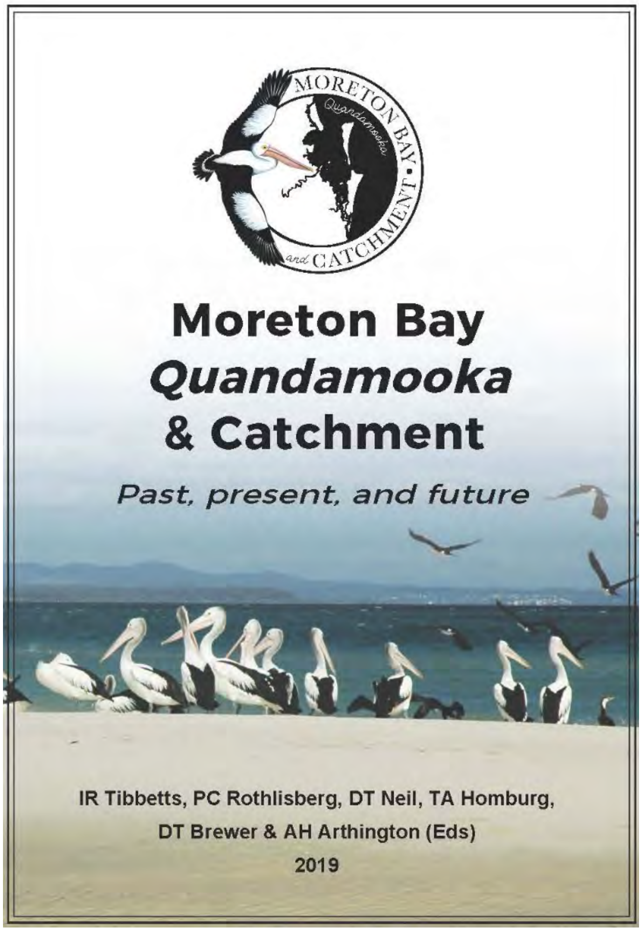

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Water quality in Moreton Bay and its major estuaries: Change over two decades (2000–2018)

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Abstract
The catchment of Moreton Bay has been significantly modified since European settlement began in the 1820s, and these changes have not only changed the type of pollutants (nutrients and sediments) and the loading rates delivered to Moreton Bay, but also impacted on marine food webs and life cycles. This paper focuses on the major changes in water quality that have occurred in Moreton Bay during the past two decades (2000–2018). We analyse long-term water quality monitoring data and mud samples to determine the impact of catchment land-use changes and management efforts to reduce pollution over this period. While improvements in water quality have been observed in some parts of the Bay in response to management actions, water quality trends indicate that population growth and land development across the catchment is having a significant impact. Specifically, sediment and nitrogen loads threaten the health of Moreton Bay into the future and management of these pollutants is critical.

Keywords: nitrogen, turbidity, sediment, Brisbane River

Background
Good water quality critical for a healthy bay
Moreton Bay is one of the largest estuarine bays in Australia, supporting a wide variety of ecosystems from intertidal wetlands and seagrass beds through to coral reefs (1, 2, Maxwell *et al.* 2019, this volume (3); Lovelock *et al.* 2019, this volume (4); Pandolfi *et al*. 2019, this volume (5)). The environmental values associated with these ecosystems provide significant socio-economic and cultural benefit to the region (6). In 1993,

Moreton Bay was declared a Marine Park to manage its many environmental, socio-economic and cultural values, with much of the Bay also declared as an internationally significant wetland for migratory shorebirds under the Ramsar Convention (7).

The health of these coastal ecosystems, and the value they represent to the community of South East Queensland, relies on good water quality. Water quality changes follow events, such as heavy rainfall and floods. These are short-term pulses and good water quality generally returns in the following weeks to months (8, 9). Changes in water quality over longer time periods can indicate a system is under pressure, with potential for loss of habitat, ecosystem resilience and overall value to the region. The interaction between the severity and extent of pulsed events combined with the background water quality prior to and after an event, will determine the ecosystem response and impact on community values and the benefits we receive from Moreton Bay.

The spatial extent and intensity of pressures on water quality can be monitored using a suite of indicators that includes nutrients and water clarity (10) Nutrients are important because estuaries and coastal areas, such as Moreton Bay, ‘consume’ nutrients, using them to stimulate primary productivity and to feed the Bay’s food web (11–13). An excess of nutrients disturbs the equilibrium between nutrient supply and consumption, and often results in increased growth of phytoplankton and algae and unnaturally high productivity (14, 15). In extreme cases overgrowth of algae can lead to the loss of critical habitats, such as seagrass meadows, and to waterways becoming anoxic (16, 17).

Suspended sediment particles, phytoplankton and algae in the water result in the water looking cloudy or dirty. This is especially important for benthic habitats because it influences a range of things, including the amount of light reaching the bottom and sediment deposition and resuspension. As a result, key habitats like seagrass (9) and corals (18) are smothered and key processes such as reproduction and growth are inhibited.

Moreton Bay water quality is under pressure

Pollutant pressures on Moreton Bay from the catchments and estuaries along its western shoreline are considerable (Fig. 1), especially during the wet season. This is due to a dramatic increase in sediment export from the catchments, caused by land clearing that has occurred since European settlement. It is estimated that current sediment export rates are approximately 100 times greater than what would have occurred from natural catchments (19). In addition, there are over 30 sewage and industrial treatment plants discharging directly into Moreton Bay and its estuaries (20), and these are a significant anthropogenic source of nitrogen and phosphorus to the Bay.

The hydrology of Moreton Bay and associated water quality switches between two modes, either driven by freshwater input associated with high rainfall events or driven

Figure 1. Water quality monitoring sites from the Ecosystem Health Monitoring Program analysed in this study. The paper presents data for Caboolture, Pine, Brisbane and Logan estuaries (crosses) and for several Bay segments grouped based on similar water quality objectives, including: western (solid triangles), Waterloo Bay (open triangles), north central (closed diamonds), south central (open diamonds), north eastern (closed squares), South Eastern (open squares), Eastern Banks (open pentagon), southern (closed circles) and Jumpinpin (open circles) zones. Closed symbols represent areas of the Bay classified as 'moderately disturbed' by the Queensland Government (24) and are discussed in detail in the paper. The Bay zones with open symbols represent areas of the Bay classified as 'high ecological value' (or HEV), and data from these zones are presented separately in the electronic appendix as additional information (30).

by wave, wind and tidal action (20). There is a strong gradient in water quality from relatively high nutrient concentrations and low water clarity in the south-western portions of Moreton Bay, to low nutrient concentrations and high water clarity in the north and east (11, 21, 22). The north-eastern section of Moreton Bay, adjacent to Moreton Island, has the best water quality due to the fact that it receives minimal pollution from Moreton Island and is regularly flushed with clean oceanic water (23). The residence time of water in major Bay estuaries and throughout much of the Bay is 43–75 days, and the Brisbane River specifically can reach residence times of 189 days (11, 20). In contrast, the eastern and northern ocean boundaries have residence times as low as 3–5 days and are therefore well flushed and less impacted by catchment inputs. Consequently, water quality within the south-western Bay tends to exceed Queensland Water Quality Objectives (Table) more frequently and by a greater margin than it does in the north and east of the Bay, where water quality is generally very good (24).

When compared with the water quality of coastal systems alongside other large cities around the world, Moreton Bay water quality is relatively good (25). However, over the past 20 years Moreton Bay's catchment has been exposed to ongoing and increasing pressure from land clearing, urban development, population growth and several extreme flood events. Over the same period there has been significant investment in reducing nutrient loads from sewage treatment plant discharges.

Table 1. Queensland Water Quality Guidelines (2009) for the four sections of the Bay analysed in this study (24). The Queensland Government classifies these zones as 'moderately disturbed'.

	Zone			
	Western Bay	**Eastern Bay (north)**	**Central Bay (north)**	**Southern Bay**
Total nitrogen (mg/L)	0.2	0.16	0.16	0.2
Total phosphorus (mg/L)	0.03	0.016	0.02	0.024
Nitrates & nitrites (mg/L)	0.002	0.003	0.002	0.002
Ammonia (mg/L)	0.005	0.005	0.005	0.005
Filterable reactive phosphorus (mg/L)	0.014	0.005	0.008	0.008
Chlorophyll *a* (µg/L)	2	1	1	2
Turbidity (NTU)	6	1	5	7

NTU: nephelometric turbidity units

The Ecosystem Health Monitoring Program (EHMP) is a long-term monitoring program used to assess the ecological condition of waterways in South East Queensland. The program was originally designed to assist local government to plan and implement of sewage treatment plant upgrades. It was broadened in early 2000 to capture regional catchment issues from non-point sources of nutrients and sediments (11). The program is presently based on sampling at 142 estuarine sites and 41 Bay sites eight times per year (in February, March, May, August, September, October, November and December). Queensland Government Department of Environment and Science sample the water quality and details of the methodology is reported in (26) and (27).

Analysis of water quality trends from the EHMP long-term monitoring dataset allows us to identify the status of Moreton Bay, how it is responding to the increasing pressures, and if investment has had observable beneficial effects on water quality. In addition, catchment models have been used to predict future trends in water quality and identify where management can focus efforts to protect the health of Moreton Bay into the future (28).

This paper will focus on changes that have occurred in nutrient concentrations and water clarity within Moreton Bay during the past two decades (2000–2018) — since the publication of the last Moreton Bay book in 1998 (11, 29). Most of the data presented were collected as part of the EHMP (30). Changes in phytoplankton observed in Moreton Bay over a similar time period are discussed in Saeck *et al*. 2019, this volume (31).

Change in water quality over the past 20 years

Nutrients – nitrogen and phosphorus

The Bay – west, east and south

Phosphorus concentrations have not been a major focus for management over the past 20 years because Moreton Bay is considered nitrogen-limited (11, 21, 32). However, excess phosphorus in coastal systems can have implications such as increasing cyanobacteria growth, with negative consequences for food webs and ecosystem status (33). The major anthropogenic source of phosphorus to Moreton Bay is sewage treatment plant discharge, such as Luggage Point treatment plant at the mouth of the Brisbane river, which delivers around 300 tonnes per year (34).

Over the past 20 years, total phosphorus (TP) has frequently reached or exceeded guideline concentrations of 0.03, 0.02 and 0.024 mg/L in the western, central and southern areas of the Bay, respectively (Figs 2–4). However, data towards the end of this period suggests that TP concentrations may be decreasing in these areas, with concentrations for the past 5 years lower than those previously. It is difficult to say if this constitutes a decreasing trend given the high annual variation in TP. However, the more obvious reduction in filterable reactive phosphorus (FRP) concentrations over the same period would indicate an emerging pattern. In contrast, the eastern Bay has instead yielded TP concentrations consistently below the more stringent guideline of 0.016 mg/L (Fig. 5). Like other parts of the Bay, there are indications that TP is also lower in this eastern segment since 2013.

Nitrogen concentrations throughout the Bay have not improved (decreased) substantially over the past 18 years, and concentrations may even be increasing in some areas, most notably in the north-central and north-eastern Bay segments (Figs. 2-3). Over 30 sewage and industrial treatment plants discharge directly into Moreton Bay and its receiving waterways (20) and are a significant source of nitrogen to the Bay. Between 1998 and 2006 more than $300 million was invested in wastewater treatment plant improvements, improving their nitrogen removal capacity and reducing nutrient loads from the sewage treatment plant discharge by 44% (34, 35). As the population of South East Queensland and the Moreton Bay catchment has increased approximately two-fold over the past two decades (36), it is likely that this investment has played a major role in total nitrogen (TN) concentrations in Moreton Bay remaining at or below guideline concentrations across much of the Bay. However, the challenge remains to maintain or improve these concentrations in the face of increasing nutrient load, due to population growth and intensification of catchment land uses.

In the eastern and central Bay zones TN concentrations have exceeded Water Quality Objectives in some areas more frequently in the last 10 years than in the decade prior (Figs 3, 5). Similarly, since 2011 the dissolved inorganic nitrogen fractions (ammonia and nitrogen oxides (nitrite+nitrate)) have more frequently been measured at concentrations higher than the detection limit, where they previously were undetectable. At these concentrations they are approaching, and in some cases exceeding, Water Quality Objectives. The same pattern has also been observed in the western Bay (Fig. 2). The concern is that higher availability of dissolved inorganic nitrogen can increase benthic and pelagic productivity, which can cause shifts in ecosystem dynamics in these naturally oligotrophic waters (37, 38).

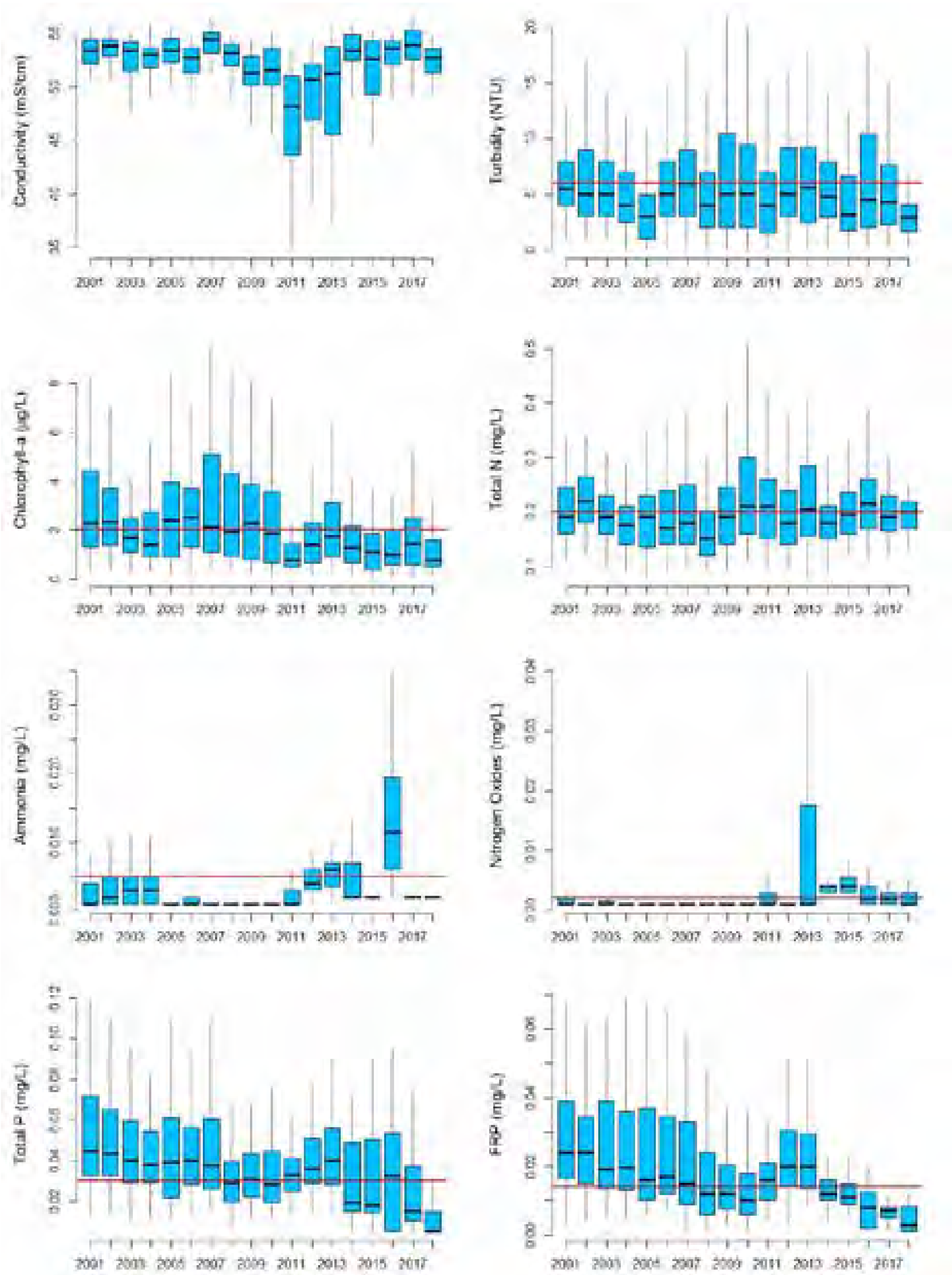

Figure 2. Results for 10 sites within the western Bay (Bramble and Deception bays) showing annual median, upper and lower quartiles for conductivity (mS/cm), turbidity (NTU), chlorophyll *a* (µg/L) total nitrogen (mg/L), ammonia (mg/L), nitrogen oxides (nitrates+nitrites) (mg/L), total phosphorus (mg/L), and filterable reactive phosphorus (FRP) (mg/L) for the financial years (July to June) 2001 to 2018. Red lines represents Queensland Government's water quality objectives as shown in Table 1.

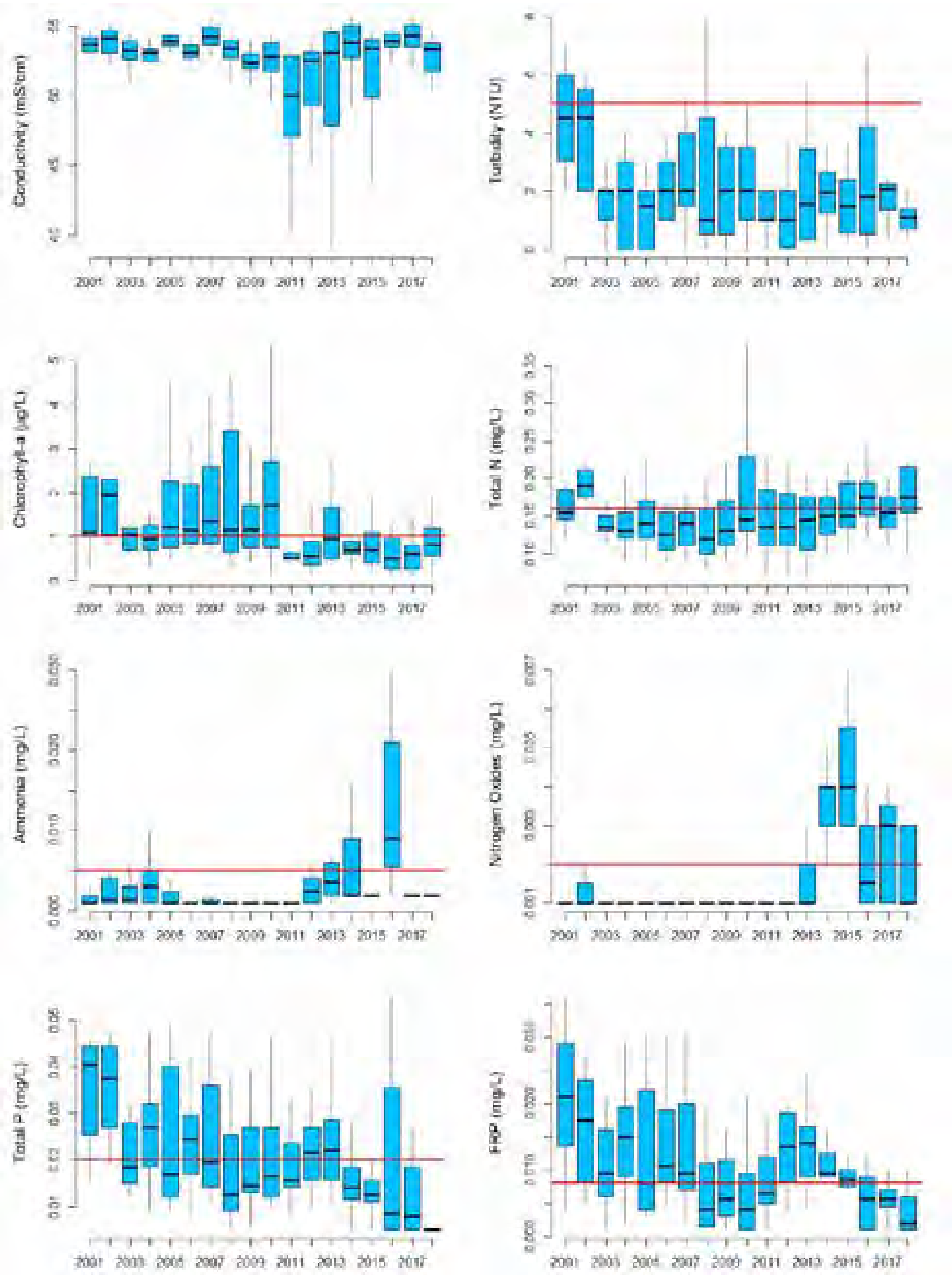

Figure 3. Box-and-whisker plots for two sites in north central Bay (See Fig. 2 caption for explanation).

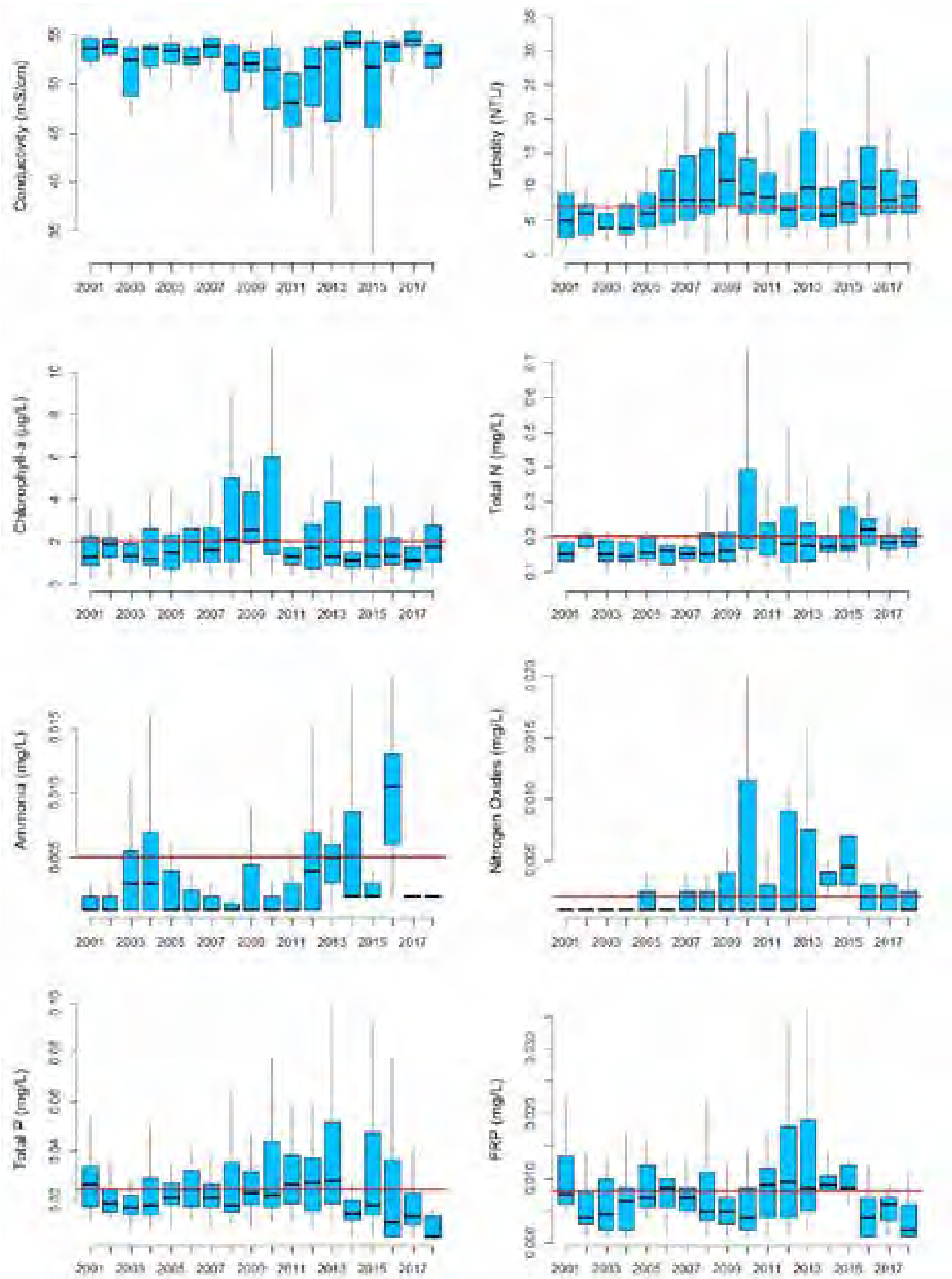

Figure 4. Box-and-whisker plots for four sites in the southern Bay (See Fig. 2 caption for explanation).

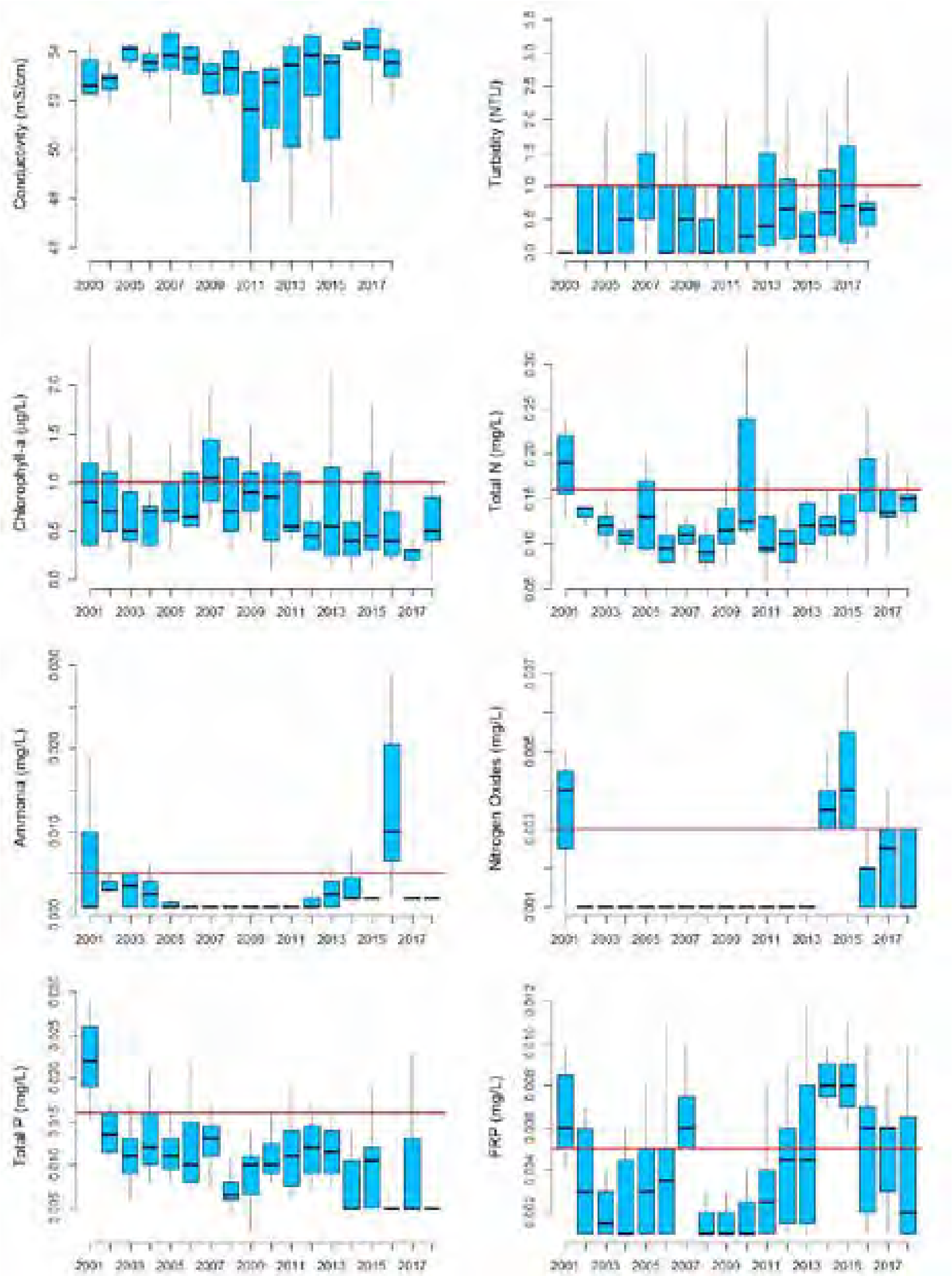

Figure 5. Box-and-whisker plots for two sites in north-eastern Bay (See Fig. 2 caption for explanation).

The specific cause of increased dissolved inorganic nitrogen across the Bay, particularly in the Eastern bay, requires further investigation. It is hypothesised that it may be linked to the deposition of catchment sediments during a couple of major floods. Sediment deposited by flood water can be a significant source of ammonium (NH_4^+), released in the period after the event as a result of microbial processing and benthic nutrient flux (38, 39). Given the timing of the increase in dissolved inorganic nitrogen (ammonia and nitrogen oxides; commencing after 2011), it is hypothesised that the catchment sediment deposited in Moreton Bay in association with the January 2011 and January 2013 flood events may be a source of dissolved inorganic nutrients. The January 2011 flood was a 1 in 100 year event for the Brisbane River catchment, and the largest since EHMP monitoring commenced (40). A total of almost 1700 mm of rain fell within the Moreton Bay catchment during the year of that flood (Fig. 6). While this hypothesis requires further investigation, the implications are that as flood frequency and intensity are predicted to increase with global warming, more such events could drive further increases in the availability of dissolved inorganic nutrients to Moreton Bay (41). Further supporting the need for catchment management of sediment loads from rural and urban areas in the face of increasing development. Such action will be critical if the ecosystem function (and nutrient assimilation capacity) of Moreton Bay is to be protected into the future.

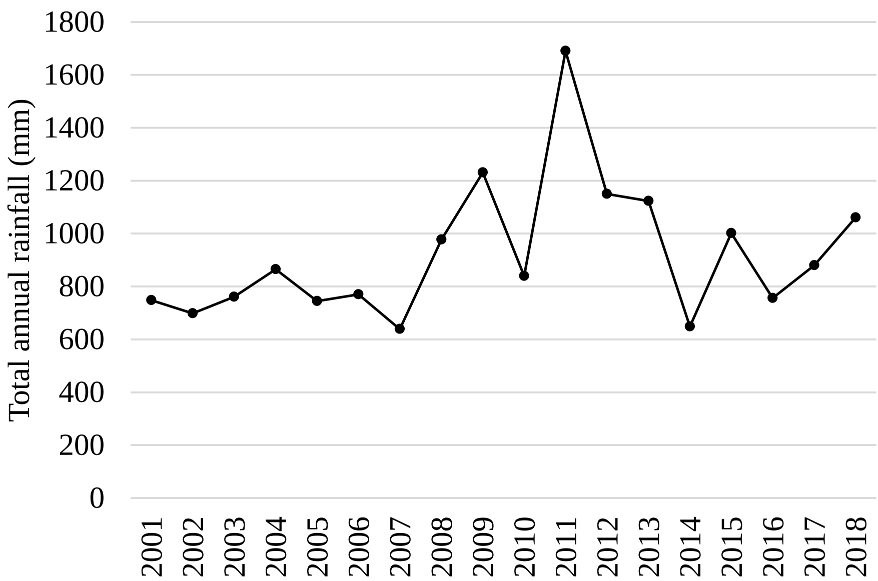

Figure 6. Total annual rainfall (mm) for the Moreton Bay Catchment between 2001 and 2018 (42)

The estuaries – Caboolture, North Pine, Brisbane, Logan

Changes in water quality and nutrient concentrations in Moreton Bay can be explained in part by processes and changes in the major rivers that drain into Moreton Bay—the Caboolture, Pine, Brisbane and Logan. The estuarine sections of all these rivers, except Caboolture, all show reductions in their total nitrogen (TN) and total phosphorus (TP) concentration since 2001 (Figs 7–10). These improvements in water quality are likely to be due to multiple changes in the extractive industry use and industrial and sewage discharges.

The largest management initiative, the reduction in nutrients discharged in wastewater, likely contributed to improvements observed in TN and TP in the Pine, Brisbane and

Logan estuaries (Figs 7–10). In addition, removal of other large industrial discharges, such as pulp from a recycling plant on the North Pine River and changes to sand and gravel extraction both in the Brisbane River and on the floodplain of the Pine River, likely reduced sediment and nutrient inputs. In contrast, nutrients remained relatively stable in the Caboolture River. The Caboolture River had similar nitrogen concentrations to the Pine River in 2000; however, it was not targeted for nutrient management to the same degree. Nitrogen concentrations in the Caboolture River are now double that of the Pine River immediately to its south. The Caboolture River experienced localised reductions in dissolved nutrients as a result of relocation of a wastewater discharge, but the lack of a reduction in total nutrients across the entire estuary suggests that the increase in diffuse nutrient loads from catchment development may have masked any improvements from reduced wastewater discharge (43).

The reduction in TP discharge from the rivers is the likely driver of the trend across Moreton Bay of declining TP (Figs 2–6). In contrast, the decline in TN concentrations in the Rivers appears to have had a smaller, if any, impact on TN concentrations across the Bay. Declines in TN concentrations in the rivers suggest that nitrogen loads to the Bay have also declined. This may not, however, manifest in observable declines in nitrogen concentrations due to substantial nitrogen recycling processes active within the Bay (12, 32, 44). For example, phytoplankton have the highest rates of productivity within the Bay, however their demand for dissolved inorganic nitrogen far exceeds dissolved inorganic nitrogen inputs delivered from the catchment (less than 1%) (38, 45). For this reason, bay productivity substantially relies on nutrient recycling, benthic nutrient fluxes and nitrogen fixation. In addition, catchment sediments deposited by previous events, particularly in the shallow western embayments, are a substantial source of nutrients that are made available by wind, and wave driven resuspension (Figure 11). The beneficial effect of declines in nitrogen load to the Bay may instead need to be measured using biological indicators, such as the observable decline of phytoplankton in parts of Bramble Bay over this 18 year period (Saeck *et al.* (31), this volume). Also, seagrass meadows have recently re-established in some areas of Bramble and Deception Bay (Maxwell *et al*. (3), this volume). These biological changes suggest improvement in Bay ecological condition, which is likely to have resulted from a reduction in nutrient loads to the Bay over an extended period.

Despite progress in reducing nitrogen and phosphorus from entering Moreton Bay over the past 20 years, notably from the Brisbane and Pine Rivers, there has been limited success in reducing the sediment load entering Moreton Bay. This is highlighted in the Caboolture, Brisbane and Logan Rivers where turbidity showed no net improvement over the past 18 years (Figs 9, 10).

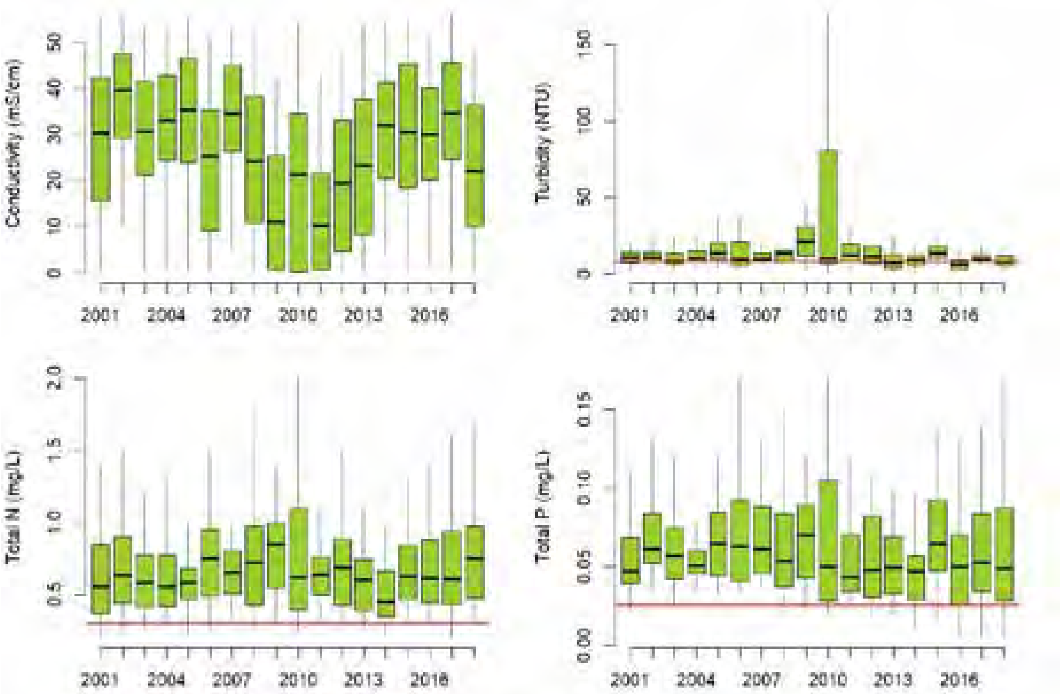

Figure 7. Box and whisker plots for 7 mid-estuary Caboolture River sites showing annual median, upper and lower quartile for conductivity (mS/cm), turbidity (NTU), total nitrogen (mg/L), total phosphorus (mg/L) for the financial years (July to June) 2001 to 2018. Red lines represents Queensland Government's water quality objectives as shown in Table 1.

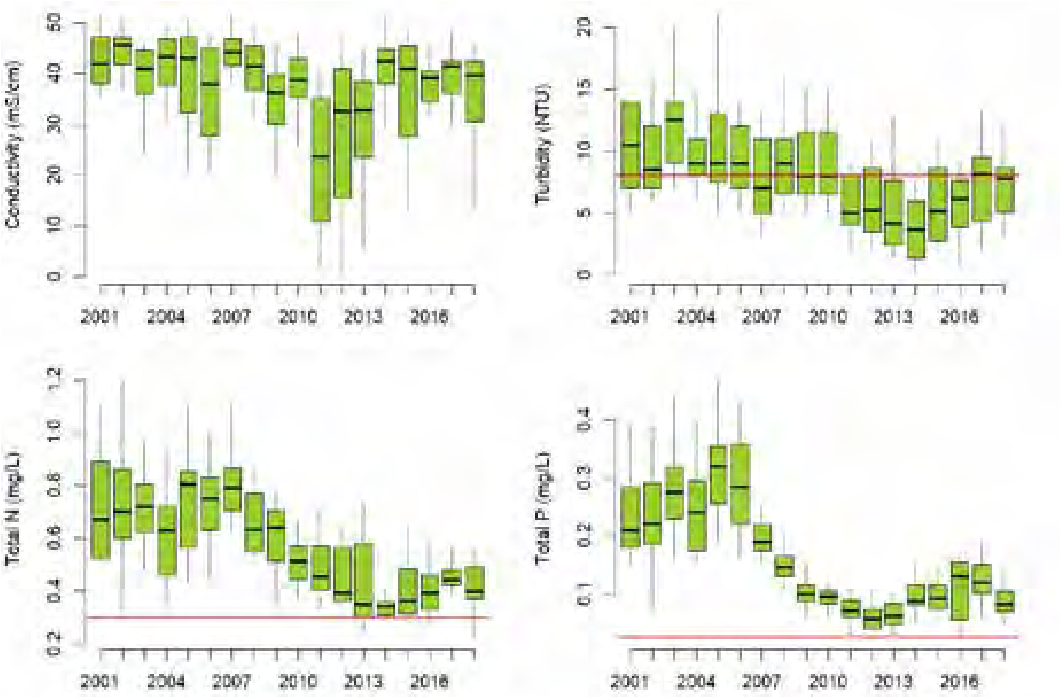

Figure 8. Box and whisker plots for 2 mid-estuary North Pine River sites as per Fig. 7.

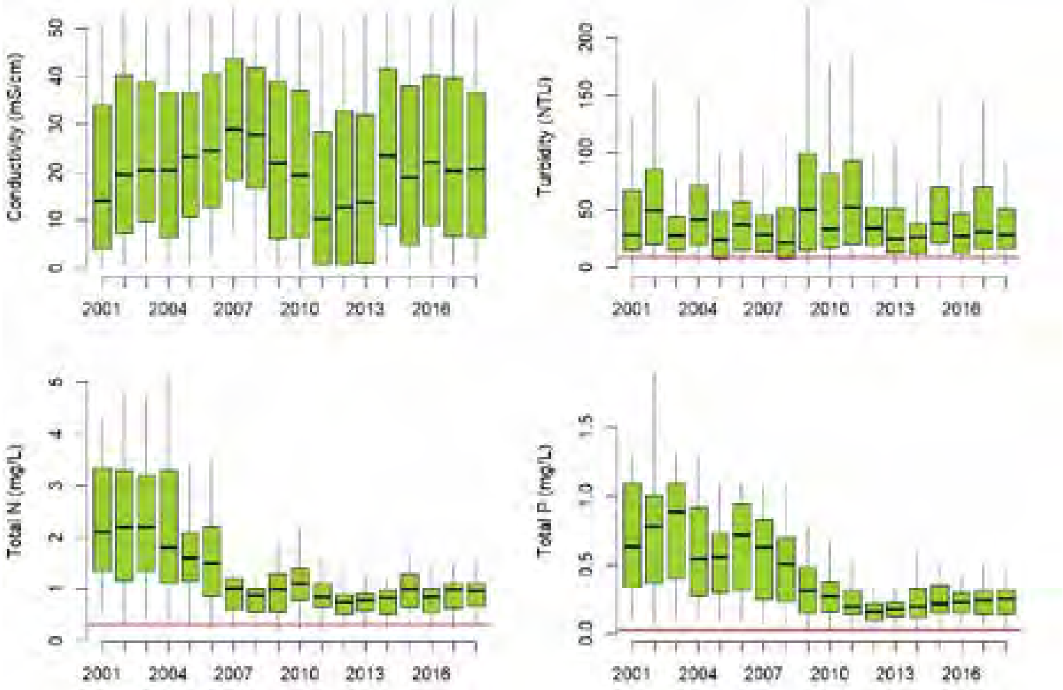

Figure 9. Box and whisker plots for 12 mid-estuary Brisbane River sites as per Fig 7.

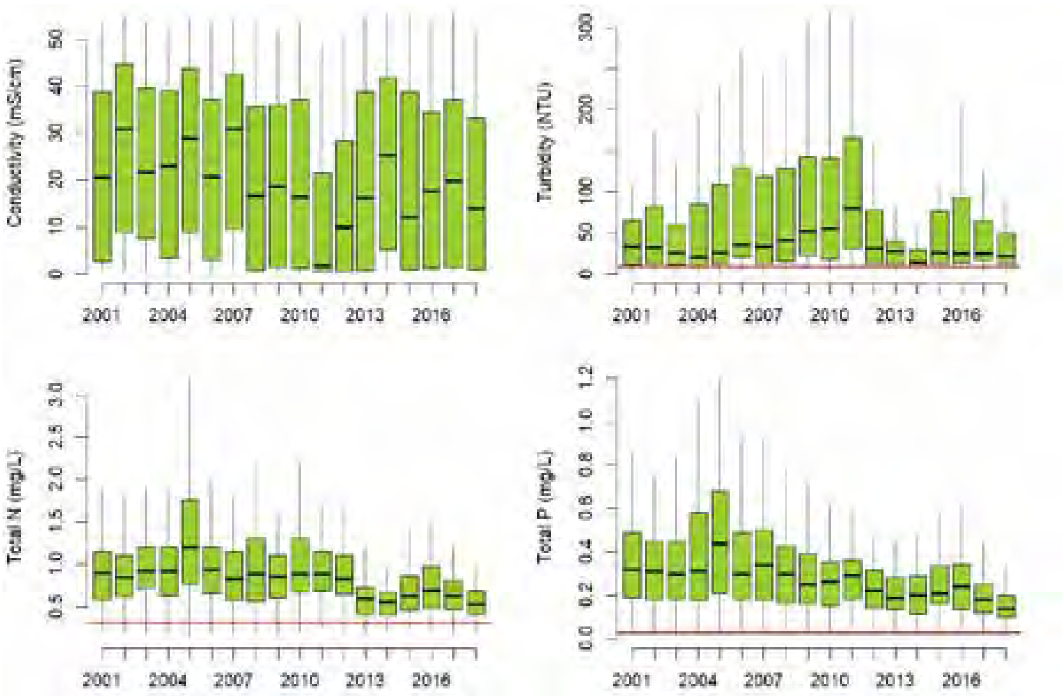

Figure 10. Box and whisker plots for 11 mid-estuary Logan River sites as per Fig 7.

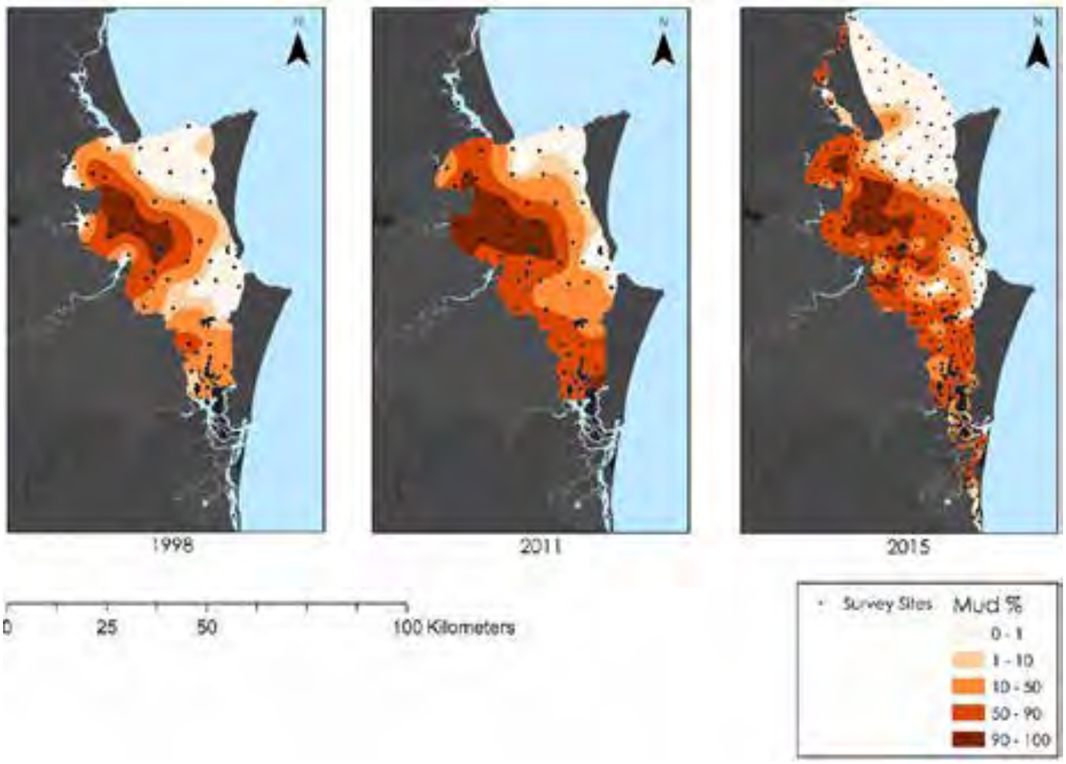

Figure 11. Estimates of mud deposited in Moreton Bay from its catchment during the past 70 years. Modified from Dennison and Abal (11), O'Brien *et al.* (61) and Lockington *et al.* (51).

Water clarity – sediment and mud

Water clarity typically declines during high rainfall and flood events due to the delivery of fine sediments from the catchment and the increased pelagic productivity (phytoplankton) stimulated by the pulse of new nutrients into the system (8, 46). Water clarity is also affected by resuspension events, driven by wind conditions, particularly in locations of sediment deposition in the Bay. Notable increases in turbidity have been observed in the western Bay when wind direction aligns with the direction of maximum fetch and wave energy is greatest (47, 48). On the western segments of the Bay, mean annual turbidity is significantly higher during years with higher than average north- or south-easterly winds (49).

Floods are the dominant source of catchment sediment entering Moreton Bay, as the major estuaries entering the Bay tend to retain river sediments under (non-flood) ambient conditions (50, 51). Between 1970 and 2015, mud cover more than doubled in area across Moreton Bay (51), much of it attributed to high rainfall events. An estimated 150 million tonnes of mud have been deposited in Moreton Bay during the last 70 years (51), where mud is defined as sediment in the finer fraction with particle diameter <63 μm.

Over 20 million tonnes of sediment were deposited in Moreton Bay during the 2011 and 2013 flood events (52). In 2015, a much larger area of the Bay had a mud contribution higher than 40% when compared with two decades prior (Fig. 11). This increase was most notable in the middle, eastern and southern Bay regions, where many areas previously had very little to no mud, suggesting a large increase in the spatial extent of mud across the Bay.

Increased muddy sediment deposition has caused a change in the benthic habitat, with muddy bottom habitats increasing from approximately 30% in 1998 to 70% in 2011 (51). While relocation of mud from shallow to deeper locations may continue and return some muddy areas to a more sandy bottom, Moreton Bay is clearly a sink for terrestrial sediment inputs (53). Given the scale of observed changes, it is hypothesised that the sediment delivered by the 2011 and 2013 floods will permanently alter many habitats of Moreton Bay from predominantly sandy to muddy. This shift in habitat is most likely to have the highest impact in the transition zones in the middle of Moreton Bay (Fig. 11). The change of bottom sediment type from sand to mud could also cause a long-term change of water quality, as mud is more easily resuspended by wind turbulence and tidal currents, reducing water clarity. Recent work around the Mud Island Dredge Placement Area highlights the persistence of the muddy bottom type despite being located in a relatively shallow area and experiencing strong tidal currents (54). Ongoing monitoring and research will be required to fully understand the long-term impacts of the expanding spatial extent of mud on water quality and benthic habitats across the Bay.

It is hypothesised that the more recent expansion in mud coverage across the Bay, and increased rates of vertical accretion, may be the result of the Bay receiving sediment at a rate that exceeds its natural capacity to move material offshore (19). Coates-Marnane *et al.* (19) suggest that infilling of deeper channels in the Bay with fine sediments has reduced the capacity of Moreton Bay to store sediments. Once the capacity of these deeper channels is exceeded, fine sediments entering the Bay will be subject to more frequent resuspension causing long-term changes in water clarity. This highlights that the negative effects of sediment are likely to increase in the future and the need for managing sediment loads is urgent.

The impact of reduced light availability in the water column and smothering of the benthos by fine sediments, creates a shift from benthic productivity to pelagic productivity, where sediment microbial nutrients are de-coupled from the benthic productivity and instead are released into the water column. Increased water column nutrient flux increases pelagic productivity, further reducing light availability and perpetuating these conditions (38, 55). The increase in dissolved inorganic nitrogen being measured across the Bay (Figs 2, 4, 6) suggests that the smothering of the benthos with fine sediments could be affecting nutrient processing, particularly in the eastern and central Bay.

The increase in mud is likely not because floods have become larger, but instead they now deliver proportionally more sediment compared with events in the past. Less than 25% of the Moreton Bay catchment remains as native vegetation (56) and more than 80,000 hectares of land has been cleared since 2001 (57). Loss of vegetation decreases interception and infiltration of rainfall run-off across the catchment and increases over-land flow. This shift to more over-land flow across the catchment results in increased erosion of catchments, particularly stream and river channels. In addition, the loss of riparian vegetation reduces channel protection by reducing channel roughness and exposing sediments. It has been estimated that catchments with no riparian vegetation export up to 200 times more sediment than catchments with intact riparian vegetation protecting the channel network (58).

In the last few decades there has been a rapid expansion of urban development (59), which poses a large risk of sediment export per hectare (Lyons *et al.* (59), this volume). The loss of sediment from recently cleared urban land during moderate to heavy rainfall events can be up to 1000 times greater than the sediment loss associated with the same area prior to disturbance, or after completion of the construction and landscaping (60). Land clearing and increasing urban developments over the past 200 years have increased sediment and nutrient loads delivered to the Bay, particularly in association with high rainfall events (19). The impact of these changes is manifested in declines in water quality within, and increased mud distribution across, the Bay.

Future pressures to Moreton Bay water quality

The population residing within the Moreton Bay catchments is predicted to reach four million by 2026. This and the associated increases in urban development and land-use change will place Moreton Bay under more pressure. Opportunities exist to reduce current sediment and nutrient loads and minimise future increases in loads, through improved management and innovative solutions. For example:

- protect, replant/regrow streambank vegetation
- best management practice in rural areas to manage fertiliser application rates and vegetation cover
- management of stormwater flow from new developments and construction sites
- innovative stormwater management designed into new developments
- innovative nutrient removal technology to upgrade sewage treatment plants.

Catchment modelling by Healthy Land and Water (28) was used to determine the benefits of applying such actions across Moreton Bay catchments, and how that would affect future sediment and nutrient loads. Current nutrient loads (baseline) were compared with predicted loads under the planned 2030 land use for two scenarios: 1) if no management techniques are changed (business as usual, or BAU); and, 2) if all currently available management techniques are applied to the urban and rural areas across the whole catchment (full investment, or FI) (Fig. 12 and Table 2).

If nothing changes (BAU), Moreton Bay will be exposed to higher sediment, nitrogen and phosphorus loads, and water quality will continue to decline; current trends indicate that this has already begun. Full investment (FI) across the whole region can halt any further increase in sediments and phosphorus from urban areas, and could reduce loads from rural areas by a factor of about 7. These investments would result in significant improvements in water clarity, and likely prevent further growth of the mud patch across Moreton Bay.

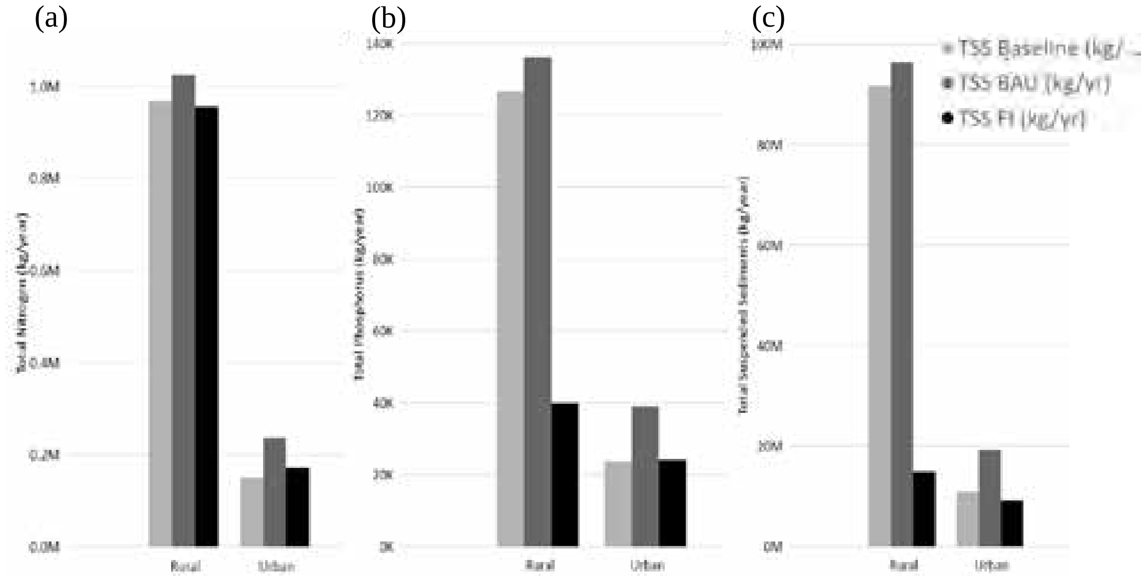

Figure 12. Pollutant loads (kg/year) under three management scenarios. Results of pollutant load generation modelling for the Moreton Bay catchment, recreated from Healthy Land and Water (28). Two future land-use management scenarios are compared with existing practices. Baseline 2015 (light grey bars) - current land management practices and existing land uses; Business-As-Usual (dark grey bar) – current land management practices, with increased population and expanded urban footprint at 2030; Full Investment (black bars) as per business-as-usual but with every land use type/management initiative undertaken to the fullest extent possible. Figures show the effect on (a) nitrogen, (b) phosphorus and (c) sediment loads generated within the catchment under each scenario. See Table 2 for details of each scenario.

Such reductions in sediment input could prevent further impacts on the benthos of the Eastern Banks and the nutrient processing in that region which appears to have started to manifest as increases in dissolved inorganic nutrients. In contrast, without better nitrogen management options, the simulation results suggest that nitrogen loads will increase slightly in the future, even under FI scenarios. This highlights that nitrogen may be a growing problem for Moreton Bay into the future.

There are a few limitations to this catchment modelling study that suggest investment in land and pollutant manage is likely to be more effective in reducing nitrogen loads to Moreton Bay than the results predict (Fig. 12). First, the model did not account for the latest engineering technology that can now further reduce the nutrient and sediment export from new urban developments. It is also anticipated that in the coming decade more progress will be made in this field. Second, targeted (and large-scale) investment in the upper catchments (e.g. riparian revegetation and increased ground cover) is likely to increase infiltration and reduce sediment and nutrient run-off during rainfall events. The effect of infiltration on nitrogen is not well understood, consequently the effect of increased riparian and ground cover on nitrogen export rates is likely to be an underestimate. Third, different land-use types generate different nutrient loads and in the model these were estimated from experimental data or derived from values in the literature. However, experimental information available for nitrogen generation from different land-uses in South East Queensland is poor, as a result, there is low confidence in the magnitude of nitrogen reductions predicted under each scenario. Our poor understanding of nitrogen behaviour and an underestimate of the effect of on-ground investment on catchment hydrology (see consideration 3) has limited the predictive capacity of this model in regard to the effectiveness of management on nitrogen load reduction to Moreton Bay. This consideration is most relevant for nitrogen, as there is a much better understanding of phosphorus dynamics from different land uses.

Total nitrogen loads were higher in the 1990s prior to the reductions in the early 2000s associated with sewage treatment plant upgrades (11, 62). During this period there were reports of very poor water quality, including high phytoplankton biomass (4–10 µg/L chlorophyll *a*) in the nearshore areas, and algal blooms that may have been implicated in fish kills and localised anoxia (23). Should TN loads increase in future, the likelihood of reversing the improvements observed is high. South East Queensland needs to invest in finding more innovative solutions to nitrogen management from both the rural and urban landscape. These solutions should include efforts to rehabilitate the stream network, particularly in the Upper Lockyer Catchment, which contributes most of sediment loading into Moreton Bay and has recently been shown to be a major source of nutrients during flood events (19, 63–65).

Table 2. Summary of the pollutant load management strategies applied to each land-use under the three catchment modelling scenarios in Fig. 12: baseline, business-as-usual and full investment. Modified from Healthy Land and Water (28).

	Baseline (2015)	**Business-as-usual (2030)**	**Full Investment (2030)**
Rainfall	1 Jul 2014–30 Jun 2015 (~long-term average)	1 Jul 2014–30 Jun 2015	1 Jul 2014–30 Jun 2015
Land-use layer	2012 (derived from Queensland Land Use Mapping Program (QLUMP)	2012 (QLUMP), with 2031 features based on the South East Queensland Regional Plan (2009-2031)	2012 (QLUMP), with 2031 features based on the South East Queensland Regional Plan (2009-2031)
Grazing			Riparian re-vegetation applied to all (90% reduction TSS & TP).
Rural-broadacre agriculture, intensive agriculture, grazing		No additional rural management practices	Riparian re-vegetation applied to all (90% reduction TSS & TP). Areas with intensive fertiliser (agriculture) (TN load reduction by 80%).
Rural - residential			Riparian re-vegetation applied to all (90% reduction TSS & TP).
Urban/dense urban		Water sensitive urban design (WSUD) features applied to new development – load reductions: 20%TSS, 15%TP, 11.25%TN; no retrofitting WSUD into existing urban;	50% of existing urban areas retro-fitted with WSUD features:WSUI to new development -load reductions: 80%TSS, 60%TP, 45%TN;

	perviousness of existing urban decrease to 0.5 (from 0.75); perviousness of new urban 0.3.	perviousness of all existing and new urban 0.5.
Construction	A portion (6.25%) of additional urban land classified as construction (bare earth for 1 year);construction site load reduction (through sediment control): 10% TSS, 10%TP & 5%TN	Construction site load reduction: 80% TSS, 80%TP & 40%TN
Wastewater treatment plants	Increased flow in proportion to population increase. No change in pollutant concentrations	Increased flow based on population increase. 50% re-use. Reduced pollutant concentrations (3mg/L TN and 1mg/L TP).

Conclusions and recommendations

To maintain the improvements in water quality (nitrogen and phosphorus) that have been achieved over the past 20 years, it is critical that we prioritise and fund management actions that reduce diffuse sediment loads, and seek-out and invest in innovations in nitrogen management from both rural and urban landscapes. Despite the dramatic reductions in dissolved nutrients discharged from the region's wastewater treatment plants two decades ago, water quality in most estuaries continues to be higher than the Queensland Government Water Quality Objectives. Water quality in the Bay indicates that the 800,000 additional people (approximately 50% increase in population) residing in the region in the last two decades has added additional nutrient loads to the catchments of Moreton Bay—replacing some of the nutrient load reductions achieved through upgrading wastewater treatment facilities. Changes in catchment land use (Lyons *et al.* (59), this volume) that have occurred and continue to occur in the catchment of Moreton Bay, are driving increases in mud and sediments across Moreton Bay. These increases are a cause of concern for water quality and ecosystem processes in the Bay. Catchment scale action is critical if we are to protect the habitats of Moreton Bay and their resilience into the future.

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