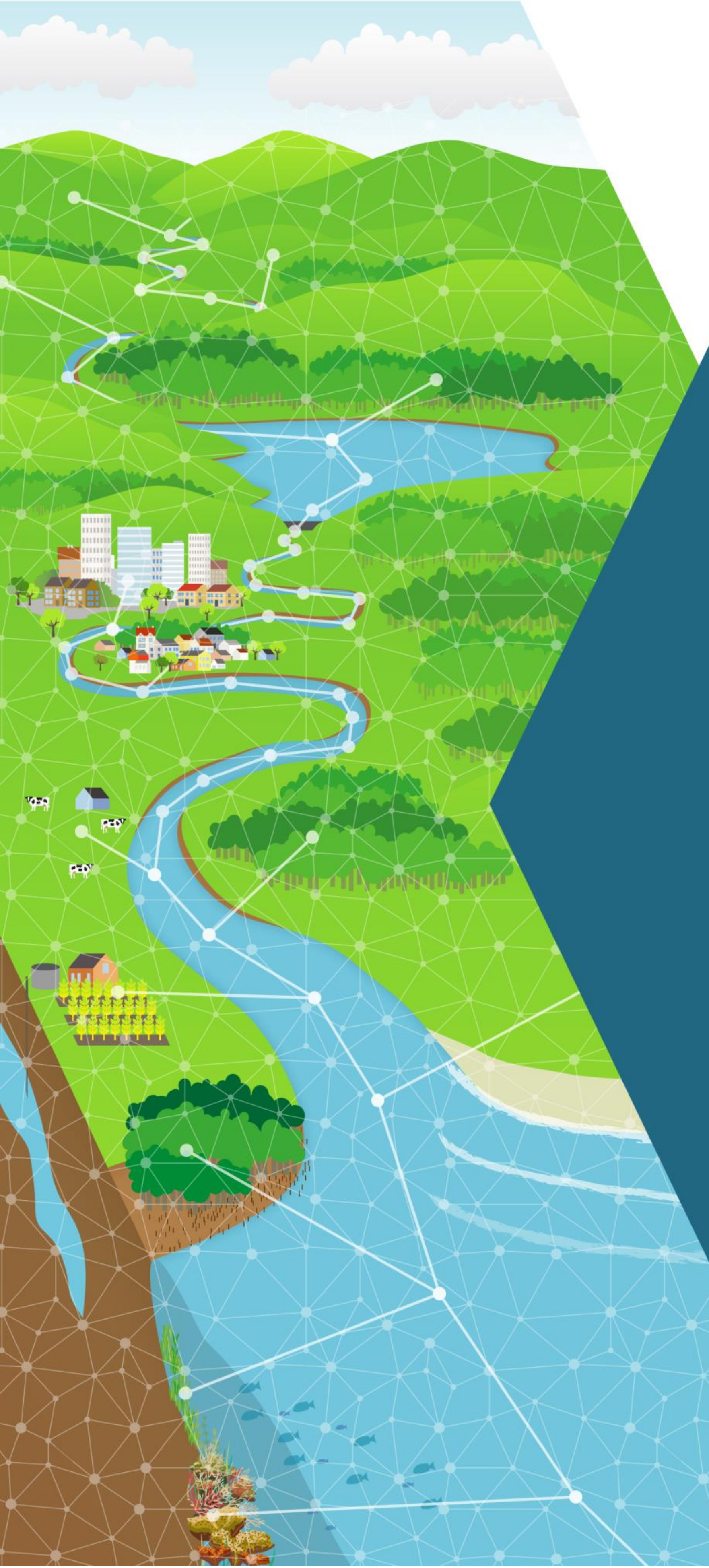
QUEENSLAND WATER MODELLING NETWORK



A modelling framework for nutrient offsets

Report prepared by

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For Queensland Water Modelling Network

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The Queensland Water Modelling Network (QWMN) is an initiative of the Queensland Government that aims to improve the state's capacity to model its surface water and groundwater resources and their quality. The QWMN is led by the Department of Environment and Science with key links across industry, research and government.

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Executive summary

Nutrient offsetting aims to provide cost-effective solutions to nutrient reduction in waterways by reducing nutrient loads from diffuse sources, to compensate for increased nutrient loads from other sources, including point sources such as Sewage Treatment Plants (STPs) and aquaculture facilities. Rather than problem-shifting, offset schemes should maintain or improve water quality, i.e., the net environmental impact of the nutrients released under the offsetting scheme should be less than the impact, which would have occurred in the absence of offsetting, and ideally providing additional environmental benefits, such as reduced sediment loads.

Different nutrient sources for offsetting are typically released from different locations at different frequencies. To ensure no net environmental impacts from offsetting, it is critical to determine the offset load based on equal environmental impacts that are generated by different nutrient sources. This project identified potential refinements to the current offset equation used in the Queensland Point Source Water Quality Offsets Policy 2019 to inform the review of the policy being undertaken by DETSI. This was done by incorporating research outputs from previous studies, expert elicitation and review from two workshops, and findings of a separate, but related, ARC Linkage project (CI Burford). The first workshop discussed nutrient offsetting and the offsetting equation from the perspective of modellers in industry, government, research institutions, experimental scientists, policymakers, natural resource management organisations, and sewage treatment operators. Existing relevant research was also discussed. At the second workshop, the focus was on road-testing proposed changes to the offsetting equation.

Based on the work undertaken in this project, we propose the following changes be made to the existing nutrient offsetting framework (point source and diffuse source offset) which is focussed on nitrogen:

- Calculate nutrient offsets based on total dissolved nitrogen (TDN) (which is dissolved inorganic nitrogen (ammonium and nitrate/nitrite) plus dissolved organic nitrogen) rather than the existing parameter, i.e., total nitrogen (TN). Algal bioassay results from the ARC Linkage project (CI Burford) showed the photosynthetic response of nitrogen-starved algae (both a marine *Nannochloropsis* and freshwater *Monoraphidium* species) was predominantly determined by the concentration of TDN, i.e., [TDN] (Lu *et al.*, 2024a b). Three nutrient sources were tested in the ARC Linkage project, i.e., discharges from 20 different STPs, 15 different aquaculture ponds, and simulated catchment runoff from 23 soil erosion sites (soil slurries) with repeated sampling from some of the sources (159 data points in total for the freshwater algal bioassay and 75 data points for the marine algal bioassay).
- Replace the current default equivalency ratio (ER = 1) with an ER value of 0.27$\pm$0.02 for the freshwater receiving waters when using soil erosion mitigation to offset TDN discharge from

STPs. In the case of aquaculture pond discharge, the proposed ER value is 0.76±0.14 when using soil erosion mitigation to offset point source TDN discharge.

- For the marine receiving environment, ER = 1 is used as the different sources resulted in the same algal response (measured by the marine *Nannochloropsis* species) for the same [TDN].
- Reconsider the delivery ratio: the current delivery ratio (DR) of 1.5 in the offset policy includes both delivery ratio and uncertainty. We therefore propose that these terms be decoupled as follows:
    - A change to a DR (Eq. S2.4, see below) of 1 between the diffuse and point source sites, since the main diffuse source for nutrient offsets in Queensland are nutrients derived from soil erosion. This occurs during storm events under high flow conditions. Under high flow conditions, when most diffuse catchment nutrient loads enter waterways, the transport of nutrients is likely to be more rapid than in-stream processing, and thus nutrient attenuation in the river is assumed to be minimal. This value of 1 is essentially a placeholder until more studies on delivery ratios is conducted.
    - We propose inclusion of an uncertainty factor (Eq. S2.5) with a value of 1.5, incorporating uncertainty from rainfall events, catchment load estimation, the effectiveness of catchment interventions, etc. This is a placeholder until there is a greater understanding of uncertainty.
- Update the nutrient offsetting equation to incorporate a factor to account for co-benefits (Eq. S2.6) of nutrient offsets (e.g., reduced erosion, flood control, carbon credits) in the modelling framework to better reflect the net environmental impacts of the offsetting projects to the receiving waterways and the upper catchment.

Based on the points outlined above, we propose the following equation for nutrient offsetting, using TDN loads of the offset period from sellers (e.g., riverbank erosion) and buyers (e.g., STPs or aquaculture ponds) and a defined equivalency ratio between the two sources:

TDN load reduced by seller (tonnes) = TDN load needed to offset from buyer (tonnes) (*S1.1)*

Or another words:

TDN load reduced by seller (tonnes) = $\sum_{t=0}^{t}([TDN]_{buyer,point\ source} \times Discharge\ (GL))$ ***(S1.2)***

$\times\ Equivalence\ ratio\ (ER)$ **[0.27-0.76 (freshwaters) or 1 (marine waters)** ***(S1.3)***

$\times\ Delivery\ ratio\ (DR)$ **[default value DR = 1]** ***(S1.4)***

$\times\ Uncertainty\ factor$ **[default value = 1.5]** ***(S1.5)***

$\times\ Co-benefits\ factor$ **[to be determined]** ***(S1.6)***

This equation synthesizes the available scientific knowledge relevant to nutrient offsetting to provide information for those interested in market-based approaches to managing nutrients. Finally, as a point of clarification, it is not designed to be a government policy document.

1. Introduction

1.1. Background and knowledge gaps for nutrient offsetting

Point source nutrient discharge and catchment/watershed degradation are two major causes of water quality degradation, including algal blooms and low oxygen conditions. Point source discharges are regulated to control nutrient loads reaching waterways, but population growth in many areas has reached a point where further point-source infrastructure updates have become very costly. In Queensland, utilities with point source nutrient discharge use the Queensland Government's Waste Management and Resource Recovery Strategy which involves a hierarchical structure for guiding and ranking waste management decisions for prevention, reduction, reuse, recycling and recovery (https://www.qld.gov.au/__data/assets/pdf_file/0028/103798/qld-waste-management-resource-recovery-strategy.pdf). Once options using this hierarchy have been exhausted, nutrient offsetting (or trading) schemes can provide an additional cost-effective approach to achieving water quality management goals in waterways, compared to infrastructure upgrades (Shortle, 2012; Bunn & Abal, 2018; Lötjönen *et al.*, 2021). Under such schemes, point nutrient source polluters invest in strategies, such as stream bank restoration and wetland construction, to reduce diffuse source nutrients to offset their nutrient discharge. There may also be co-benefits related to ecosystem services, e.g., carbon storage, biodiversity, and flood mitigation (Mueller, Soder & Springer, 2019; Cole, Stockan & Helliwell, 2020). The core offset principle is that the avoided impact (i.e., the impact that the avoided load would have had at, or downstream, of the offset site, had it been released) must be greater than or equal to the additional load generated by the offset buyer.

As a market-based approach to catchment restoration, the nutrient offsetting concept has gained significant traction throughout Australia. A recent assessment of nutrient offsetting opportunities and threats for the Australian water industry identified a number of examples where nutrient offsetting provided considerable benefits for the water industry, the environment, and the public (Burford & Lu, 2023). The report also identified a number of scientific challenges, including a lack of information on meaningful nutrient equivalency and delivery ratios for comparing nutrient loads from point sources, e.g., sewage treatment plants (STPs), and diffuse sources, e.g., catchment soil erosion, urban stormwater runoff (https://environment.des.qld.gov.au/__data/assets/pdf_file/0033/97845/point-source-wq-offsets-policy-2019.pdf).

A recent review of the international literature on nutrient offsetting approaches identified knowledge gaps in assessing the relative environmental impacts of diffuse and point source nutrients, including the need for improved water quality models (Lu *et al.*, 2023). New information on equivalency and delivery ratios is needed to help tackle such water quality model inputs. A recent ARC Linkage project (CI Burford) "Innovative tools needed for market-based nutrient offsetting" examined point and diffuse sources of nutrients in southeast Queensland, Great Barrier Reef catchments, and from NSW (Sydney region), including an assessment of the discharges from a range of STPs (Urban Utilities, Sydney

Water), pond aquaculture facilities (barramundi, prawns), and the impacts of soil samples used to generate simulated catchment runoff (multiple catchments). Researchers identified the key nutrient parameters across these different nutrient sources which gave maximum ecosystem responses, using algal and bacterial bioassays. The novel approaches to understanding and quantifying cause-effect relationships between nutrients and receiving water environments in these experimental studies provide a critical component needed for improvements to model capability for designing and assessing nutrient offsetting.

1.2. Project brief as per contract

In the QWMN contract, we planned to use information generated by the ARC Linkage project (CI Burford), and any other relevant information, to propose improvements to models used for nutrient offsetting. Specifically, the project aimed to achieve the following:

1. Develop a simple mechanistic model, based on data generated from the ARC Linkage project and any other relevant recent research, specifically for:
    a. Ecosystem responses to point and diffuse nutrient sources, and
    b. Attenuation rates (needed for determining delivery ratios) of diffuse source nutrients in river systems.
2. Map the current models used for delivery ratios and identify other studies with relevant information on nutrient attenuation in rivers (Aim 1).
3. Develop a framework for configuring the simple model from Aim 1 into current models to improve the robustness of model outputs and reduce uncertainty.

In this project, we proposed to bring together key participants in nutrient offsets: 1) the nutrient offsets policymakers in Queensland and NSW (QLD DETSI, NSW EPA); 2) researchers and consultants undertaking experimental studies and using models for nutrient transport and attenuation (Alluvium, Griffith University, University of Queensland, University of Western Australia, Water Technology, Aurecon); 3) proponents of offsetting in the water industry (Sydney Water, Urban Utilities, Unity Water, TasWater) and aquaculture industry; and 4) natural resource managers (Healthy Land and Water, Resilient Rivers southeast Queensland). The rationale for this was to ensure that the outcomes of the study are directly useful and relevant to sectors involved in nutrient offsetting, including the buyers of offsetting, such as the sewage treatment plant operators, as well as State Governments, particularly the regulation and policy areas.

2. Key findings

We ran two workshops with participants from key organisations interested in nutrient offset (see list above) to discuss the major knowledge gaps for determining the nutrient delivery ratio for offset projects. These workshops, which provided a platform for open and collaborative discussions, were instrumental in shaping the development of the offsetting model framework. Following the first workshop, a literature review was conducted on catchment and river water quality models to identify how the nutrient delivery ratio has been modelled for offset projects. This review, along with insights from the workshops, formed the basis for developing a modelling framework to revise the nutrient offset equations used for offset projects in Queensland.

2.1. First workshop: Discussion of the nutrient offset equation with experts and stakeholders

A total of 19 participants attended the first in-person workshop. The aim of the first workshop was to:

1. examine the current state of knowledge of implementing nutrient offsetting projects and

2. identify the nutrient delivery ratio used in the nutrient offsetting equation currently being used in the nutrient offsetting policy in Queensland (https://environment.des.qld.gov.au/__data/assets/pdf_file/0033/97845/point-source-wq-offsets-policy-2019.pdf).

The nutrient offsetting equation (Eq. (1)) in the current policy is:

$$Offset\ (tonnes)\ to\ be\ delivered\ by\ proponent\ proposal\ = Tonnes\ to\ be\ offset\ (TN, TP\ or\ TSS) \times Environmental\ equivalency\ ratio\ [=1] \times Delivery\ ratio\ [=1.5] \quad (1)$$

For nitrogen offsetting, this is based on total nitrogen (TN) load discharge from point sources (buyers) and diffuse sources (sellers). The current environmental equivalency ratio is 1, which assumes that an equal mass of TN from the point and diffuse sources will have the same environmental impact. The current delivery ratio in the equation is 1.5, reflecting that buyers need to offset 50% more of the TN loads from diffuse sources than point sources to ensure that the offset results in an overall improvement in waterway health. In the current offset policy in Queensland, this delivery ratio of 1.5 is a measure of uncertainty of comparing nutrient equivalencies (environmental equivalency ratio) as well as attenuation from different sources, and the effectiveness of diffuse source pollution abatement actions. At the first workshop, the rationale for this ratio, and the possibilities for updating this ratio with new science were discussed. These discussions were synthesized at the workshop, and the key output was a recommendation to update the existing offsetting equation (Equation 1) as follows:

- Predict ecological response (equivalency ratio) based on concentrations of total dissolved nitrogen, i.e., [TDN]. This deviates from the current measure, i.e., TN, which was shown to be a poor measure of ecosystem response in the bioassays which involved testing three nutrient sources (STPs, soil erosion, aquaculture pond discharge) are included. [TDN] was a better measure than either concentrations of TN or DIN. This is based on the results of an ARC

Linkage project (CI Burford) on nutrient equivalency ratios which measured algal responses from a marine *Nannochloropsis* and freshwater *Monoraphidium* green algal species to the nutrient sources (*Table **1***) (Lu *et al.*, 2024a b).

- Explicitly separate uncertainty from delivery ratio (DR) in Equation 1. This delivery ratio attempts to capture the attenuation of nutrients within an offsetting project from upstream diffuse catchment sources (e.g., soil erosion sites) to a downstream point (e.g., discharge point from a sewage treatment plant). The decoupled uncertainty includes uncertainties from rainfall events, catchment load estimation, the effectiveness of catchment interventions, etc. Further research is needed to more accurately estimate delivery ratios for individual rivers.
- Include an additional factor in Equation 1 to account for co-benefits, i.e., additional benefits from the offsetting project.

Existing catchment and river models can be run to generate a nutrient delivery ratio output, but the accuracy of these outputs can be highly variable. For example, models need to be configurable and adaptable enough to incorporate new science, and there is a need to develop concentration-based, rather than load-based, models to better describe ecosystem responses. There should be a feedback loop between policy, modelling, and monitoring/research to achieve the most efficient way of improving each component of the loop for nutrient offsets.

A few principles to parameterize the updated offsetting equation were also discussed at the workshop, including:

1. The use of multiple lines of scientific evidence for measures in the nutrient offsetting equation to reduce uncertainties.
2. Factoring in co-benefits with rigorous assessment would make nature-based solutions more (financially) attractive.
3. Consideration of the cumulative impacts of nutrient concentrations, rather than just focusing on nutrient loads.
4. Decoupling uncertainty from the delivery ratio will enable a more accurate assessment of the delivery ratio and explicitly address the sources of uncertainty.

Table 1. [TDN] was the best predictor of algal response (photosynthetic yield) across the three different sources (soil slurries, aquaculture and STPs) based on linear correlation (adjusted R^2) of the algal response (both freshwater and marine algal species) to concentrations of total nitrogen [TN], dissolved inorganic nitrogen ([DIN] = [ammonium] + [nitrate]), and total dissolved nitrogen ([TDN] = [DIN] + [dissolved organic nitrogen]).All results at p<0.01 level). From Lu et al., (2024a, b).

Algal species	Nutrient sources		No. of samples	[TN]	[DIN]	[TDN]
				(Linear correlation adjusted R^2 of algal response with the nutrient parameter above)		
Freshwater *Monoraphidium* species	Individual sources	Soil slurries from erosion	90	0.22	0.39	0.55
		Aquaculture ponds	45	0.51	0.53	0.58
		STPs (Sewage treatment plants)	24	0.58	0.59	0.58
	Across all three sources		159	0.06	0.41	0.50
Marine *Nannochloropsis* species	Across all three sources		75	0.04	0.25	0.32

2.2. Review of previous studies on model inputs and development of algorithms relevant to offset ratios

A literature review was conducted investigating offset ratios for previous and existing projects. Point and diffuse sources of nutrients enter waterways at different concentrations and with different proportions of nutrient forms. The frequency and duration of discharge and location in the catchment also varies. Therefore, the impacts of point- and diffuse nutrient sources on receiving waters are likely to be different (Lu *et al.*, 2024a b). Providing the scientific basis for determining offset ratios between point and diffuse sources is a fundamental step in implementing a fair and transparent nutrient offset program (Puzyreva, Roy & Stanley, 2019). This would involve the use of monitoring, as well as modelling, however it can be difficult to determine statistical differences, based on monitoring, as a result of restoration works.

Higher ratios may be used in nutrient offsetting equations to provide a precautionary approach. However, if the ratios are too high, they may also reduce the willingness of point-source polluters to engage in nutrient offsetting (Horan & Shortle, 2017). This is because treating waste on-site might then be more cost-effective than offsetting (King & Kuch, 2003). In contrast, low offset ratios may not sufficiently mitigate the point source nutrient discharge, resulting in poorer environmental outcomes.

Additional findings on delivery ratios in the literature were:

1. The dominant mechanisms for nutrient attenuation in rivers include: settling of particulate matter (especially for phosphorus); denitrification (for nitrogen); and plant uptake of inorganic forms of both nutrients (Mulholland *et al.*, 2000; Peterson *et al.*, 2001; Withers & Jarvie, 2008).
2. The driving factors for nutrient attenuation (especially for nitrogen attenuation) in rivers include: nitrate concentrations (for denitrification); sediment grain size and turbidity; water residence time; and organic carbon loads, etc. (Seitzinger *et al.*, 2002).
3. In models, nutrient attenuation rates were mainly determined for total nutrients only (e.g., TN), with no nutrient partitioning.
4. Nutrient attenuation rates were typically determined using catchment and river water quality models coupled with hydrological models, e.g., AED, WARMF, TUFLOW. These are process-based models, which include physical transport processes, abiotic chemical reactions, and biological processing of nutrients. The degree to which models are parameterised and validated with data from the relevant river system is highly variable.
5. Nutrient attenuation rates can vary between different rivers mainly driven by residence time (hydrological conditions). For example, in the Ohio River Basin, the TN attenuation per km was 0.19–1.6% for smaller rivers, 0.14–1.3% for medium rivers, 0.13–1.1% for large rivers, and 0.04–0.42% for the largest rivers studied (Keller *et al.*, 2014).

In order to develop an improved algorithm relevant to delivery ratios for different nutrient sources and river systems, the data from the ARC Linkage project (CI Burford) on nutrient equivalency ratios and attenuation were used (Figure 1). We aimed to make a simple measure relevant to the nitrogen offsetting policy. The ARC project found:

1. [TDN] is a more meaningful measure to determine algal growth responses to three different nutrient sources (STPs, aquaculture pond discharge, and simulated catchment runoff from soil erosion), compared with the current metric, i.e., TN, for both freshwater and marine algal species (Lu *et al.*, 2024a b). Therefore, [TDN] is the most relevant variable for the nutrient offsetting equation, especially for comparing soil erosion-related runoff with either aquaculture or STP discharge. It should be acknowledged that the algal response bioassay examines short-term responses, not the longer-term transformation of nitrogen which may ultimately lead to impacts on water quality.
2. Attenuation of nitrogen from catchment runoff (where sediment is the primary source) within the river is therefore driven by the attenuation of [TDN], which has been shown to be affected by organic carbon and carbon to nitrogen (C:N) ratios in both the nutrient sources and the receiving waters, as well as the hydrological conditions and the geomorphological features of the river (which affect water residence time).
3. A conceptual algorithm for accounting the attenuation was generated, as outlined in Figure 1. This included attenuation of [TDN], per km of river, per day (Eq. (2)) for sellers.

$$Attenuation\ per\ km\ per\ day = \frac{\frac{[TDN]_{in} - [TDN]_{out}}{[TDN]_{in}}}{Length\ of\ reach \times Residence\ time} \quad (2)$$

Where:

1. $[TDN]_{in}$ and $[TDN]_{out}$ are the concentrations of sellers' TDN at the offset and point source site, respectively. Those two sites are used in this report for [TDN] attenuation calculations because we assume the nutrient attenuation occurs between them, rather than at the coastal receiving waters.
2. Length of reach is the reach distance between the seller's site and the buyer's site.
3. Residence time is the transport time between the offset site and the point source.

This is the simplest scenario, which ignores other inputs within the river system, e.g., inflow from tributaries. As such, it is a theoretical attenuation if there were no other confounding factors. It is also acknowledged that when suspended sediments from erosion processes reach coastal/marine environments, TDN can also be released from desorption due to salinity changes and mineralisation processes during the offsetting period (Garzon-Garcia *et al.*, 2021), which may lead to DR < 1.

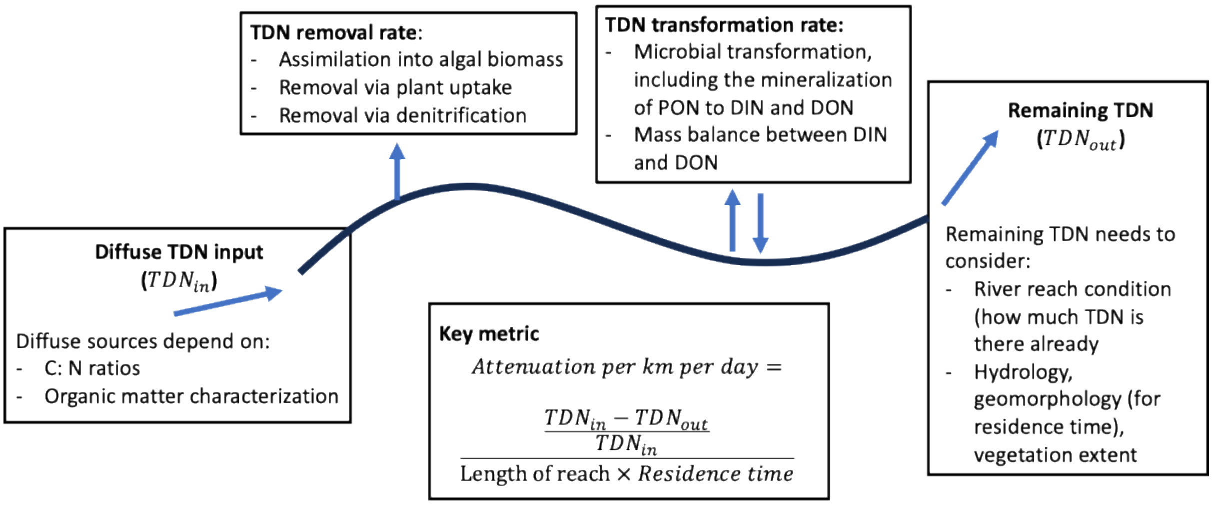

Figure 1. Conceptual diagram with an algorithm for the nutrient delivery ratio within a river reach, based on research from the ARC Linkage project (CI Burford). TDN = total dissolved nitrogen. DIN = Dissolved inorganic nitrogen. DON = Dissolved organic nitrogen.

2.3. Reviewing the revised nutrient offset equation and second workshop

A six-step modelling framework was developed for the revised nutrient offset equation (Eqns. (3.1)–(3.5)) based on discussions from the first workshop and findings from the offset ARC Linkage project (CI Burford), i.e., [TDN] was the best single nutrient parameter that explains the algal growth response, based on 3-day short-term bioassays (*Table **1***). Therefore, we proposed that TDN is a better metric for offsets between different nutrient sources as follows:

TDN load reduced by seller (tonnes) = TDN load needed to offset from buyer (tonnes) *(3.1)*

$$\times \, Equivalence \; ratio \; (ER) \qquad (3.2)$$

$$\times \, Delivery \; Ratio \; (DR) \qquad (3.3)$$

$$\times \; Uncertainty \; factor \qquad (3.4)$$

$$\times \; Co - benefits \; factor \qquad (3.5)$$

In its generic form, this proposal for a revised offset equation (Eqns. (3.1) – (3.5)) is a mass balance over a river reach that establishes how much TDN must be saved upstream (sellers) for the TDN discharged downstream (buyers) per year. The left-hand side of the equation (Eq. (3.1)) is the resulting load of TDN *(t* y^{-1}*)* that needs to be saved at the offset site (the seller's TDN load). On the right-hand side (Eqns. (3.2) – (3.5)), the TDN load released by the offset buyer *(t* y^{-1}*)* at the point source (Eq. (3.2)) is adjusted by accounting for the equivalency *(t* t^{-1}*)* of the seller's and buyer's TDN based on the algal bioassay response from the ARC Linkage project (ER: Eq. (3.2)), TDN losses/increases *(t* t^{-1}*)* via attenuation/mineralisation processes in the river or coastal/marine environments (DR: Eq. (3.3)), uncertainty (Eq. (3.4)) attached to any element in the offset equation, and co-benefits (Eq. (3.5)) that the offset may accrue.

To obtain feedback on the revised equation (Eqns. (3.1) – (3.5)), a second workshop was held with nutrient offset stakeholders. A total of 36 people were invited to a virtual workshop (Qld DETSI, consultants, water industry, academics). A total of 16 people attended from across QLD DETSI, consultancies, the wastewater industry in QLD and NSW, natural resource management groups, and NSW EPA. The proposed modelling framework was presented by the research team, followed by a Q&A session. A summary document outlining the framework was also subsequently sent to all invited people, including those who could not attend, seeking comments and feedback.

At this workshop, the revised offset equation was presented in six steps, as outlined below (Sections 2.3.1 – 2.3.6), to explain how each component was determined. It is acknowledged that the revised equation is based on riparian zone/riverbank erosion being a key source of diffuse nutrients to rivers in Australia (Wasson *et al.*, 1998; Prosser *et al.*, 2001; Brooks, Olley & Spencer, 2014). Therefore, the offset example in this report focused on riverbank erosion as the primary diffuse source of nitrogen (*Figure* 2).

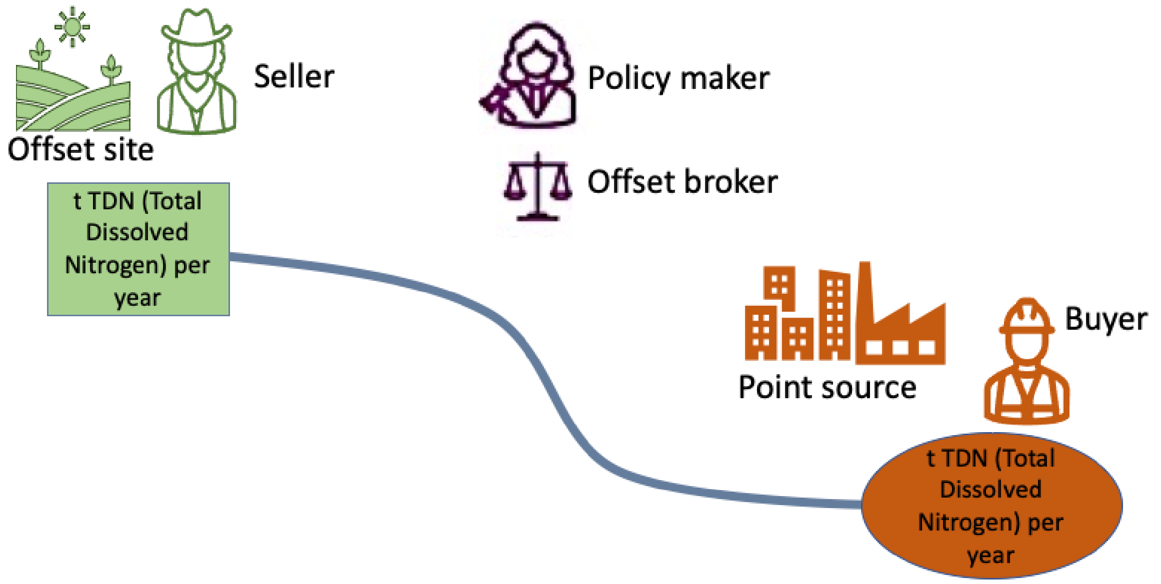

Figure 2. A conceptual model of the offset equation illustrating the key stakeholders in the offsetting process and where they are situated. The offset seller is upstream of the offset buyer, and the two are connected through the river reach, which is impacted by the nutrients released from the offset site. The third and fourth perspectives are the policy maker and offset broker, who set the boundaries of the agreement as well as how the offset load can be calculated.

2.3.1 Step 1: TDN load calculation for buyer (point sources)

The load of TDN from point sources is the [TDN] (mg L^{-1}) in their effluent multiplied by the associated discharge over the period of time selected for offsetting (t = 0 to t) (Eq. (4)).

$$TDN\ load\ needed\ to\ offset\ from\ buyer\ \ (tonnes) = \sum_{t=0}^{t}([TDN]_{buyer,point\ source} \times Discharge\ (GL)) \quad (4)$$

2.3.2 Step 2: Determine the environmental equivalency ratio

The second step was to calculate the environmental equivalency ratio (ER) using the same environmental impacts, i.e., algal photosynthetic yield, that [TDN] of the buyers and sellers can cause at the point source discharge site. This assumes that the offsets between the sellers and buyers occur at the buyer's site (e.g., at the STP discharge site). The measured relationship between [TDN] and photosynthetic yield for buyer's [TDN] (e.g., STP source) and seller's [TDN] (e.g., soil source) were derived for the freshwater alga, *Monoraphidium,* used in the ARC Linkage project (CI Burford; Figures 3, 4 & Table 2). This relationship was developed from a Monod-type equation typically used for measuring algal responses to nutrients (Hecky & Kilham, 1988) (Eq. (5)).

$$y_i = Ymax_i \frac{[TDN]_i(mg\ L^{-1})}{K_i(mg\ L^{-1}) + [TDN]_i(mg\ L^{-1})} \quad (5)$$

Where:

1. y_i is the photosynthetic response to [TDN] for the nutrient source i, i.e., $[TDN]_i$ (i could be either point or diffuse sources, i.e., the buyer or seller).
2. $Ymax_i$ is the maximum algal photosynthetic response to nutrient source i.
3. K_i is a half saturation constant for nutrient source i (the buyer or seller), representing the concentration at which the photosynthetic productivity is 50% of $Ymax_i$.

In the Michaelis-Menten model fitting for the three nutrient sources, we assumed that *Ymax* (the maximum achievable algal response) is the same for all nutrient sources. This means that all nutrient sources can reach the same *Ymax* for the algal growth when the TDN concentration is sufficiently high. This assumption is based on a fact that all TDN would eventually become bioavailable to algae after an extended period of mineralisation.

The calculation of ER (Eq. (6)) was based on the calculated [TDN] from the seller at the point source site ($[TDN]_{seller,\ point\ source}$) that would have the equivalent environmental response to [TDN] from the buyer ($[TDN]_{buyer,\ point\ source}$).

$$[TDN]_{seller,point\ source}(mgL^{-1}) = ER \times [TDN]_{buyer,\ point\ source}\ (mgL^{-1}) \quad (6)$$

For the freshwater environment, the algal response differed for [TDN] from different sources with the same *Ymax* (the maximum achievable algal response) (Figure 3 & Table 2). Therefore, an equality constraint (Eq. (7)) is imposed to compare the algal photosynthetic response from both offset participants at the point source site based on the algal photosynthetic yield response and [TDN] relationships developed in Eq. (5) and the same *Ymax* for nutrient credit buyers and sellers.

$$y_{buyer} = y_{seller} \quad (7)$$

Therefore, the calculation of ER was:

$$ER = \frac{K_{seller}}{K_{buyer}} \quad (8)$$

The constants K_{seller} and K_{buyer} in Eq. (8) were derived from the measured relationship in Eq. (5) (Figure 3 and Table 2). The resulting equivalency ratio is a generally applicable equation accounting for differences in the natural variability of soils, STPs, and aquaculture pond effluents (Figure 3 and Table 2).

We tested a range of potential *Ymax* values ranging from 1-2. Based on this testing, the change in Equivalency Ratio (ER) showed little variation but the uncertainty decreased as *Ymax* increased (Figure 4) for the buyer when trading with soil erosion control. For example, if the buyer is discharging from aquaculture ponds, the mean ER varies between 0.68 and 0.86; if the discharge is from STPs, the mean ER varies between 0.26 and 0.27. This indicates that the change of *Ymax* does not significantly impact ER calculations. However, to achieve a minimum uncertainty in the model fitting for all nutrient sources, as seen in Figure 4 (with smaller root-mean-square deviation (RMSE) and higher R^2 as seen in Table 2), *Ymax* was set to 1.21 for all nutrient sources in Figure 3 and Table 2.

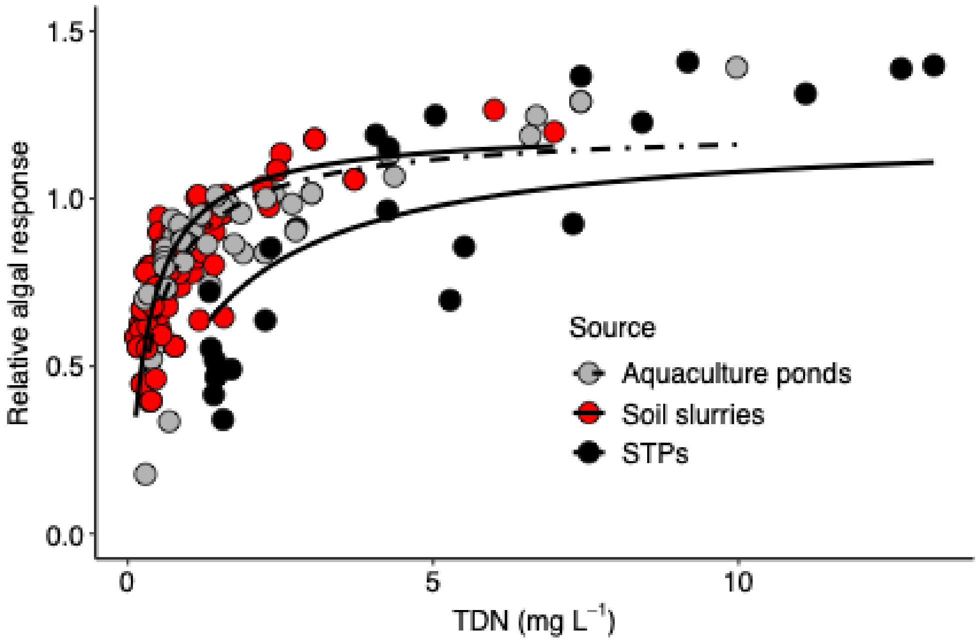

Figure 3. The Michaelis-Menten model fitting of the relative algal responses (dimensionless standardized photosynthetic yield) after three days of incubation of the green freshwater algal species, Monoraphidium *spp. in a range of total dissolved nitrogen concentration (TDN, mg L^{-1}) in samples from STPs (solid black curve), aquaculture ponds (dashed black curve) and soil slurries (solid black curve with red circles). The data are from Lu et al. (2024a, b).*

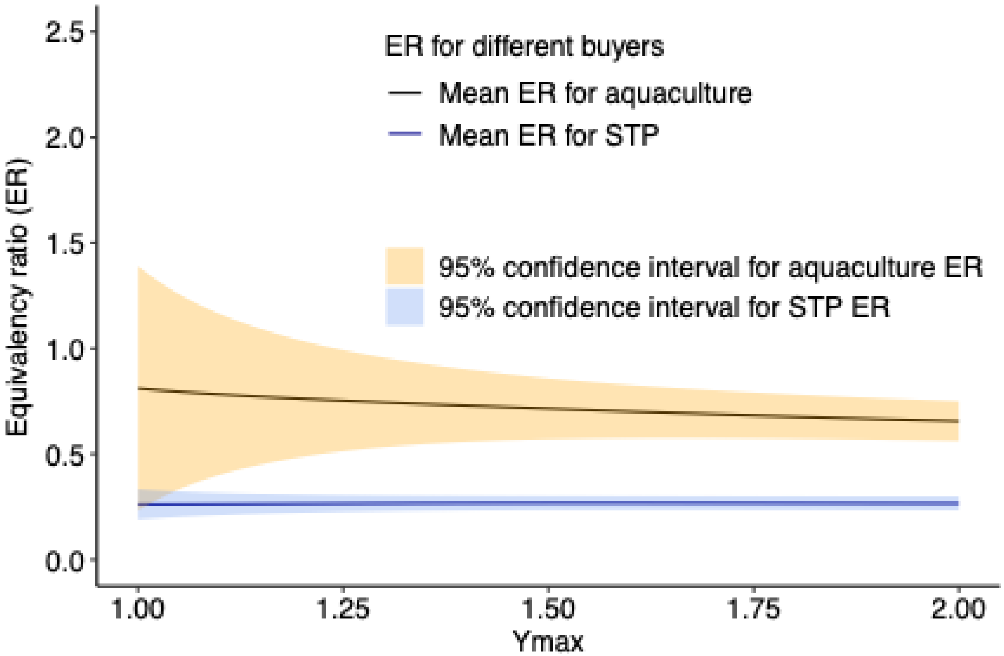

Figure 4. Equivalency ratio (ER) variation for the same algal response (freshwater Monoraphidium*) of TDN from STP and soil slurries, or from aquaculture ponds and soil slurries, at the same location of the waterway when Ymax (the maximum achievable algal response) changes from 1 to 2.*

Table 2. The Michaelis-Menten model fitting statistics (R^2 and RMSE) and the half-saturation concentration (K) together with the associated standard errors for Equation 5 when Ymax = 1.21 for the freshwater algae, Monoraphidium *responses to three* nutrient sources *(data from Figure 3, Lu et al.2024a, b). Nutrient source samples were taken from twenty different STPs, fifteen aquaculture ponds, and twenty-three different soil sites with repeated samples for each source from sites in southeast Queensland and New South Wales area.*

Nitrogen sources	Typical trading role	No. of samples	*K*	R^2	RMSE
Sewage treatment plants (STPs)	Buyer	24	1.20 ± 0.14	0.58	0.22
Aquaculture ponds	Buyer	45	0.42 ± 0.14	0.70	0.13
Soil slurries (a proxy for catchment erosion)	Seller	90	0.32 ± 0.03	0.50	0.13

It is worth noting that the validity of this model fitting is likely stronger below 5 mg L^{-1} due to the limited data points at higher TDN concentrations, especially for soil slurries. The algal bioassays in Lu et al. (2024a, b) were designed to test soil slurries with a range of TSS concentrations (0.25 – 14 g L^{-1}) that might occur in the catchment runoff of erosion during storm events, including TSS concentrations up to 26,000 mg L^{-1}. At these TSS concentrations, [TDN] in 98% of the tested soil slurries was < 5.0 mg L^{-1}. However, algal bioassays in the ARC Linkage project did not examine eroded soils with significant fertilizer loads, which would have higher [TDN]. Further research on soils with a higher [TDN] may impact the range of the ER equations.

During the discussions at the second workshop, it was also proposed that point sources that have higher [TDN] in the discharge (e.g., discharge from aquaculture ponds > 3.0 mg L^{-1} and [TDN] discharge from STPs > 5 mg L^{-1}) should focus on reducing the [TDN] in the discharge first, rather than considering nutrient offsetting. This is because these concentrations are not typical for either STPs with tertiary treatment, or well managed aquaculture ponds. Therefore, the use of the constant ER from Equation 8 for nutrient offsetting should be in combination with the regulations on [TDN] for point sources. This also aligns with the Queensland Government's Waste Management and Resource Recovery Strategy for utilities, which involves a hierarchical structure for guiding and ranking waste management decisions for prevention, reduction, reuse, recycling and recovery (https://www.qld.gov.au/__data/assets/pdf_file/0028/103798/qld-waste-management-resource-recovery-strategy.pdf). Nutrient offsetting can be considered once options using this hierarchy have been exhausted.

We have also explored other models with relevant modellers and applied mathematicians that may provide better model fittings for the data in Figure 3. For example, adding a linear component to the Michaelis-Menten model improved the model fitting (R^2) for soil slurries at higher [TDN]. However, due to a lack of evidence for the ecological meaning of adding a linear component to the commonly used Michaelis-Menten model to describe the algal response to nutrients, we used the commonly used Michaelis-Menten model outlined above to develop the ER equations (Eq. (5-8)). However, we acknowledge that better model fittings for the data in Figure 3 may serve as alternative approaches to developing the ER equations when further research on the mechanism of algal response to TDN becomes available.

For the marine environment, using the green alga, *Monoraphidium*, there was a similar algal response for the same [TDN] from both offset participants (Figure 5). Therefore, the ER can be equal to 1, resulting in a much simpler process for calculation of response.

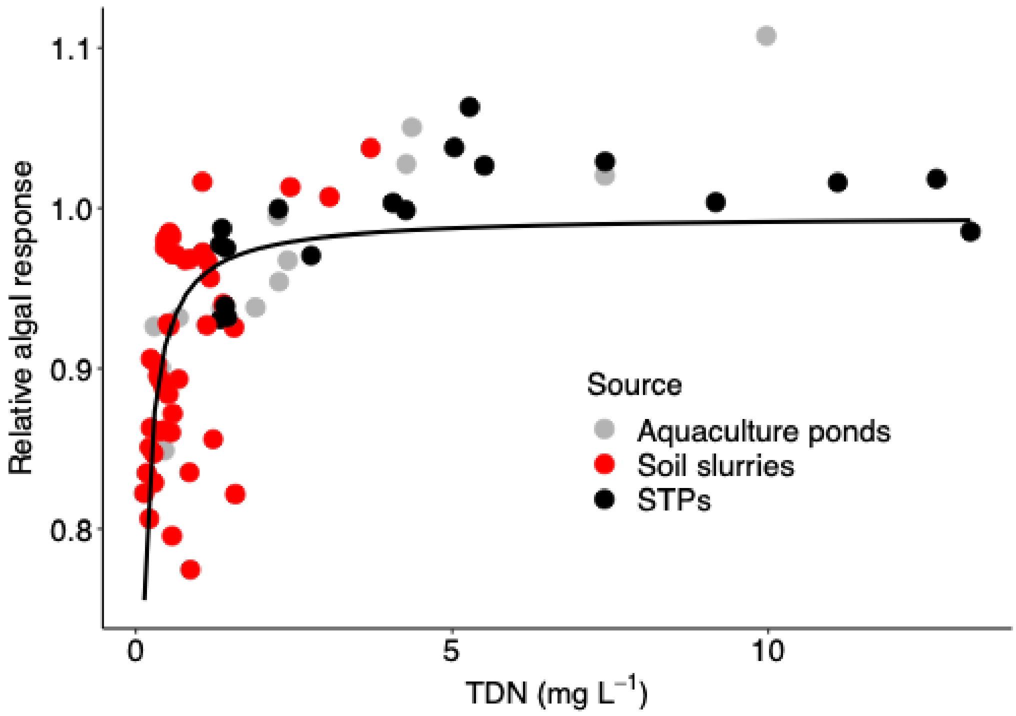

Figure 5. The Michaelis-Menten model fitting for the relative algal responses (standardized photosynthetic yield) of the green marine algal species, Nannochloropsis oceania, *to three nutrient sources after three days of incubation.*

2.3.3 Step 3: Account for processing/attenuation during delivery

The delivery ratio in the revised offset equation accounts for the attenuation of [TDN] from the diffuse source (seller) that the river reach achieves before the material arrives at the buyer's location, and can be used to calculate the [TDN] at the offset site (Eq. (9)):

$$[TDN]_{seller,offset\ site}\ (mgL^{-1}) = DR\ \times\ [TDN]_{seller,\ point\ source}\ (mgL^{-1}) \qquad (9)$$

As shown in Section 2.2 and *Figure* 1, [TDN] attenuation processes in rivers depend on a range of factors. Currently, there is limited information on attenuation processes to calibrate and validate models. Therefore, nutrient monitoring is required to cover the spatial and temporal variability over a long enough time frame to account for seasonality. Additionally, there is a need for process studies of attenuation, rather than relying only on long-term nutrient modelling. For the purposes of this report, it was assumed that the DR would be fixed at a value of 1:1, assuming that most flows that liberate soils occur during large flow events where the water residence time is short (between the offset site and the point source) and the ability of the river to process nitrogen is reduced. For example, analysis of long-term water quality river water quality and point source monitoring data for the Brisbane River estuary showed that TN from large flood events largely passes through the estuary without detectable removal processes (Newham *et al.*, 2024). However, nitrogen loading resulting from major floods has been found to cause significant long-term impacts due to sediment resuspension, e.g., ammonium release from the porewater of the deposited sediment from major floods in Moreton Bay (Grinham *et al.*, 2024). Therefore, [TDN] attenuation and/or release under different flow and receiving water conditions warrants further research to better define DR in the revised offset equation (Eqns. (3.1) – (3.5)) for different offset scenarios.

2.3.4 Step 4: Define and quantify co-benefits

Catchment abatement actions that reduce nutrient loads into waterways may also provide a range of co-benefits to the environment, such as a reduction in sediment loads, carbon credits, higher biodiversity, flood control, improved habitat connectivity and refugia, groundwater recharge, and river aesthetics (Gundersen *et al.*, 2010; Fortier *et al.*, 2015; Dixon *et al.*, 2016). Assessing co-benefits in natural capital markets is an emerging field, and therefore, this project was not able to quantitatively assess these co-benefits. However, we are proposing changing the structure of the offsetting equation to allow more flexibility to account for co-benefits in the future, via a dimensionless co-benefit factor.

In terms of accounting for co-benefits, two types of co-benefits can be considered: 1) co-benefits for parameters that are directly related to nutrients (i.e., the co-benefit factor can be expressed in equivalent mass of TDN, e.g., the contribution of particulate nitrogen to TDN); 2) co-benefits not directly related to nutrients (e.g., carbon sequestration, terrestrial biodiversity, flood damage reductions, reductions in downstream sedimentation and associated dredging works).

Both types of co-benefits should be considered in the offsetting model, and both types have a level of uncertainty in quantification. In addition, a clear mechanism for governance and a framework that shows which co-benefits should be considered for offsetting projects should be developed in these natural capital markets. A broker or a credit bank that facilitates credit trading would be helpful. For example, a Nutrient (both nitrogen and phosphorus) Credit Trading Scheme in Pennsylvania, targeting Chesapeake Bay, uses a trusted third party for active engagement and mediation (Boleman & Jacobson, 2021). These kinds of schemes can deliver broader-scale environmental benefits but require leadership and coordination. It requires leadership from the water industry to champion this approach and a willingness of various levels of government to engage (Burford & Lu, 2023).

2.3.5 Step 5: Incorporate uncertainty.

It was identified that it was important to include uncertainty in any nutrient offsetting equation. The uncertainty factor should be a ratio and dimensionless, which allows for the quantification of multiple sources of uncertainty. The units of the numerator and denominator in the uncertainty factor are, therefore, flexible as long as they cancel each other out. A higher than 1:1 offset ratio (= equivalency ratio x delivery ratio) was typically used in offset projects to account for the uncertainties for each component of the offset modelling framework. In the current work, the uncertainty quantification from the equivalency and delivery ratio was decoupled to identify strategies to reduce the overall uncertainties for offset projects. An uncertainty factor of 1.5 is proposed to account for the uncertainties listed below. This default value can be modified as further evidence is provided. Those uncertainties and identified strategies include:

1) Uncertainties derived from the natural stochasticity of nutrient load generation from diffuse sources due to variability in weather, climate, and soil characteristics (Horan & Shortle, 2005, 2017). This is less of a confounding factor for point sources than diffuse sources. Catchment water quality models can be important tools to address this uncertainty. However, there are also high model uncertainties in estimating diffuse source nutrient loads due to the lack of sufficient data to calibrate or validate models. Therefore, more diffuse source load monitoring is needed to improve models in order to substantiate the validity of nutrient load estimation from diffuse sources.
2) Uncertainties in the effectiveness of abatement actions on nutrient load reduction from diffuse sources. This requires technological and scientific input to improve monitoring approaches. A standardised approach to monitoring offset project efficacy across natural capital markets is also needed.
3) Uncertainties related to environmental equivalency ratios for different nutrient sources in the offset project. This has been explored by investigating uncertainty ranges of ER based on the uncertainty in estimated model parameters (95% confidence intervals of K in Eq. (5) (Table 2) and changes of *Ymax* from 1 to 2 in Figure 5). The ER uncertainty range (Figures 5, Table 2) is 0.27 ± 0.02 when using soil erosion mitigation to offset TDN discharge from STPs, and the range is 0.76 ± 0.14 when using soil erosion mitigation to offset TDN discharge from aquaculture ponds.
4) Uncertainties related to the nutrient attenuation rates (delivery ratio) for diffuse nutrient sources transported in the river from upstream to downstream (Arabi *et al.*, 2007). As discussed in Section 2.2, more research is needed to quantify the impacts of a range of factors on nutrient attenuation during transportation from upstream to downstream in rivers. This includes impacts of diffuse source nutrient characteristics, river water quality, and river flow and topography conditions (*Figure* 1).
5) The uncertainties related to co-benefits and how they can be defined for nutrient offset projects.

Other overseas studies have accounted for uncertainty in nutrient offsetting by setting aside a proportion of nutrient credit in the credit reserve to address pollutant reduction failures and uncertainty. For example, the nutrient credit calculation in the Pennsylvania nutrient credit trading program in Chesapeake Bay, USA, must include 10% set aside for credit reserve (Boleman & Jacobson, 2021).

In summary, reducing uncertainty should come with financial benefits, i.e., a lower uncertainty factor will reduce the offset amount in the equation to make offsetting projects feasible and incentivise the offsetting scheme. Therefore, an investment into a nutrient offsetting project is not only an investment in the actual project but, to a degree, also an investment into reducing uncertainty in future offsetting projects if enough information can be gathered from it.

2.3.6 Step 6: Estimate the offset load needed at the offset site

After determining ER, DR, co-benefits, and uncertainty, the seller's TDN load needed at the offset site can be calculated using Equations 3.1-3.5. The amount of soil needed to be stabilised at the riverbank can be calculated based on the [TDN] in the fine particles of the eroded soils. This [TDN] in the fine particles of the eroded soils can be measured at an analytical laboratory using the soil slurries generated from the offset site soil. This methodology is routinely used, for example, at the QLD DETSI chemistry laboratory.

3. Areas for future research

This study also identified a number of areas requiring additional work:

1. Nutrient attenuation in rivers has been poorly studied. There are a limited number of studies where water quality data has been used to determine attenuation, and based on this, hypotheses were posed about potential reasons for this. However, very few process studies to test hypotheses have been undertaken. Therefore, there is a critical need for more process studies.
2. Nutrient offsetting does not account for longer term, far-field impacts of nutrients. This includes the longer-term fate of particulate nutrients, such as from soil erosion. The reprocessing and increased bioavailability of these nutrients may occur beyond the river system in bays and estuaries. Therefore, studies should also examine the fate of nutrients in the longer term and the degree to which cumulative effects, such as deposition of sediments in coastal environments, can have chronic effects on ecosystem health.
3. The algal bioassay for a marine and a freshwater algal species was a useful tool to compare the impacts of different nitrogen sources in a standardized way. However, future work should also examine the impacts on situ algae, not just cultured algae, and also focus on methodology for phosphorus. This needs to be combined with modelling to examine the full range of factors promoting and limiting algal growth, e.g., light availability.

4. Summary and conclusions

This project identified potential refinements to the current offset equation used in the Queensland Point Source Water Quality Offsets Policy 2019 to inform the review of the policy being undertaken by DETSI. Based on the work undertaken in this project, we propose the following changes be made to the existing nutrient offsetting framework (point source and diffuse source offset), focussed on nitrogen:

- Calculate nutrient offsets based on total dissolved nitrogen (TDN) (which includes both dissolved inorganic nitrogen (ammonium and nitrate/nitrite) and dissolved organic nitrogen) rather than the existing metric of Total Nitrogen (TN).
- Replace the current default equivalency ratio (ER = 1) based on different receiving water environments. For the marine receiving environment, ER = 1 based on a comparable algal response (measured by the marine *Nannochloropsis* species) for the same [TDN] in different nutrient sources. However, for the freshwater receiving environment, calculate an ER based on the [TDN] from sellers (usually diffuse sources in the upper catchment), which would produce the same algal response as the [TDN] released from buyers (usually point sources in the lower catchments)
- Reconsider the delivery ratio: the current delivery ratio (DR) of 1.5 in the offset policy includes both delivery ratio and uncertainty. We propose that these terms be decoupled as follows:
  - We propose a DR of 1 between the diffuse and point source sites, since the main diffuse source for nutrient offsets in Queensland are nutrients derived from soil erosion. This value of 1 is essentially a placeholder until more studies on delivery ratios is conducted
  - We propose inclusion of an uncertainty factor with a value of 1.5 to match the current offsetting equation, incorporating uncertainty from rainfall events, catchment load estimation, the effectiveness of catchment interventions, etc.
  - The default values for DR and uncertainty could be revised if/when more information is provided that DR < 1 (e.g., nutrient release from eroded sediment in the marine receiving environment during the offsetting project) or uncertainty < 50 % (e.g., via validated spatial and temporal hydro-biogeochemical modelling).
  - Update the nutrient offsetting equation to incorporate a factor to account for co-benefits of nutrient offsets (e.g., reduced erosion, flood control, carbon credits) in the modelling framework to better reflect the net environmental impacts of the offsetting projects to the receiving waterways and the upper catchment.

Based on the points outlined above, we propose the following modelling framework for nutrient offsetting, based on [TDN] from sellers (e.g., riverbank erosion) and buyers (e.g., STPs or aquaculture ponds):

TDN load reduced by seller (tonnes) = TDN load needed to offset from buyer (tonnes) (*S1.1)*

Or another words:

TDN load reduced by seller (tonnes) = $\sum_{t=0}^{t}([TDN]_{buyer,point\ source} \times Discharge\ (GL))$ ***(S1.2)***

$\times\ Equivalence\ ratio\ (ER)$ **[0.27-0.76 (freshwaters) or 1 (marine waters)** ***(S1.3)***

$\times\ Delivery\ ratio\ (DR)$ **[default value DR = 1]** ***(S1.4)***

$\times$ $Uncertainty\ factor$ **[default value = 1.5]** ***(S1.5)***

$\times$ $Co - benefits\ factor$ **[to be determined]** ***(S2.6)***

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