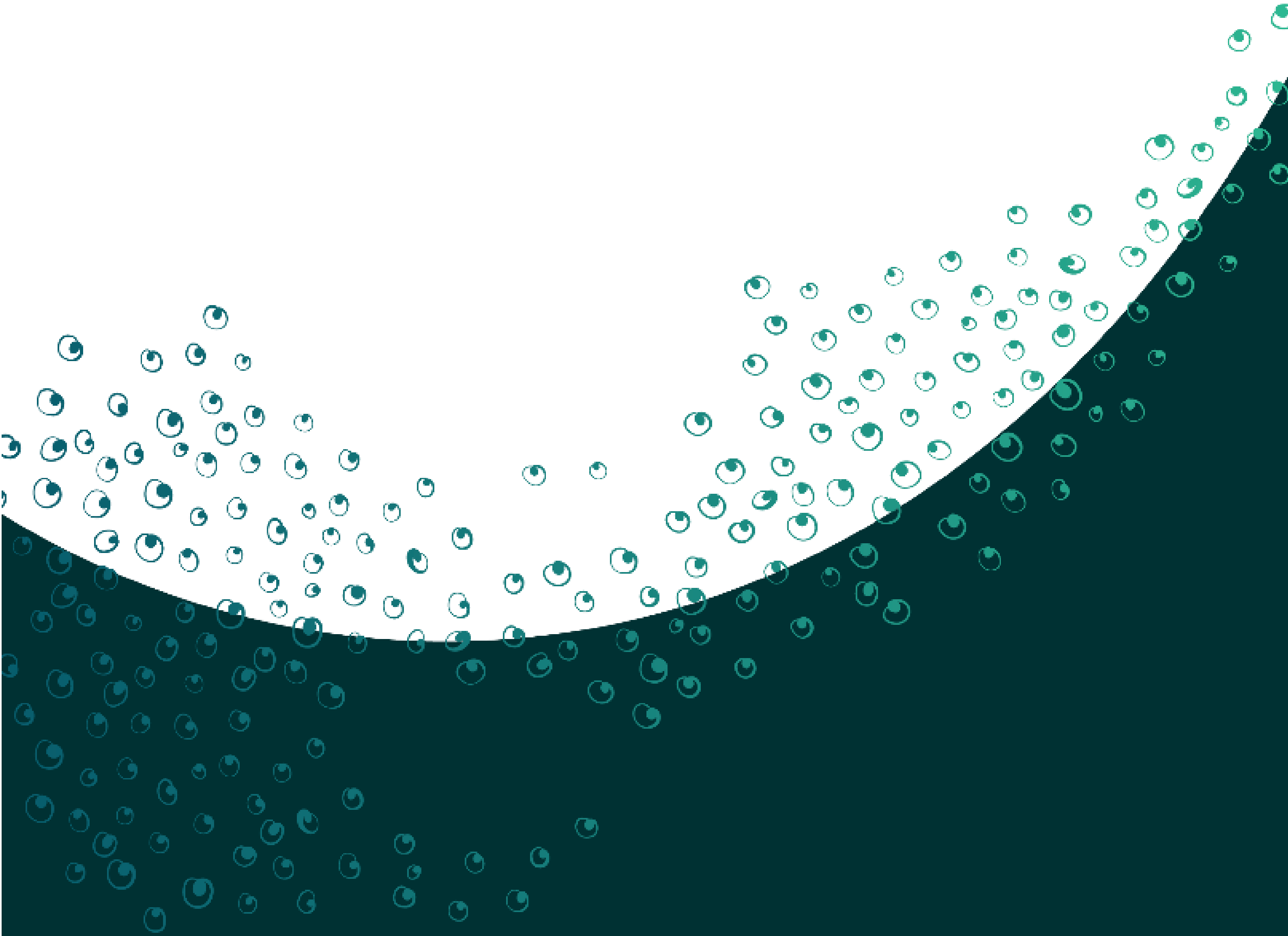

Fine Scale Water Quality Monitoring in the Herbert Catchment

Communications Report

Queensland
Government

Prepared by: Water Quality & Investigations, Department of Environment, Science and Innovation.

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June 2024

Executive Summary

This report provides an overview of the findings from the fine-scale water quality monitoring network installed within the Lower Herbert River catchment and is part of the larger RP232 Fine-scale Monitoring program (The RP232 project is funded through the Queensland Government's Queensland Reef Water Quality Program) that seeks to demonstrate the utility of near real time nitrate probes for the delivery of water quality data to a range of stakeholders, including land and resource managers. The network aims to quantify and communicate the nitrate dynamics within the catchment. Through a project coordinated by the Queensland Department of Environment, Science and Innovation, the Water Quality & Investigations team was contracted to expand its real-time monitoring network. The project included the installation of up to 40 fine-scale monitoring sites (micro-sites) across the two priority catchments; the Lower Burdekin and Lower Herbert. This report summarises the data output from the Lower Herbert catchment to date.

The data collected over the past three years has already provided new insights into nutrient dynamics in the region. In contrast to the RP232 Lower Burdekin communications report released in 2023, the Lower Herbert has presented a much simpler story. Nitrate concentrations were demonstrated to be much lower at the upstream reference sites than downstream impact and end-of system sites. The medians of nitrate concentrations measured at reference sites over as many as three wet seasons and three dry seasons were below scheduled water quality objectives (WQOs) for Wet Tropics waterways. In contrast, median nitrate concentrations at impact sites and end-of-system sites were more variable with respect to WQOs, and the range of concentrations recorded were often far wider, exceeding on some occasions, a New Zealand guideline for nitrate toxicity.

Trends displayed along some systems suggest that the extent of wetland ecosystems, and the services that these ecosystems provide, affect the nitrate concentrations. For example, based on the observations so far, there is a reduction in nitrate concentration between sites in the lower network separated by a series of lagoons and wetland environments. At some sites, downstream nitrate concentrations were lower than a corresponding upstream site, and this was concluded to be a consequence of denitrification processes in sections of streams where residency time was high and/or the presence of aquatic macrophytes facilitated such processes. The data collected also suggested that nitrate-contaminated groundwaters may be influencing surface water nitrate concentrations well into the dry season.

Monitoring in this project has occurred during a prolonged period of La Niña and its associated climate conditions (increased rainfall, earlier onset monsoon, increased number of cyclones). As a consequence, the reported nitrate concentrations may not be representative of average climatic condition or El Niño conditions. It is recommended that monitoring be conducted over varied climatic conditions to provide further context to end-users.

The data summarised in this report provides value that cannot be found in any other sampling strategy and demonstrates that this program is a crucial tool for the identification of specific drivers affecting nutrient and sediment run-off to the Great Barrier Reef (GBR), and thereby, will support improvement of agricultural practices. This program collects a significant amount of data and major advancements have been made in operationalising anomaly detection algorithms and techniques developed in collaboration with the Queensland University of Technology. Frameworks proposed as part of the ARC Linkage project with QUT have been implemented by the department leveraging the in-house expertise in sensor technology, with plans to integrate the more complex spatial-temporal and machine learning models in the future.

Overall, the Fine-scale Monitoring program has provided valuable insights into the benefits of near real time monitoring as well as some of the limitations. Some technical failures in the monitoring infrastructure have resulted in site down-time and data gaps in the time series. As the data is displayed publicly in near real time, the data gaps are more noticeable than those in traditional monitoring programs. Data gaps presented publicly without further details can affect confidence in the data and its interpretation. Many of the technical issues have been addressed and can now be more readily dealt with by collaborators in the region. These include the identification and replacement of wiper units incompatible with the installation setup and modification of installation setups to facilitate a more modular approach, where equipment may be rapidly swapped should failures occur. The knowledge gained from these issues has improved the capacity to identify these and similar issues remotely.

As an outcome of this Fine-Scale Monitoring program, the Queensland Government is now in a position to set the standard for future probe-based water quality monitoring programs.

Contents

Project Overview

In 2015, the Australian and Queensland Governments released the Reef 2050 Long-Term Sustainability Plan to focus on actions to address key threats and directly boost the health and resilience of the Great Barrier Reef (GBR) (The Commonwealth of Australia, 2023). A major component of that plan is the Reef 2050 Water Quality Improvement Plan (State of Queensland 2018), which identifies the land-based runoff of nutrients, pesticides, and sediment from agricultural lands to be a major cause of poor water quality in GBR catchments.

Through a project coordinated by the Queensland Department of Environment, Science and Innovation, the Water Quality & Investigations (WQI) team expanded their real-time monitoring network. This involved the installation of 40 additional fine scale nitrate monitoring sites across the Lower Herbert and Lower Burdekin catchments. These catchments have been listed as high priority for the reduction of Dissolved Inorganic Nitrogen (DIN), of which nitrate is a major constituent. Water quality data collected at this fine scale were expected to achieve the following:

- raise community awareness of water quality issues in their local waterways.
- help local industry and natural resource management groups understand the relationship between land use management practices and water quality.
- contribute to improving Paddock to Reef model outputs for investigation at the sub-catchment scale to identify sources of pollutants.

Monitoring sites were selected via a co-design process with local stakeholders (see acknowledgments), best placed to provide knowledge. To compile the final site list considerations were given to current and historic water quality projects, flow and irrigation regimes, and local land use (see **Appendix A**). Site installation in the Herbert catchment began in October of 2020, with most sites operational by June 2021. There are a total of 17 monitoring sites across the catchment (see Figure 1). The monitoring undertaken by the program has produced a spatially and temporally dense dataset. The monitoring locations had a variety of drivers influencing the selection process. With the objective to identify concentration differences and emerging issues and trends, they have been separated into three groups: reference, impact, and end-of-system. They can be defined as follows:

- **Reference** – Situated higher in the catchment above contaminant sources, provide a natural baseline for the water quality within each region.
- **Impact** – Sites located directly downstream of urban areas, highways, sewage treatment plants or intensive agricultural areas, used to determine the influence of these sources of nutrients.
- **End-of-system** – Sites located at the most seaward practical monitoring point along the river or creek. The intent is to capture the maximum extent of upstream land use while avoiding the complexities of monitoring in the estuary.

This nested design aims to improve community understanding by clarifying changes in water quality between reference sites high up in the catchment, impacted sites within agricultural and urbanised areas and the final pollutant loads delivered to the GBR.

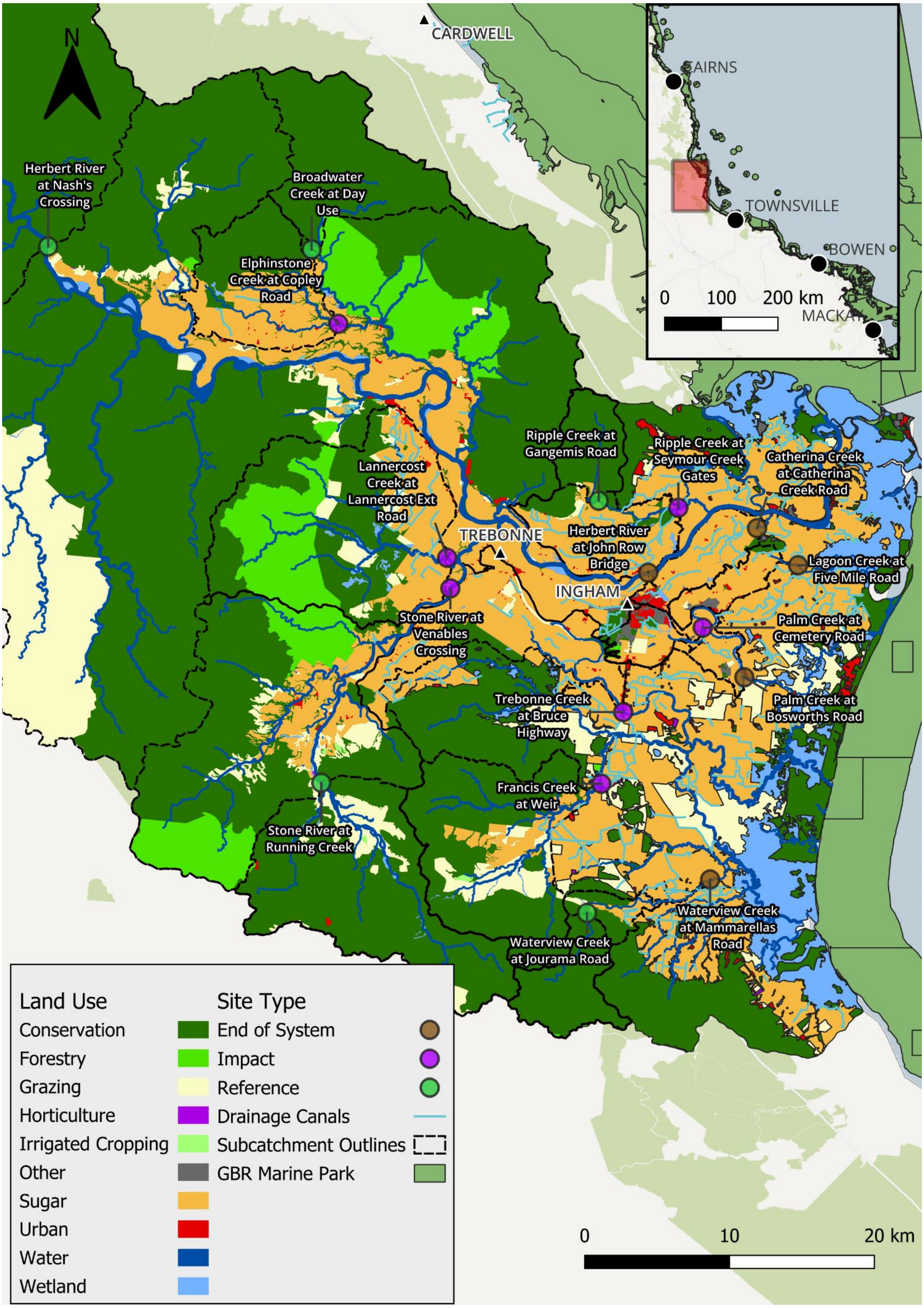

Figure 1. Map of the Herbert fine scale monitoring sites and broad land use types.

Site Setup

The WQI team designed and implemented remote monitoring systems for the ready deployment of in-stream spectral nitrate sensors. The deployments are referred to as micro-sites because of the minimal approach taken compared to a traditional monitoring station. The typical infrastructure requirements for the installation of long-term water quality monitoring stations are greater in terms of cost, labour, and time. The aim of the micro-site installations was to balance durability, cost-efficiency, and installation times.

The installations were designed around the TriOS™ Opus spectral sensors (hereafter referred to as Opus). These sensors primarily measure the nitrogen component of the nitrate molecule (NO_3-N) and total suspended solids equivalent units (TSS_{eq}). The installations use pressure transducers alongside the Opus to record water level providing context to the concentration data. The in-stream components are secured within a PVC pipe extending from the bank to the water (Figure 2).

The on-bank control and logging setup (Figure 2), consists of a weatherproof electronics enclosure with:

- Campbell Scientific data logger
- telemetry equipment (modem and antenna)
- self-contained power systems (solar panel, regulator and battery)

Data were recorded every 15 minutes in the logger and transmitted hourly to the WQI's online data portal, eagle.io.

Figure 2. Examples of on-bank infrastructure from Herbert River at Nash's Crossing and river-end setup from Elphinstone Creek at Copley Road.

Quality Assurance and Quality Control

This network collects a high frequency data-stream of more than 70,000 individual reportable data points per day. To verify that the data are of good quality, an algorithm and automated data pipeline has been developed, adapted from the proposed framework by (Leigh et al. 2019). It processes substantial amounts of data and allocates quality codes indicative of probable causes (i.e. dry reads / out of range / spikes in data). The algorithm uses the following features:

- Manufacturer's detection limits for absorbance at wavelengths associated with nitrate, organic matter, and turbidity.
- Limits on parameter outputs (NO_3-N / TSS_{eq}) which are specific to the instrument configuration at each site.
- The Opus' internally calculated spectral quality index.
- Spike detection.
- Constant value detection.

The automated quality assurance and quality control pipeline functions as follows:

1. Ingestion of data from the online data platform for a given site.
2. Process the data using a defined ruleset for the given probe configuration.
3. Application of relevant quality codes dependent on ruleset (summarised in dot points above).
4. A modified data stream, inclusive of quality codes, becomes accessible within the online data platform.
5. Repeat for each site.

This process is hosted on cloud-computing infrastructure and runs hourly. The modified data stream has resulted in substantial efficiencies in anomaly detection. Specifically, it has improved efficiency in the identification of wiper failure, lens obstructions, dry readings, and saltwater interference. These anomalies can appear like typical sensor variability when viewed in isolation. Manual efforts now focus on inspecting flagged values that require specialist technical investigation and site-specific insights, freeing up valuable expert time and resources.

Manual inspection of the data is completed periodically, both to confirm the outputs of the automated process and to identify any major deviations from expected values (spikes / sensor drift / biofouling). Quality codes are then applied to the raw data source in WQI's data platform (eagle.io). The automated script will not modify any manually applied quality codes. This cleaned and processed NO_3-N and water level data is exported to the CSIRO 1622wq public web portal. At present, the TSS_{eq} data are not published. The WQI team are investigating options to clean and validate this dataset for public consumption through an alternative platform.

The path length is the distance between the lenses of the probe through which the light passes while traversing the sample medium (water) before reaching the spectrometer. The accuracy and precision of the probe can be calibrated for best results by adjusting the path length. Path length selection for the Opus probe installations were based on local manual grab samples to better understand typical concentrations. In the absence of local sample data, path length selection was defined using estimated concentrations that were based on an understanding of site condition and upstream land use.

Reference sites capturing natural systems were expected to have lower turbidity and lower NO_3-N values, so longer path lengths (10 mm) were deployed. With sites downstream of intensive cropping, sugarcane agriculture or other horticulture, it was expected there would be higher NO_3-N values, so shorter path lengths (2 mm and 5 mm) were deployed. Overall, where possible, shorter paths (2 mm) were installed to capture the peak NO_3-N concentrations, albeit at the expense of capturing a consistent trace for low range values. When interpreting the data from each of the probes, it is important to consider the specific path length as each has different operational ranges (Table 1; **Appendix A**).

Table 1. TriOS Opus Probe limits based on the optical path length (TriOS Mess- und Datentechnik GmbH 2017).

Path length (mm):	**2**	**5**	**10**
NO_3-N **(mg/L)**	0.15 to 50	0.06 to 20	0.03 to 10
Total Suspended Solids (equivalent) **(mg/L)**	20 to 650	8 to 260	4 to 130

Currently, data below the probe limits are not reported on the 1622wq public web portal (i.e. they appear as data gaps); however, those data are informative with respect to seasonal trends and have been retained in the graphical elements of this report to provide a fuller picture at each of the sites.

Nitrate Guidelines

The Australian and New Zealand Water Quality Guidelines for Fresh and Marine Water (ANZECC & ARMCANZ 2000) recognises that most waterways in Australia and New Zealand possess aquatic ecosystems as one of their environmental values. Three levels of protection are recognised:

- high ecological value (HEV)
- slightly to moderately disturbed (SMD)
- highly disturbed (HD)

The Queensland Environmental Protection (Water and Wetland Biodiversity) Policy 2019 defines four corresponding levels of protection:

- high ecological value (HEV)
- slightly disturbed (SD)
- moderately disturbed (MD)
- and highly disturbed (HD)

Each level of protection is assigned a specific management intent. For HEV waters, the management intent is to maintain natural values/condition. For waters identified as SD, MD or HD, the intent is to progressively improve them towards the HEV condition (ANZG 2018).

ANZECC & ARMCANZ (2000) provided a toxicity-based guideline for nitrate for each level of protection for freshwater aquatic ecosystems. However, the guideline is deemed unsuitable, marked for revision, and not currently in use. In the interim, ANZG (2018) recommend using the nitrate guidelines derived by the New Zealand National Institute of Water and Atmospheric Research (NIWA). NIWA have derived a set of nitrate guidelines using the same method that will be used as a basis for the revision of the Australian and New Zealand guidelines. Therefore, as an interim working guideline, we have adopted the NIWA guideline for nitrate (Hickey 2013) as a reference indicator of risk to aquatic ecosystems in Queensland. Specifically, we have adopted the grading guideline (2.4 mg/L) for slightly to moderately disturbed aquatic systems (Table 2). In the previous report (Roberts et al. 2023), we adopted the surveillance guideline (3.5 mg/L). However, we have subsequently determined that the grading guideline is more closely aligned with the ANZG (2018) methodology for the development of toxicant guidelines for protection of aquatic ecosystems.

Table 2. Nitrate toxicity guidelines. Adapted from: NIWA (2014) and Hickey (2013)

Ecosystem Condition	Toxicity Guideline Value NO_3-N (mg/L)
High Ecological Value	1.0
Slightly Disturbed	1.0
Moderately Disturbed	**2.4**
Highly Disturbed	6.9

Regional water quality objectives (WQOs) for oxidised nitrogen (N-NO_x) are also scheduled within the Queensland Environmental Protection Policy. Oxidised nitrogen represents the sum of nitrite and nitrate; however, in oxygenated waters, nitrite is usually present in negligible concentrations, and NO_x can be used as a proxy for NO_3^-. WQOs are calculated for waterways based on the available data from local waterways, with greater emphasis placed on data from waterways with few anthropogenic impacts. Table 3 provides the WQOs for the Herbert basin. The data are calculated from data collected in the Herbert upper basin and other Wet Tropics catchments. The data used to derive the high flow WQOs for this basin comes from the neighbouring Tully catchment where WQI has a long-standing monitoring station. For the purpose of this report, all data were assessed against the WQO for other developed freshwaters (0.14 mg/L) within the Wet Tropics, as the WQO best representing Lower Herbert land uses.

Note that there is a large difference between the toxicity-based guidelines and WQOs, both in terms of the magnitude of the values and their intent. Toxicity based guideline values are intended to give guidance on the threshold between low risk and moderate to high risk to the integrity of aquatic ecosystem. WQOs provide an indication of the desired state of an aquatic ecosystem. The assessment of water quality against toxicity guidelines and WQOs requires different statistical approaches. For assessment against the toxicity-based guidelines, the 95th percentile of the water quality dataset is calculated and compared to the guideline, whereas the median of the water quality dataset is calculated and compared to WQOs. Graphical elements in this report utilise box and whisker plots that show both the median and 95th percentile for the data collected each month.

Table 3. Adapted from: Environmental Protection (Water and Wetland Biodiversity) Policy 2019 – Herbert River Basin Environmental Values and Water Quality Objectives (updated September 2022).

** HEV = High Ecological Value systems, MD = Moderately Disturbed*

Water type	Ecosystem condition	WQO for N-NO_x (mg/L)
Wet Tropics	HEV	Not defined
Upper Herbert developed fresh waters	MD	<0.02
Other developed freshwaters within the Wet Tropics	MD	<0.14
Wet Tropics wetlands	MD	<0.01
Wet Tropics enclosed coastal/ lower estuary waters	MD	<0.01
Wet Tropics region high flow	Apply to all fresh waters during high flow periods where discharge is above local baseflow	0.005 – 0.066 - 0.101 (20th - 50th - 80th %iles)

The Nitrogen Cycle

Nitrogen is an essential macronutrient for plant growth and its abundance can be a limiting factor in productivity of many crops. Nitrogen is essential to facilitate plant growth, photosynthesis, and in the case of sugarcane, sugar production. Although maintaining productive and economically viable crops needs to be taken into consideration, so too should be the management and sustainable use of these nutrient inputs, and their flow on effects on aquatic ecosystems (Calcino et al. 2018). There are demonstrable examples where the reduction of fertiliser runoff in agricultural catchments has resulted in an improvement in both economic and environmental benefits (Skocaj et al. 2013).

While atmospheric deposition of nitrogen contributes to soil nitrate concentrations, artificial application of manufactured fertilisers is of greater significance. Urea is the most common form of nitrogen fertiliser applied to sugarcane crops in Australia (Calcino et al. 2018). Urea N is transformed through microbial processes to ammonium, with some volatised in the process depending on the soil conditions. Volatilisation is defined as the loss of N to the atmosphere through conversion of ammonium to ammonia gas. When in solution, ammonia is in an equilibrium state between ammonium and ammonia ($NH_4^+ \rightleftharpoons NH_3$). Soil microorganisms facilitate the transformation between ammonium and nitrate (NO_3^-) - the process of nitrification. Nitrogen in the form of nitrate is then available for uptake in plants for metabolic synthesis of proteins and other organic molecules. Subsequent decomposition of this plant matter recycles organic nitrogen back into the soil, thus re-entering the nitrogen cycle.

Nitrogen in the form of nitrate is highly soluble and mobile in the soil profile. This facilitates losses to groundwater via subsurface drainage and surface water through rainfall driven runoff events (Hunter & Walton 2008; Wang et al. 2015). In the aquatic environment or in waterlogged soils, denitrification processes transform nitrate into nitrite and subsequently nitrogen gas which is lost to atmosphere ($NO_3^- \rightarrow NO_2^- \rightarrow N_2, N_2O$). This occurs primarily within anoxic soils and sediments, through microbial action (Martínez-Espinosa et al. 2021). Wetland ecosystems facilitate the denitrification process due to the presence of anoxic soil rich in organic matter (Adame et al. 2019).

Further information on the detailed processes within nitrogen cycling in the environment can be found at the Queensland Governments Wetland*Info* page.

Basin Overview

The Herbert drainage basin comprises 45% of the Wet Tropics region, spanning a total of 9,873 km^2, making it the largest catchment within the region. The dominant land use is grazing, comprising much of the upper catchment and 53% overall (see **Appendix B**). Conservation is the second largest land use in the basin, positioned mainly around the bottleneck between the upper and lower basin. This project is focused on the lower Herbert basin where the most prevalent land use is sugarcane cultivation.

Due to the distribution of land use types in the lower catchment, the monitoring network can potentially capture runoff from several sources. The reference sites (Waterview Creek at Jourama and Ripple Creek at Gangemis Road) capture inputs from conservation dominated areas. However, at other reference sites, we may capture additional inputs, albeit minimal, from forestry (Broadwater Creek at day use area) and grazing (Stone River at Running Creek). For example, waters from the upper catchment (majority grazing) flow down the main channel of the Herbert, and pass through significant conservation areas to arrive at the Herbert River at the Nash’s Crossing site. The impact and end-of-system sites are typically capturing a majority of sugarcane land use, with some sites capturing secondary inputs from urban (Palm Creek at Bosworths Rd) and grazing (Francis Creek at weir). Due to the flat, low-lying nature of this region, derivation of sub-catchment outlines is difficult. Exact flow boundaries may not be completely accurate in the maps provided in this report but will approximate reality.

Due to its outstanding universal value, the Wet Tropics has received World Heritage status for much of the region bordering the Great Barrier Reef (UNESCO 1988). Much of the coastal plains adjacent to its major rivers host the sugarcane industry. Various land uses in the region, including sugarcane and grazing, have been associated with the runoff of fertilisers, pesticides, and sediments in freshwater and marine environments (Deane et al. 2018; Waterhouse et al. 2012). The 2017 Scientific Consensus Statement (Waterhouse et al. 2017) lists the Herbert basin as having the greatest contribution of dissolved inorganic nitrogen (DIN = ammonium + nitrate + nitrite) in the Wet Tropics.

Rainfall and Hydrology

The Herbert basin receives, on average, 1.2m of rainfall per year, with intense rain events and flooding common (The Australian and Queensland Governments 2019). This basin receives considerably less rainfall than others within the Wet Tropics region. The Herbert basin has the most variable rainfall patterns outside of the monsoon season and has recorded occasional dry season showers (Bureau of Meteorology & CSIRO 2019). Data in Figure 3 shows that on average most rainfall in the lower catchment occurs between November and April, with a pronounced ‘dry’ period between May and October.

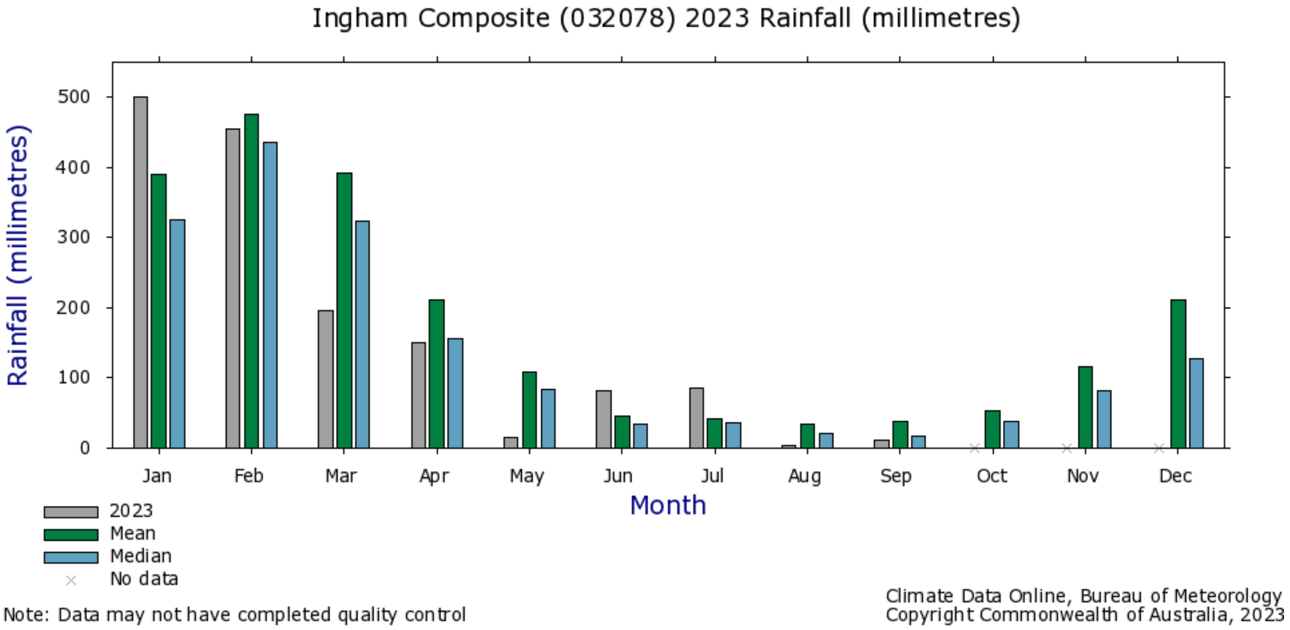

Figure 3. Long-term mean monthly rainfall for the Ingham composite rain gauge. Chart extracted from Bureau of Meteorology, 2023.

Gridded rainfall data have been utilised as available through the Queensland Governments SILO (Scientific Information for Landowners) database. The gridded data is interpolated from raw weather observations from the Bureau of Meteorology. SILO provides a spatially and temporally complete dataset for comparison against WQI's monitoring data. This project has mostly occurred within the La Niña weather patterns that have dominated the climate from 2020 up to 2023. This has produced rain events outside of the typical wet season compared to the long-term average rainfall in the region (Bureau of Meteorology 2023).

The 2020-21 wet season fell between December and April followed by a pronounced dry season (Figure 4). Subsequent years show an earlier onset (November 21 – May 22 and October 22 – April 23) with more consistent rainfall between wet seasons. Having rainfall conditions persist for so long will have an influence on soil moisture and hence capacity for pollutant mobilisation through runoff events (Wasko et al. 2021).

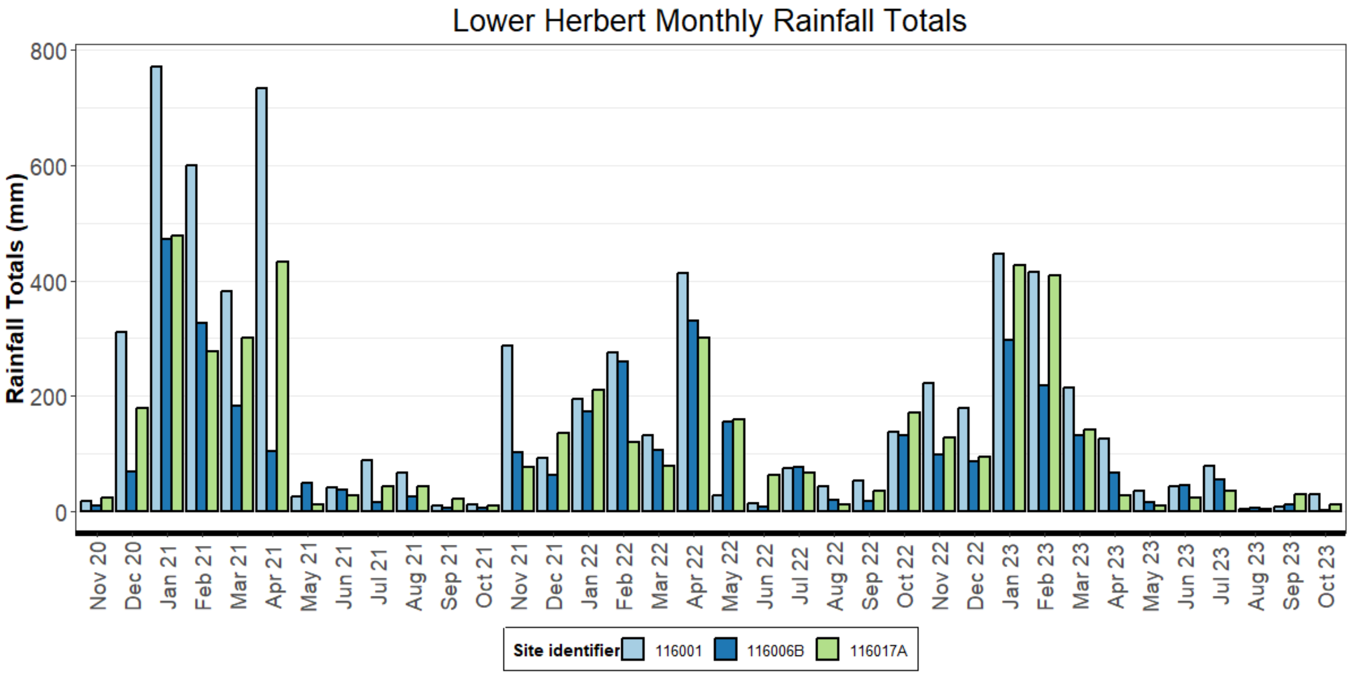

Figure 4. Monthly rainfall totals across three monitoring stations in the lower Herbert catchment, Gowrie Creek at Abergowrie (116008B), Herbert River Ingham (116001F) and Stone River Running (1160127). Source: Water Monitoring Information Portal (State of Queensland 2023a)

The relationship between rainfall and in-stream nitrate concentration is complex (Saavedra et al. 2022). From the observed data, timing of rainfall and where it falls within the catchment can yield different results depending on the time of year. This can be further complicated by on-ground activity. Landholders will have insights about what was happening in the catchment prior to rises in NO_3-N concentrations. Although run-off of fertiliser is the most likely source of nitrate in a cropping landscape, other sources are also possible (e.g. septic systems, livestock, urban contributions).

The typical way to visualise and interpret concentration data over time is to overlay them on a hydrograph, where the relationship between nitrate concentration and river level becomes evident. As mentioned above, this relationship can vary over time. Early in the wet season the expectation is that large rain events drive increases in both river levels and NO_3-N concentrations. By the end of the wet season, when NO_3-N inputs are exhausted, rain events may have a dilution effect on NO_3-N concentrations (Figure 5).

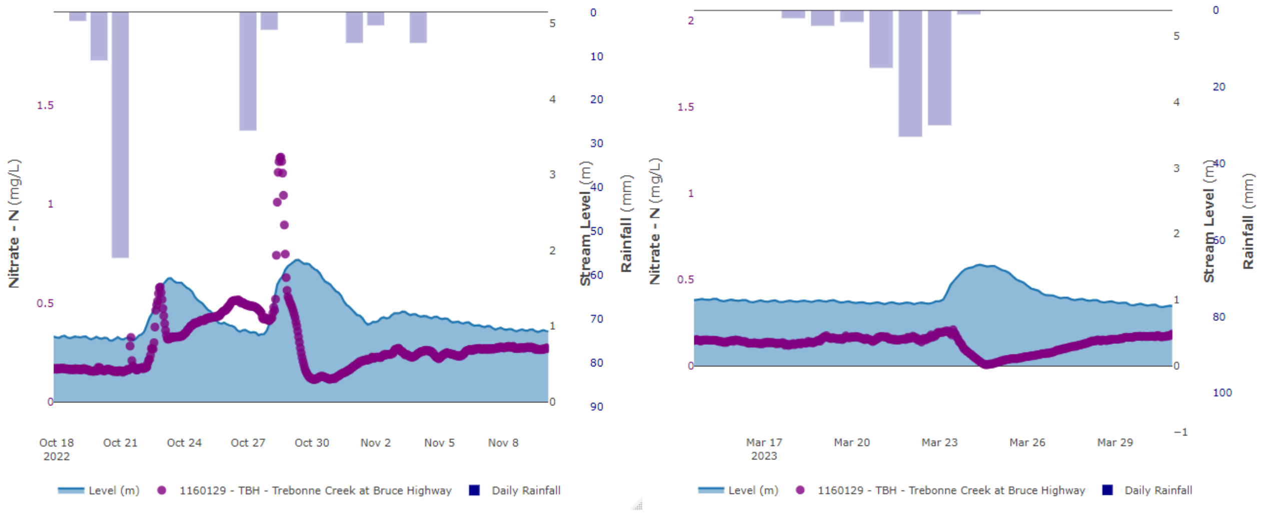

Figure 5. Hydrographs showing an event at the start of the wet season (left) against an event toward the end of the wet season (right). Please note the rainfall axis is inverted.

Monitoring Sites and Results

Site placements in the Lower Herbert monitoring network allow comparison between sites located on the same waterway. The hydrologic connectivity of the sites is mostly unimpeded, with the exception being tidal gates (Catherina Creek, Ripple Creek) and weirs (Lagoon Creek) located at the outflows to the lower estuaries. It is also important to note the differences in dilution between major river systems such as the Herbert River and smaller creeks and tributaries (Weaver et al. 2001). Because the Herbert River discharge profile is characterised by short duration discharge events yielding large concentrations of dissolved or particulate contaminants, sampling this system is difficult utilising traditional sampling methods (discrete grab samples). The continuous monitoring systems implemented in this project allow for the high frequency capture and quantification of data throughout these events.

Not all sites have paired comparative sites, which makes interpreting the catchment story incomplete in some areas. Where appropriate, comparisons have been made between sites along the same system to quantify differences observed between upstream land use. Also, not all sites have been online for the same duration and comparisons relied on the best available data. Figure 6 shows the distribution of NO_3-N concentrations collected at each site from installation (between December 2020 & June 2021) to September 2023. Sites have been arranged in descending order by median concentration.

Ordering the sites by median concentration, the reference sites have clustered at the base of the graph. This is consistent with the expectation that sites with fewer anthropogenic influences yield lower concentrations of nitrate. Notably, Palm Creek at Bosworths Road and Ripple Creek at Seymour Gates also demonstrate lower median concentration. Both systems include wetland areas that may be aiding denitrification processes. Unlike the Palm and Ripple Creek sites, Catherina Creek at Catherina Creek Road is situated on the upstream fringe of a wetland ecosystem and does not tend to return to the lower median concentration.

Catherina Creek at Catherina Creek Road site shows the highest peak concentrations, exceeding the NIWA guideline of 2.4 mg/L. Ripple Creek Seymore Gates and Lannercost Creek at Lannercost Ext Road also exceed the NIWA guideline during event conditions. Notably, the two sites along Waterview creek are at opposite ends of the chart (Figure 6). They are separated by approximately 11 km of creek and with extensive sugarcane cropping above the end-of-system site at Mammarellas Road.

Several of the impact and end-of-system sites exceed the WQO for the Herbert River for much of the year, whereas the reference sites rarely exceed the WQO during event flows.

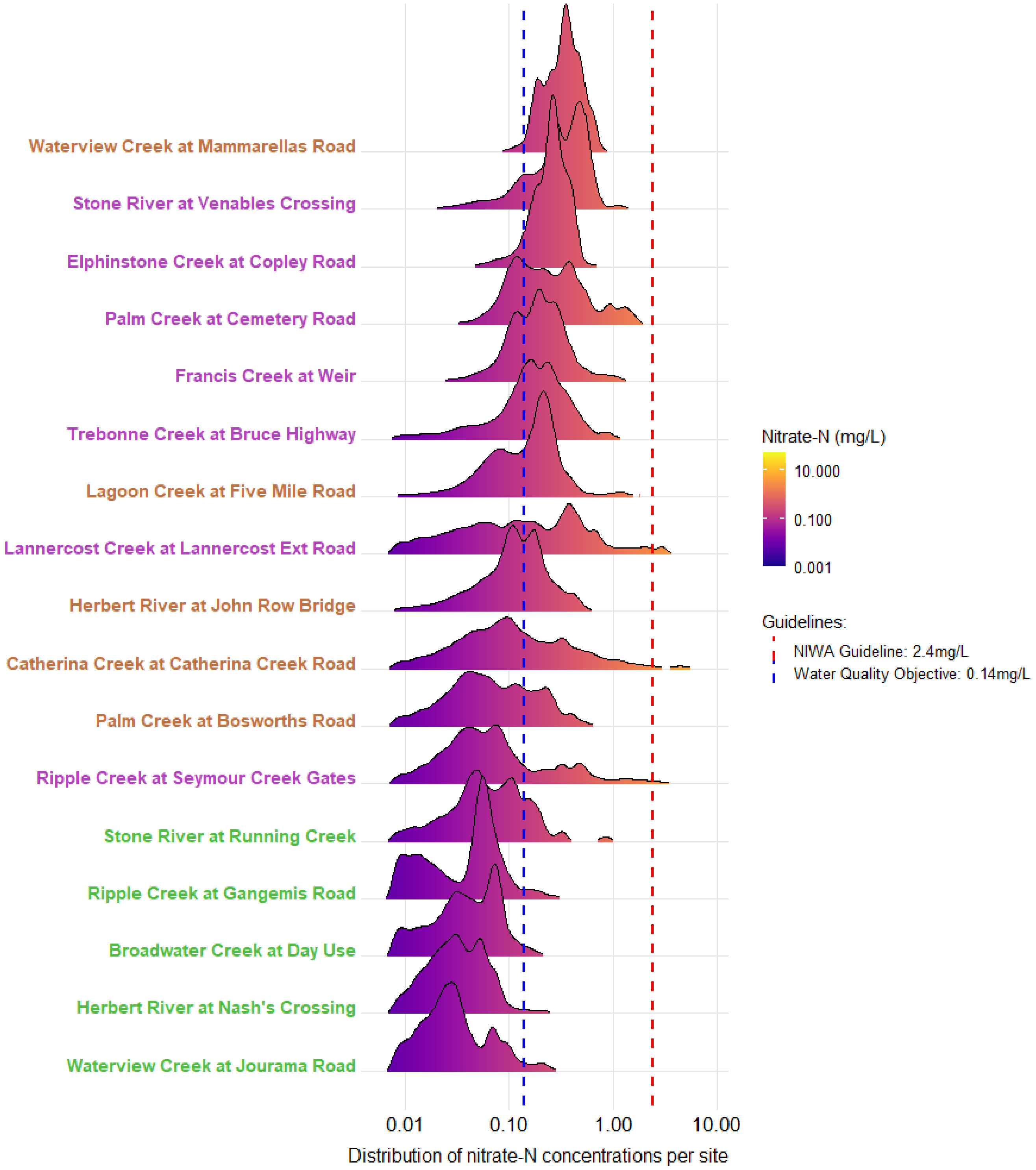

Figure 6. Ridgeline plot showing the distribution of nitrate concentrations observed in the Herbert catchment. The sites listed in descending order based on the median nitrate concentration. Text colour of site labels on the x axis denote the site type: ***reference****,* ***impact,*** *and* ***end-of-system****. NIWA toxicity guideline adopted from NIWA (2014) and Hickey (2013).*

Broadwater Creek at Day Use Area

The Broadwater Creek at Day Use Area (BCD) site was installed in May 2021 and is situated within the Abergowrie State Forest. It was selected as a reference site for the northwest Lower Herbert catchment as it captures predominantly runoff from conservation land use. There is some forestry adjacent to the site; however, reduced access and likelihood of no flows higher in the catchment meant that this location was the most suitable location. The site is downstream of a popular recreational swimming area but there has been no interference with the equipment to date.

Due to the angle of the stream bank, the placement of the probe in the cross section is relatively high at base flow levels. Consequently, there are periods of time when the probe is ‘out of water’ resulting in data-gaps. There are also periods of time when the nitrate concentrations are below the limit of reporting of the installed probe (5 mm path length, Table 1). On the CSIRO public platform 1622wq, these periods appear blank or are flagged as ‘no data’. Although much of the data collected at this site fall below the probe limit (<0.06 mg/L of NO_3-N for a 5 mm Opus) the data are included in Figure 8.

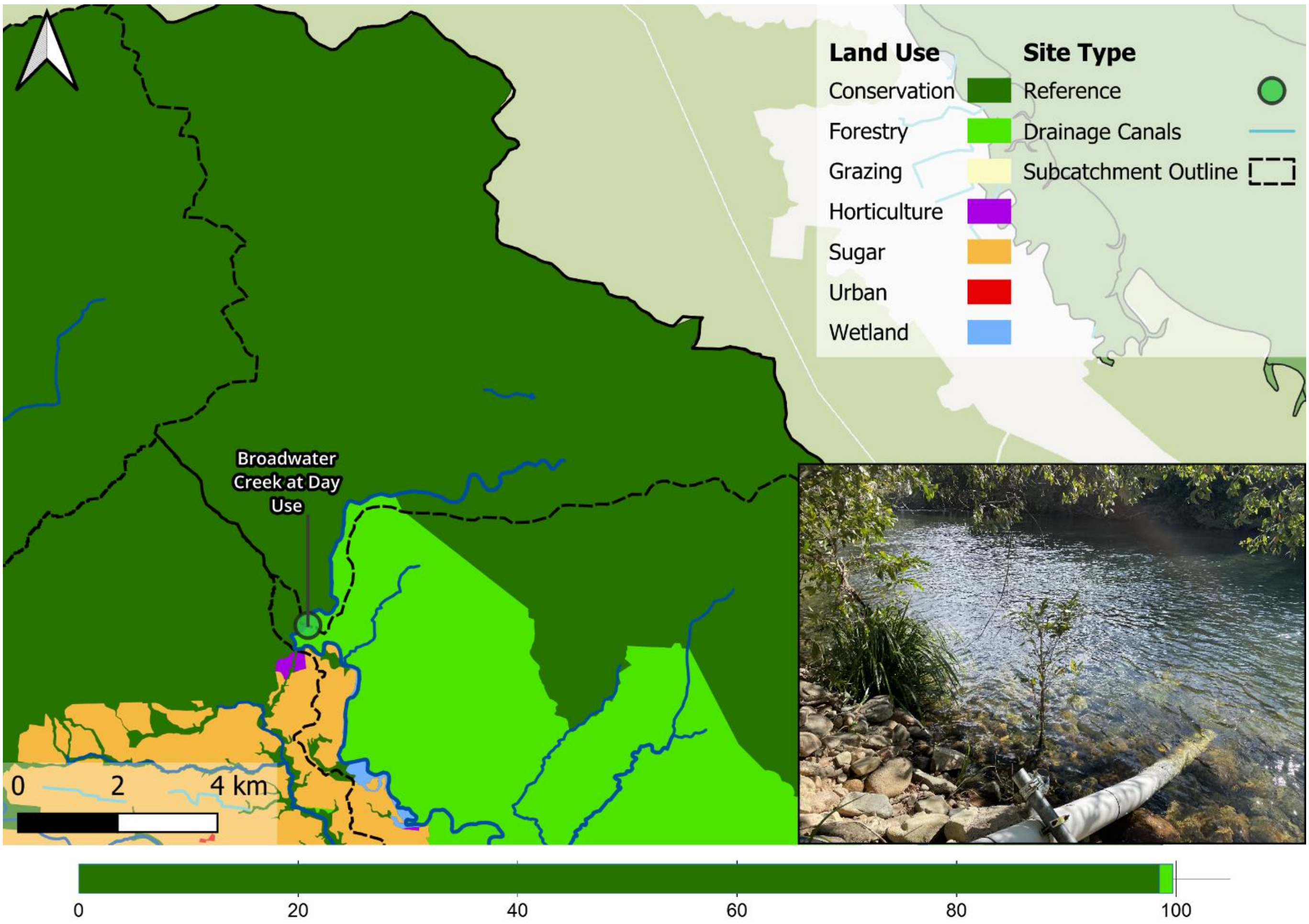

Figure 7. Sub-catchment land use for Broadwater Creek at Day Use Area (BCD). Map shows the distribution of land use types in the sub-catchment while the bar chart (bottom) shows the proportional contributions. Photo (bottom right) shows probe placement in the stream.

Data capture across the monitoring period (June 21 – February 2024) has been good, with a notable decrease in reportable data points across the lower concentration ranges. The first two months of observations (June and July 2021) presented the highest *median* concentrations and number of observations as shown on Figure 8. Without splitting the data into categories for high-flow and low-flow conditions, comparison to WQOs is open to some interpretation as both flow conditions will have occurred each month. Keeping in mind that these values are considered the desired state of the ecosystem, not a reflection of risk. Monthly median values at Broadwater Creek are all well below the WQO (0.14 mg/L).

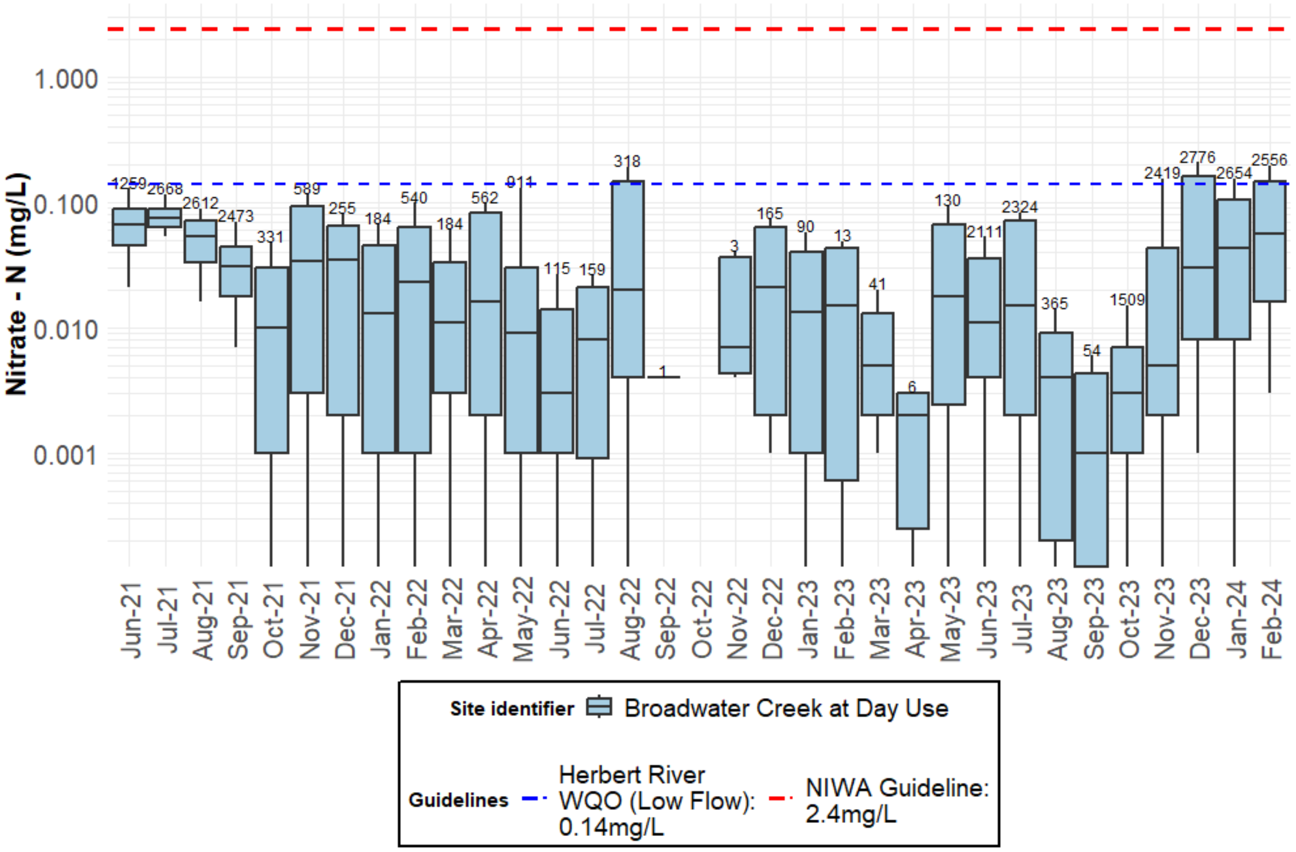

Figure 8. Box and whisker plot showing the monthly distribution of NO_3-N over time for Broadwater Creek at Day use area. Please note custom delineations have been utilised for the box and whisker plots showing ***minimum, 5th percentile, median, 95th percentile and maximum values*** *per month. The number at the top of each whisker represents number of reportable observations. NIWA toxicity guideline adopted from NIWA (2014) and Hickey (2013).*

Localised rainfall appears to be the primary driver for nitrate response in Broadwater Creek. Throughout the monitoring period, nitrate concentration has fluctuated in response to rainfall events. Following rainfall, and the subsequent rise in N levels, the concentrations fall, sometimes to below the limits of the probe resulting in periods of ‘no data’. Consistent rainfall through June and July 2023 have resulted in a high-quality NO_3-N trace as seen in Figure 9. This shows much of the NO_3-N flux is in response to rainfall inputs.

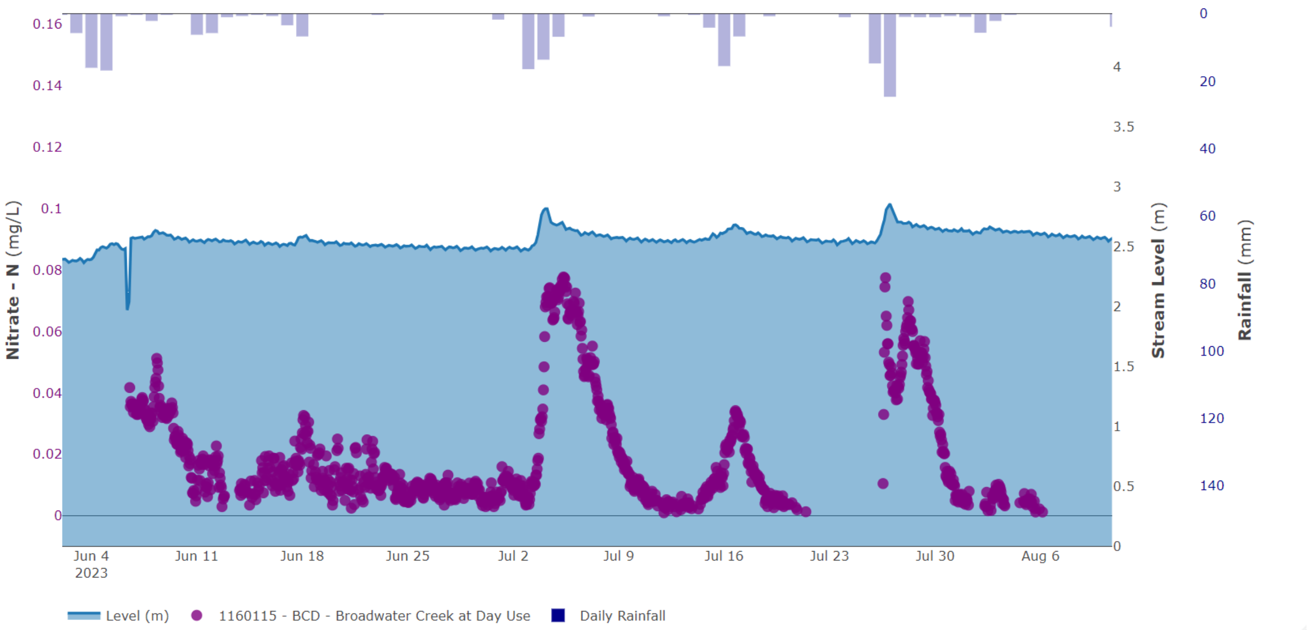

Figure 9. Hydrograph showing NO_3-N response in Broadwater Creek at Day use area against rainfall. Rainfall data has been extracted from SILO for the gridded area encompassing the site.

Catherina Creek at Catherina Creek Road

The Catherina Creek at Catherina Creek Road site is situated northeast of the Ingham township. Catherina Creek joins the Herbert River downstream of the Herbert River at John Row Bridge end-of-system site. Sugarcane is the dominant land use in this sub-catchment (Figure 10); however, urban influence from the Ingham township likely also contributes nutrients to the waterway. There is also a quarry operating in the immediate vicinity; however, its impacts are typically linked to elevated suspended sediment concentration rather than nitrate inputs.

The outflow of this site to the Herbert River is controlled by a tidal gate to minimise the saltwater intrusion into the system. This site is located on the upstream limit of a palustrine wetland ecosystem. Palustrine wetlands in this context are defined as vegetated water bodies. These ecosystem types can act as natural filters helping denitrification processes.

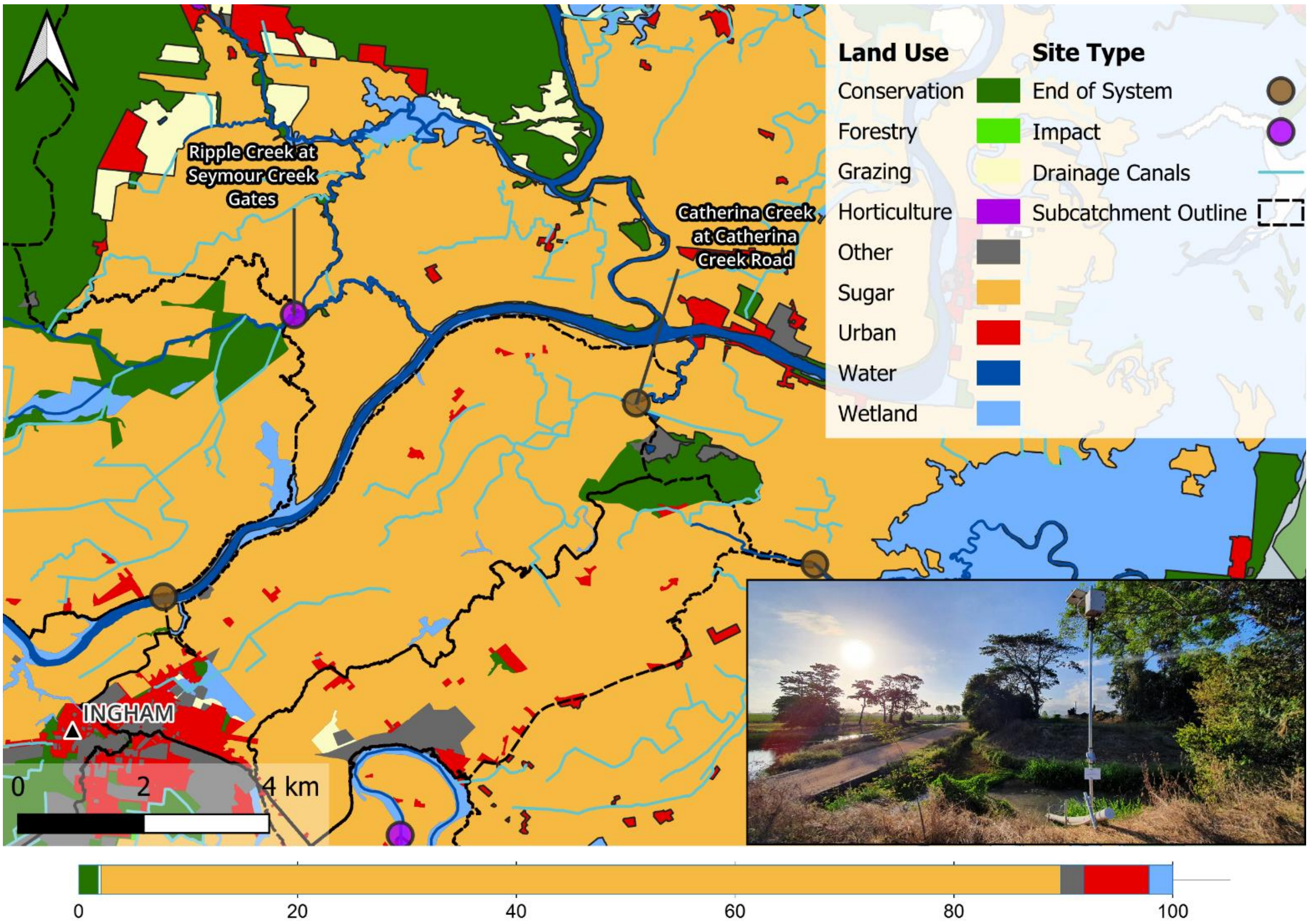

Figure 10. Sub-catchment land use for Catherina Creek at Catherina Creek Road. Map shows the distribution of land use types in the sub-catchment while the bar chart (bottom) shows the proportional contributions. Photo (bottom right) shows probe placement in the stream.

This system performs in line with expected catchment dynamics; i.e., increased flow conditions result in increased concentrations of nutrients. Therefore, the wet season (October – April) represents a period of increased risk with respect to nutrients. This seasonality in monthly concentration is evident in Figure 11. This has been the pattern since installation in December of 2020 when concentrations above the NIWA toxicity guideline of 2.4 mg/L were observed. This was repeated in December 2021 and December 2023. Wet season medians generally exceed the WQO, whereas dry season median concentrations rarely exceed the WQO (0.14 mg/L).

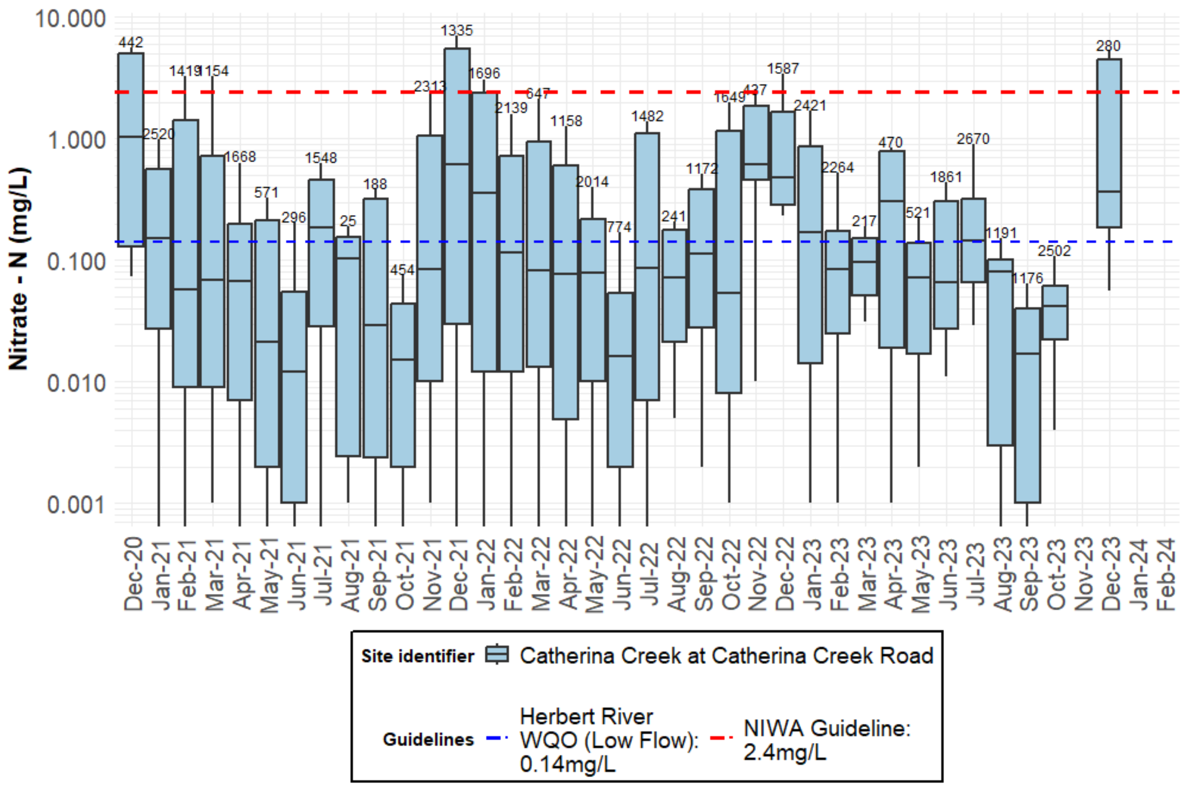

*Figure 11. Box and whisker plot showing the monthly distribution of NO_3-N over time for Catherina Creek at Catherina Creek Road. Please note custom delineations have utilised for the box and whisker plots showing **minimum, 5th percentile, median, 95th percentile and maximum** values per month. The number at the top of each whisker represents number of observations. NIWA toxicity guideline adopted from NIWA (2014) and Hickey (2013).*

The varied response to rainfall can be viewed over the course of the 2021-22 wet season (Figure 12). The event in January of 2022 shows the highest concentrations (6.9 mg/L of NO_3-N) measured at the site over the three years. Over the same period of time, manual grab sampling for analysis of oxidised nitrogen was performed to provide validation data for the probes and those data are in close agreement with the probe; however, this dedicated manual sampling regime completely missed the event. It provides an example of the enhanced understanding that continuous monitoring can provide. These probes provide an improved resolution over even the most dedicated manual sampling program.

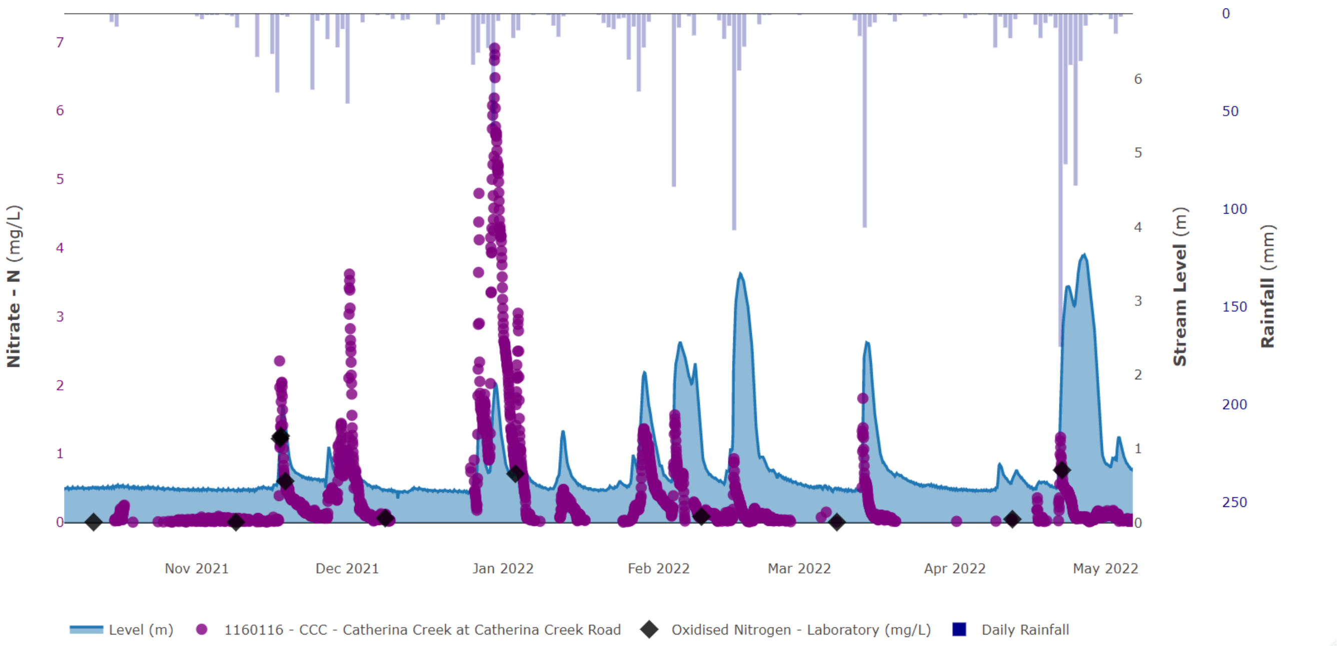

Figure 12. Hydrograph showing the response in NO_3-N water level and rainfall at Catherina Creek. Please note the rainfall axis has been inverted to reduce overlapping data points.

Elphinstone Creek at Copley Road

Elphinstone Creek at Copley Road is an impact site that captures an almost even split of sugarcane land use and conservation (Figure 13). Riparian vegetation in the area adjacent to the equipment is higher than typical in this region, with Figure 13 showing some riparian buffer primarily on the northern upstream branch. The creek adjoins the Herbert River main channel downstream. The monitoring equipment is situated downstream of a culvert in a standing pool and remains submerged in the water for most of the year, even during dry periods.

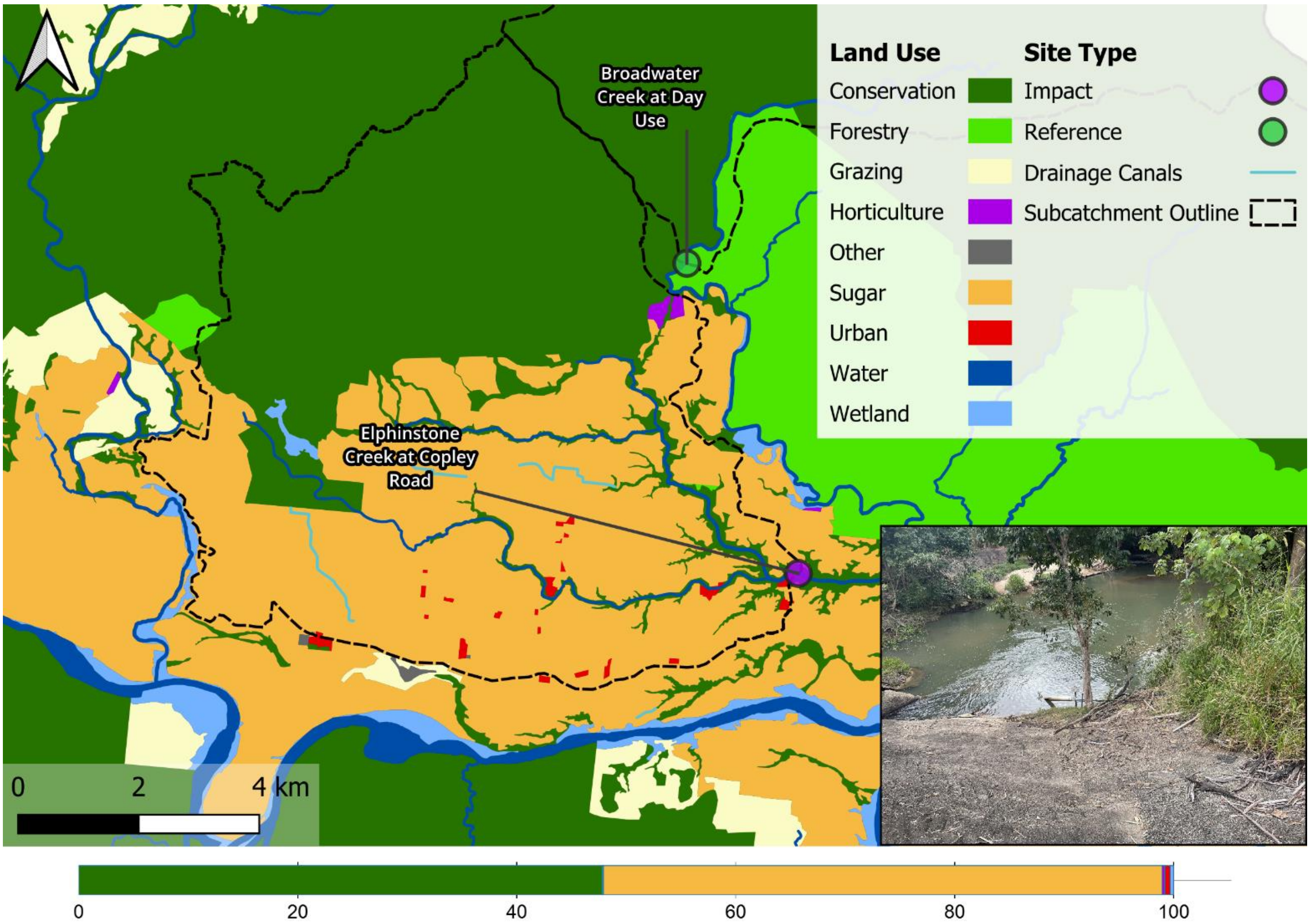

Figure 13. Sub-catchment land use for Elphinstone Creek at Copley Road. Map shows the distribution of land use types in the sub-catchment while the bar chart (bottom) shows the proportional contributions. Photo (bottom right) shows probe placement in the stream.

The site was inundated in December of 2021 during a large stream flow event resulting in damage to the on-bank electronics and infrastructure. Equipment and logistical constraints meant the site could not be re-installed until July 2021, resulting in a substantial data gap (Figure 14). The electrical components were moved to an elevated location closer to the road.

The median concentrations remain above the WQO at all times of the year (Figure 14). There is some seasonality in the data that indicates that there is less variability in the range of the data during dry periods (April – August). Peak concentrations are evident through the wet season; i.e. in October 2022 peak concentration of 1.6 mg/L were evident over the first flush. First flush can be defined as the first day after July 1 of each year when stream flow and/or height is increased coupled with a subsequent increase in nitrate concentrations.

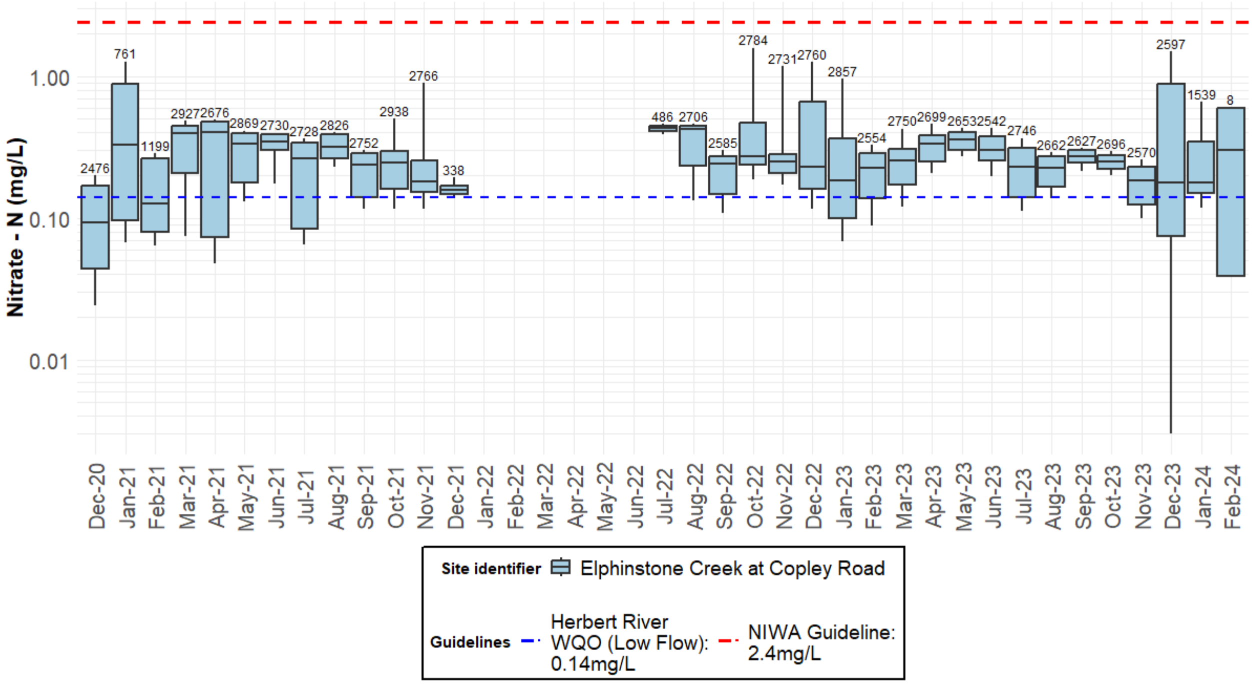

*Figure 14. Box and whisker plot showing the monthly distribution of NO$_3$-N over time for Elphinstone Creek at Copley Road. Please note custom delineations have utilised for the box and whisker plots showing **minimum, 5th percentile, median, 95th percentile and maximum** values per month. Number at the top of each whisker represents number of observations. NIWA toxicity guideline adopted from NIWA (2014) and Hickey (2013).*

The high-resolution time series data collected at this site in the first half of 2023 is shown in Figure 15. In January of 2023, elevated concentrations are seen across the hydrograph associated with rainfall events. Subsequent events, however, result in dilution, with a rebound in concentration values after the events. The event on March 26, 2023 clearly demonstrates how concentrations are diluted, then steadily climb back to a baseline nitrate concentration. This may indicate a groundwater fed baseflow in this system, where inputs from groundwater have higher nitrate concentrations than those from surface waters (Wherry et al. 2021).

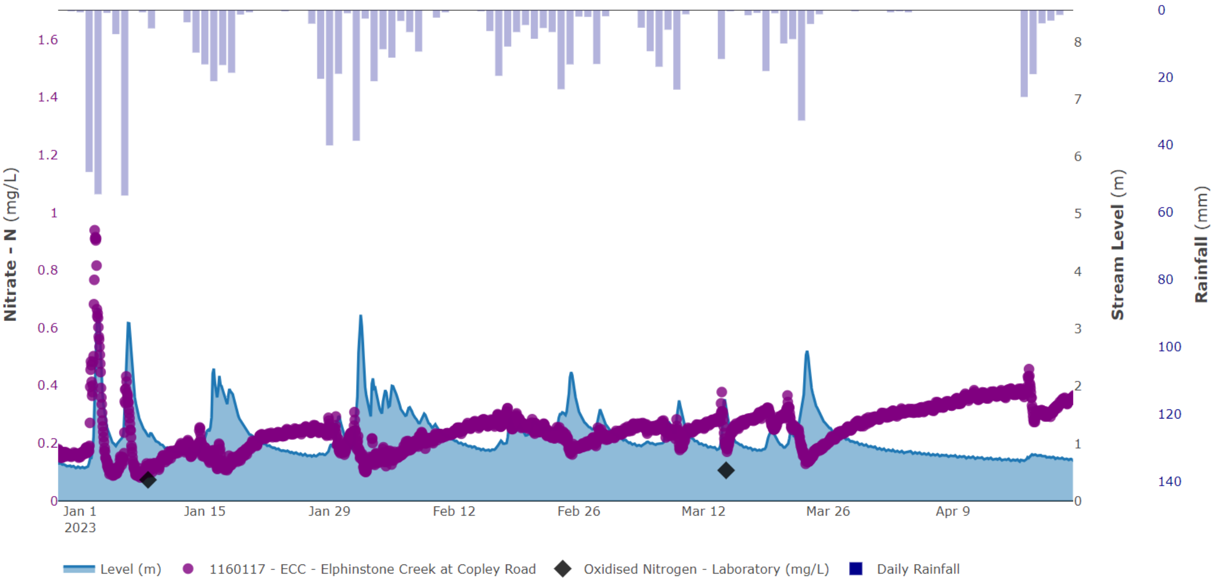

Figure 15. Hydrograph showing the response in NO$_3$-N to water level and rainfall. Please note the rainfall axis has been inverted to reduce overlapping data points.

Francis Creek at Weir

The Francis Creek at Weir site is situated south of Ingham adjacent to the Bruce Highway. Francis Creek flows into Cattle Creek downstream before discharging via a network of wetlands to the GBR lagoon. Cattle Creek has some connectivity with Trebonne Creek downstream of both respective monitoring sites. The Francis Creek site captures a large portion of conservation area with a mix of sugar and grazing. The grazing portion was the driving factor in site selection as it provides an example of a more grazing dominated (ignoring the conservation) sub-catchment.

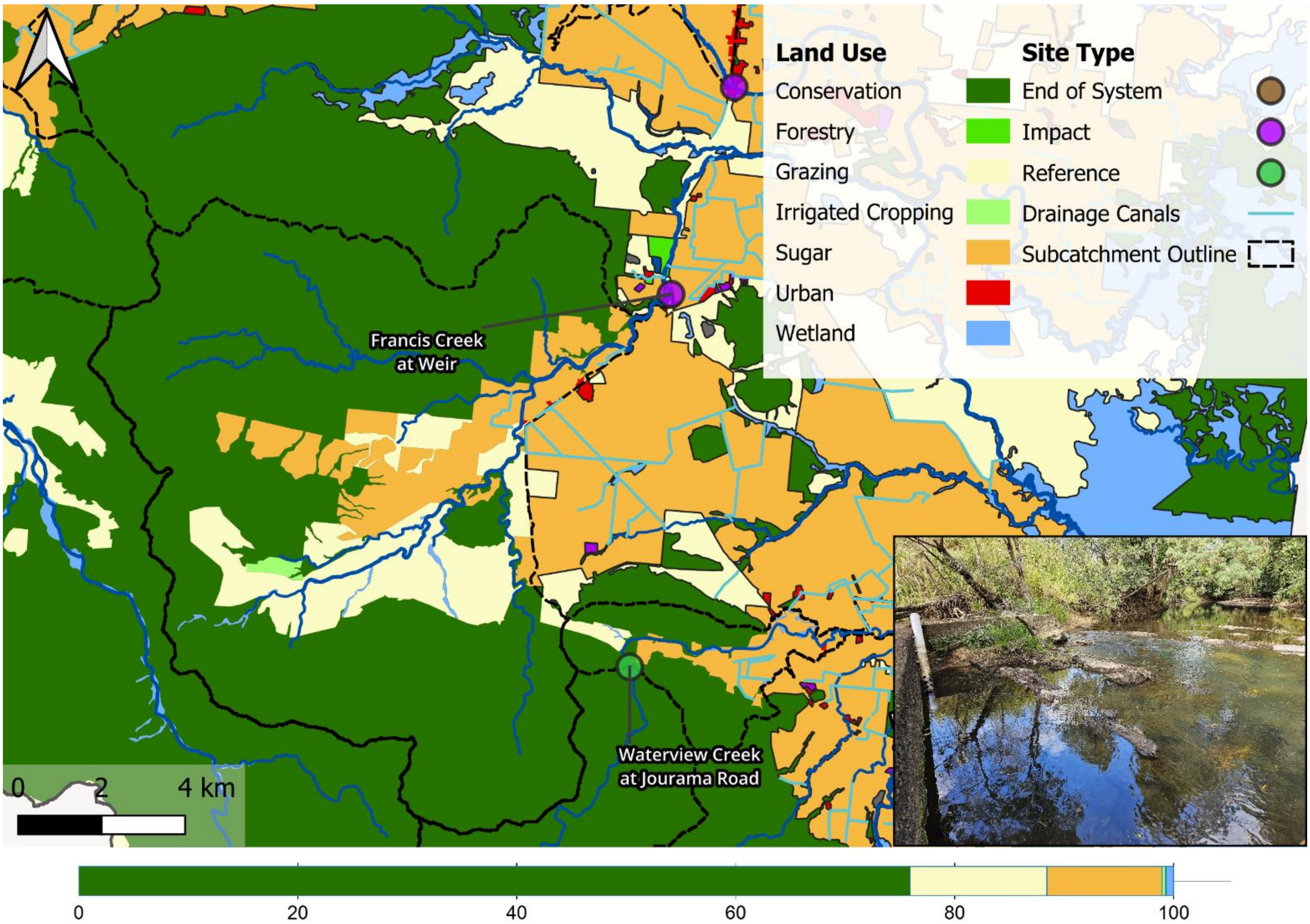

Figure 16. Sub-catchment land use for Francis Creek at Weir. Map shows the distribution of land use types in the sub-catchment while the bar chart (bottom) shows the proportional contributions. Photo (bottom right) looking upstream shows the in-stream placement of the probe.

The data captured at this site has been sparse (Figure 17) because of the intermittent nature of the system and the location of the probe in the creek. Install constraints meant that the probe was attached to the concrete weir (Figure 16). Consequently, the site only captures data when flow is high enough to overflow the weir-pool. The site has also suffered some technical failures that have resulted in further data gaps.

From the data captured, primarily during event flows, the concentrations routinely exceeded the WQO, and at times, the toxicity guideline. For the 2022–23 wet season, the time series data showed a clear rainfall-runoff response in stream from November to February (Figure 18), after which the event concentrations become less pronounced, likely due to exhaustion of input sources.

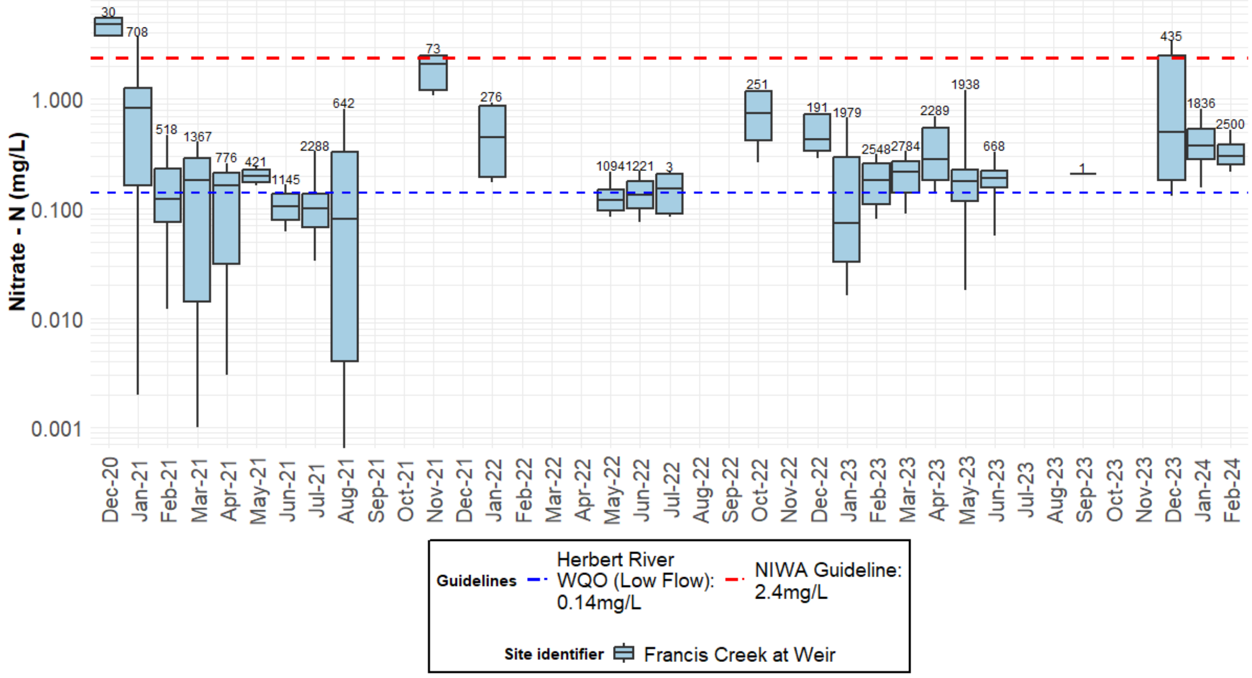

*Figure 17. Box and whisker plot showing the monthly distribution of NO_3-N over time for Francis Creek at Weir. Please note custom delineations have been utilised for the box and whisker plots showing **minimum, 5th percentile, median, 95th percentile and maximum** values per month. Number at the top of each whisker represents number of observations. NIWA toxicity guideline adopted from NIWA (2014) and Hickey (2013).*

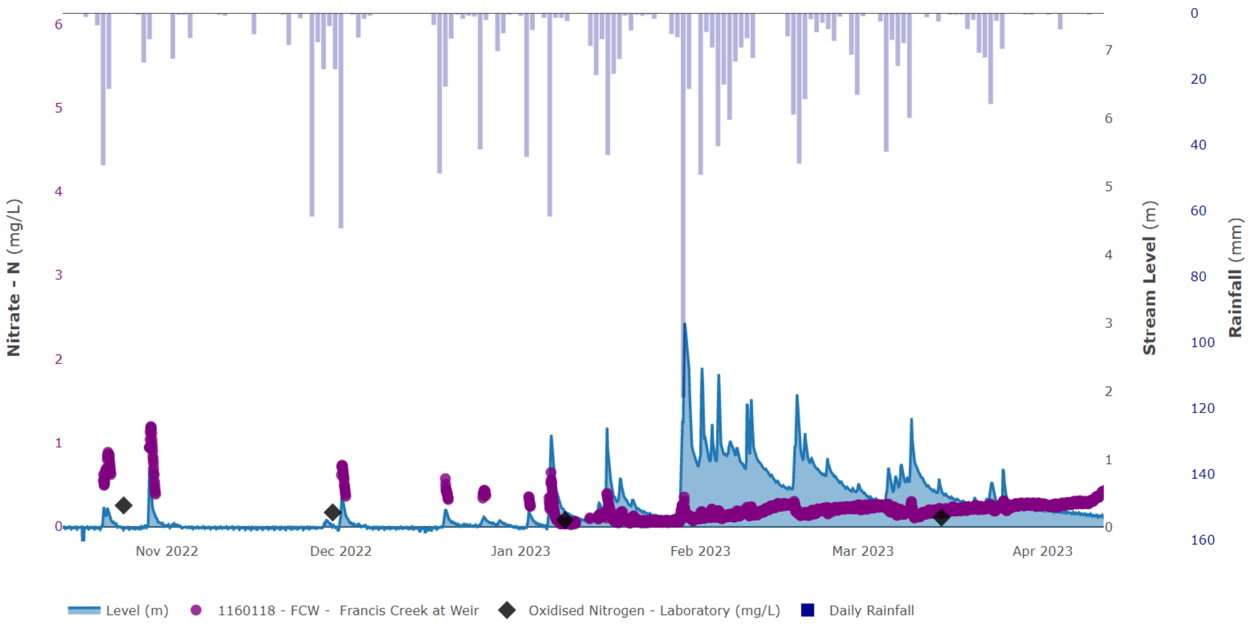

Figure 18. Hydrograph showing the response in NO_3-N to water level and rainfall. Please note the rainfall axis has been inverted to reduce overlapping data points.

Trebonne Creek at Bruce Highway

Trebonne Creek at Bruce Highway is situated south of Ingham and downstream of the Bruce Highway at the Toobanna locality. Land use primarily consists of sugarcane with portions of urban, grazing and conservation (Figure 19). This site was installed in November 2020 and has captured nearly three full wet seasons. It is one of the few sites to capture the entirety of the monitoring period albeit with some water-level sensor failures.

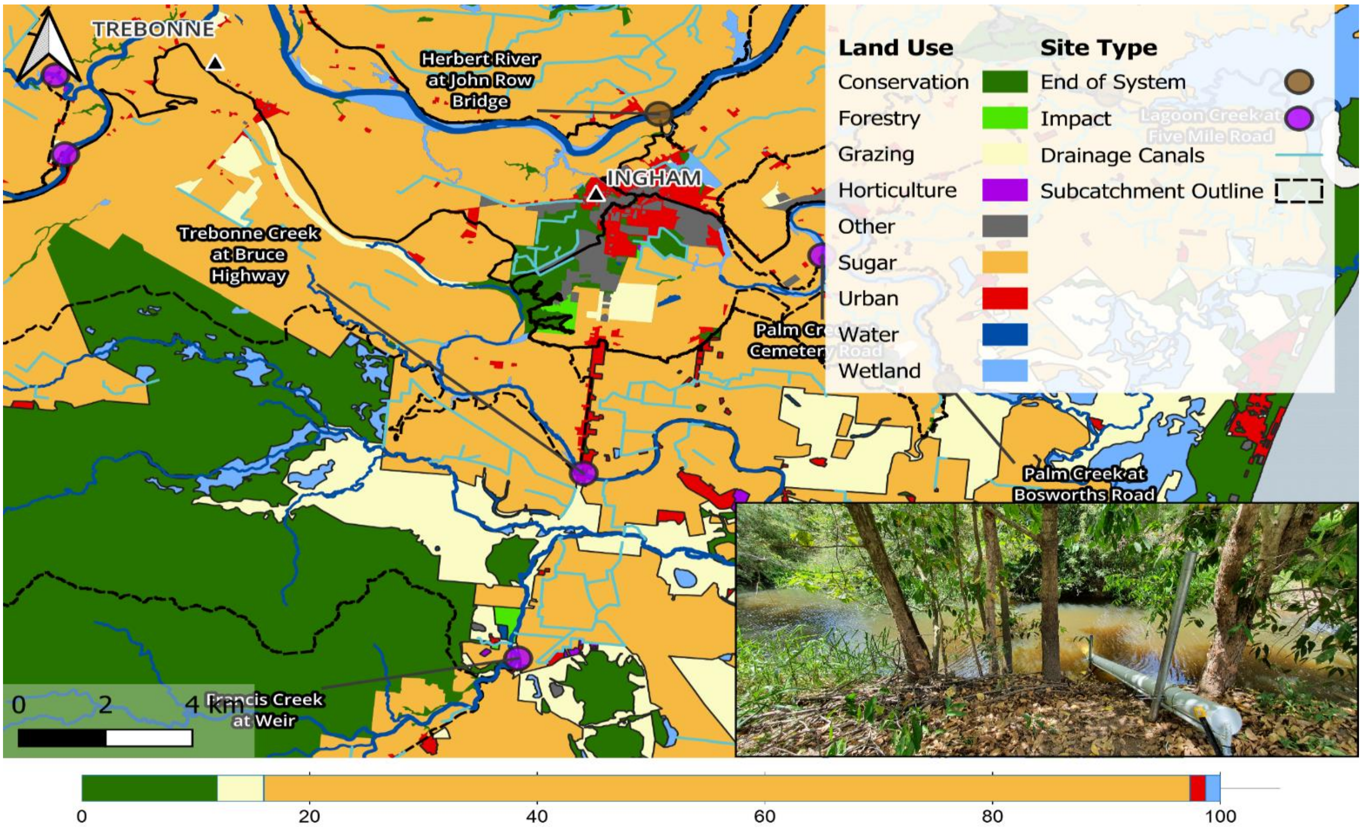

Figure 19. Sub-catchment land use for Trebonne Creek at Bruce Highway. Map shows the distribution of land use types in the sub-catchment while the bar chart (bottom) shows the proportional contributions. Photo (bottom right) shows the in-stream placement of the probe.

The monthly data at Trebonne demonstrate a distinct seasonality compared with other sites in the region (Figure 20). There exists a clear demarcation for the start of the wet season in December 2020, 2021 and 2022 with elevated concentrations likely driven from first flush events. The 2022 dry season was less pronounced than the previous or subsequent year (Figure 4) and as a consequence, nitrate concentrations did not drop as low as they did towards the end of the 2021 and 2023 dry seasons. Apart from those two dry season periods, nitrate concentrations (medians) have consistently exceeded the WQO throughout the three-year monitoring period (Figure 20).

As is the case at other sites in the network (e.g. Elphinstone Creek at Copley Road – see above), groundwater is likely an important source of nitrate that maintains a baseline concentration for most of the year, up to the late dry season when connectivity with surface water is broken. The comparatively low nitrate concentrations evident during the dry season months of October 2021 and September 2023, strongly suggest that groundwater is not an important source of nitrate in Trebonne Creek at that time late in the dry season. Local bore level data support this contention. The Blackrock bore is situated 4.7 km to the northeast of our site. Data from the Blackrock bore, extracted from the Queensland Government Water Monitoring Information Portal (WMIP), were compared to the Trebonne monitoring site water level data. The two sets of data were normalised (scaled between 0 and 1) to improve comparability across the different reference datums and presented in Figure 21. Over the relevant time-period, bore levels were very low during October 2021 and September 2023. This aligns well with the periods of concentration decline indicated in Figure 20. Noting that levels remained high at Blackrock from December 2022 to April 2023, the two datasets indicate a degree of surface water groundwater connectivity that likely dictates the surface water concentrations and base load of nitrate delivered by these systems.

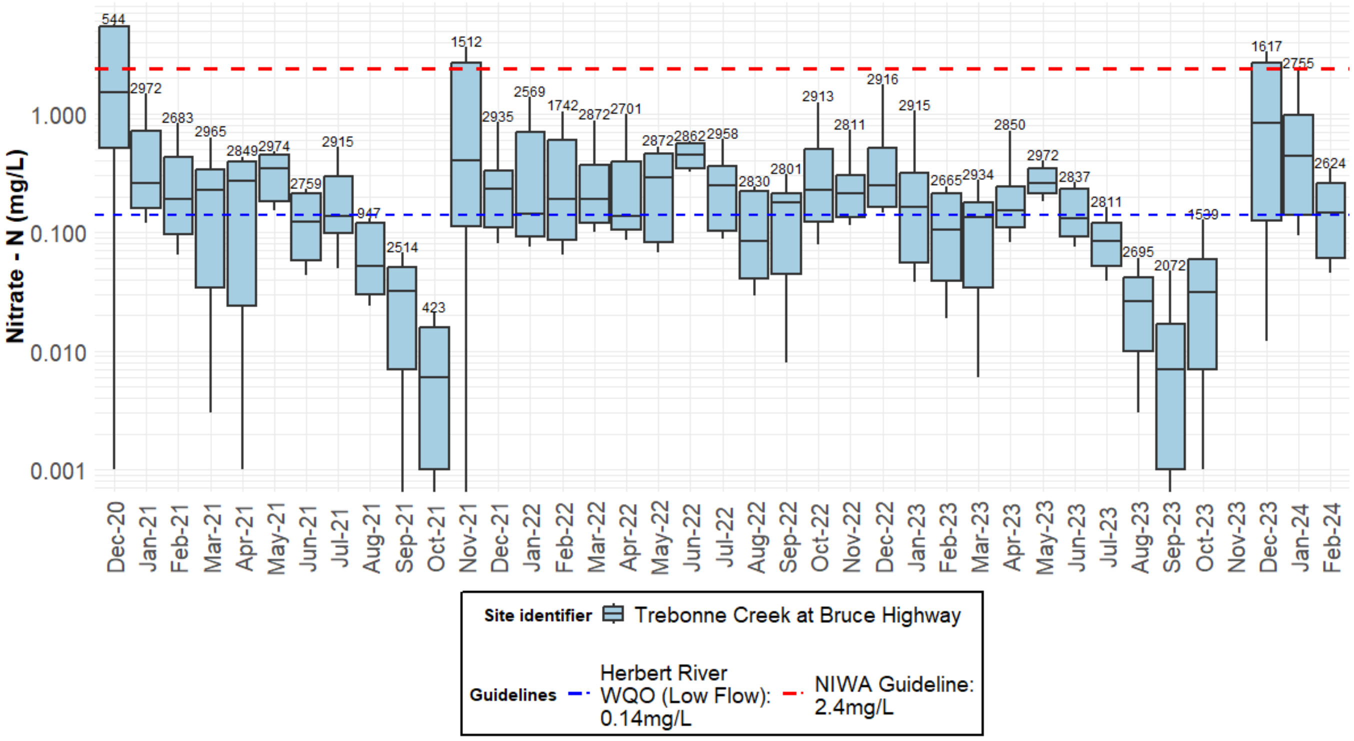

*Figure 20. Box and whisker plot showing the monthly distribution of NO_3-N over time. Please note custom delineations have been utilised for the box and whisker plots showing **minimum, 5th percentile, median, 95th percentile and maximum** values per month. Number at the top of each whisker represents number of observations. NIWA toxicity guideline adopted from NIWA (2014) and Hickey (2013).*

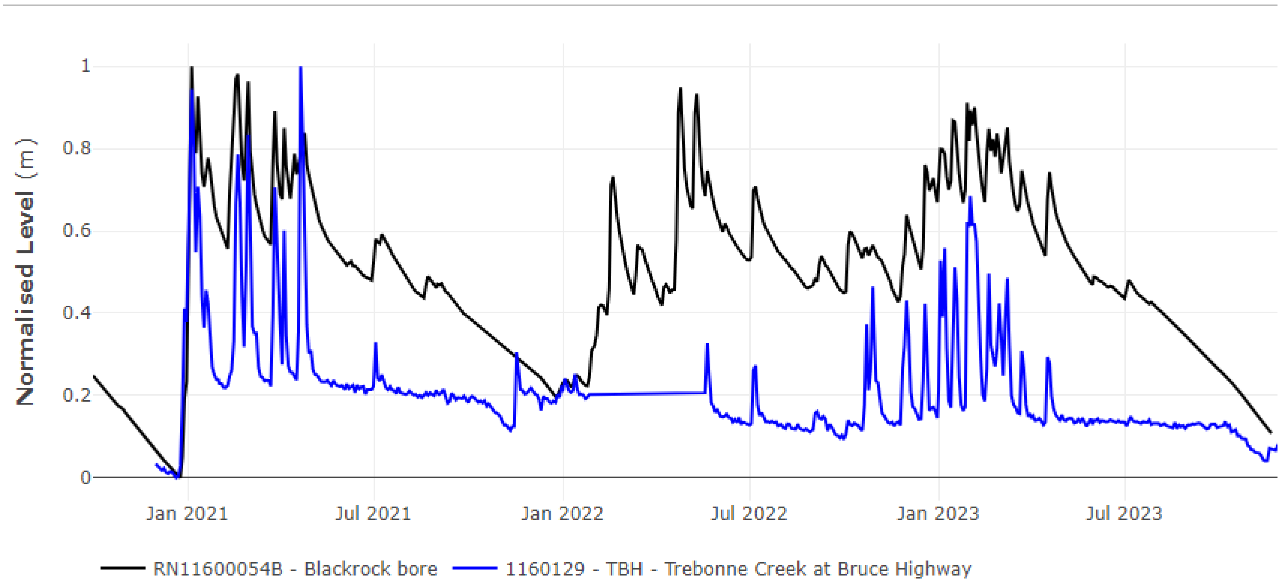

Figure 21. Normalised level data from the Blackrock monitoring bore (RN11600054B) and Trebonne Creek at Bruce Highway surface water site (1160129). Data is collected on different height datums (bore level = depth below surface and surface water level = water height above sensor). A scaler has been applied to each dataset to improve comparability.

Palm Creek

Two sites have been installed along Palm Creek. One is an end-of-system site at Bosworths Road, and the other is an Impact site at Cemetery Road upstream of the Victoria Sugar Mill. Land use for both sites is primarily sugar, with a smaller urban contribution from Ingham township upstream. At the Cemetery Road site, the creek is classified as a hydrologically modified riverine wetland, whereas at the downstream Bosworth Road, the creek is listed as a palustrine wetland hosting aquatic plants depending on the time of year. The system discharges to the ocean via a complicated network of low-lying wetlands.

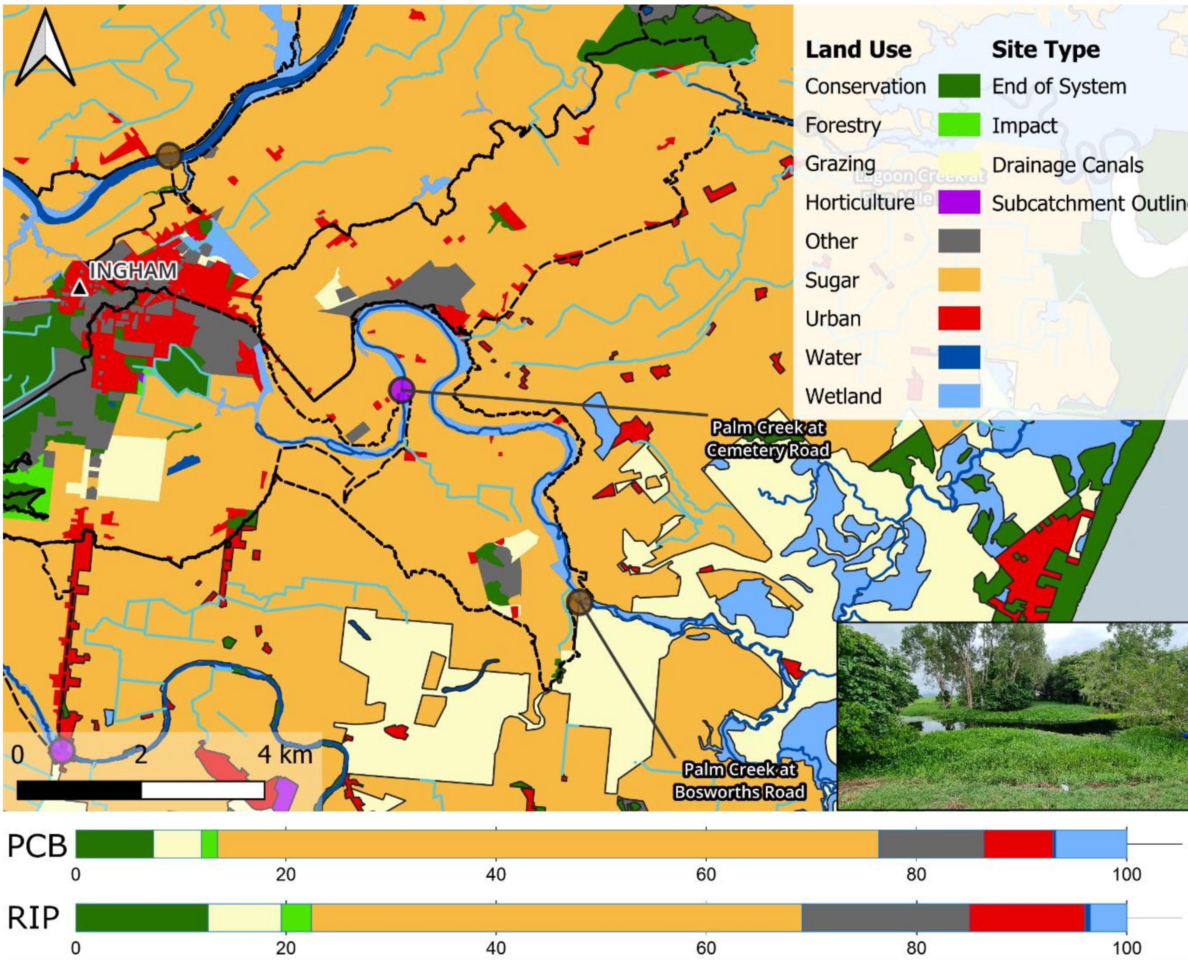

Figure 22. Sub-catchment land use for Palm Creek at Bosworths Road (PCB) and Palm Creek at Cemetery Road (RIP). Map shows the distribution of land use types in the sub-catchment while the bar chart (bottom) shows the proportional contributions. Photo (bottom right) shows the stream at the Palm Creek at Bosworth Road site.

The concentration data produced from the Palm Creek sites showed the upstream site to yield greater NO_3-N concentrations than downstream (Figure 23). The Cemetery Road location consistently exceeded the WQO and only dropped below the WQO in the late dry season in each of the three years. In contrast, at Palm Creek at Bosworths Road, dry season concentrations approached or decreased below the WQO (0.14 mg/L). This reduction in NO_3-N between sites might indicate denitrification processes are occurring while in transit between the two sites. This system hosts a large amount of aquatic vegetation and has a long-standing lagoon immediately downstream of the Cemetery Road site. Environmental conditions such as these with high residence times of nitrate in the system and abundant aquatic vegetation can facilitate improved denitrification processes (Bu et al. 2022; Soana et al. 2023).

Some seasonality was observed with NO_3-N concentrations declining most notably toward the end of the dry season (Oct 21/ Sept 22/ Sept 23) (Figure 23). This is comparable to trends observed in Trebonne Creek where there appears to be a relationship between the level of the groundwater table and the baseflow and baseline concentrations of NO_3-N in the system during the dry season. As is the case in many agricultural areas, elevated nitrate concentrations have been observed in groundwater sampled from bores in the Herbert River basin (see **Appendix C**). Much of the lower catchment geology consists of quaternary alluvium and lacustrine deposits. This is formed by riverine deposits over floodplains and is commonly associated with unconfined aquifers and surface water - groundwater connectivity.

From the data seen in Figure 21 and strong correlation to surface water level, the groundwater table in this region is shallow, with connectivity with the streams very likely. Further information on the groundwater – surface water interactions in alluvial systems can be found at the Queensland Governments Wetland*Info* page.

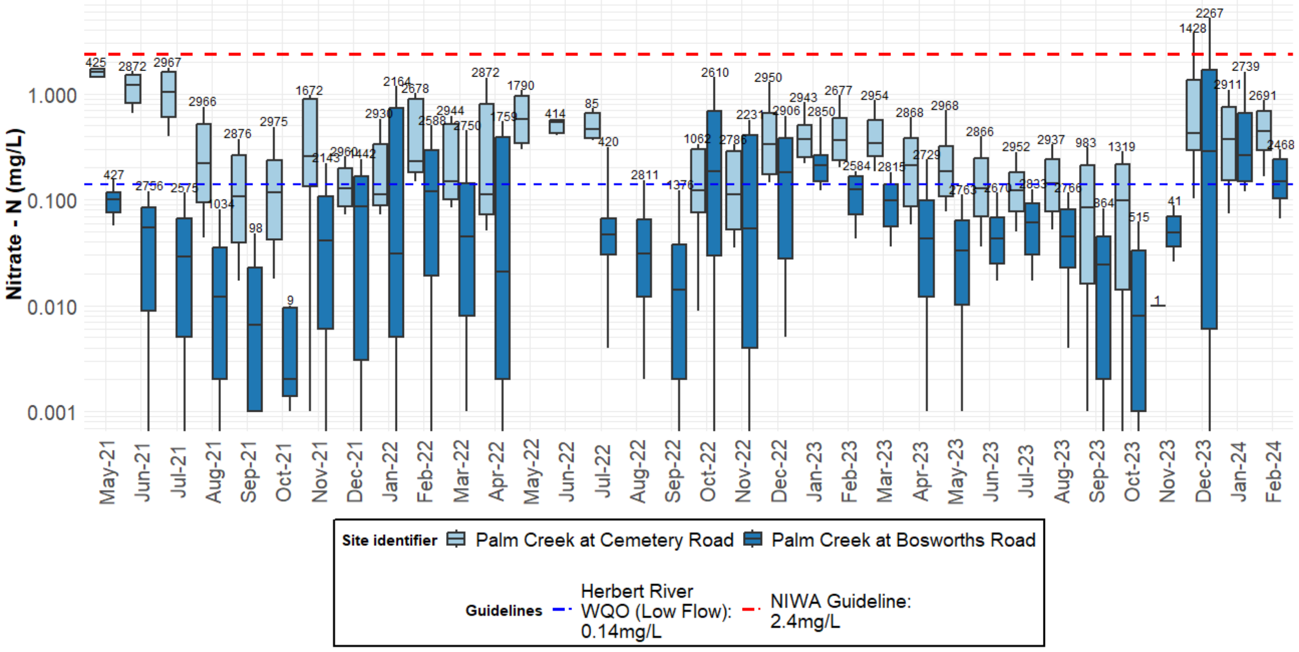

*Figure 23. Box and whisker plot showing the monthly distribution of NO_3-N over time. Please note custom delineations have been utilised for the box and whisker plots showing **minimum, 5th percentile, median, 95th percentile and maximum** values per month. Number at the top of each whisker represents number of observations. NIWA toxicity guideline adopted from NIWA (2014) and Hickey (2013).*

Using the available data for Blackrock bore extracted from the WMIP showed that in in October-November 2021 and October-November 2023, there was a reduction in groundwater level that is reflected in surface water level seen at the Palm Creek at Cemetery Road site (Figure 24). Figure 24 shows a notable correlation between surface water events and bore level. Considering the geology in this region and what is observed in the bore data, a highly connected and shallow aquifer is expected. A similar drop in surface water level was observed at the Palm Creek at Bosworth Road site, but the Cemetery Road site is upstream and geographically closer to the Blackrock bore than the Bosworths Road site (Figure 22). The maintenance of elevated nitrate concentrations in surface waters during the dry season appears to be dependent on the connectivity with nitrate-contaminated groundwater at many sites within the Lower Herbert. Bore water in this sub-catchment in the vicinity of the Palm Creek at Cemetery Road site displays relatively high nitrate concentrations (see Appendix C).

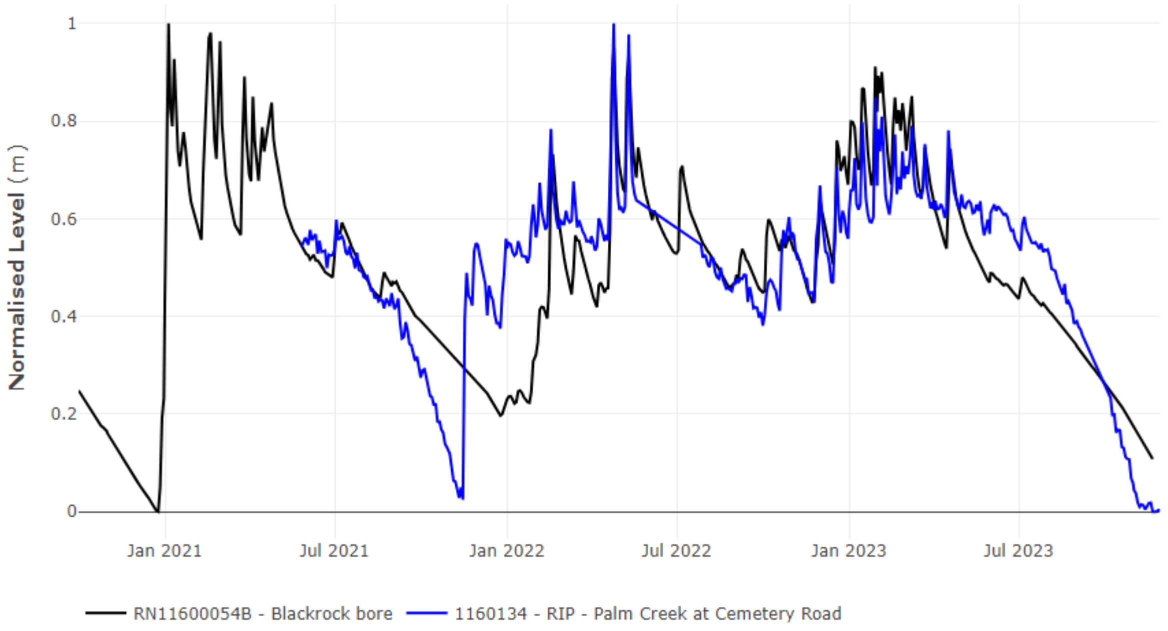

Figure 24. Normalised level data comparison for Blackrock monitoring bore (WMIP 2023) and Palm Creek at Cemetery Road surface water site. Data is collected on different height datums (bore level = depth below surface & surface water level = water height above sensor). A scaler has been applied to each dataset to improve comparability.

Lagoon Creek at Five Mile Road

The Lagoon Creek at Five Mile Road monitoring site is located south of the Herbert River and northeast of Ingham township. It is a small catchment capturing mainly sugarcane land use flowing into Victoria Creek before discharging to the GBR lagoon. The site is situated within a lagoon created by a rocky ford downstream that restricts saltwater intrusion from the estuary.

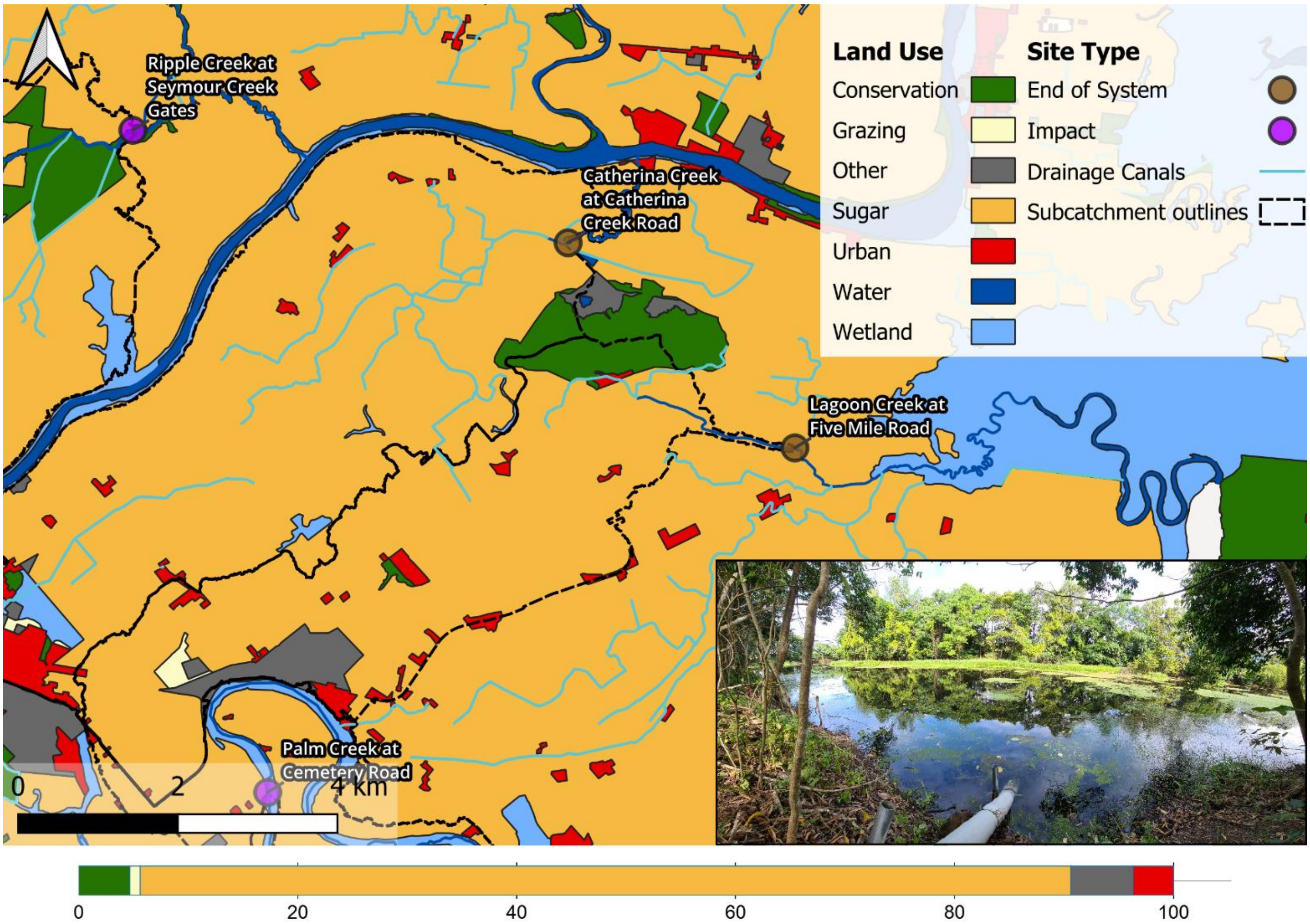

Figure 25. Sub-catchment land use for Lagoon Creek at Five Mile Road. Map (left) shows the distribution of land use types in the sub-catchment while the bar chart at the bottom shows the proportional contributions. Photo (bottom right) shows the in-stream placement of the probe.

Monthly median concentrations showed little variation in Lagoon Creek (Figure 26), except during July to October 2021. Compared to other sites, there were few reportable data to generate these box and whisker plots, which may be skewing the data. With few points to summarise monthly concentrations, data are easily skewed dependent on when a measurement was taken in relation to rainfall or flow conditions. Concentrations often exceeded the WQOs for both high and low flows throughout the year.

Elevated concentrations in May to June 2023 and on-site wiper issues prompted a maintenance visit to the site that identified decaying organic matter (dead bird) located within the river-end pipe infrastructure.

Unreasonably large concentrations (>10 mg/L) have been coded as BAD and excluded from this analysis as they are more representative of the local instrument interference (decaying organic matter caught in the housing) than representative of the system. There remains an elevated nitrate signature across this period likely attributable to the organic interference.

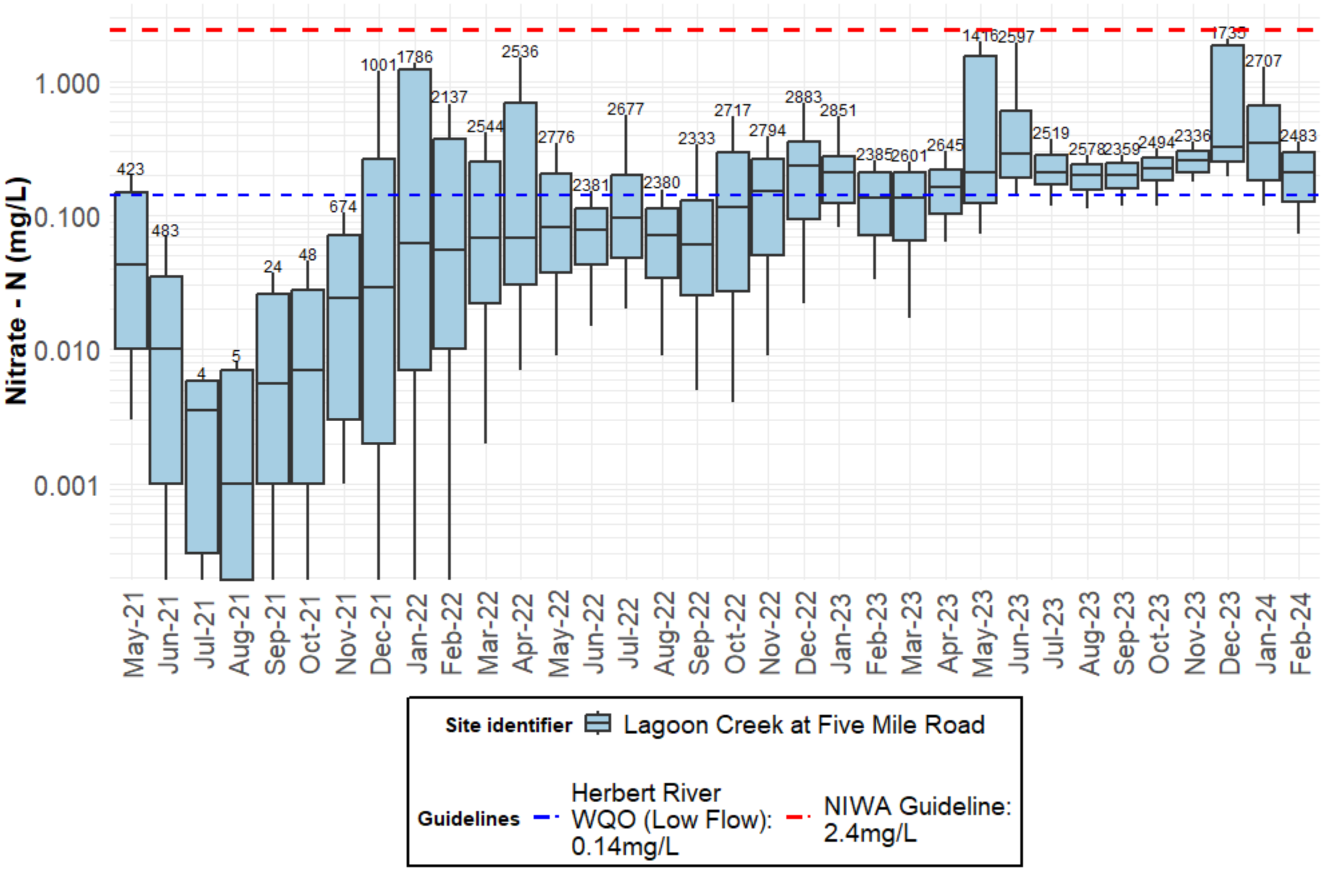

Figure 26. Box and whisker plot showing the monthly distribution of NO_3-N over time. Please note custom delineations have been utilised for the box and whisker plots showing ***minimum, 5th percentile, median, 95th percentile and maximum*** *values per month. Number at the top of each whisker represents number of observations. NIWA toxicity guideline adopted from NIWA (2014) and Hickey (2013).*

Stone River

Two sites have been installed along the Stone River, with three in the broader Stone River sub-catchment (inclusive of Lannercost Creek at Lannercost Extension Road). The Stone River at Running Creek site (Figure 27) captures majority conservation area, with additional contributions from grazing. Both monitoring stations along Stone River have been selected to be co-located with RDMW gauging stations. This provides the convenience of existing land access agreements, as well as redundancy in water level and discharge monitoring. Downstream, the Stone River at Venables Crossing monitoring station captures additional inputs from sugar, forestry, and small amounts of urban land use.

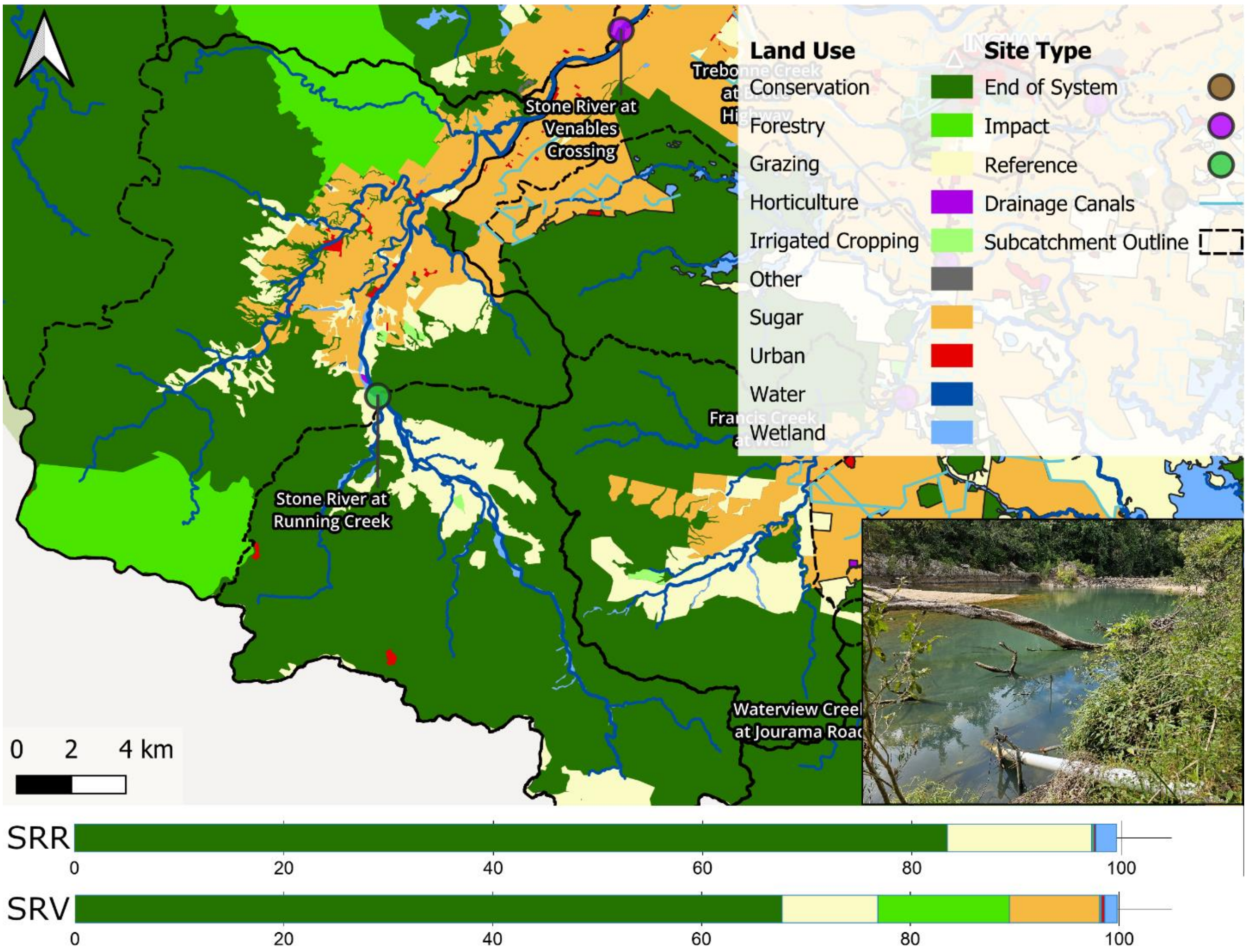

Figure 27. Sub-catchment land use for Stone River at Running Creek (SRR) and Stone River at Venables Crossing (SRV). Map shows the distribution of land use types in the sub-catchment while the bar charts (bottom) show the proportional contributions. Photo (bottom right) shows the in-stream placement of the probe at SRR.

The Stone River at Running Creek monitoring station was installed in March of 2021. The site reports nitrate data sporadically as concentrations are often below the lower limits of the probe (5 mm probe: <0.06 mg/L). This is shown in Figure 28 where the sparse nature of these data can be attributed to event conditions producing measurable nitrate concentrations. Data from Venables Crossing consistently exceed the WQO, which given the difference in land use, was expected. Conversely, concentration at Running Creek appears to stay below the WQO (0.14 mg/L). In the 2021–22 wet season, concentrations at the upstream Stone River at Running Creek site were comparable or even exceeded the downstream site at Venables Crossing. Without information from landholders in the region on specific practices leading up to this event, it is difficult to identify drivers, but it can be assumed that there was a nitrogen source (e.g. livestock, septic system) that was a contributing factor.

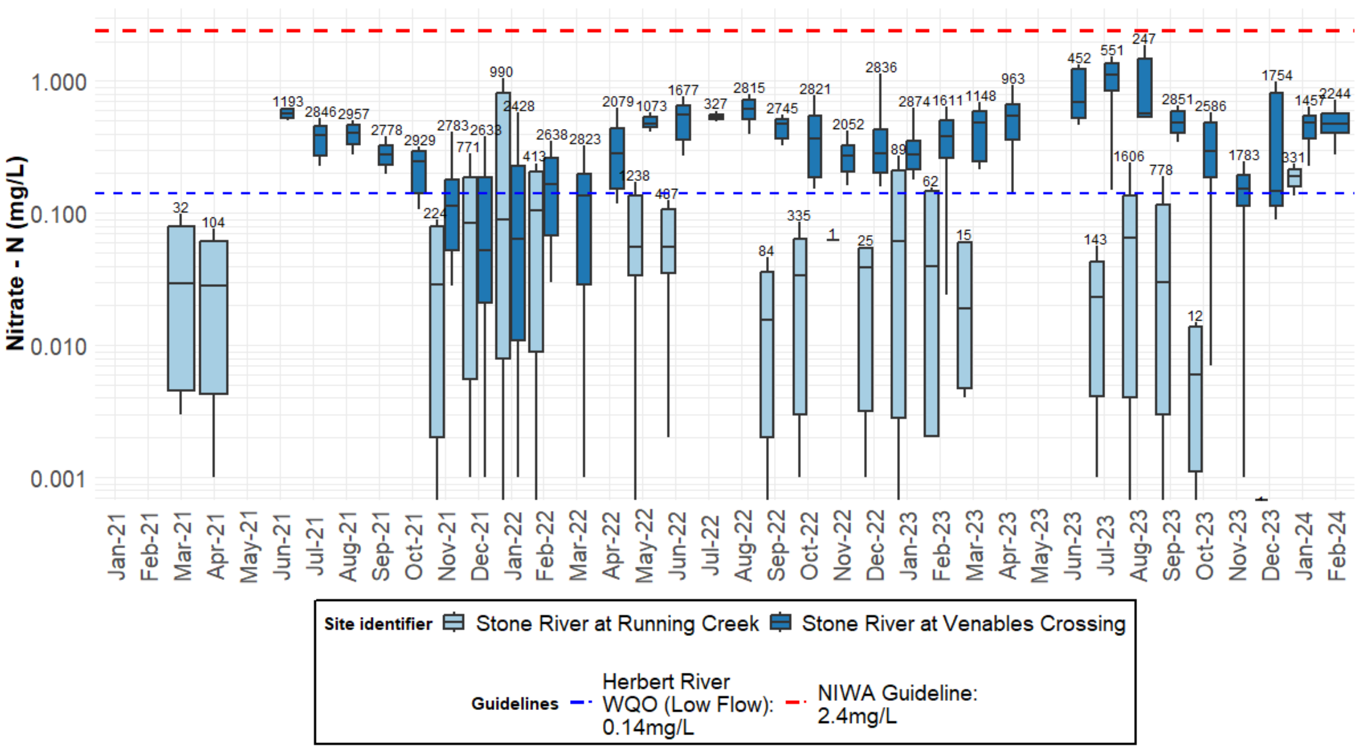

*Figure 28. Box and whisker plot showing the monthly distribution of NO_3-N over time. Please note custom delineations have been utilised for the box and whisker plots showing **minimum, 5th percentile, median, 95th percentile and maximum** values per month. Number at the top of each whisker represents number of observations. NIWA toxicity guideline adopted from NIWA (2014) and Hickey (2013).*

Lannercost Creek at Lannercost Extension Road

The Lannercost Creek at Lannercost Extension Road monitoring site is situated on a tributary of the Stone River as near as practical to the confluence between the two. This sub-catchment captures mixed land use, with sugar dominating the lower reaches and forestry areas higher in the catchment (Figure 29). It is situated downstream of the road and rail bridges. This site was offline for periods of time due to wiper failure and damage to electrical components from local fauna.

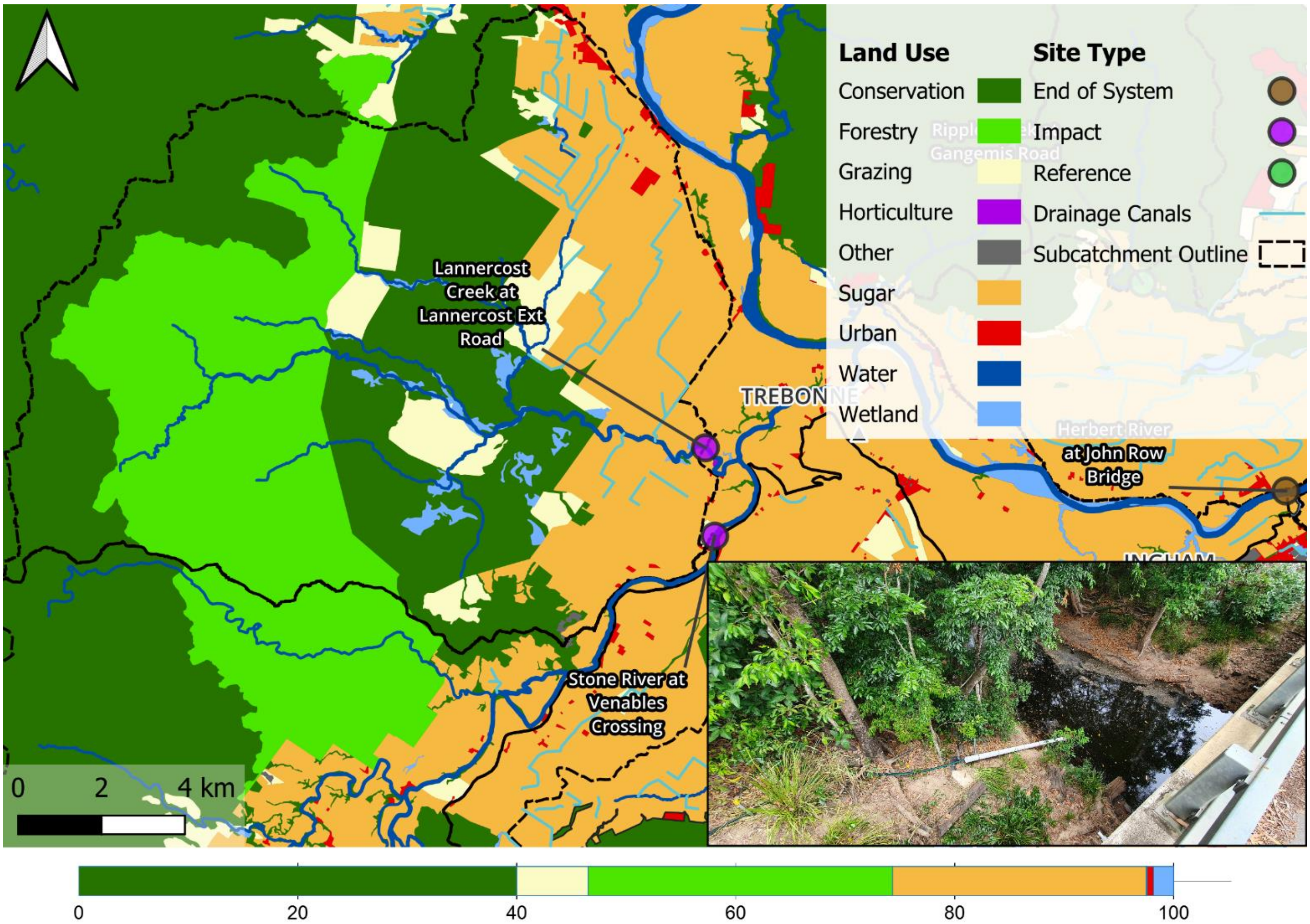

Figure 29. Sub-catchment land use for Lannercost Creek at Lannercost Ext Road. Map shows the distribution of land use types in the sub-catchment while the bar chart (bottom) shows the proportional contributions. Photo (bottom right) shows in-stream placement of the probe.

Concentrations at this site (Figure 30) are more variable than those at the nearby Stone River at Venables Crossing site (Figure 28), although median concentrations for the available data remained below the WQO throughout the wet and dry seasons. The first few months of data at this site produced the highest concentrations, at times exceeding the NIWA toxicity guideline, peaking at 4.6 mg/L on the 29th of December 2020 (Figure 31).

Looking at the time series hydrograph for this site (Figure 30), most of the nitrate concentrations were reported across event conditions in response to rainfall. Ambient conditions approach, and at times fall below, the lower limit of reporting of the probe (2 mm probe; 0.15 mg/L). Much of the monthly variability seen in Figure 30 was likely driven by event conditions.

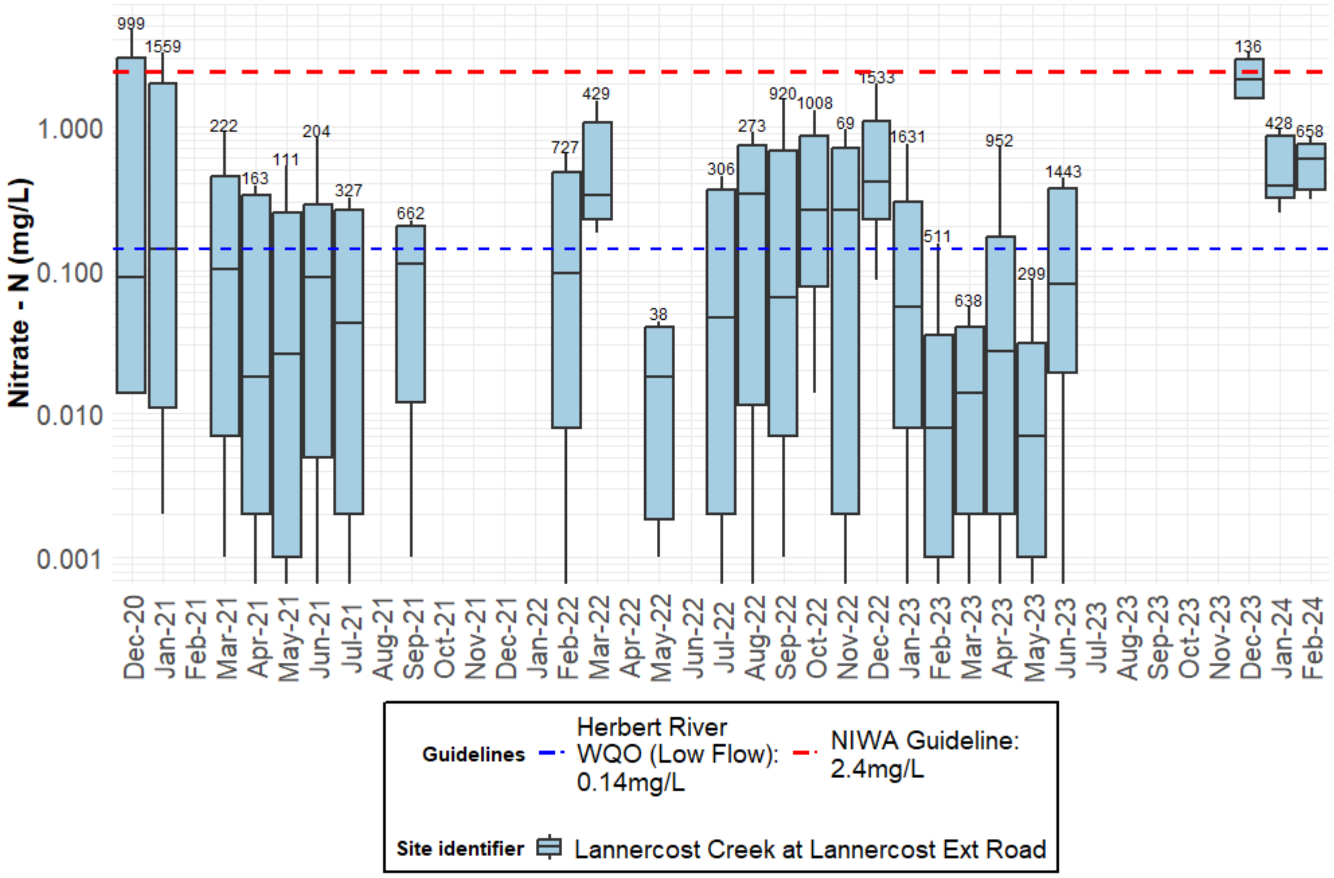

*Figure 30. Box and whisker plot showing the monthly distribution of NO3-N over time. Please note custom delineations have been utilised for the box and whisker plots showing **minimum, 5th percentile, median, 95th percentile and maximum** values per month. Number at the top of each whisker represents number of observations. NIWA toxicity guideline adopted from NIWA (2014) and Hickey (2013).*

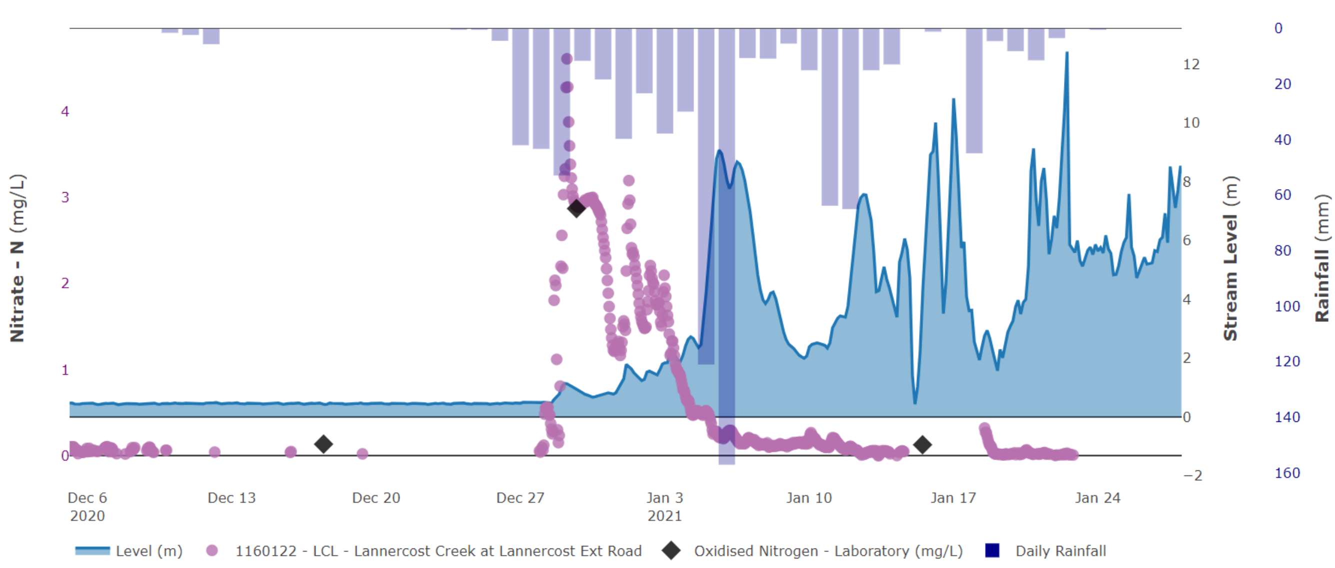

Figure 31. Time series hydrograph showing event conditions at Lannercost Creek in December 2020 - January 2021. Please note the rainfall axis is inverted to reduce datapoint overlap.

Ripple Creek

Two sites have been installed along Ripple Creek to the North of Ingham. Ripple Creek at Gangemis Road was selected as a reference site as the location captures majority conservation land use. While the Ripple Creek at Seymour gates site was selected to quantify the impacts of more intensive sugarcane land use in the lower catchment (Figure 32). Seymour gates is named after a diversion channel located downstream of the monitoring infrastructure, which at times, connects this system to the nearby Seymour River. In the absence of the diversion channel, this creek joins the Herbert River before discharging to the GBR lagoon. The Seymour gates site is situated within some palustrine wetland. The waterway hosts aquatic vegetation upstream and at the monitoring location (Figure 32).

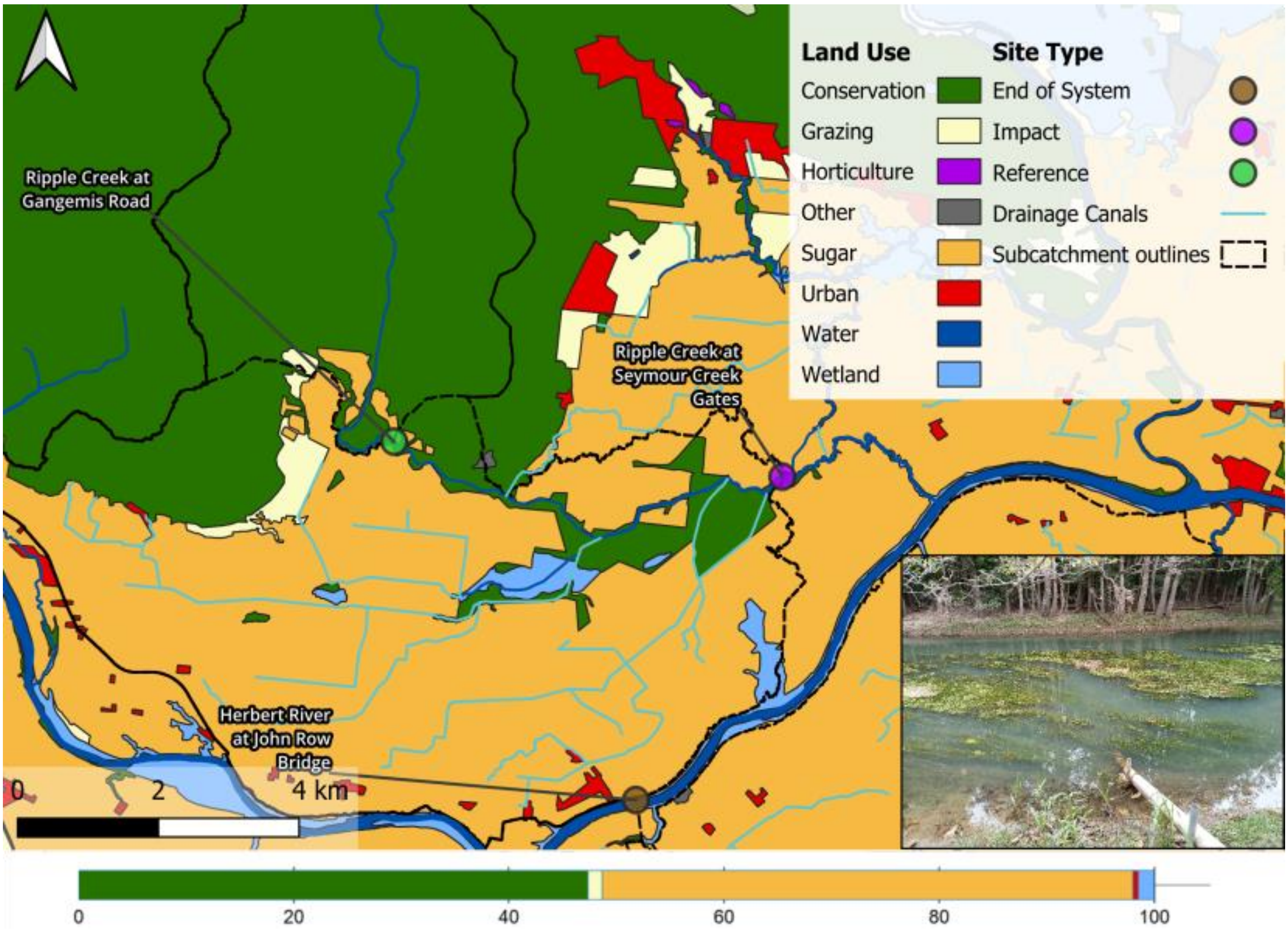

Figure 32. Sub-catchment land use for Ripple Creek at Seymour Gates. Map (left) shows the distribution of land use types in the sub-catchment while the bar chart (bottom) shows the proportional contributions. Photo (bottom right) shows the in-stream placement of the probe.

The downstream Seymour Gates site typically yields higher peak concentrations (i.e., event conditions). Median concentrations are often comparable at both sites, only exceeding the WQO in the 2021-22 wet season at the downstream site. Concentrations measured in November and December of 2021 show the highest concentrations of nitrate measured in this system, exceeding the NIWA toxicity guideline. Concentration spikes of this magnitude and seasonal timing would indicate first flush events for the system.

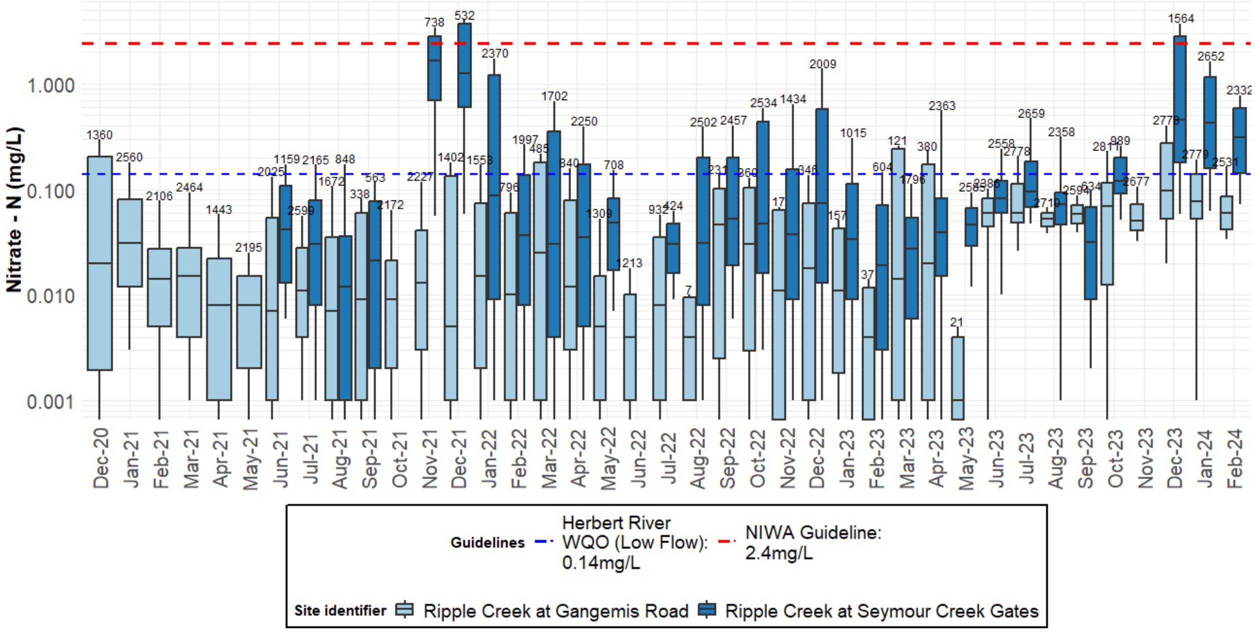

*Figure 33. Box and whisker plot showing the monthly distribution of NO_3-N over time. Please note custom delineations have been utilised for the box and whisker plots showing **minimum, 5th percentile, median, 95th percentile and maximum** values per month. Number at the top of each whisker represents number of observations. NIWA toxicity guideline adopted from NIWA (2014) and Hickey (2013).*

Figure 34 shows the period November to December 2021 in greater detail. The probe measurements at Seymour Gates are supported by the strong relationship between grab sample concentrations and probe data displayed on the chart. Both sites demonstrated a strong positive relationship between rainfall, water level and NO_3-N. Concentrations are observed to return to lower ambient conditions soon after these rainfall-runoff events. As expected, the magnitude of response is considerably greater at the impact site than the reference. One possible explanation for the rapid return to lower ambient conditions at the Seymour Gates site may be denitrification processes provided by the upstream wetland areas and the vegetated waterways of this system.

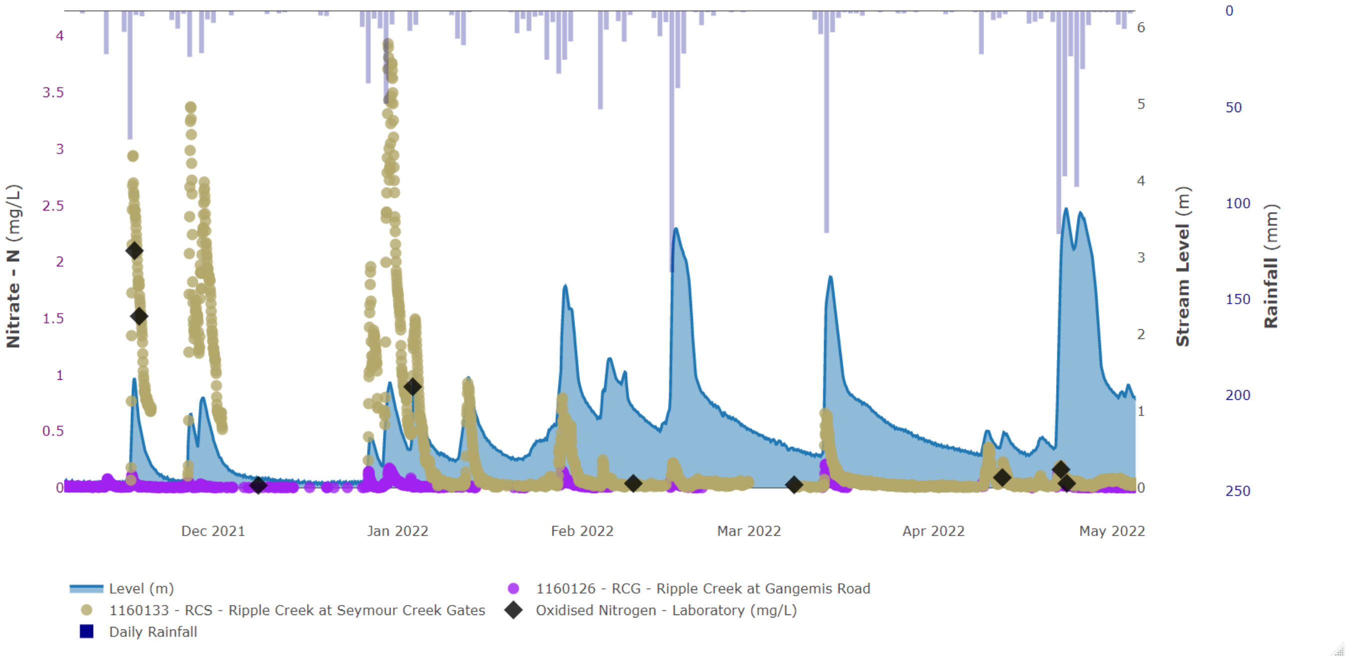

Figure 34. Hydrograph showing the response in NO_3-N to water level and rainfall in Ripple Creek. Rainfall has been extracted from SILO for the grid location at the Seymour Gates site. Lab data-points are for water samples collected at the Seymour Gates site.

Waterview Creek

The Waterview Creek sub-catchment is located on the southern fringe of the Herbert Basin. This system joins Cattle Creek downstream of our monitoring infrastructure before discharging to the GBR lagoon. Two sites were installed, the Waterview Creek at Jourama Road and Waterview Creek at Mammarellas Road. Jourama Road captures predominantly conservation land use, situated just downstream of the Paluma Range National Park. The Mammarellas Road site captures the same conservation areas as Jourama Road with the addition of a relatively small amount of sugarcane land use.

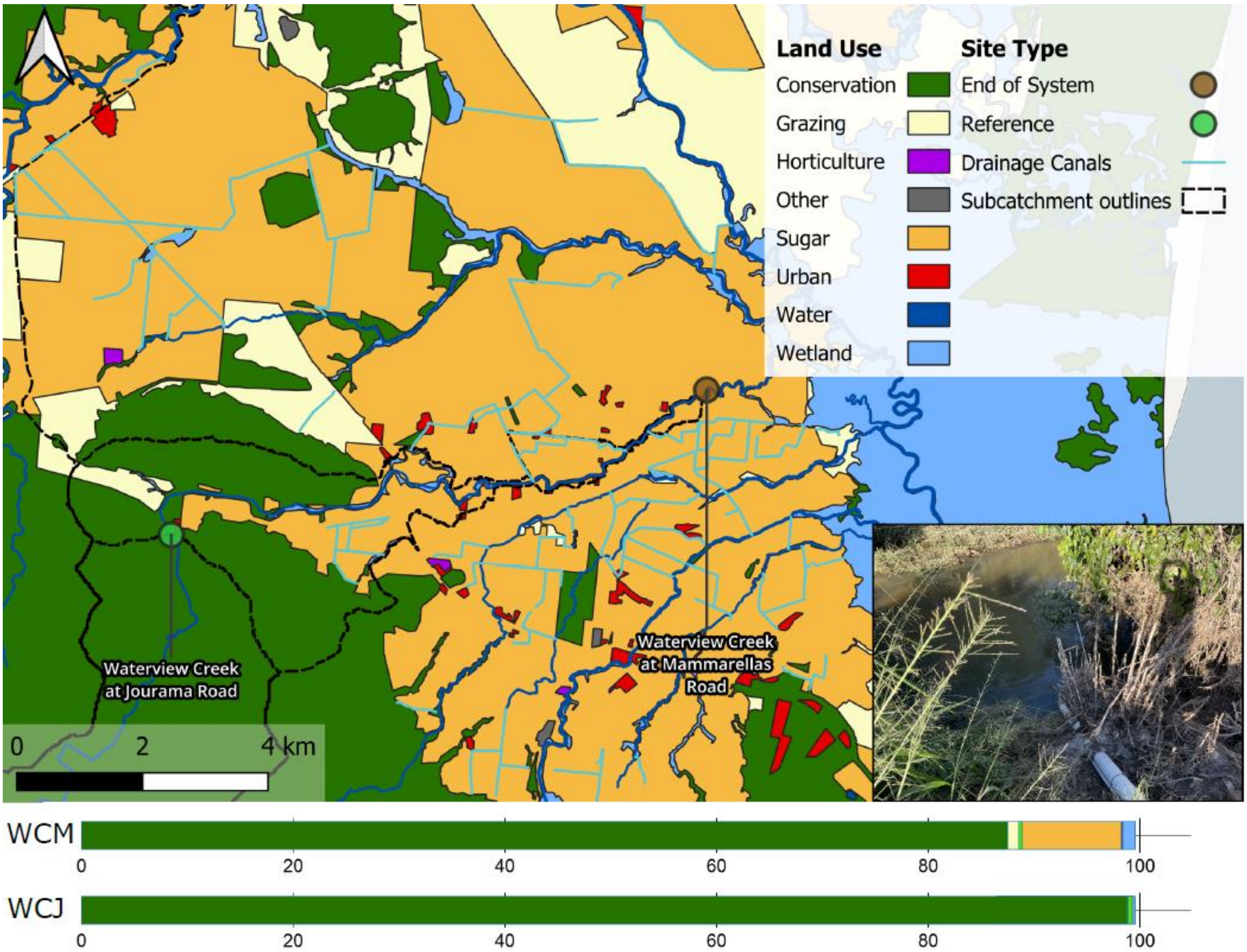

Figure 35. Sub-catchment land use for Waterview Creek at Mammarellas Road (WCM) and Waterview Creek at Jourama Road (WCJ). Map (left) shows the distribution of land use types in the sub-catchment while the bar chart (bottom) shows the proportional contributions. Photo (bottom right) shows the in-stream location of the probe.

Monthly concentrations are shown in Figure 36. At the end-of-system (Mammarellas Road) site, nitrate concentrations consistently exceeded the WQO in all but one month. The upstream reference (Jourama Road) site shows expected seasonality, where wet season conditions (October - April) result in elevated concentrations.

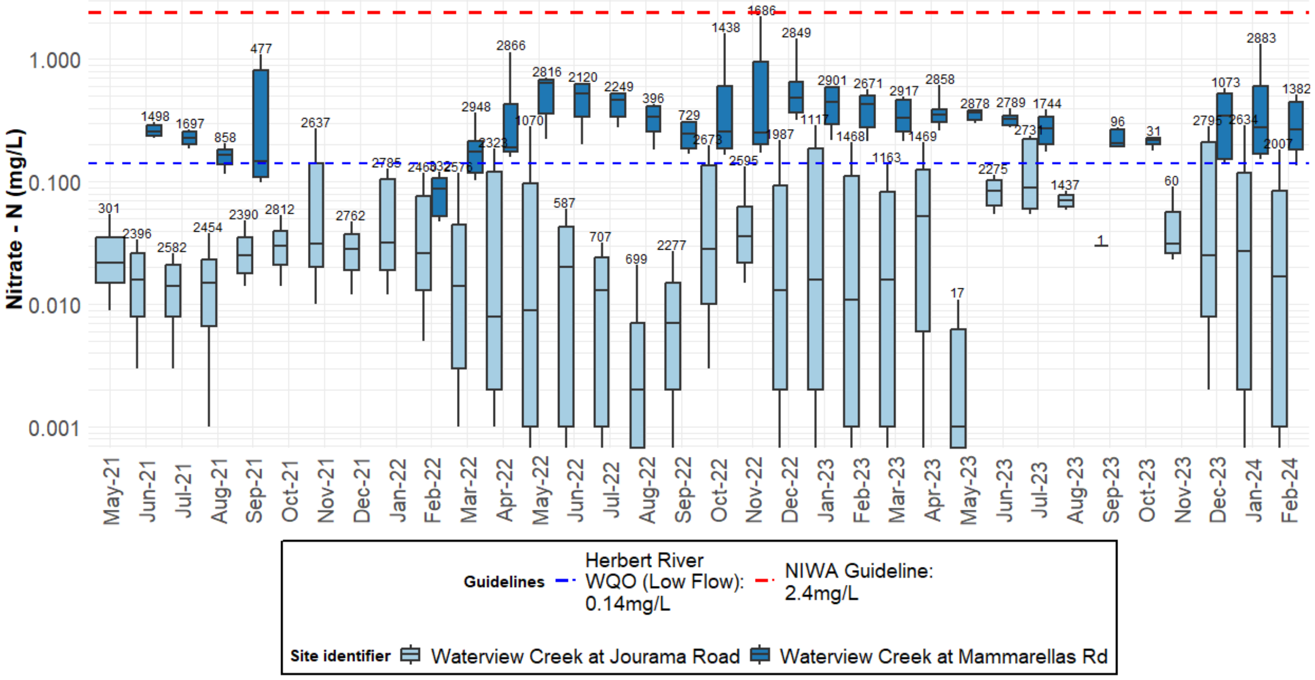

*Figure 36. Box and whisker plot showing the monthly distribution of NO_3-N over time. Please note custom delineations have been utilised for the box and whisker plots showing **minimum, 5th percentile, median, 95th percentile and maximum** values per month. Number at the top of each whisker represents number of observations. NIWA toxicity guideline adopted from NIWA (2014) and Hickey (2013).*

Figure 37 shows the time series hydrograph and NO_3-N concentrations for both sites. The Jourama Road water level feed has been utilised for these comparisons. Concentration data for Jourama Road shows a strong relationship with rainfall and water level.

Early events in December of 2022 elicited a typical runoff response for the Mammarellas site, with a sharp and pronounced spike in nitrate concentrations, while subsequent events resulted in a reduction in NO_3-N concentrations with rainfall. This post-event dilution signal is followed by a steady rise in nitrate concentration between events. Like observations at Elphinstone, Trebonne and Palm Creek, there may be a shallow groundwater table in this region influencing the baseflow and nitrate concentration. Bore water in this sub-catchment upstream of the Mammarellas site displays relatively high nitrate concentrations (see Appendix C).

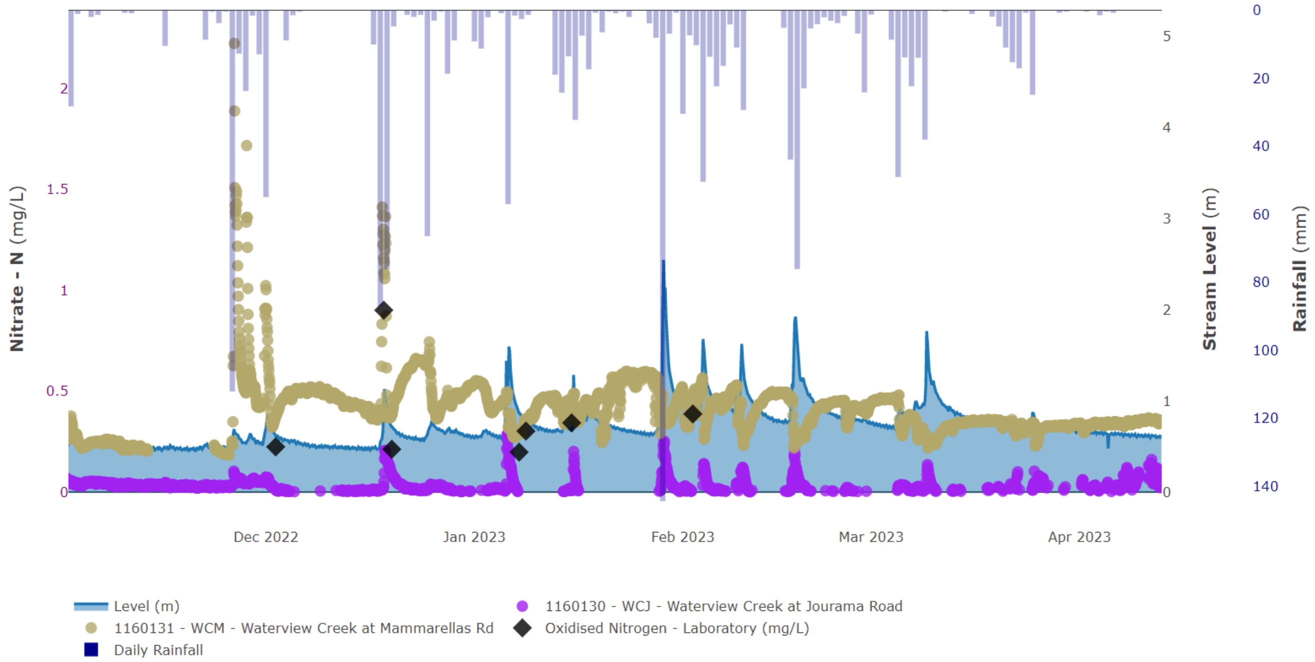

Figure 37. Hydrograph showing the response in NO_3-N to water level and rainfall in Waterview Creek. Rainfall has been extracted from SILO for the grid location at the Mammarellas Road site. Lab data-points are for water samples collected from the Mammarellas Road site.

Herbert River

The Herbert River at John Row Bridge monitoring site infrastructure has been co-located with the long-term catchment loads monitoring site. This location is the primary end-of-system monitoring site for the entire Herbert River basin (see Figure 1 and Figure 38). The upstream reference site at Nash's Crossing was selected as it captures the inflows from the upper catchment which is dominated by conservation (Figure 1). The lower catchment is dominated by sugarcane land use, while the upper is primarily grazing. These two sites are separated by approximately 68 kilometres of waterway with multiple inflows. There are many tributaries that may contribute nutrients to the Herbert River between the sites as well as opportunities for nutrient cycling.

Figure 38. Herbert River at John Row Bridge monitoring infrastructure (looking upstream).

There is some seasonality occurring in the data collected from Herbert River at John Row Bridge (Figure 39). Elevated concentrations at the start of the wet season were observed in November of 2021, through much of 2022 and the 2023 wet season. These increases preceded a drop in concentrations over subsequent wet season months, followed by a steady increase through the dry season where median monthly concentrations exceeded WQOs. The Nash's Crossing site suffered some down-time because of interference with the equipment by a crocodile. Most of the data collected at this site were below the high flow WQO.

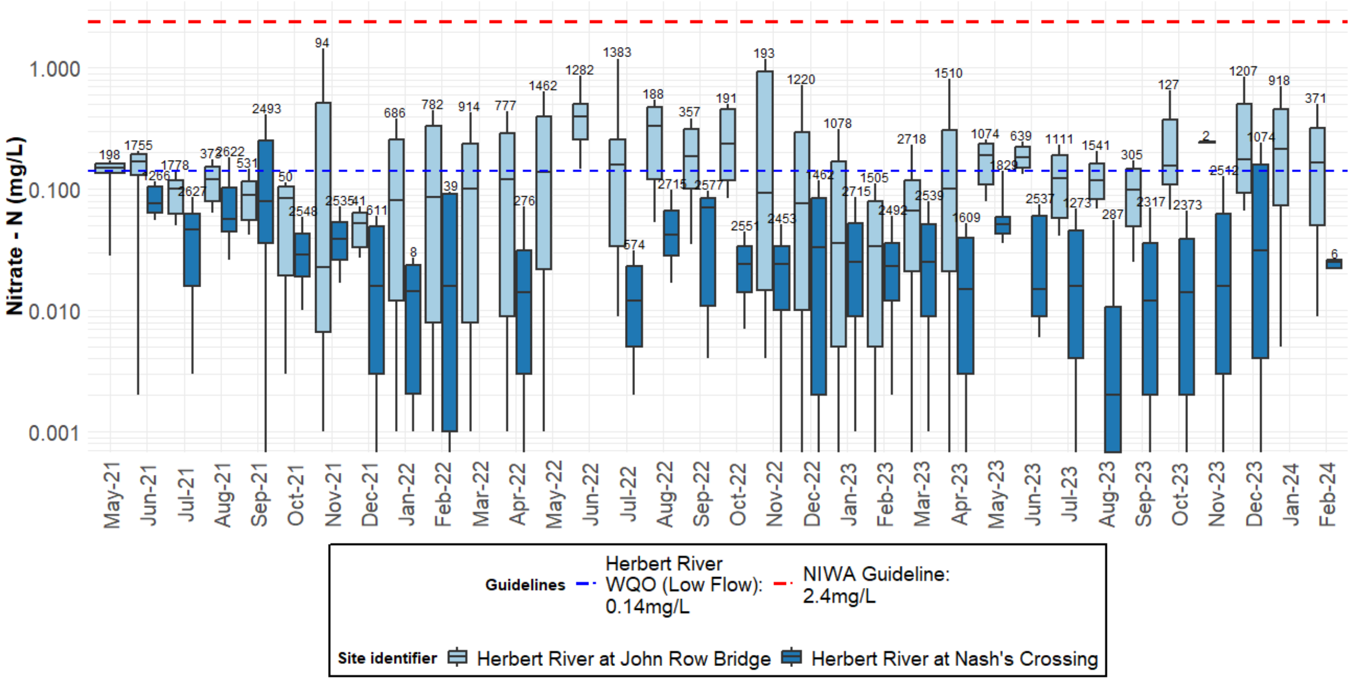

*Figure 39. Box and whisker plot showing the monthly distribution of nitrate as N over time. Please note custom delineations have been utilised for the box and whisker plots showing **minimum, 5th percentile, median, 95th percentile and maximum** values per month. Number at the top of each whisker represents number of observations. NIWA toxicity guideline adopted from NIWA (2014) and Hickey (2013).*

Herbert River at John Row Bridge showed typical elevated runoff concentrations in the early wet season (Figure 40). This site is sampled manually at a high frequency over wet season events because of its importance in deriving end-of-system loads for the Great Barrier Reef Catchment Loads Monitoring Program (GBRCLMP) and these grab sample data are presented in Figure 40.

As with other sites in the Lower Herbert (i.e. Trebonne Creek, Palm Creek, Waterview Creek, Elphinstone Creek), the data observed at the John Row Bridge site (Figure 40), showed the same peaks in nitrate concentrations coinciding with first flush events, dilution of nitrate during subsequent event conditions followed by an increase in nitrate between events because of surface water – groundwater interactions. Bore water in this sub-catchment in the vicinity of the John Row Bridge site displays relatively high nitrate concentrations (see Appendix C). In March and April 2023, some small runoff events appear to produce sizable response in NO_3-N concentrations (Figure 40). These peaks were comparable to the first flush events of the season and suggest application of fertiliser in the weeks prior.

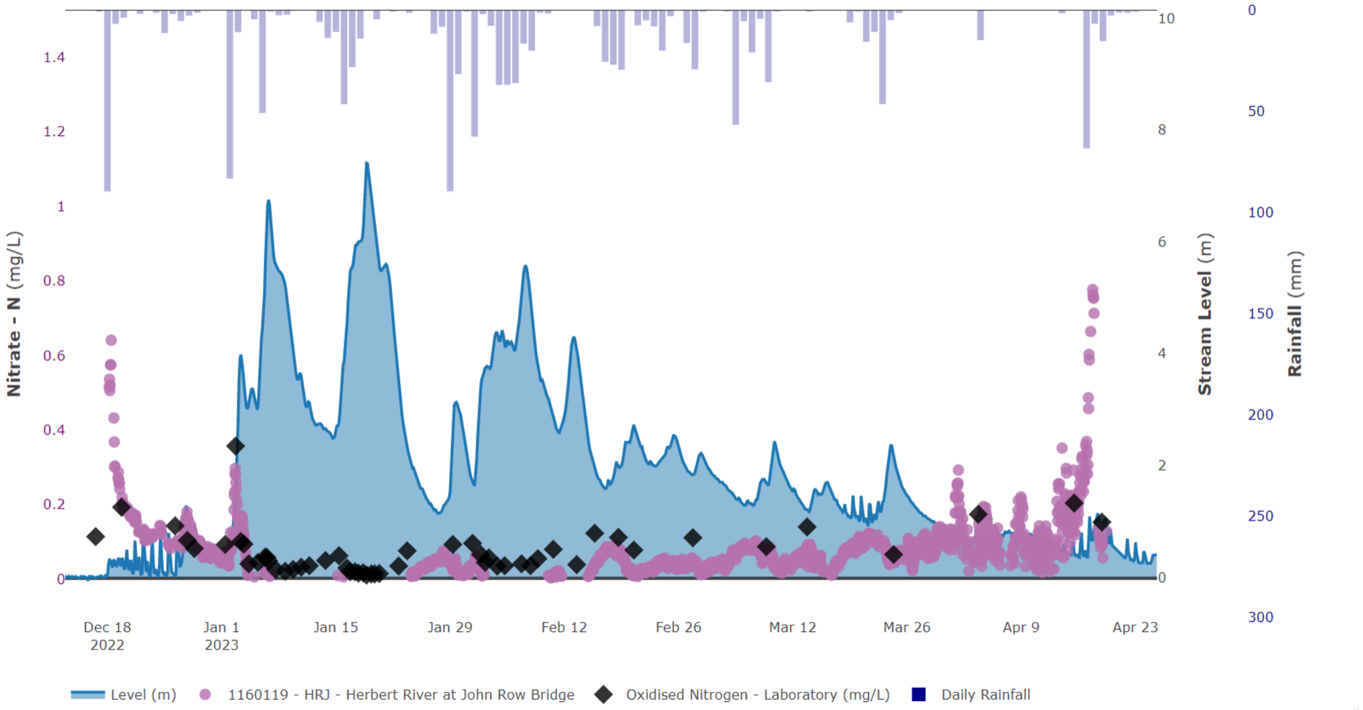

Figure 40. Hydrograph showing the response in NO_3-N to water level and rainfall at Herbert River at John Row Bridge. Rainfall has been extracted from SILO for the local grid location.

Discussion

This fine scale water quality monitoring network in the Lower Herbert basin has been recording nitrate concentration values since 2020. This has produced a spatially and temporally dense dataset of water quality data in some of the smaller creeks and rivers in the basin. As a community engagement tool, this data is available to the public via CSIRO online platform 1622wq.

Because nitrate is a natural chemical, it is important to distinguish nitrate that is present due to natural process from that introduced to waterways via agricultural or other anthropogenic activities. The network of 17 probes in the Lower Herbert River has provided a unique insight into the sources and fate of nitrate in the waters that ultimately discharge to the Great Barrier Reef lagoon.

The data captured by this monitoring network has demonstrated that the lowest concentration ranges of NO_3-N occur at the reference sites high in the catchments above intensive sugarcane cropping. On the assumption that agricultural activity in lower catchment is contributing nitrogen to the waterways, The Reef Water Quality Improvement plan (State of Queensland 2018) prescribed end-of system targets for the reduction of dissolved inorganic nitrogen (which includes nitrate) in the Herbert River.

There are several mechanisms for improving water quality. Changes to farm management practices can influence water quality; however, direct benefits might only be observable through early wet season runoff events. Upstream riparian vegetation buffers and healthy wetland environments are other mechanisms for improved water quality, and observations from this project highlight their environmental significance in the facilitation of denitrification processes (Adame et al. 2019). Vegetation growing in waterways and cane drains may also offer benefits in reducing nitrate concentrations and reducing downstream movement of nitrogen (Soana et al. 2023). An example of this was provided by the probes in Palm Creek; the downstream probe presented lower concentrations in nitrate than the upstream probe, despite the higher proportions of sugarcane land use upstream of the site. The observation was consistent with the presence of aquatic vegetation prevalent in the palustrine wetlands in this section of the creek (Figure 41) and demonstrated the value of wetland systems for denitrification processes.

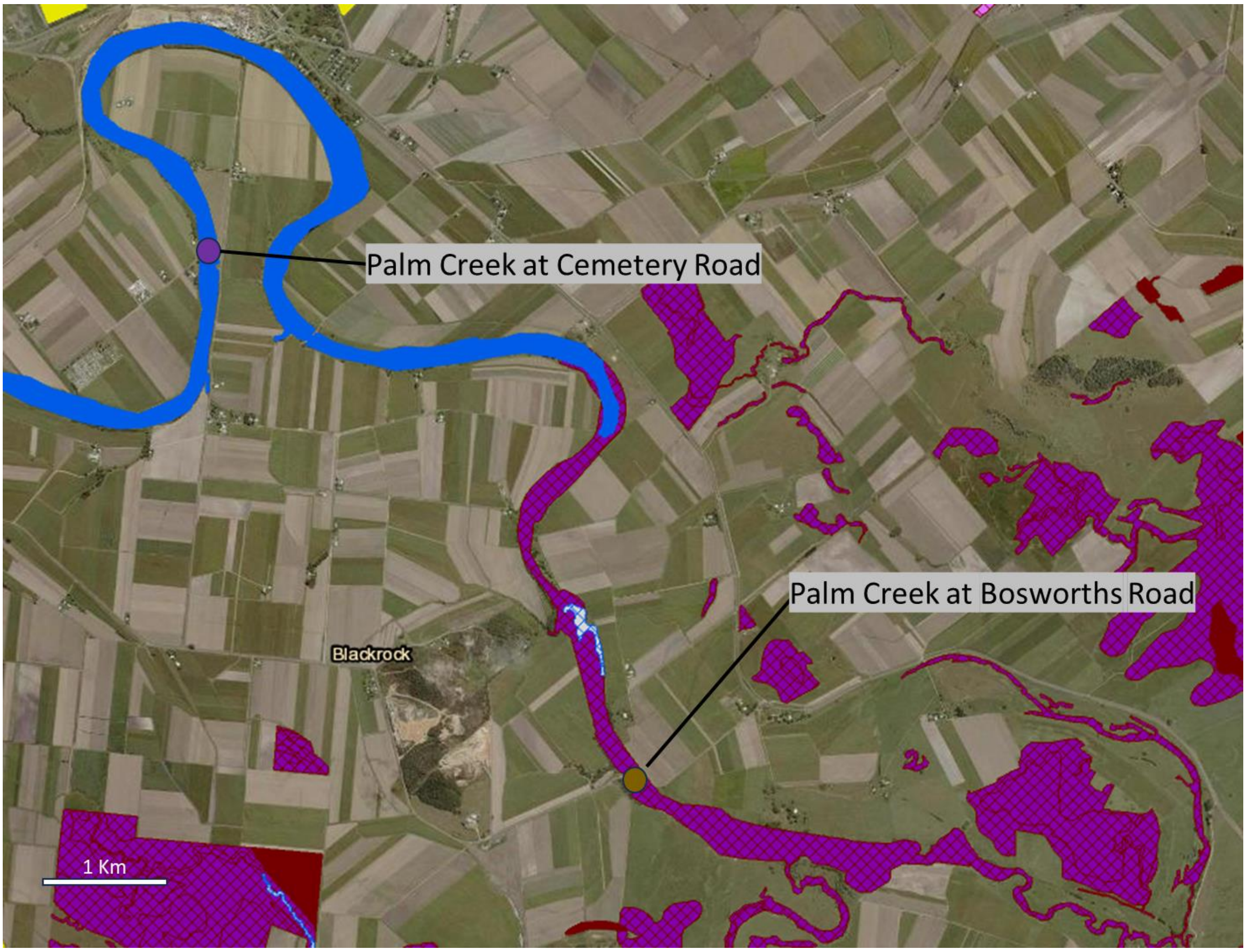

*Figure 41. Queensland Wetland Mapping (Wetland*Info*) wetland categories in the vicinity of the Palm Creek sites at Cemetery Road and Bosworths Road. Blue shading indicates Riverine Wetlands (hydrologically modified or artificial), hatching indicates Palustrine Wetlands (hydrologically natural) and purple shading indicates Coastal and sub-coastal floodplain wet heath swamps.*

Many of the lower catchment sites and the Elphinstone Creek site are demonstrating concentration patterns that indicate groundwater influence during base flow conditions (Misra et al. 2011). From the available data in the region, it is likely the groundwater table is shallow to the surface through much of the year. As is common in many areas with extensive agricultural land use, the available groundwater data suggests moderate to high levels of nitrate in the Herbert basin groundwaters and where connectivity with groundwater is maintained through the dry season, nitrate concentrations can remain elevated. Residence times of nitrate in aquifers is variable (years to decades) and the concentrations that are discharged back into the streams may not be related to recent infiltration events (Clague et al. 2019; Stewart et al. 2011). Further investigation would be required to assess whether fertiliser is finding its way directly into local streams via this avenue.

Water quality guidelines and water quality objectives provide reference thresholds that can be used to gauge the condition of the aquatic ecosystem. Aquatic ecosystem protection guidelines (i.e. toxicity guidelines) were only exceeded on rare occasions within this monitoring network, only at sites nominated as impacted or end-of-system sites, and invariably only during first flush events in November / December. These exceedances may warrant further investigation if they are observed to be a regular occurrence in the waterways concerned. WQOs provide an indication of a desired state and should be interpreted as such. Exceedances of WQOs were rare at reference sites, but comparatively frequent at downstream impact and end-of-system sites. Only the low (base) flow WQOs were used in this report. WQOs for high flow conditions are also scheduled (Table 3) and a more thorough data analysis that reclassified high frequency data into event and ambient condition types would provide a better understanding of the water quality in these waters. Given that all of the high flow objectives are lower than the base flow WQO used in this report though, it can be said that water quality at several lower Herbert catchment sites fails to meet WQOs.

Near real-time probes offer considerable advantages over traditional manual or automated grab sampling methods. As observed through our monitoring, upper catchment sites in the region are very flashy in nature, with rapid rises and falls in both river level and nitrate concentration. Capturing adequate samples across varied flow conditions would be challenging using traditional discrete grab sample methods. Traditional grab sample monitoring relies heavily on appropriate sample timing to get an accurate picture of concentration flux across runoff events. Depending on logistic constraints, it can be difficult to achieve at scale. Near real-time *in situ* probes can better capture the water quality flux seen in waterways (Juncal et al. 2020) because they can provide a near constant data trace.

The immediacy of the data offers great advantages to land managers. When the data are delivered via an online dashboard (such as 1622wq), land managers can subsequently use the information to adjust management actions for improved efficiencies with respect to farm inputs (e.g. fertilisers); the subsequent benefit being that the outcomes of management actions can be determined in near-real time, without the, often, substantial delays for laboratory analysis and loads calculations.

The high data density captured during events also offers substantial advantages in the calculation and accuracy of loads for the catchment, although a measurement or estimate of flow would be required. These probes are also advantageous in capturing dry season dynamics, where manual sampling is not as frequent as in the wet season. Data collected in this system has demonstrated the likely changes in surface water nitrate concentrations resulting from groundwater intrusion into the water ways at several sites.

The use of near-real time probes has provided an alternative to grab sampling, which removes the potential uncertainty at each point of the chain of custody for manual grab samples (e.g. logistic requirements for on-site preservation, refrigeration, sampler error, contamination, strict holding times prior to analysis and analytical errors in the lab analyses). It is however, acknowledged that *in situ* probes come with their own uncertainties that need to be managed. The validation of these probes is still an important quality step requiring periodic sampling efforts.

There are several limitations to be aware of for this type of monitoring regime which are important to emphasise. The necessity for the probes to have in-stream contact is a physical limitation which influences where the probes are installed and has prevented installation at some sites. The equipment design also limits the monitoring to edge sampling. There is an assumption inherent in monitoring programs of this type, that the concentrations of dissolved constituents will be uniform throughout the stream cross-section. Water turbidity will dictate the pathlength used in the probe, and thereby affect the sensitivity of the probe. Longer pathlengths will impute greater sensitivity. Ideally, the longest pathlength possible is chosen; however, in turbid streams this is not always possible. As a consequence, the sensitivity of the optical probes cannot always match the detection limits of laboratory based spectrometric analyses. In agricultural systems where nitrate concentrations are expected to be high, this will not present a barrier to their use, but may limit their value for the development of reference site based WQOs and guidelines.

Another limitation which has been observed and noted in previous sections, is the potential for interference by wildlife which can influence the sensor readings. Crocodiles have damaged some in-water equipment and local mammals and even ants have caused damage to above-water electrical components. Fouling of sensors because of the presence of organic matter (e.g. algae and even dead birds) can impact the accuracy of readings, but can be mitigated through scheduled maintenance. Water Quality & Investigations is currently developing computational algorithms that may permit predictive modelling to alert the team to early signs of fouling and thereby trigger corrective maintenance earlier.

One final limitation of this style of water quality monitoring is the absence of flow measurements, although this would also be true for more traditional grab sampling. Flow monitoring would permit for the calculation of nitrate loads, thus providing data that can more readily be interpreted with respect to farm and land management. Water Quality & Investigations is currently exploring several options for estimating flow at these sites.

This fine scale water quality monitoring network has dramatically improved our understanding of the Lower Herbert basin nutrient dynamics and allows for a more targeted insight into local, seasonal flow dynamics. Continued upkeep of this monitoring network will allow for longer term insights into these flow dynamics, not just seasonally but at a longer climactic scale with an ability to understand the impacts of events such as La Nina and El Nino.

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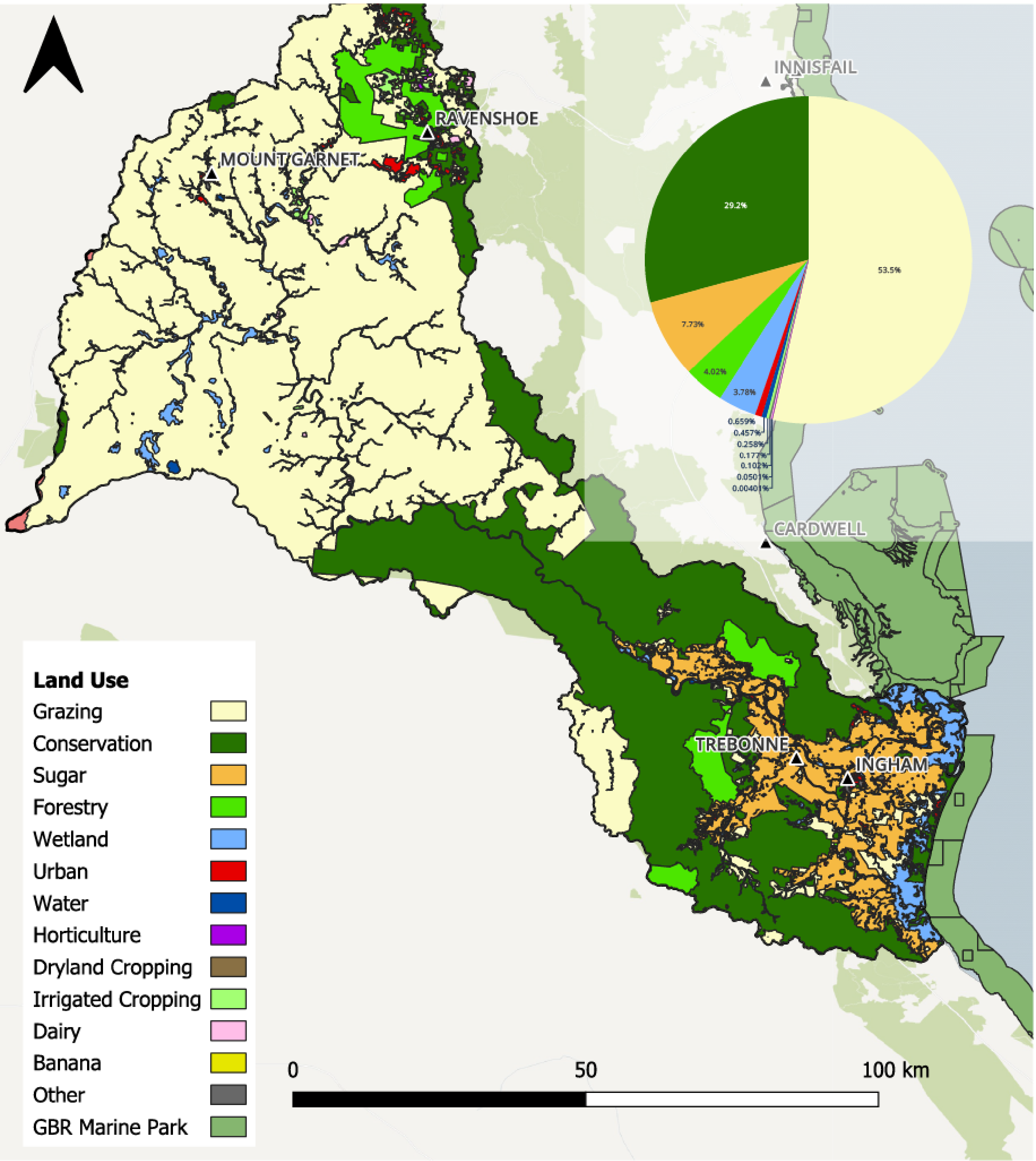
Appendix A. Table containing site information for the Lower Herbert real-time monitoring network.

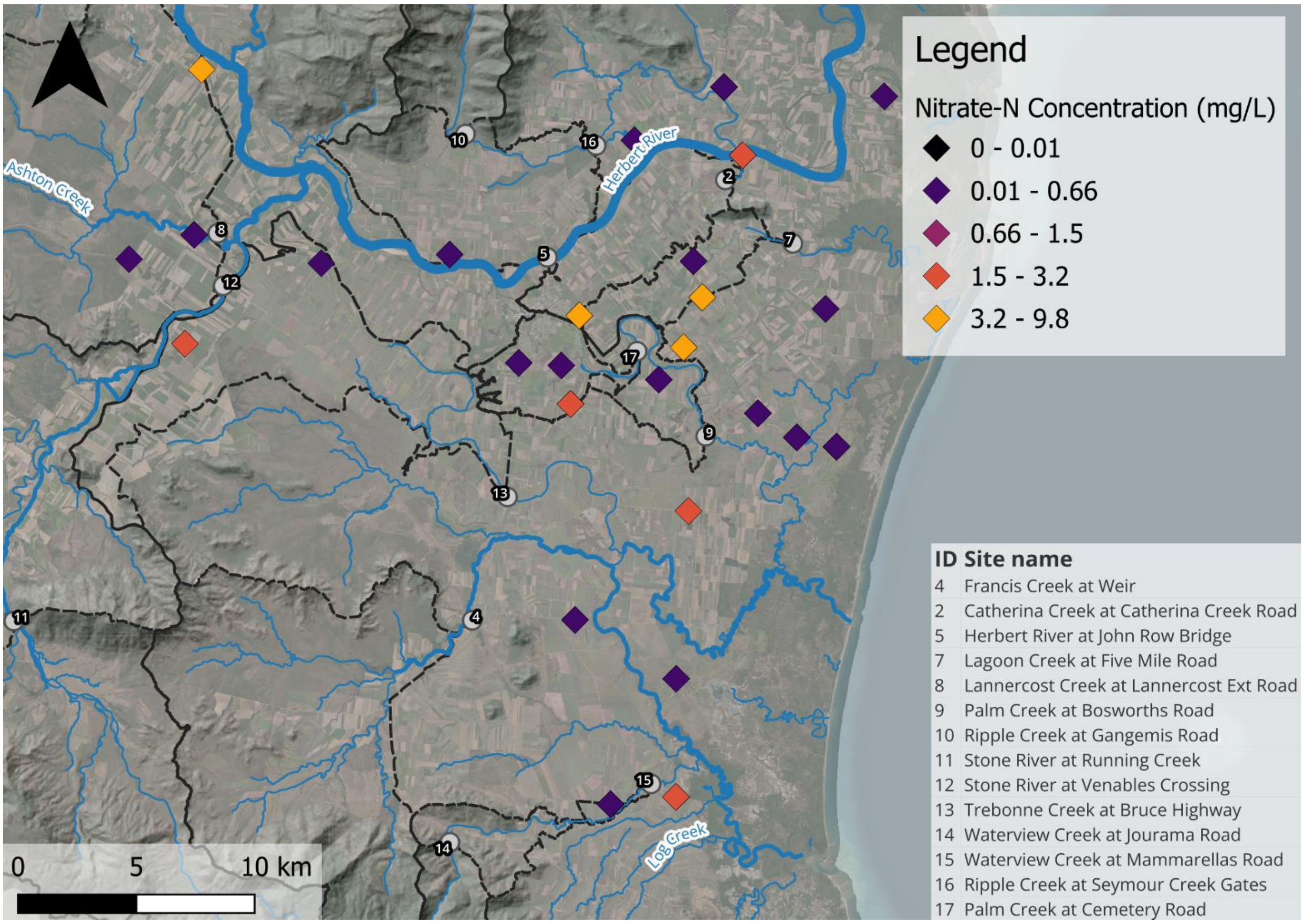
Catchment	Site ID	Site name	Site code	OPUS path length	Lat	Lon	Datum	Site type	Stream order	Stream habit
Herbert River	1160115	Broadwater Creek at Day Use	BCD	5mm	-18.42	145.94	GDA2020	Reference	4	Natural
Catherina Creek	1160116	Catherina Creek at Catherina Creek Road	CCC	5mm	-18.60	146.24	GDA2020	End of System	3	Natural
Herbert River	1160117	Elphinstone Creek at Copley Road	ECC	2mm	-18.47	145.96	GDA2020	Impact	4	Natural
Francis Creek	1160118	Francis Creek at Weir	FCW	2mm	-18.77	146.13	GDA2020	Impact	5	Ephemeral
Herbert River	1160119	Herbert River at John Row Bridge	HRJ	2mm	-18.63	146.16	GDA2020	End of System	7	Tidal
Herbert River	1160120	Herbert River at Nash's Crossing	HRN	10mm	-18.41	145.77	GDA2020	Reference	7	Natural
Victoria Creek	1160121	Lagoon Creek at Five Mile Road	LCF	2mm	-18.62	146.26	GDA2020	End of System	3	Lagoon
Lannercost Creek	1160122	Lannercost Creek at Lannercost Ext Road	LCL	2mm	-18.62	146.03	GDA2020	Impact	5	Natural
Palm Creek	1160124	Palm Creek at Bosworths Road	PCB	5mm	-18.70	146.23	GDA2020	End of System	3	Natural
Ripple Creek	1160126	Ripple Creek at Gangemis Road	RCG	5mm	-18.58	146.13	GDA2020	Reference	3	Natural
Stone River	1160127	Stone River at Running Creek	SRR	5mm	-18.77	145.95	GDA2020	Reference	5	Natural
Stone River	1160128	Stone River at Venables Crossing	SRV	2mm	-18.64	146.03	GDA2020	Impact	5	Natural
Palm Creek	1160129	Trebonne Creek at Bruce Highway	TBH	5mm	-18.72	146.15	GDA2020	Impact	4	Natural
Cattle Creek	1160130	Waterview Creek at Jourama Road	WCJ	10mm	-18.85	146.12	GDA2020	Reference	3	Natural
Cattle Creek	1160131	Waterview Creek at Mammarellas Road	WCM	5mm	-18.83	146.21	GDA2020	End of System	3	Natural
Herbert River	1160133	Ripple Creek at Seymour Creek Gates	RCS	2mm	-18.59	146.18	GDA2020	Impact	4	Lagoon
Palm Creek	1160134	Palm Creek at Cemetery Road	RIP	5mm	-18.66	146.20	GDA2020	Impact	3	Natural

Appendix B. Map displaying the land use breakdown for the entire Herbert Basin.



Appendix C. Map showing groundwater NO_3-N concentration through the lower Herbert basin.

Data displayed was collected between July 2022 and July 2023 (The State of Queensland 2023b).



ID	Site name
4	Francis Creek at Weir
2	Catherina Creek at Catherina Creek Road
5	Herbert River at John Row Bridge
7	Lagoon Creek at Five Mile Road
8	Lannercost Creek at Lannercost Ext Road
9	Palm Creek at Bosworths Road
10	Ripple Creek at Gangemis Road
11	Stone River at Running Creek
12	Stone River at Venables Crossing
13	Trebonne Creek at Bruce Highway
14	Waterview Creek at Jourama Road
15	Waterview Creek at Mammarellas Road
16	Ripple Creek at Seymour Creek Gates
17	Palm Creek at Cemetery Road