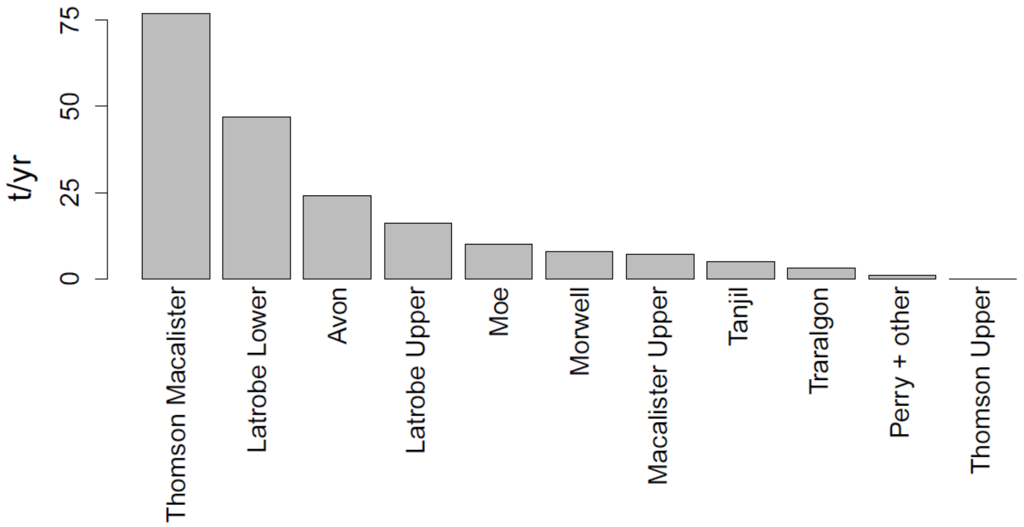

Figure 25: Nitrogen loads to the Gippsland Lakes from bank erosion – west catchments

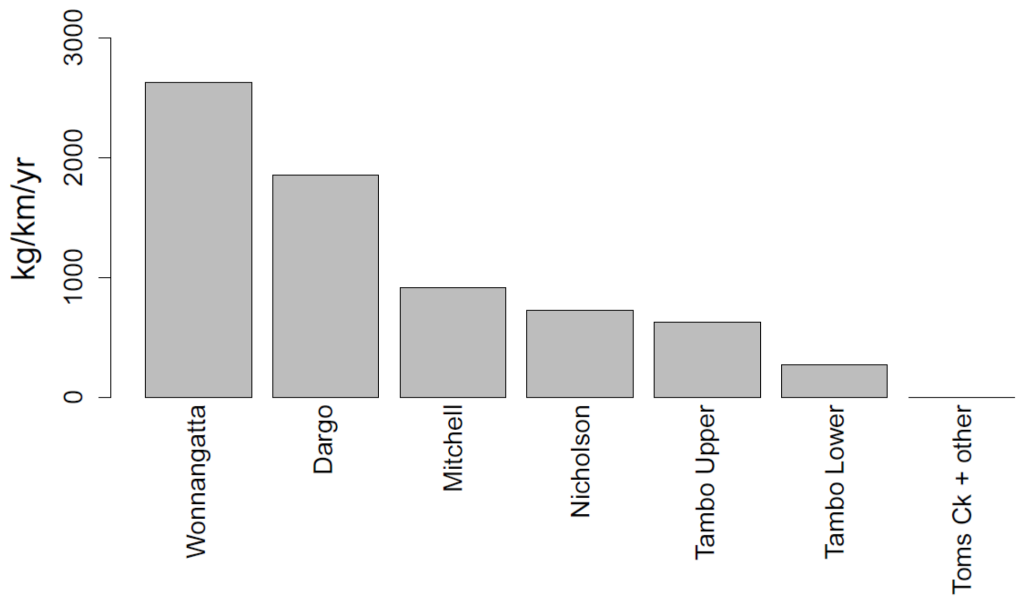

Figure 26: Nitrogen loads to the Gippsland Lakes from bank erosion per km of actively eroding bank– east catchments

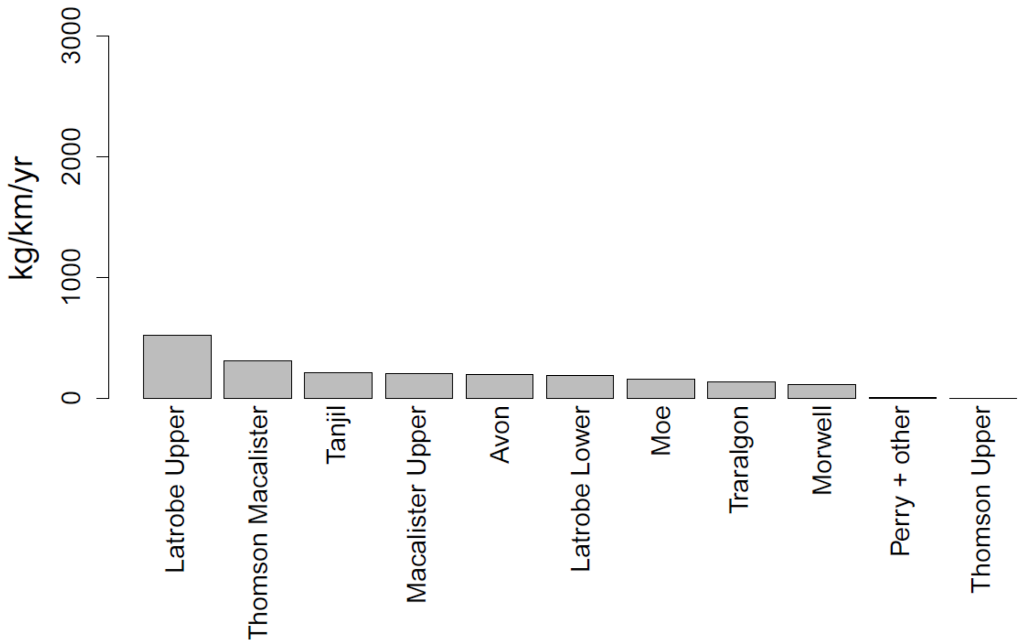

Figure 27: Nitrogen loads to the Gippsland Lakes from bank erosion per km of actively eroding bank – west catchments

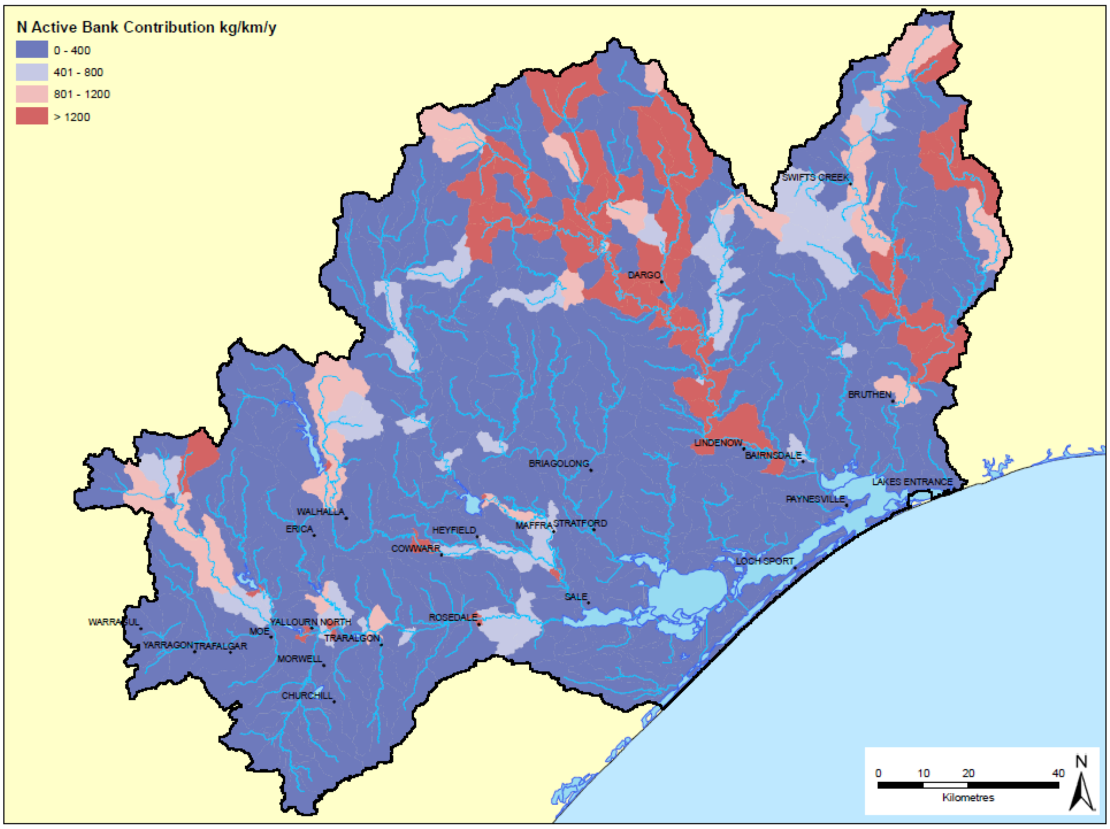

Figure 28: Contribution of nitrogen to the Gippsland Lakes from bank erosion (Hancock et al., 2007)

4.5 Gully erosion as a source of nitrogen

Gully erosion is a relatively minor source of nitrogen to the Gippsland Lakes providing only 2% of the total nitrogen load; 1.5% from the east catchments and 0.5% from the west catchments. The main source catchments in the east are the Mitchell and Upper Tambo (Figure 29) while in the west the lower Latrobe and Avon are most important (Figure 30). The spatial location of gullies is shown in Figure 31. It may be possible to treat these gullies to reduce nitrogen loads, but the effect on total loads to the Lakes will be minor.

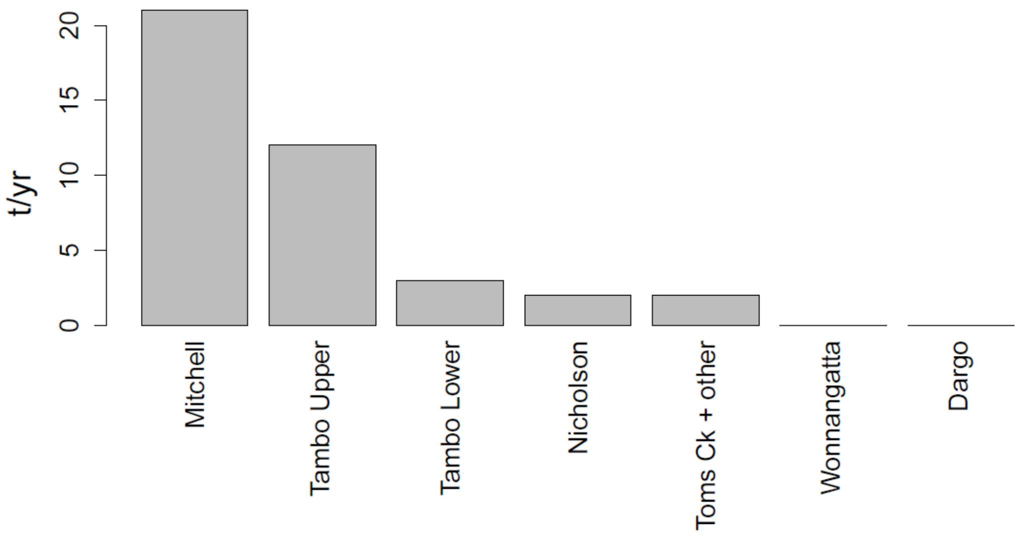

Figure 29: Contribution of nitrogen to the Gippsland Lakes from gully erosion – east catchments

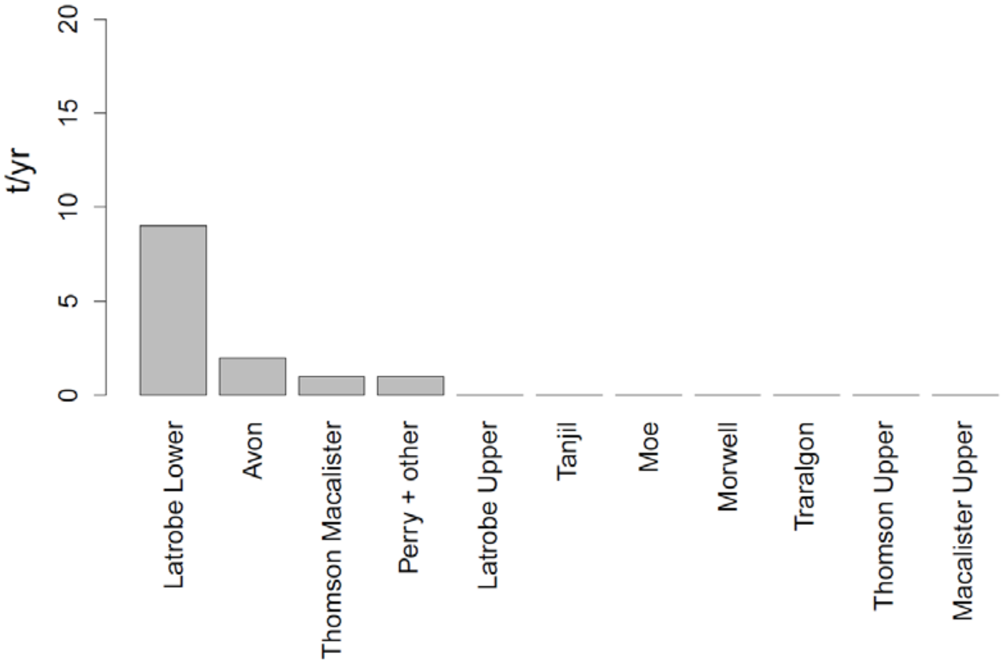

Figure 30: Contribution of nitrogen to the Gippsland Lakes from gully erosion – west catchments

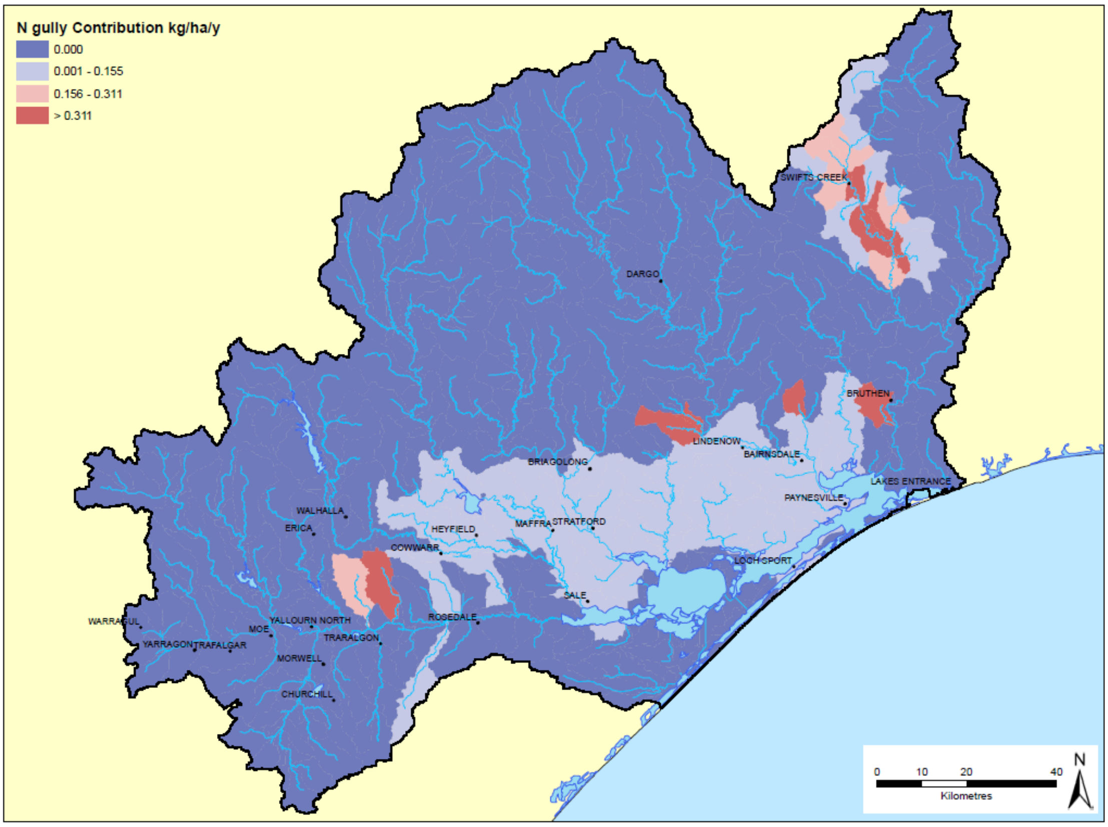

Figure 31: Contribution of nitrogen to the Gippsland Lakes from gully erosion (Hancock et al., 2007)

4.6 Point sources of nitrogen

Point sources represent about 3.6% of the total nitrogen load to the Lakes. The dominant point sources are the Maryvale Mill, Yallourn Power Station and Moe Wastewater Treatment Plant (Figure 32). There are likely to be management options to reduce these loads.

Table 4: Point source loads of nitrogen (Hancock et al., 2007)

Facility	Total N (t/yr)
Warragul Wastewater Treatment Plant (WTP)	0.5
Moe (WTP)	17.2
Morwell (WTP)	0.4
International Power	0.04
Yallourn Power Station	27
Maryvale Mill	40.3
Bairnsdale (WTP)	1.7
Total	**87**

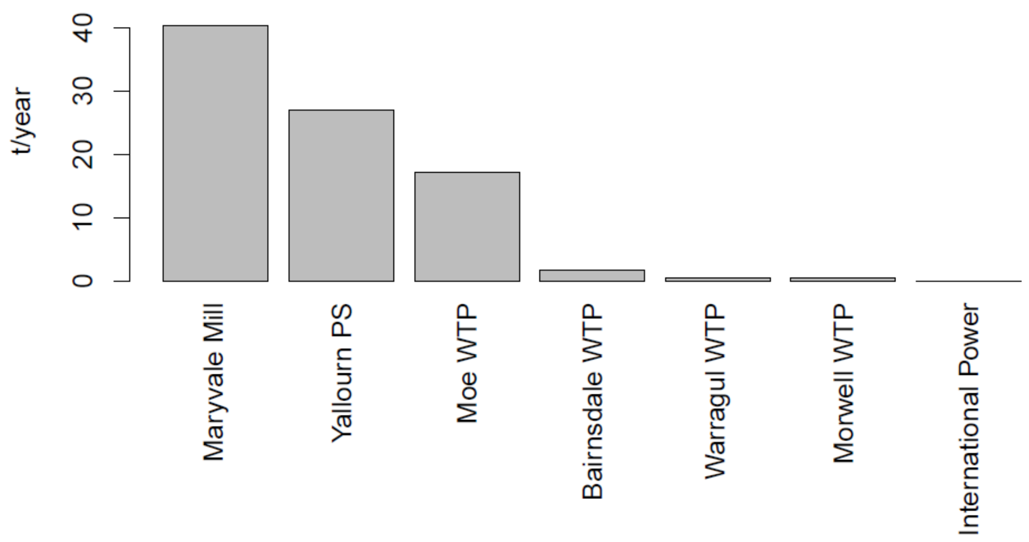

Figure 32: Point source loads of nitrogen

4.7 Loads from different land uses

Nitrogen loads associated with different land uses are reported in Grayson (2006). Highest loads are associated with grazing/pasture and forests (Figure 33) but these also occupy very large areas. The nitrogen load per ha shows that irrigation is the standout land use in terms of nitrogen loads to the Lakes (Figure 34). ‘Irrigation’ land use provides 4 kg/ha/yr compared to background levels of 1 kg/ha/yr. However, the total load from this land use is reasonably small. Irrigation provides about 7% of the total nitrogen load to the Lakes, so even a 40% reduction in load would result in an important but relatively minor 3% decrease overall.

To date, phosphorus rather than nitrogen has been the focus of nutrient management in the Macalister Irrigation District. The drains from the MID are monitored to determine their phosphorus load (EPA, 2009a) but there is much less data on nitrogen emanating from the MID and no current monitoring of nitrogen loads. Grayson and Argent (2002) mention nitrogen data analysed by SKM (2002), but we have not been able to locate this report. There is no mention of nitrogen in the work of Fox (2003) who analysed Southern Rural Water's drain monitoring data.

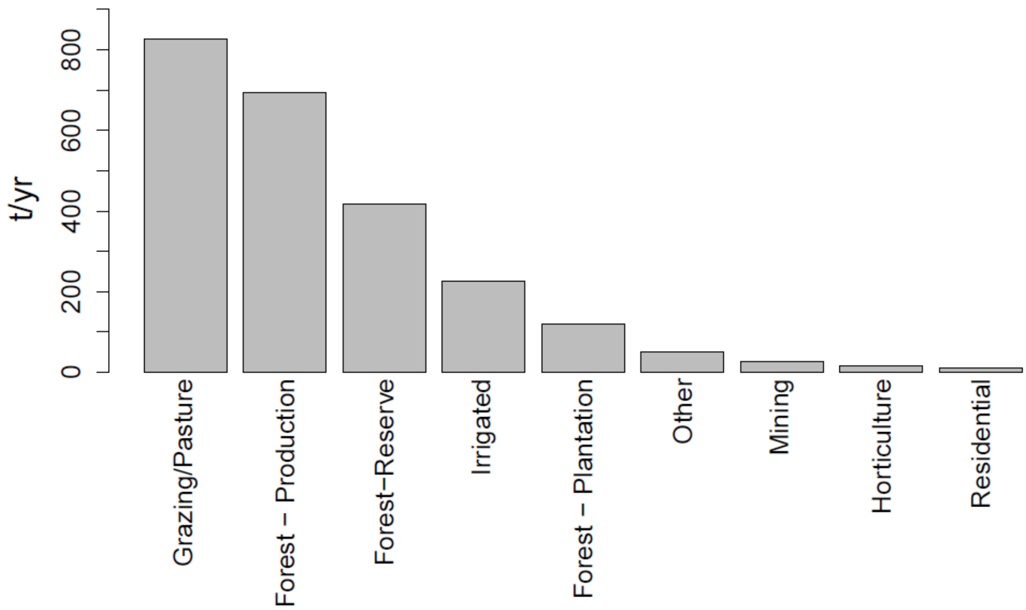

Figure 33: Loads from different land uses (Source: Grayson, 2006)

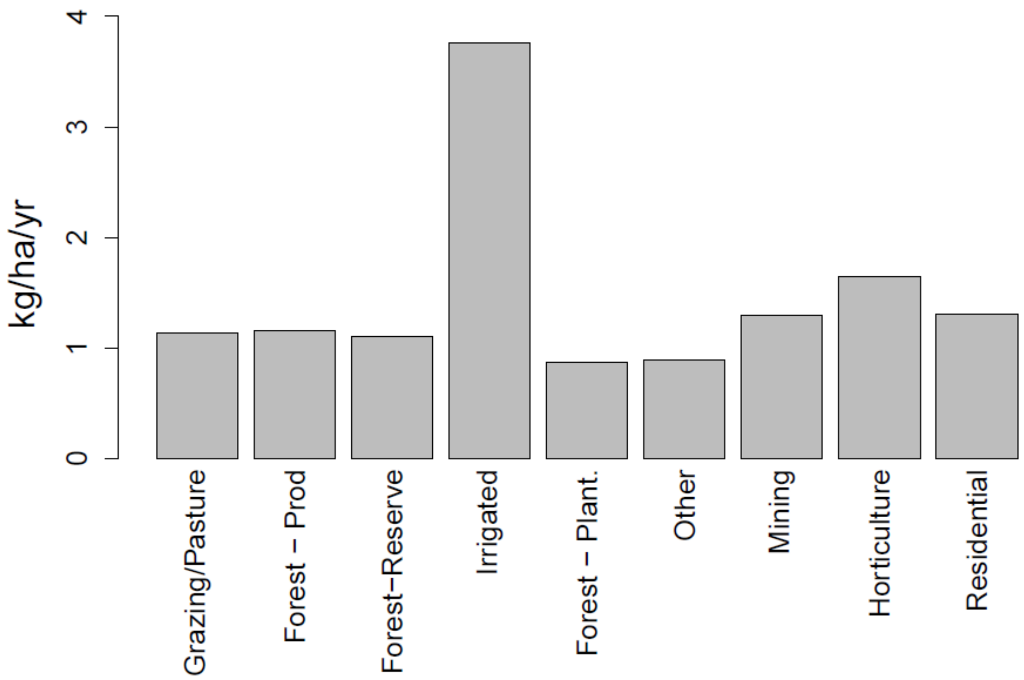

Figure 34: Loads per ha from different land uses (Source: Grayson, 2006)

4.8 Atmospheric sources of nitrogen

Although there is no direct monitoring of atmospheric sources of nitrogen there are a range of estimates available. Turner et al. (1996) found nitrogen deposition in rainfall in NSW state forest to range from 0.18 to 10.9 kg ha^{-1} yr^{-1}, with an average (of the log transformed values) of 1.75 kg ha^{-1} yr^{-1}. Specific studies in Gippsland found values of 1.4 to 3 kg ha^{-1} yr^{-1} which included both wet and dry deposition (Pooley et al., 1978; Ayers et al., 1995). Dry deposition was about 75% of the total N load. Ayers et al. (1995) showed these were similar to other Australian sites.

The total area of the Lakes is 400 km^2. If atmospheric deposition is 1 kg ha^{-1} yr^{-1}, then total deposition is 40 tonnes/year or about 2% of the total annual load to the Lakes of around 2000 t.

In low rainfall years, atmospheric sources will be a higher percentage of the load to the Lakes. For example, in 2006, total riverine load was 300 tonnes. If atmospheric source was 35 tonnes[3], this would represent 12 % of the riverine load.

[3] Assume in an average year 40 t of N is deposited, 30 from dry deposition processes and 10 from rainfall. In a dry year, we may halve the rainfall contribution, reducing atmospheric sources to 30 + 5 = 35 t.

It is likely that atmospheric deposition of nitrogen is increasing throughout the Gippsland Lakes catchment, and world-wide. Humans have doubled the rate of nitrogen entering the land based nitrogen cycle through the production and use of nitrogen fertilisers and burning of fossil fuels (Vitousek et al, 1997; Galloway, 2004; EPA 2011). Atmospheric reactive nitrogen deposition has increased globally by about a factor of 3 since 1860, from 32×10^6 t per year to about 112×10^6 t per year (Penuelas et al., 2012). Recent work suggests that reactive nitrogen first became more plentiful around 1895 with a further acceleration around 1970 as the use of artificial fertilisers spread (Holland et al., 2005; Holtgrieve et al., 2011). Holtgrieve et al. (2011) suggest that reactive nitrogen in the atmosphere primarily as NH_3, NO, and NO_2 can be transported and deposited to the most remote ecosystems. Artificial reactive nitrogen from atmospheric deposition has been shown to be affecting many of the world's ecosystems (Elser, 2011).

If atmospheric nitrogen deposition is increasing, this will increase loads to the Lakes both through direct deposition on the lake surface and through increased supply to the catchment that subsequently runs off to the Lakes. This is potentially a significant influence on the nitrogen balance of the Lakes that is currently not well understood.

4.9 Bushfires as a source of nitrogen

It is well documented that nitrogen is released from soil and plant material as a result of bushfires. Nitrogen loads to receiving waters can be particularly high when there is erosion of fire-affected areas. A study of a fire affected forest near Warburton following the Ash Wednesday fires of 1983, found that erosion-related nitrogen loads were 82 kg/ha. This load occurred in a single event when a short duration thunderstorm resulted in the loss of soil and burnt material that contained an estimated 2900 kg of nitrogen. This can be compared to background nitrogen loads of about 1 kg/ha/yr (Leitch et al., 1983). As noted in Section 3.2.1, nitrogen loads to the Lakes were about 4,000 t higher than expected following the 2007 fire and floods. Further details on the water quality implications of bushfires are provided in Sinclair Knight Merz (2008). Given the importance of this source of nitrogen, additional work on quantifying and mitigating bushfire impacts is warranted as described in Section 6.

4.10 Fertilisers as a source of nitrogen

Nitrogen is imported into the catchments of the Gippsland Lakes in the form of agricultural fertilisers. Although there is limited data available on fertiliser use, the data that are available suggest the quantity of nitrogen applied as fertiliser has the potential to be an important source of nitrogen to the Gippsland Lakes. In this section, two main sources of fertiliser information are discussed:

1. Broad scale assessments extracted from reporting by the Australian Bureau of Statistics; and
2. Small scale assessments undertaken within the Macalister Irrigation District.

4.10.1 Fertiliser use in the Gippsland Lakes catchment

The Australian Bureau of Statistics has collected data on fertiliser use in the East and West Gippsland NRM regions as part of their agricultural census. This information is available as part of reporting on 'Land Management and Farming in Australia' for 2007-08 and 2009-10[4] (ABS, 2009; 2011). Although the East and West Gippsland NRM regions are larger than the catchment of the Gippsland Lakes, most of the agriculture, and therefore most of the fertiliser application in these districts occur within the Gippsland Lakes Catchment[5]. Six types of nitrogenous fertiliser are in included in ABS reporting:

1. Urea
2. Ammonium sulphate
3. Urea ammonium nitrate
4. Potassium nitrate
5. Ammonium phosphates
6. Animal manure

In addition there is a category 'All other manufactured fertilisers' which likely includes some fertilisers that contain nitrogen.

The total amount (tonnes) of each of these fertilisers applied in the East and West Gippsland NRM districts is listed in Table 5. For each fertiliser the percentage of elemental nitrogen is also listed allowing calculation of the total amount of nitrogen applied in fertiliser in the annual periods 2007-08 and 2009-10 (Figure 35). This suggests that approximately 17,000 t of nitrogen was imported into the Gippsland Lakes catchment during each of these years. Where applied, the average application

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[4] Data cubes on fertiliser use and fertiliser application rates are available from the ABS website see http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/4627.02009-10?OpenDocument and http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/4627.02007-08?OpenDocument

[5] Maps of the NRM regions are available at http://www.nrm.gov.au/about/nrm/regions/vic-egip.html and http://www.nrm.gov.au/about/nrm/regions/vic-wgip.html. These regions are similar to the areas of responsibility of the East and West Gippsland Catchment Management Authorities.

rate was about 60 kg N/ha. This is a low rate by Australian and international standards (DPI, 2005).

Table 5: Nitrogenous fertiliser use in East and West Gippsland NRM regions

Fertiliser	%N[1]	2007-08			2009-10		
		Area (ha)	Fertiliser (tonnes)	Nitrogen (tonnes)	Area (ha)	Fertiliser (tonnes)	Nitrogen (tonnes)
Urea	45	122,600	25,700	11,565	125,621	30,454	13,704
Ammonium sulphate	21	1,100	200	42	109	62	13
Urea ammonium nitrate	33	5,600	600	198	2,033	130	43
Potassium nitrate	13	9,700	1,600	208	2,674	158	21
Ammonium phosphates	10	24,100	4,900	490	25,072	4,398	440
All other manufactured fertiliser	10	107,200	40,100	4,010	104,283	31,109	3111
Animal manure	1	14,800	41,100	411	9,720	31,234	312
Total		**285,100**	**114,200**	**16,924**	**269,511**	**97,545**	**17,644**

1 – The percentage of nitrogen contained in each fertiliser has been estimated as follows: for urea, ammonium sulphate, urea ammonium nitrate, potassium nitrate, ammonium phosphates information has been taken from published NPK information e.g. http://chemicalland21.com/industrialchem/inorganic/NPK.htm. For animal manure, an approximate proportion of 1% N has been adopted (DPI, 2005). For 'All other manufactured fertiliser' no information was available. A value of 10% N has been adopted so there is significant uncertainty in the estimate of nitrogen from this source.

This amount of nitrogen imported in fertiliser (17,000 t/yr) is 8.5 times the estimated total annual load of nitrogen to the Gippsland Lakes (2,000 t/yr). The key issue is how much of this nitrogen 'leaks' from agriculture to waterways and then to the Lakes.

Research at the farm scale suggests that the amount of nitrogen lost in drainage and runoff is highly variable but is commonly in the range of 3% to 9% of the quantity applied in fertiliser (Singleton et al., 2001; Eckard et al., 2004; DPI, 2005). Note that it is not necessarily the fertiliser that is being lost directly; rather the application of fertiliser allows more grass growth, increased stocking rates, increased production of dung and urine and increased organic matter in soil. Overall, the amount of on-farm nitrogen increases, and some of this leaks off-farm. Monitoring of farm drainage water in irrigation areas in northern Victoria shows high rates of nitrogen export particularly in sub-surface drainage (Hydro Technology, 1995).

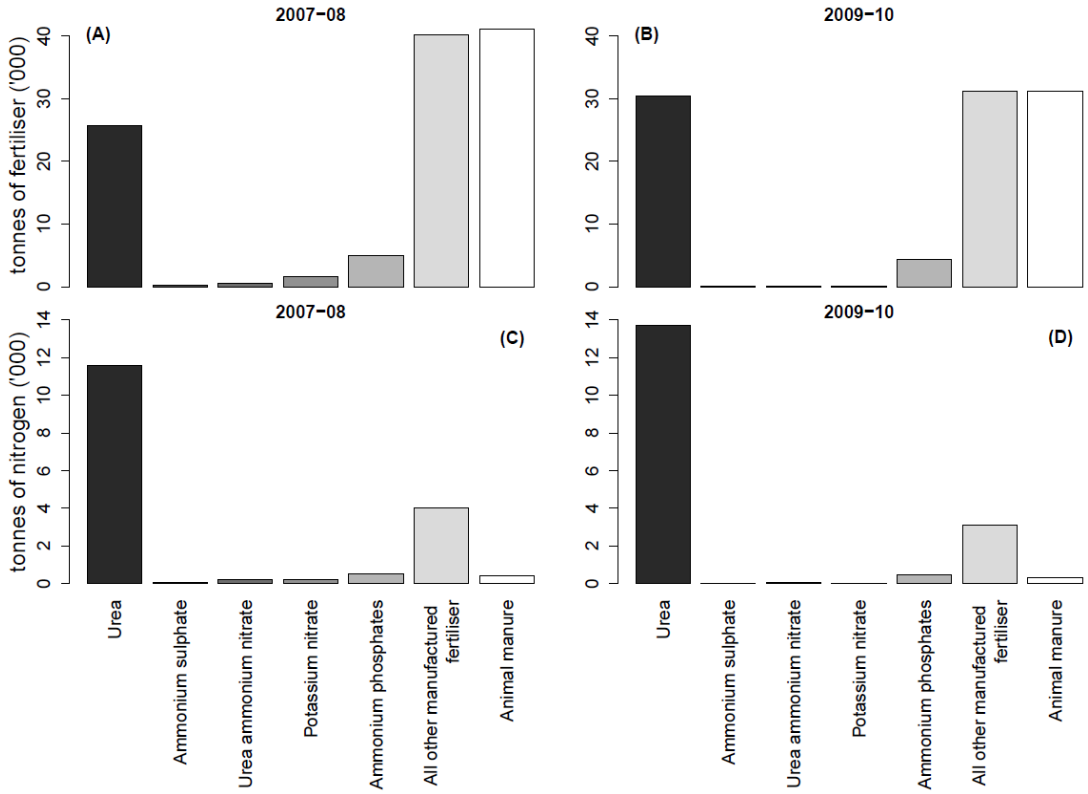

Figure 35: The amount (tonnes) of different types of nitrogenous fertilisers applied to the catchment of the Gippsland Lakes in the annual periods (A) 2007-08 and (B) 2009-10. Tonnes of nitrogen associated with these fertilisers in the annual periods (C) 2007-09 and (D) 2009-10. Approximately 17,000 tonnes of nitrogen was applied in each of the years.

If we assume leakage of 3% of the 17,000 t of applied N fertiliser this would result in a load of 540 t to the Lakes i.e. 25% of the estimated annual load. This is likely to be an overestimate as other work suggests that irrigation areas in the Gippsland Lakes catchment, an area where there is likely to be high rates of fertiliser use, only contributes about 7% of the total annual load of 2000 t.

Unfortunately there does not appear to have been any recent information on nitrogen loads from the intensively farmed irrigation areas. Drain monitoring is restricted to phosphorus only[6] and the work by Hancock et al. (2007) did not research this issue. The most recent data seems to be provided in SKM (2002). As mentioned previously,

[6] MID nutrient monitoring http://www.srw.com.au/page/page.asp?page_id=177

the difference between the load estimates of CSIRO (Hancock et al. 2007) and those reported by Grayson (2006) relate to load estimates from irrigation areas and these must be considered an important source of uncertainty in the determination of the nitrogen load to the Lakes.

4.10.2 Fertiliser use in the Macalister Irrigation District

Information on fertiliser use in the MID was reported by Gallienne and Freeman (2002) based on a survey of farmers in the Macalister Irrigation District in two catchments: Central Gippsland Drain No. 3 (CG3) and the Land Wellington Main Drain (LWMD). For irrigated dairy, nitrogen fertiliser application rates were 56 kg N/ha in the CG3 catchment and 47 kg N/ha in the LWMD catchment (Figure 36). There was insufficient information to determine a reliable average application rate for irrigated beef. These average application rates are similar to those reported by the ABS as discussed in Section 4.10.1 although they predate the ABS data by about 10 years, so may not be directly comparable. Application rates of nitrogen fertiliser and timing of fertiliser applications may have changed since this data was collected in 2000/01. Unfortunately, recent data is not available.

The number of fertiliser applications by month is shown in Figure 37. Nitrogen fertiliser applications are usually higher in the colder months because they are made to compensate for the reduced N fixation by clover when soil temperatures are low (DPI, 2005). Although the link between fertilizer application and N loads to the lakes is complex and uncertain; it is likely that if there is nitrogen inputs to the Gippsland Lakes during winter this may promote *Nodularia* blooms while inputs in summer tend to suppress them (see Section 2).

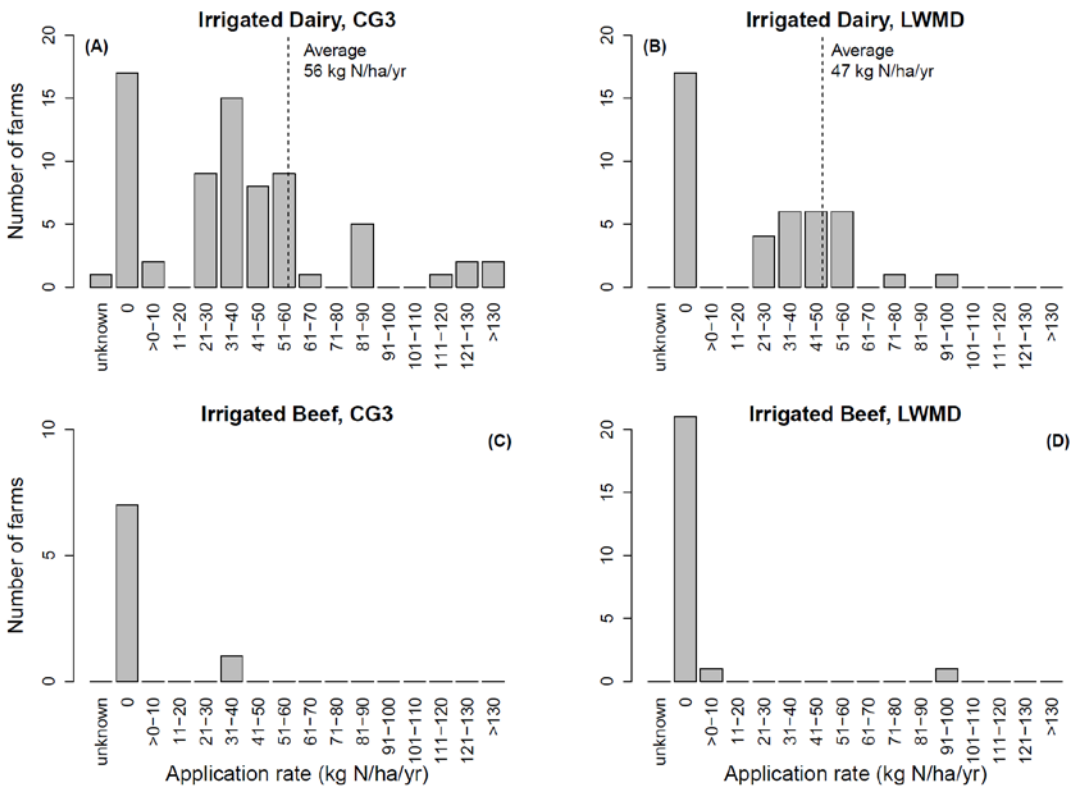

Figure 36: Nitrogen fertiliser application rates in the MID for different farm types and catchments (A) irrigated dairy in the Central Gippsland Drain No. 3 catchment, (B) irrigated dairy in the Lake Wellington Main Drain catchment, (C) irrigated beef in CG3, (D) irrigated beef in LWMD (Gallienne and Freeman, 2002).

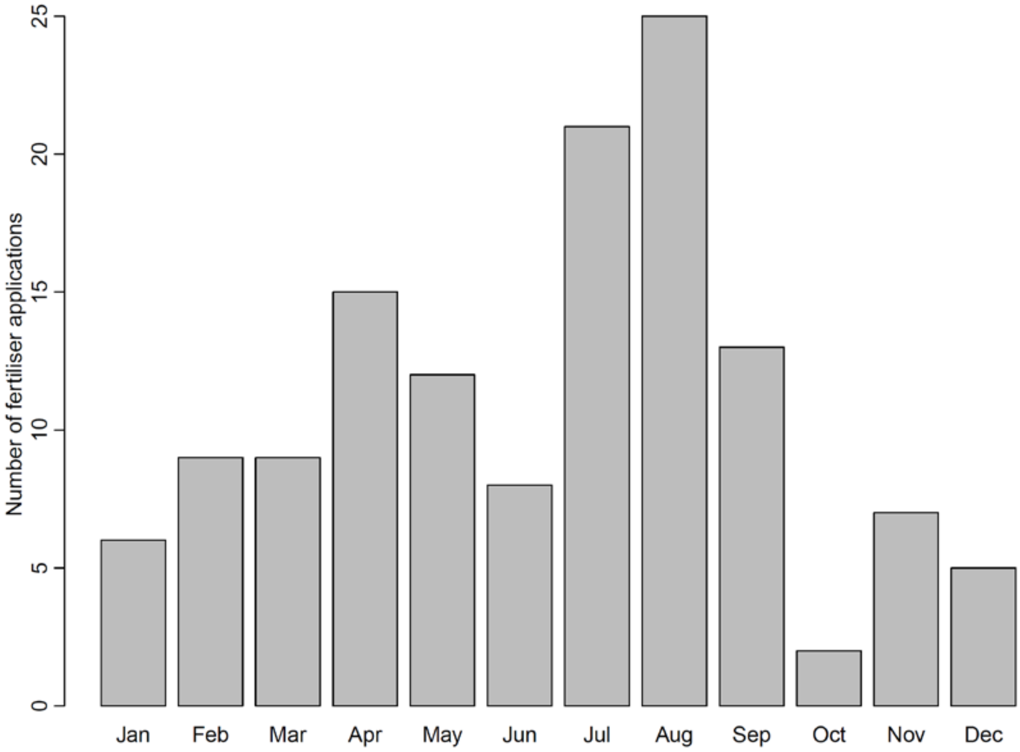

Figure 37: Number of fertiliser applications in each month (Gallienne and Freeman, 2002)

5. Nitrogen concentration in the Lakes

Catchment-sourced nitrogen ultimately finds its way into the Gippsland Lakes where it is processed by the Lakes' ecosystem. In general, all the nitrogen that comes in will be removed, either by flushing to the ocean or because it is lost as a gas following denitrification, or through burial.

The concentration of nitrogen in the water of the Lakes depends on the relative rates of inflow and loss. If there is a large pulse of nitrogen, as occurred in 2007, the nitrogen concentration of lake water will temporarily increase until the processes that remove nitrogen can catch up.

Nitrogen concentration of the Gippsland Lakes is monitored by the EPA at 5 fixed sites (Figure 38, Table 6). The large nitrogen pulse of 2007 can be seen which increased nitrogen concentrations throughout the Lakes (Figure 39). Nitrogen concentrations then slowly decayed to background levels. The relationship between nitrogen loads to the lakes and flows was discussed in Section 3. With further work it may be possible to relate high nitrogen concentrations to specific inflow events such as the floods of 1990, 1993 and 1998.

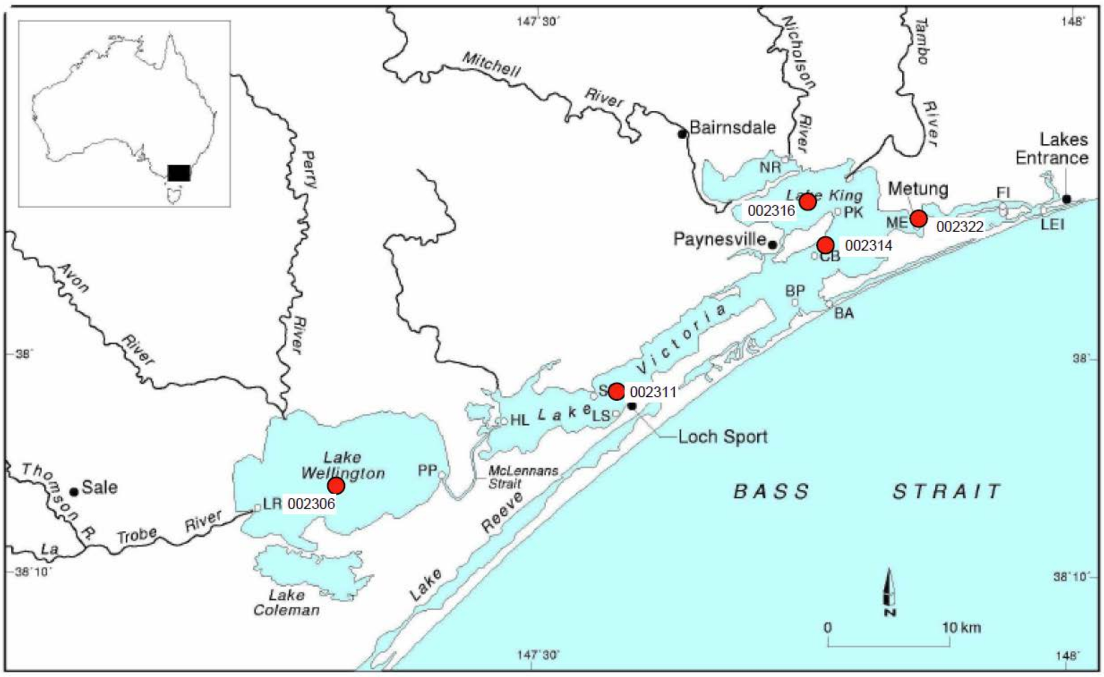

Figure 38: Location of water quality monitoring sites which measure nitrogen concentration

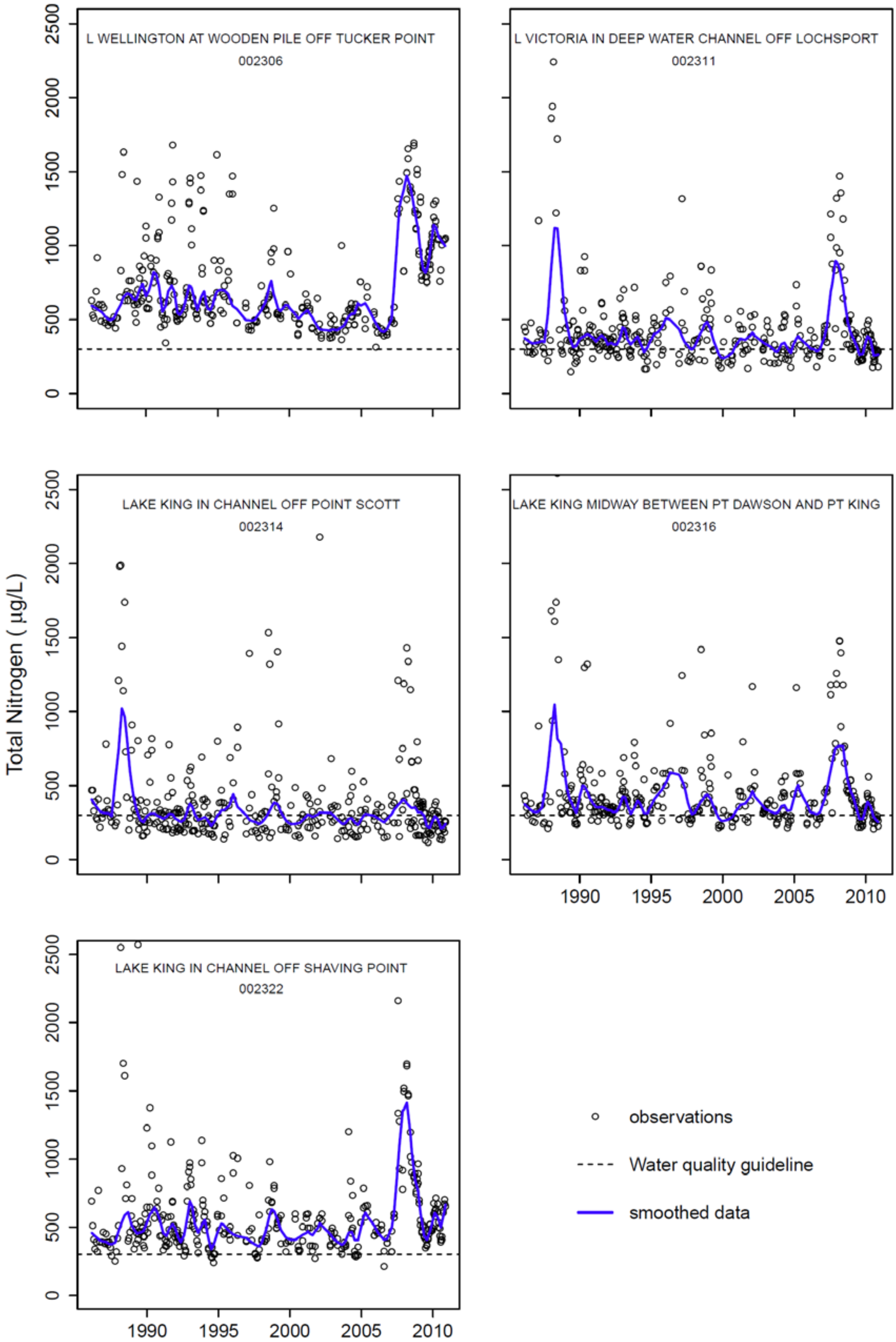

Figure 39: Observed total nitrogen concentration at EPA monitoring stations. The ANZECC trigger level of 300 (µg N L^{-1}) is shown (ANZECC, 2000)

Table 6: Location of water quality monitoring sites which measure nitrogen (Stephens and Biggins, 2004)

Site Code	Site Name	Lake
002306	Lake Wellington at Wooden Pile off Tucker Point[2]	Wellington
002311	Lake Victoria in deep water channel off Loch Sport	Victoria
002314	Lake King in Channel off Point Scott	Victoria
002316	Lake King Midway between Pt. Dawson and Pt. King	King
002322	Lake King in channel off shaving point	King

6. Towards mitigation of nitrogen inputs

The health of the Gippsland Lakes would benefit from decreased nitrogen inputs. In particular, the large inputs of nitrogen in wet years are likely to prime the Lakes for an algal bloom in the following summer. Mitigating nitrogen loads in these years is likely to be challenging but it is important to consider feasible actions to reduce loads, and in particular, loads of bioavailable material.

Although not the focus of this report, a preliminary assessment suggests it may be feasible to reduce nitrogen loads by 25% as follows.

- Hillslope
  A 25% reduction in hillslope sourced nitrogen would reduce loads by 290 t or 11.7%.
- Bank erosion
  A 25% reduction in nitrogen derived from bank erosion would decrease total loads to the Lakes by 180 t or 7.4%.
- Gully erosion
  A 25% reduction in gully erosion would reduce loads to the Lakes by 26 t or 1%.
- Point sources
  A 50% reduction in point sources would reduce loads to the Lakes by 44 t or 1.7%.
- Irrigation related sources
  A reduction of nitrogen loads from irrigated areas by 40% would reduce overall loads to the Lakes by about 60 t or 3%.

Emphasis should be on reducing erosion sources because they are likely to be significant contributors in wet years. Work by CSIRO (Hancock et al., 2007) has identified the general location of these sources and this could assist in the development of detailed strategies. The costs and benefits associated with N reduction activities require further analysis. Reducing N loads by 25%, as described here, will not eliminate algal blooms but will likely reduce their frequency.

7. Additional work

The work undertaken for this report confirms that catchment-sourced nitrogen has an important influence on the health of the Gippsland Lakes and that understanding and managing nitrogen loads should be given a higher priority in the Gippsland Lakes Future Directions and Actions Plan (Cottingham, 2008). The sections below briefly outline additional work that would support better management of nitrogen.

7.1 Understand risk of high nitrogen inputs

The 2007 event provided a very large input of nitrogen and is unprecedented in the historical record. It would be worth undertaking work to find out if other extreme events have occurred in the past and how often they occur. Palaeoecological tools are likely to be useful for this research (e.g. Saunders et al., 2008; Cook pers. comm.)

7.2 Characterise the likely range of riverine nitrogen inputs

Analysis in this report suggests that nitrogen load is largely determined by flow. Long sequences of tributary flows to the Lakes have been developed as part of water resource planning, for example, as part of the Gippsland Sustainable Water Strategy (DSE, 2010). These could be used to understand the likely annual inflow volumes, and therefore nitrogen loads under historical climate e.g. the last 50 to 100 years.

It would also be possible to match inflows and nitrogen concentrations at a daily or monthly scale using the historical record. This would allow development of simple models to predict nitrogen concentrations in the short term, based on inflows and seasonal effects on nitrogen inputs. This information could inform assessment of the risk of algal blooms.

7.3 Review Best Management Practices to reduce nitrogen inputs

Best management practices to reduce phosphorus inputs were reviewed and prioritised by Ladson and Tilleard (2006). A similar approach could be used to identify the best approaches to nitrogen reduction.

7.4 Understand changes in atmospheric deposition

Atmospheric nitrogen deposition to the Gippsland Lakes and its catchment is likely to be increasing, because of the world-wide increase in reactive nitrogen. However, there seems to be very little specific and local data on loads derived from the atmosphere. Improved monitoring would help in understanding how this source is changing. This would probably be best conducted as a state-wide initiative rather than being focused specifically on the Gippsland Lakes. All Victorian ecosystems are likely affected by increases in reactive nitrogen (EPA, 2011).

7.5 Review catchment load estimates and improve monitoring

As noted in Section 4, there are some discrepancies between the nitrogen source estimates of Hancock et al. (2007) and those of Grayson (2006), particularly those related to loads from the MID. It would be worth gathering the available information on measured nitrogen loads from the MID and assessing the accuracy of the estimates made by Hancock et al. (2007) and adjusting their load estimates if necessary. Improved monitoring of nitrogen loads from the MID should also be a priority, as there does not appear to have been any monitoring for more than a decade.

7.6 Mitigate bushfire effects

Bushfires can result in a major increase in nitrogen loads and current planning should be expanded to include tasks that will improve understanding and mitigate impacts. Tasks, recommended in SKM (2008), include:

- Quantification of the effect of fires on loads to the Lakes. This would build on the work of Feikma et al. (2005) and expand the Gippsland Lakes model (Grayson and Argent, 2002) to incorporate the additional areas that were burned in 2006/07, compared to 2002/03.
- A review of the effectiveness of best management practices in reducing fire impacts. This would build on SKM (2008) but would need to quantify the effectiveness of proposed activities. The approach would be similar to that documented in Ladson and Tilleard (2006), where a simple computer model was created to calculate load reduction and used to guide discussion at a workshop to identify key management activities.
- Incorporation of bushfire loads and mitigation effectiveness into the framework developed by Cottingham et al. (2006) to determine priorities for all the nutrient management activities in the Gippsland Lakes catchments. This would allow activities to reduce nutrient loads from burned areas to be compared to, for example, best management practices to decrease runoff from the Macalister Irrigation District.

7.7 Link nitrogen mitigation to soil erosion management

Both the East and West Gippsland CMAs have developed soil erosion management plans but it is not clear if the priorities in these plans are informed by information on erosion-related sources of nitrogen. Spatial information on the main sources of nitrogen linked to erosion are provided in Hancock et al., (2007), and is this report, and these could be used to inform priorities for soil erosion works.

7.8 Develop additional strategies

Further work should be undertaken to develop strategies to reduce nitrogen loads to the Lakes building on the recommendations in Section 6. This would be similar to the extensive work that has been undertaken to identify and implement strategies to reduce phosphorus loads (e.g. Cottingham et al., 2006).

The result of this work would provide a defensible and reliable guide to future investments in managing nutrient inputs to the Lakes.

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Appendix A – Further details on statistical analysis

A.1 Annual load as a function of flow

Annual nitrogen load is plotted as a function of flow in Figure A.1. There is clearly a strong relationship between load and flow with higher flows contributing more load. The relationship also appears to be approximately linear (apart from the point for 2007). As noted on the figure, the nitrogen load in 2007 was much higher than would be expected from the flow.

A trial model is:

$$L = \beta_0 + \beta_1 F + \beta_2 Y \qquad \text{(A.1)}$$

Where:

L is annual load of nitrogen (tonnes)

β (0, 1, 2) are fitted values

F = annual flow (GL)

Y = Year

The value for 2007 is excluded from the linear modelling as this is a clear outlier. Weighting of the response variable to take account of differences in estimated uncertainty (standard errors) has not been implemented in the following. This was trialled but the approach presented here produced more satisfactory results.

Regression was carried out using the statistical package, R (R Development Core Team, 2011). Results are summarised below. Regression diagnostics are shown in Figure A.2, with a marginal model plot in Figure A.3 and an added variable plot in Figure A.4. These diagnostics all suggest the model is a good fit to the data.

Note that this analysis suggests that time (Year) is not a significant explanatory variable. The p value for predictor variable, Year, is 0.993 which is not significant and the added variable plot shows that Year has no effect on TN loads. A plot of the residuals of equation A.2 against Year is shown in Figure A.5. There is clearly no influence of time once the effect of flow has been removed.

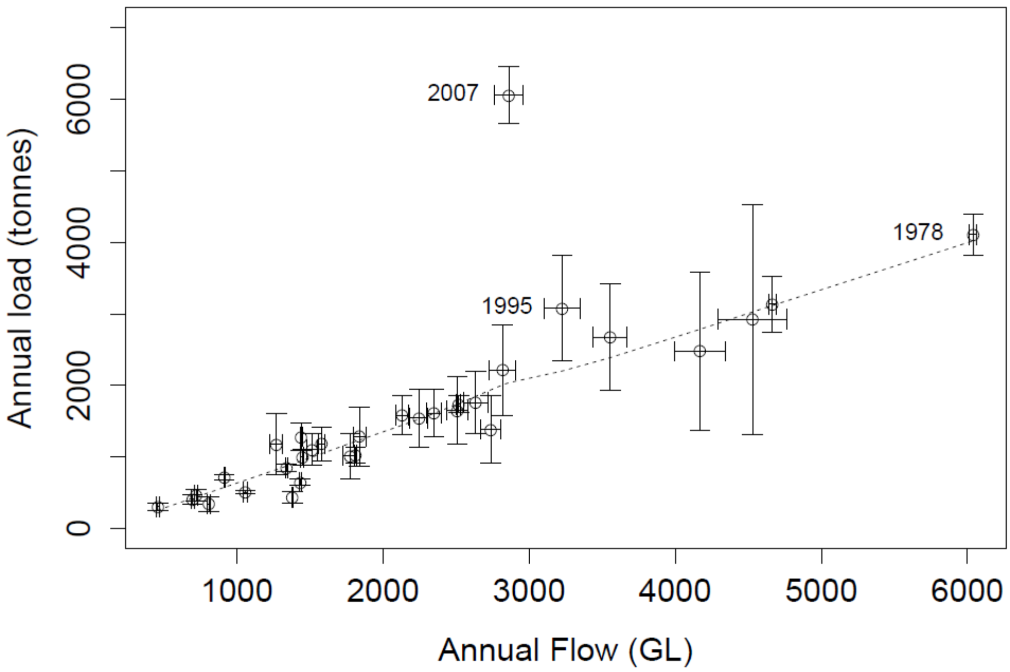

Figure A.1: Annual load as a function of flow. Error bars show standard error in estimated load and flow. Dashed line is based on locally weighted regression. Key points are highlighted.

The final model, which is just a function of flow, is:

$$L = -43.2 + 0.695F \qquad \text{(A.2)}$$

$(R^2 = 0.92)$

This suggests that it would be possible to reconstruct nitrogen loads to the Gippsland Lakes based on measured or estimated historical inflows. This could be used to give the range of likely input loads under current land use and the climate over the last 50 to 100 years.

```
Call:
lm(formula = TN ~ Flow + Year, data = loads, subset = sub.1 (i.e.
2007 is removed)

Residuals:
   Min     1Q Median     3Q    Max
-482.71 -173.69   7.77 107.14 879.69

Coefficients:
              Estimate Std. Error t value Pr(>|t|)
(Intercept) -1.477e+02 1.217e+04 -0.012   0.990
```

```
Flow      6.955e-01 4.261e-02 16.324 7.73e-16 ***
Year      5.224e-02 6.083e+00  0.009  0.993
---
Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 272.4 on 28 degrees of freedom
Multiple R-squared: 0.9234,    Adjusted R-squared: 0.9179
F-statistic: 168.7 on 2 and 28 DF, p-value: 2.412e-16
```

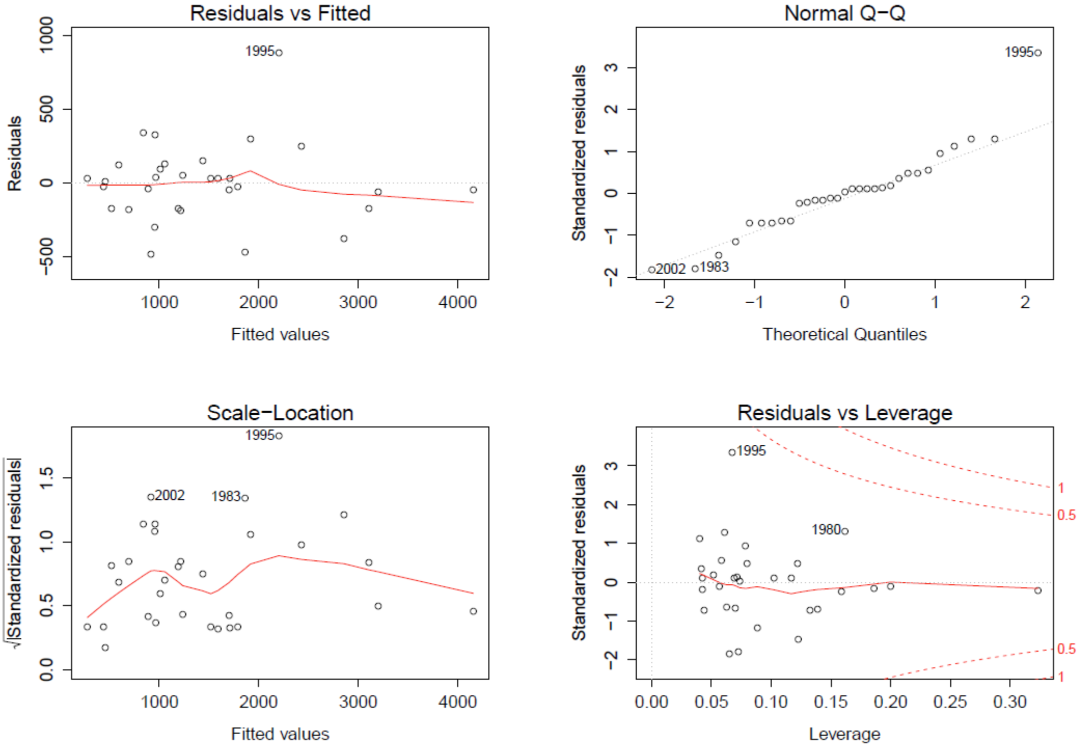

Figure A.2: Diagnostic plots for model A.1

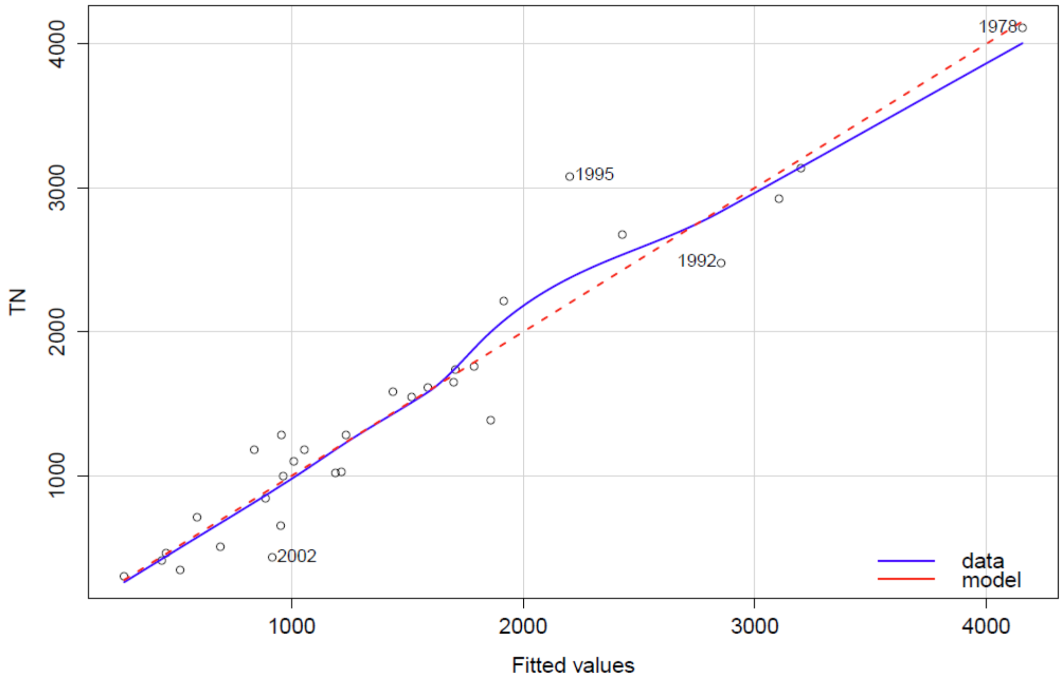

Figure A.3: Marginal model plot (for model A.1) (2007 has been excluded)

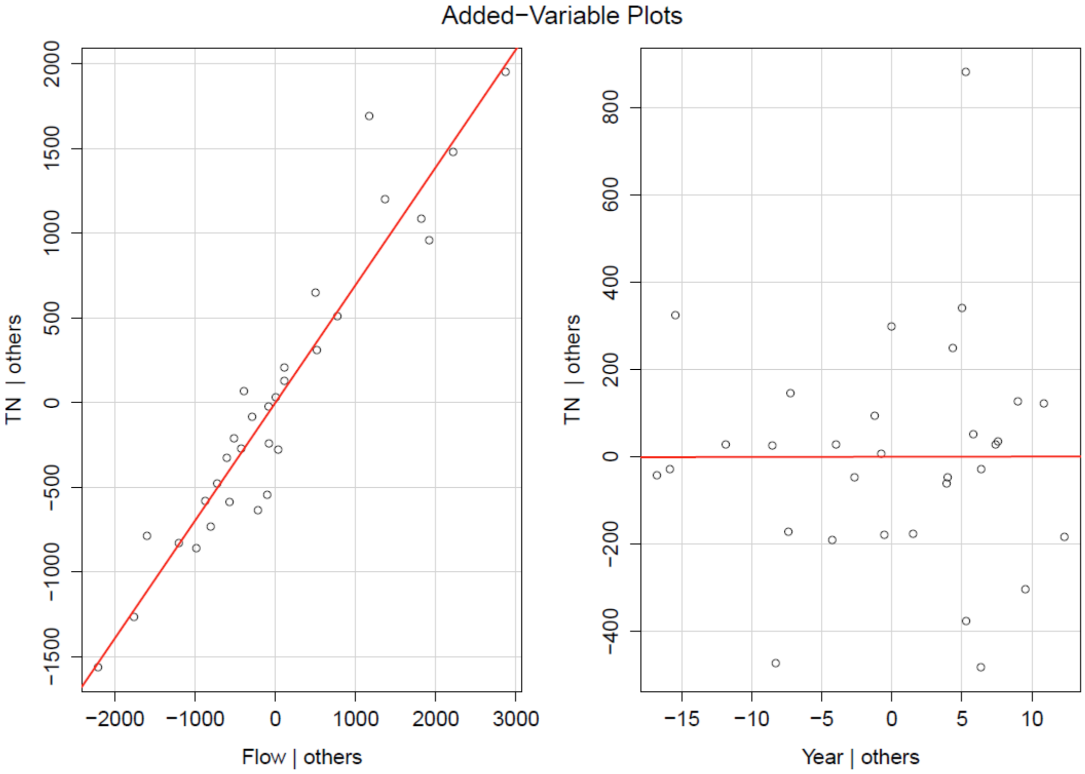

Figure A.4: Added variable plot (for model A.1) (2007 has been excluded). Red line shows linear fit.

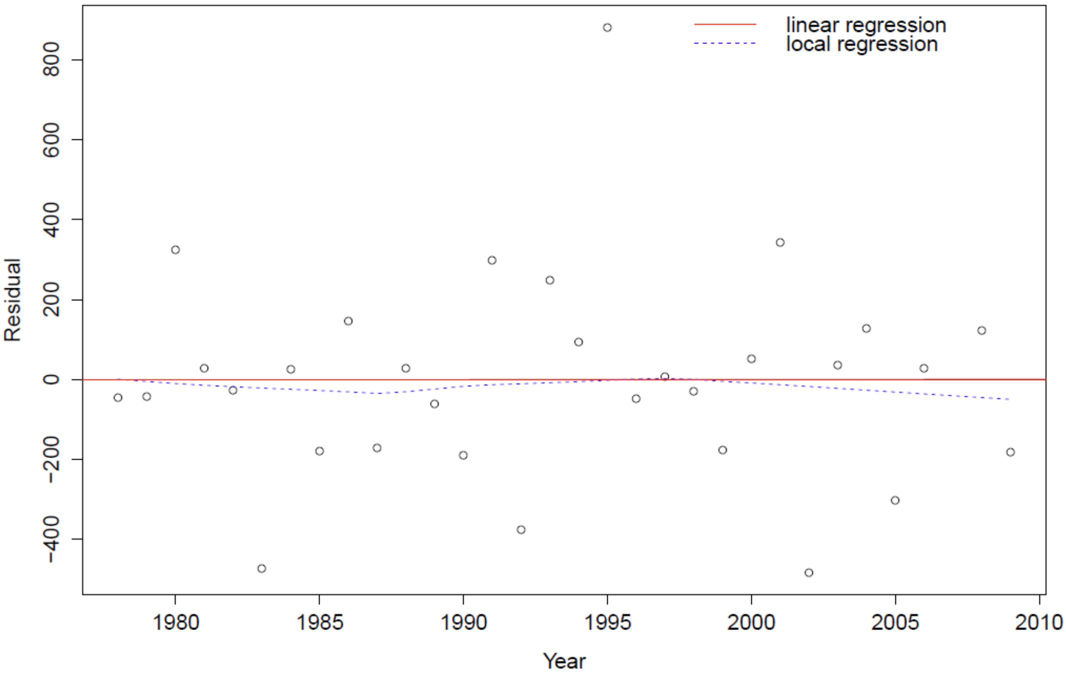

Figure A.5: Relationship between time (Year) and nitrogen load once the effect of flow has been removed