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Monitoring guidelines

To quantify nitrogen removal in vegetated water treatment systems (constructed treatment wetlands and vegetated drains)

January 2024

Queensland Government

This publication has been compiled by Dr Fabio Manca and Carla Wegscheidl of Department of Agriculture and Fisheries.

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The authors acknowledge the valuable edits and input from stakeholders in the Treatment System Community of Practice and colleagues in the Queensland Government. This document was prepared as part of the Agriculture Water Treatment project funded through the Queensland Government's Queensland Reef Water Quality Program.

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Purpose of this document

This document provides guidance on designing water monitoring programs for calculating nitrogen removal by vegetated water treatment systems, including constructed treatment wetlands or vegetated drains. The document focuses on monitoring of vegetated water treatment systems used to reduce nitrogen leaving farms prior to entering natural waterways and wetlands in tropical and sub-tropical Queensland. It aims to enable estimation of nitrogen reduction as accurately as possible within the constraints of monitoring in highly variable environments.

This document aims to provide consistency in monitoring approaches, enabling comparison of different vegetated water treatment systems and synthesis of information across different projects and sites to further knowledge on the performance (and limitations) of vegetated water treatment systems in different climatic regions, farm types and water regimes. The target audience includes research personnel, natural resource managers and land managers interested in monitoring vegetated water treatment systems to assess water quality improvement.

The document is written with the specific conditions and constraints of agricultural production areas in mind. Although vegetated water treatment systems are also used to treat urban stormwater and wastewater such as treated sewage effluent, the design, operating environment, and monitoring budget can be different. The principles in these guidelines can be adapted to these other land uses, although the objective of the vegetated water treatment system, flow regime(s) and nitrogen form(s) may be different thereby influencing the purpose of the monitoring project.

The methods outlined in this document have been compiled from methodologies described in both peer-reviewed publications and reports, together with technical input and advice from scientists and natural resource management officers involved in implementing and monitoring vegetated water treatment systems in Queensland. As monitoring methods, technologies and equipment are constantly evolving, the reader should undertake their own investigations in designing the monitoring program to ensure it meets the specific purpose of the monitoring project.

Detailed information on different types of vegetated water treatment systems and treatment processes are available on the Queensland Government Wetland*Info* website wetlandinfo.des.qld.gov.au.

Contents

Acronyms

A_{aq}: aquifer saturated area transmitting groundwater

A_{cs}: cross-sectional area of a measured watercourse

C_i: outlet tracer concentration of the i^{th} sample is collected during a tracer test

DEM: digital earth model

DIN: dissolved inorganic nitrogen

DKN: total dissolved Kjeldahl nitrogen

DON: dissolved organic nitrogen

Δt_i: time interval between tracing samplings during a tracer test

ET: evapotranspiration

Φ: aquifer porosity

G_{in}: groundwater discharge entering a vegetated water treatment system (infiltration)

G_{ex}: groundwater discharge exiting a vegetated water treatment system (exfiltration)

HRT: hydraulic residence time

i: hydraulic gradient

K: hydraulic conductivity

N_{GWin}: nitrogen concentration of groundwater entering a vegetated water treatment system

N_{GWex}: nitrogen concentration of groundwater exiting a vegetated water treatment system

NO: nitric oxide

NO_2^-: nitrite

NO_3^-: nitrate

NO_x–N: dissolved oxidised nitrogen

N_2: dinitrogen (nitrogen) gas

N_2O: nitrous oxide

NH_3: ammonia

NH_4^+: ammonium

P: precipitation

Q_g: groundwater discharge

Q_s: surface water discharge

S_{in}: surface water discharge measured at the inlet of a vegetated water treatment system.

S_{out}: surface water discharge measured at the outlet of a vegetated water treatment system.

TAN: total ammonia nitrogen

TDN: total dissolved nitrogen

TKN: total Kjeldahl nitrogen

TN: total nitrogen

τHRT: tracer hydraulic residence time

t_i: time an i^{th} sample collected during a tracer test

v: groundwater velocity

VWT: vegetated water treatment

Glossary

Baseflow: steady-state flow conditions when the surface runoff from rainfall is absent, and it consists primarily of groundwater discharge to watercourses.

Concentration: the abundance of a constituent divided by the total volume of a solution.

Data logger: device with 1-2 sensors installed for continuous logging of parameters.

Denitrification: microbially mediated conversion of oxidised nitrogen forms to gaseous nitrogen forms.

Discharge: the measure of the quantity of water flow over a unit of time.

Flow depth: depth at which uniform flow occurs in an open channel.

Gauging station: a station located on a section of a watercourse equipped with water level measuring devices where the flow depth is monitored.

Groundwater exfiltration: surface water exiting a vegetated water treatment system between the inlet and outlet and recharging the surrounding groundwater system.

Groundwater infiltration: groundwater entering a vegetated water treatment system from the surrounding groundwater system between the inlet and outlet.

Flow event: non-steady state flow conditions consisting of discharge above average monthly baseflow induced by rainfall (or irrigation tailwater).

Hydraulic gradient: change in water table level per unit of distance along the direction of maximum head decrease.

Hydrograph: graph showing the discharge versus time at a specific point in a watercourse.

Inlet: the point(s) where water usually flows into a vegetated water treatment system.

Loading: total amount of mass or mass per area basis of any substance entering or leaving a system.

Mass balance: quantification of the substances that enter, leave, and accumulate in a system.

Outlet: the point where the water usually flows out of a vegetated water treatment.

Overbank flow: surface water flow that enters or leaves a vegetated water treatment system other than the usual inlet/s or outlet/s.

Piezometers: vertical pipes installed in the ground to monitor groundwater.

Portable sensors: portable devices connected to sensors to measure parameters in situ by immersing the sensor in a subsample of the grabbed sample.

Probe: device with multiple sensors used to collect in situ or continuous measurements of multiple parameters.

Treatment wetland: engineered system that replicates and enhances the physical, biological, and chemical treatment processes occurring in natural wetlands to remove pollutants, often fine sediments, nutrients, and pesticides.

Vegetated drain: open channel for conveying water, where vegetation covers most of the bank and bed.

1 Introduction to vegetated water treatment systems

The ongoing function and resilience of Queensland's aquatic ecosystems, including the internationally recognised Great Barrier Reef and Moreton Bay wetlands are a key priority for the Queensland Government.

It is recognised that pollutants have increased since European settlement, leading to water quality decline in the Great Barrier Reef lagoon (Kroon *et al.* 2016).

Excess nitrogen is one of the primary pollutants that cause algal growth that can lead to reductions in dissolved oxygen levels in the water column and, in extreme cases, toxicity to aquatic organisms (Saeed and Sun 2012). Elevated nitrogen making its way into the Great Barrier Reef lagoon has also been linked to crown-of-thorns starfish outbreaks (Waterhouse *et al.* 2017), with dissolved inorganic nitrogen (DIN) loads from agricultural land uses being identified as a primary source (Bartley *et al.* 2017).

Treatment systems are a field-based option that can reduce nitrogen, and other pollutants, leaving agricultural areas. They are designed to intercept, slow down, and remove water pollutants, including sediment, nutrients, and pesticides. When used in conjunction with best-practice land management, treatment systems can improve water quality and aquatic ecosystem health at a catchment scale (DES 2022b).

There are different treatment systems options for use in agriculture to remove specific pollutants. They include bioreactors, algae treatment, sediment basins, vegetated buffers and swales, vegetated drains and constructed treatment wetlands (subsequently referred to as treatment wetlands) (DES 2022a).

> Refer to the Queensland Government Wetland*Info* website (DES 2023b) for information on treatment systems options (DES 2022a) and a description of, and information on site selection, construction and maintenance of vegetated drains and treatment wetlands for water quality improvement (DES 2022b; d).

Vegetated water treatment (VWT) systems utilise vegetation, such as reeds, sedges and grasses, to facilitate various treatment processes including sedimentation, nitrification/denitrification, adsorption and plant uptake (DES 2022a) (Figure 1).

Vegetated drains and treatment wetlands have been shown to be effective at reducing DIN in Queensland's tropical and sub-tropical climate (Kavehei *et al.* 2021a). As more VWT systems are used to improve catchment water quality, robust monitoring will be required to further develop knowledge of their performance (and limitations) in different contexts, as well as allow for the assessment of their cost-effectiveness and capacity to attract credits or offsets as part of emerging environmental markets (Kavehei *et al.* 2021a).

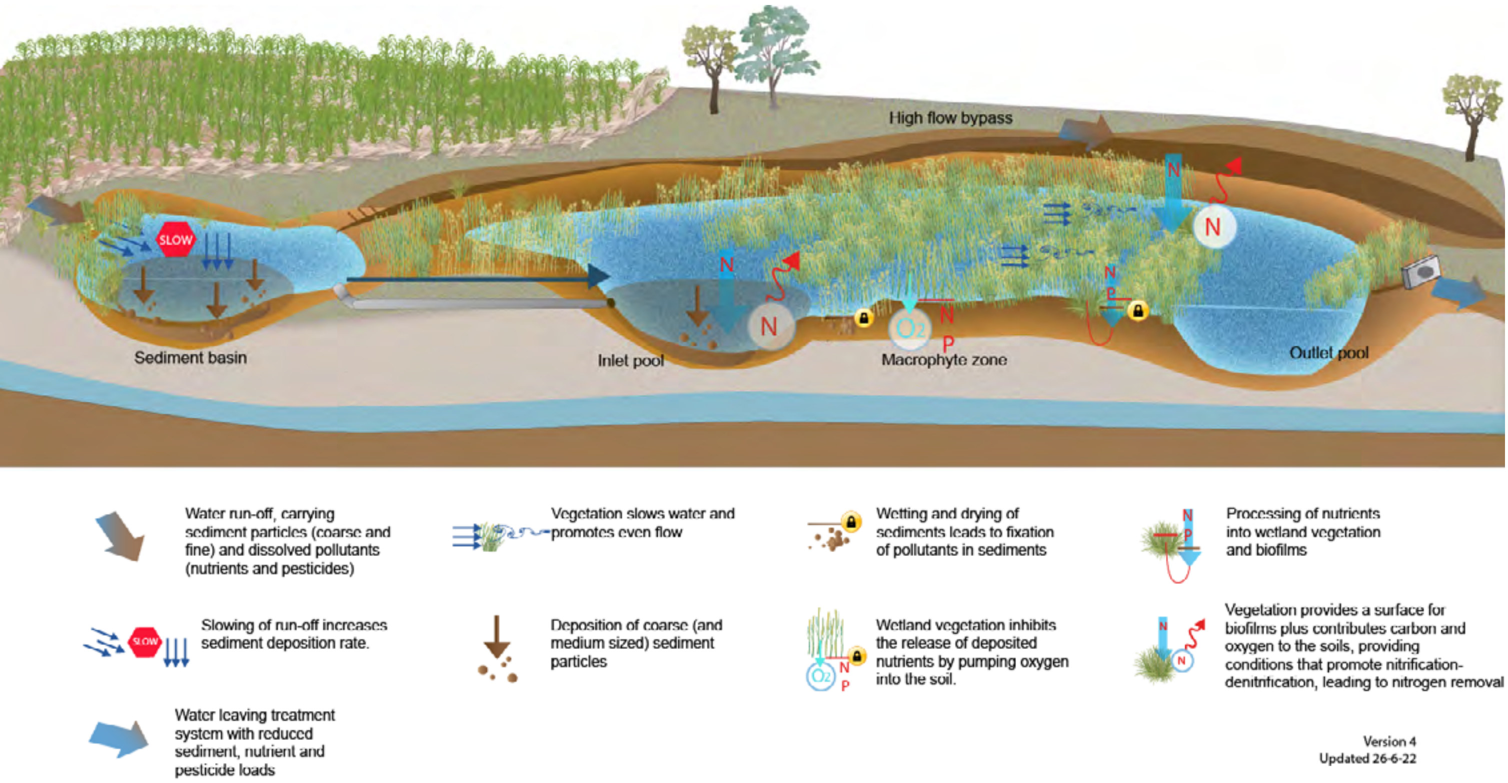


Figure 1: Conceptual diagram of a vegetated water treatment system showing pollutant removal processes. Source: DES (2022b).

2 Introduction to monitoring nitrogen reduction

This document focuses on VWT systems for the primary purpose of improving water quality, specifically nitrogen reduction in predominantly freshwater systems. Two VWT systems are covered: vegetated drains and treatment wetlands treating diffuse surface run-off (rainfall or irrigation) and shallow groundwater.

This document provides guidance on designing monitoring programs to quantify the nitrogen reduction of VWT systems based on a mass balance approach using loads (load = discharge x concentration) (Von Sperling *et al.* 2020). Although VWT systems can remove various pollutants, this document focuses on nitrogen, as nitrogen reduction is often the primary purpose of VWT systems in agricultural areas in Queensland.

There are complex physical, chemical and biological nitrogen processes occurring concurrently in the water column, soil, sediments and plants in VWT systems (Lee *et al.* 2009). Nitrogen inputs and outputs occur via water, soil, and atmosphere (Figure 2) (DES 2021c), with nitrogen cycling including both conversion and removal processes (described further in nitrogen forms).

Reduction of nitrogen is calculated by subtracting nitrogen loads into and out of the VWT system and equating any imbalance to the net effect of in situ removal processes. Therefore, the calculated nitrogen reduction rate will include all the nitrogen removal [i.e., denitrification, plant uptake, volatilisation, etc (Table 1)] occurring at the VWT system without differentiating them. Although nitrogen removed (temporarily) thorough vegetation uptake or sedimentation could potentially be released (unlike removal through denitrification), it makes a relatively small contribution to overall nitrogen reduction in a system (Figure 2). If the purpose of the monitoring project requires accounting for temporary removal and release of nitrogen, monitoring should be conducted over a long period of time.

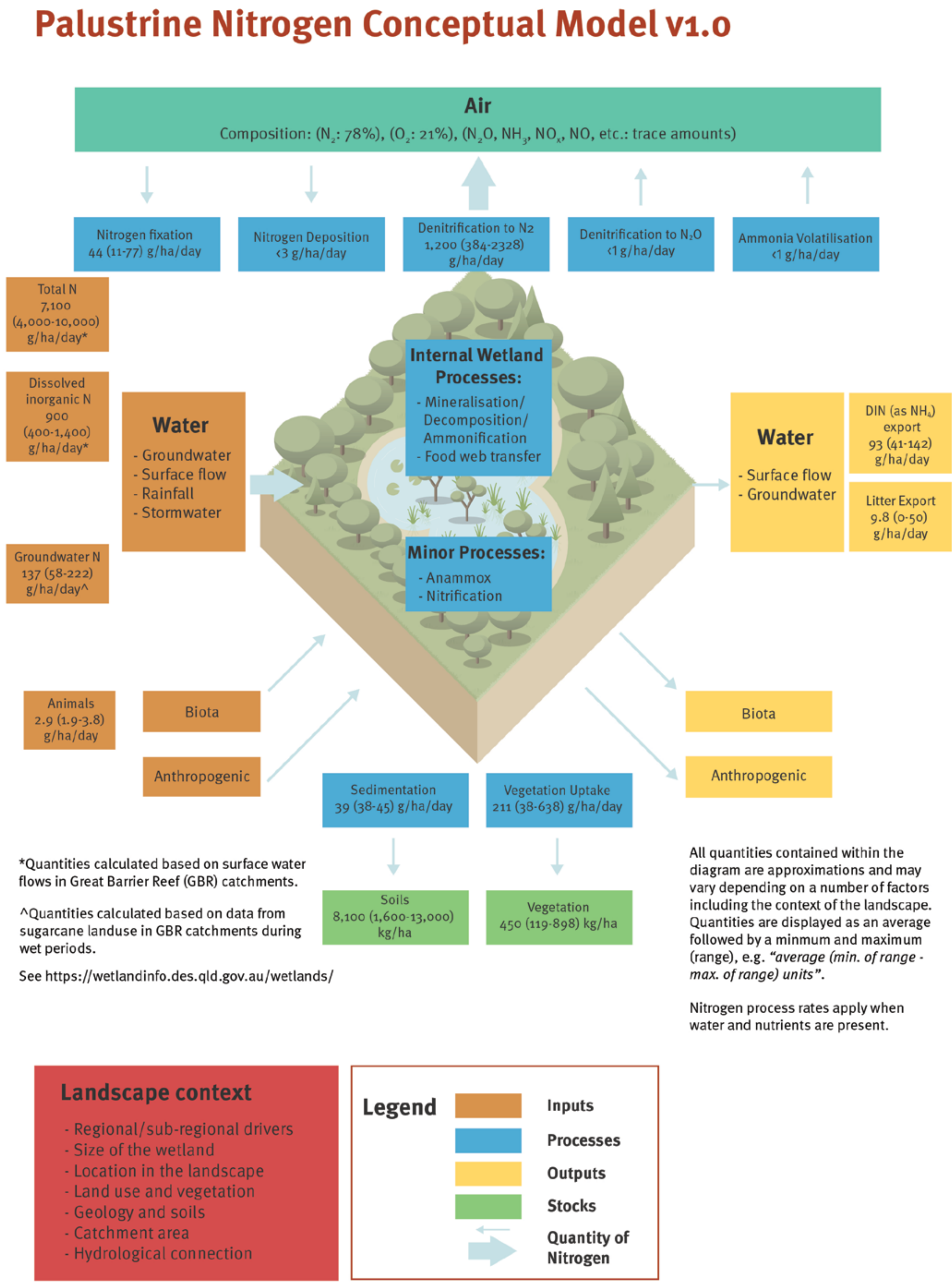


Figure 2: Conceptual model of nitrogen processes in a palustrine wetland (VWT systems are a type of artificial palustrine wetland), showing the inputs, outputs and processes. Source: DES (2021c).

2.1 Limitations and assumptions

The calculation of nitrogen reduction involves measuring both water discharge and nitrogen concentrations. Therefore, uncertainty and limitations in measuring discharge and/or nitrogen concentrations will transfer into errors in the nitrogen reduction calculations. It is challenging to accurately quantify all the discharge and nitrogen concentrations across the range of conditions experienced in VWT systems, and it is unlikely that the water balance will fully close (i.e., that all inputs and outputs can be accurately quantified).

If accounting for overland flow events is critical to the purpose of the monitoring project, then a different approach to estimating nitrogen reduction may be required, such as modelling [i.e., Wallace and Waltham (2021)].

Modelling approaches for quantifying nitrogen reduction in wetlands is beyond the scope of this document and is being investigated elsewhere [see Queensland Water Modelling Network (DES 2023a)].

Most VWT systems are designed to treat water under a specific range of flow conditions and above that design flow, there will be overland flow directly into, or out of the system from multiple locations and overtopping, flooding or water bypass, which will be very challenging and often unsafe to monitor. These guidelines do not outline an approach to dealing with these events as they are site specific, but the likelihood and potential contribution of these events to the VWT system's overall discharge and nitrogen loading should be assessed. The probability of these events occurring and their potential impact on achieving the purpose of the monitoring program and how the results will be interpreted, should be noted in the design of the monitoring program. The monitoring results will need to be interpreted carefully based on best available knowledge of the system and site with the limitations and assumptions clearly defined. This document aims to highlight limitations to be aware of but cannot detail the exact nitrogen reduction quantification errors and uncertainty ranges, due to a shortage of published data in this area.

NOTE

There are limitations and assumptions associated with quantifying nitrogen reduction in VWT systems, particularly given the climatic extremes in Queensland. This document aims to provide guidelines for monitoring VWT systems, which are practical and relatively affordable to implement. However, it is challenging to account for all variables and therefore there are limitations in the monitoring presented in this guideline. The document aims to highlight these limitations so that they can be considered when interpreting the results.

With the challenges and limitations associated with monitoring VWT systems, key assumptions in this document include:

- The direct contribution of nitrogen into the VWT system from precipitation and animals is considered negligible (see Figure 2).
- The calculated nitrogen reduction by the VWT system includes nitrogen temporarily removed (i.e., via plants, sedimentation) as well as permanent removal via denitrification. It does not specifically monitor individual nitrogen removal processes and does not account for active vegetation harvesting or sediment extraction.
- The VWT system is designed for certain flow events, and there will be periods of overland flow, overtopping and bypass that exceed the design flows for effective treatment which cannot be measured safely or effectively.

- The storage volume of the VWT system does not change significantly over time. There will be periods when water levels increase in the VWT during flow events, increasing storage temporarily, but not permanently. It is assumed that the monitoring scheme will be designed to capture these variations.

Note, this document does not cover site assessment and design of VWT systems, other than highlighting that the first stage of any VWT system project is understanding of the system (DES 2022c), including assessing site hydrology and evaluating whether groundwater infiltration/exfiltration occurs. This is critical for designing the monitoring program, which relies on understanding the flow regime.

2.2 Using the document

The flow diagram in Figure 3 illustrates the layout of the different topics in the document, required to plan the monitoring of vegetated drains and treatment wetlands. Each box represents a section in the document. Hyperlinks (in orange font) direct the reader to the relevant section in the document.

The first step in planning the monitoring is to establish the of the purpose of the monitoring project in terms of targeting the flow regime and nitrogen form(s) to be investigated. The project budget will dictate the monitoring program (which needs to consider monitoring strategy and monitoring structures) for discharge and water quality monitoring. This will include surface water discharge monitoring and surface water sampling to quantify nitrogen concentration at the system's inflow and outflow points, which in this document will be called inlet and outlet, respectively. Additional groundwater discharge monitoring and groundwater sampling may be required if the VWT system is subject to groundwater infiltration/exfiltration.

The last section of this document includes three levels of recommended monitoring named gold, silver, and bronze, to be applied across a range of flow regimes (i.e.,baseflow, flow event and water-year) in both vegetated drains and treatment wetlands. The levels are indicative of cost and accuracy, with the gold level providing a greater level of confidence in the results, usually at higher cost. Some research projects will require a more comprehensive monitoring program to address a specific question and this will require tailored experimental design and is beyond the scope of this document.

Steps to designing a VWT system monitoring project:

1. Project purpose:
   - flow regime
   - nitrogen form(s)
2. Project budget
3. Design monitoring program considering conceptual model, information required and limitations and identify:
   a. monitoring points/structures
   b. monitoring strategy, including duration, frequency, method and scheme
   c. suitable monitoring devices and techniques.
4. Check equations to estimate nitrogen reduction and determine if planned monitoring program will be adequate, otherwise refine.

The recommended monitoring program level in section 10 is informed by project budget, which will impact the choice of the monitoring devices, the monitoring frequency and, consequently, the degree of accuracy for the nitrogen reduction quantification. The recommended monitoring is indicative of what could be undertaken. Alternatively, a mix of monitoring devices/tests from different monitoring levels can be used depending on the project budget and purpose.

The monitoring devices/tests covered are based on what has been trialled and documented in published literature. This is an evolving field of work and as technologies advance, there will be new devices, tests, and efficiencies in estimating nitrogen concentrations. The reader should use the steps outlined to plan the types of monitoring required, however alternative devices or tests can be used, where available and appropriate. Similarly, this document does not detail existing sampling techniques where these are outlined in other guidelines, instead links will be provided to these complementary documents throughout the text and in Appendix.

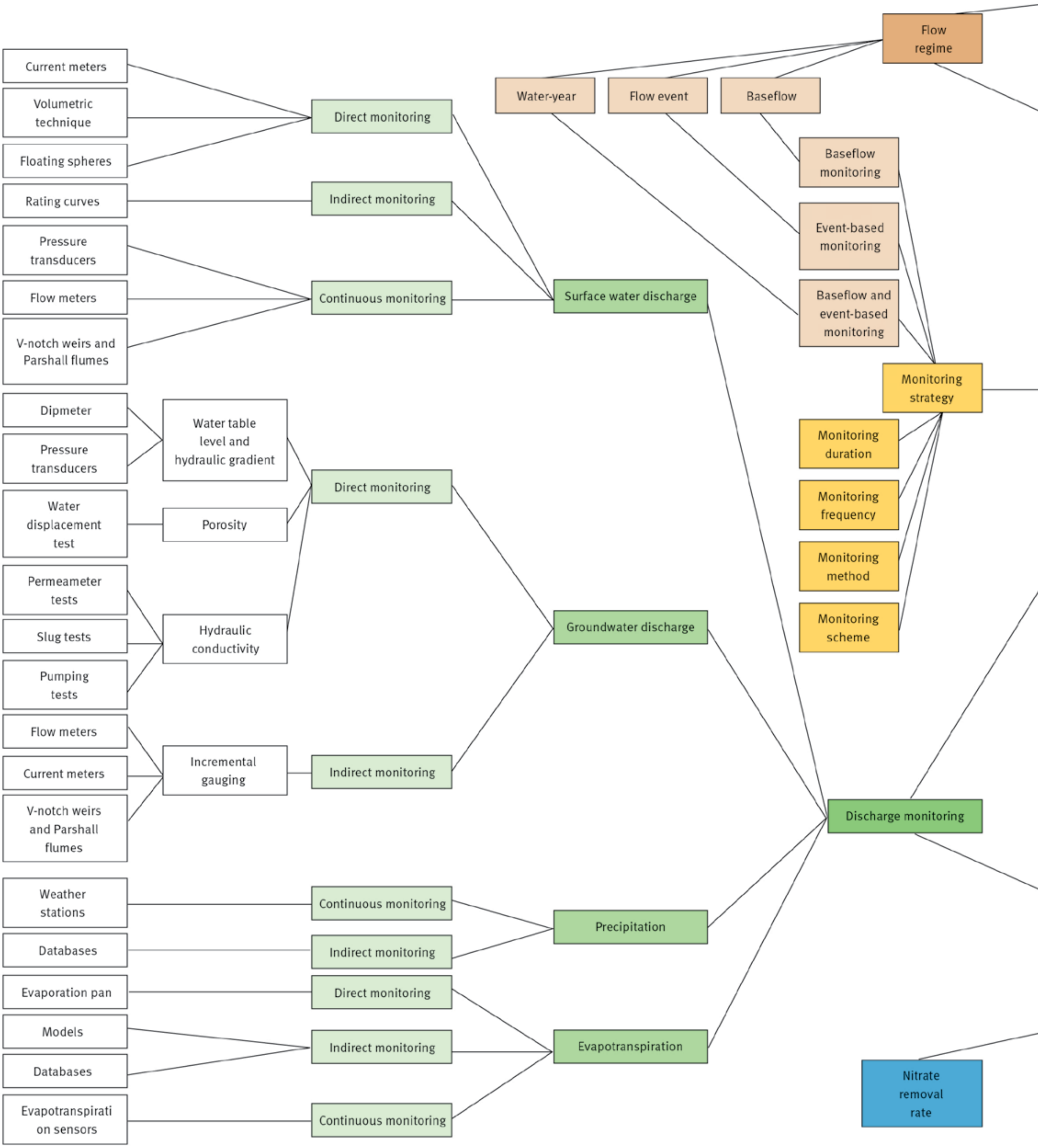
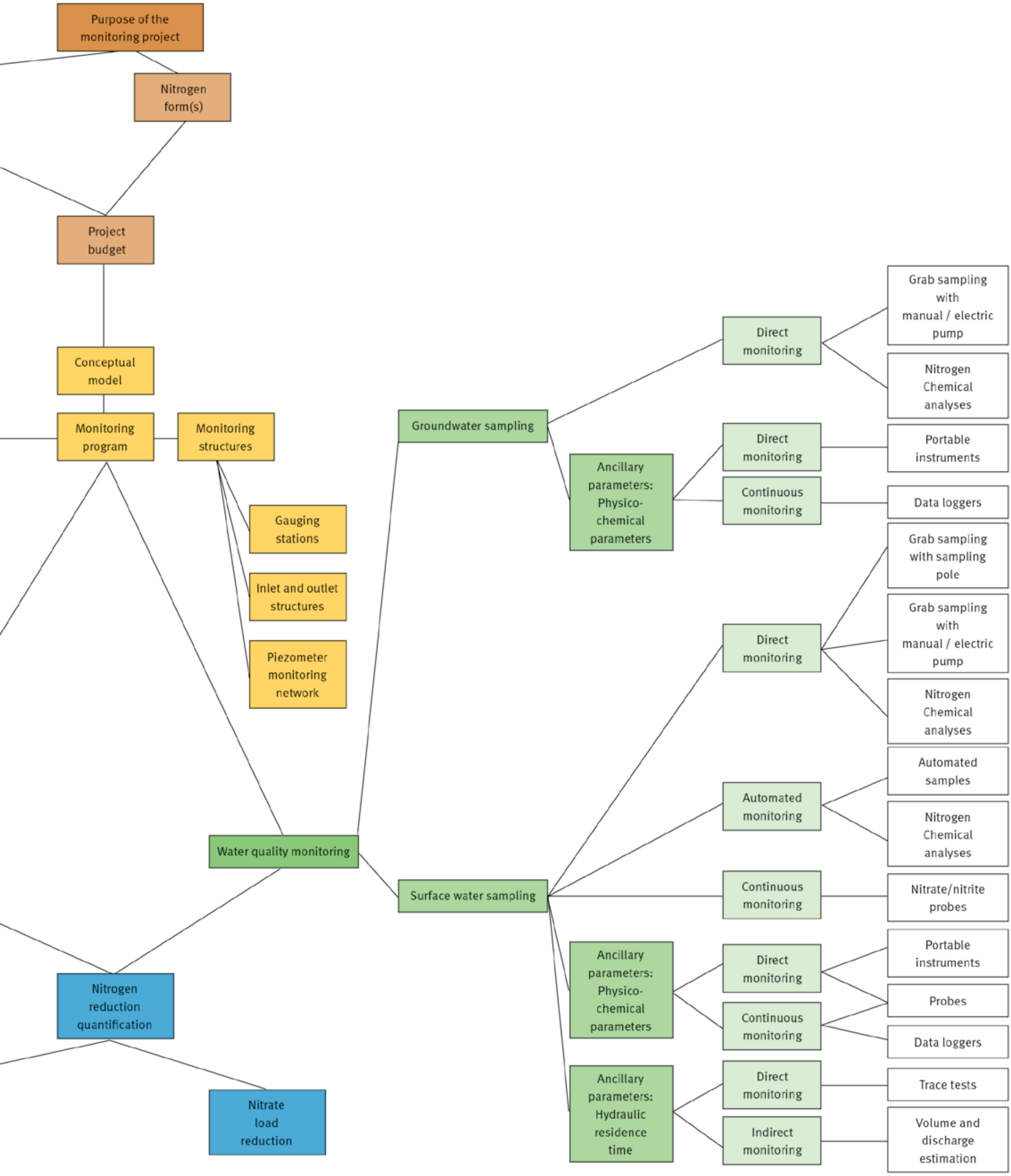


Figure 3: Flow diagram of the steps to planning monitoring of a VWT system. The first step is to define the project's purpose (orange) targeting a specific flow regime and nitrogen form and the project budget (light orange). This informs the design of the conceptual model and the monitoring program, which needs to consider both the monitoring strategy and monitoring structures (yellow). The monitoring program (green) encompasses discharge and water quality of surface water and groundwater (if present) via different devices/tests (white). Once the data are collected, the nitrogen removal is estimated based on a mass balance approach (blue).



3 Purpose of the monitoring project

Designing a monitoring program for a VWT system will depend on the monitoring project's purpose. To define the purpose of the monitoring project, consider:

- The question(s) the monitoring project aims to answer (i.e., what is the most representative flow regime? Does the VWT system effectively remove nitrogen? Does the VWT system meet the targeted nitrogen load reduction over a specific period? Under which flow or climatic conditions is the VWT system more efficient at removing nitrogen? Etc).
- The spatial boundaries of the monitoring program (i.e., one or multiple VWT systems).
- What information is needed to answer these questions (i.e., nitrogen concentrations in vs nitrogen concentrations out and discharge during a specific hydrologic event).
- The temporal boundary of the monitoring program (i.e., one year project, etc).
- The use of the collected information (i.e., reporting on performance vs input to modelling).
- Required accuracy of results (i.e., high accuracy needed to demonstrate compliance with licence conditions, or indicative results to highlight water quality improvements).
- The limitations and risks associated with the monitoring program (i.e., safe site access, weather conditions, etc).

Generally, a project aims to address a specific question related to compliance, ambient water quality monitoring, treatment performance assessments, or to input to modelling/model calibration.

> **NOTE**
>
> This document provides guidance on monitoring nitrogen reduction in VWT systems. If the primary purpose of the monitoring is to assess other values (i.e., fish habitat, biodiversity) or natural wetlands refer to Assessment, monitoring and inventory (Department of Environment and Science) (des.qld.gov.au) (DES 2019).

A common purpose is to quantify nitrogen loading and reduction in a VWT system, which is achievable by monitoring a targeted nitrogen form(s) over a hydrograph stage characterised by a specific flow regime, that lasts for a specific time (days, months, or years).

The nitrogen loading of a VWT system over time can be estimated with reasonable precision by monitoring both surface water discharge and performing surface water sampling to measure nitrogen concentrations (Littlewood 1992) at the inlet and outlet, when overbank flow does not occur. If the VWT system is subject to groundwater infiltration/exfiltration, then groundwater discharge measurements and groundwater sampling in the piezometer monitoring network is required for accurate estimation of nitrogen reduction.

Water discharge will be monitored to quantify the nitrogen reduction at selected flow regimes (i.e., baseflow, flow event, water year). These regimes are described below. The flow regime(s) most relevant to the project purpose (including project duration), budget and the site conditions should be selected. For example, to assess the performance of a VWT system in a rainfed sugarcane production system without groundwater interaction, the priority flow regime would be the flow event regime to capture events with the greatest potential for nitrogen loss, being the first few events following fertiliser application.

The form of nitrogen monitored will depend on the purpose of the monitoring project, funding availability, and compliance with regulations or water quality targets. For example, the Reef 2050 Water Quality Improvement Plan (State of Queensland 2018) developed by the Australian and Queensland Governments identified the monitoring of DIN and particulate nitrogen as a requirement to improve water quality from agricultural catchments adjacent to the Great Barrier Reef. Therefore, a monitoring project that aims to address the Reef 2050 Water Quality Improvement Plan targets should focus on these nitrogen forms. Similarly, the Queensland Government regulates environmentally relevant activities, and in the Model Operating Conditions for Aquaculture (DES 2021a), for example, the recommendation is to monitor annual nitrogen loading calculated as total nitrogen (TN). In this instance, the focus should be TN.

3.1 Flow regimes

The discharge of VWT systems is subject to variation over time in response to rainfall, or irrigation events, and it is described using a hydrograph. Projects usually aim at monitoring different stages of the hydrograph as pollutant concentration varies significantly at different stages (Figure 4) and projects are designed to target a specific flow regime type, such as baseflow (steady-state), flow event (non-steady state) or water-year (both).

3.1.1 Baseflow regime

Baseflow (or dry weather) regime is characterised by steady-state flow conditions when the surface runoff from rainfall is absent, and it consists primarily of groundwater discharge to watercourses.

3.1.2 Flow event regime

Flow event regime is characterised by non-steady-state flow conditions during increased discharge due to rainfall (or irrigation tailwater). This flow regime is often monitored to investigate the first flush effect, which occurs due to the transport of material and pollutants accumulated during the dry season or elevated nitrogen losses following crop fertilisation.

3.1.3 Water-year regime

Water-year regime, also called discharge year, flow year, or hydrologic year, aims to measure flows across the whole year. It is characterised by both steady-state and non-steady-state flow conditions for 12 months, including the dry and wet seasons. Water-year monitoring should be performed for multiple years to increase the accuracy of results. This flow regime is monitored to assess the dynamics of a VWT system across a whole annual hydrograph.

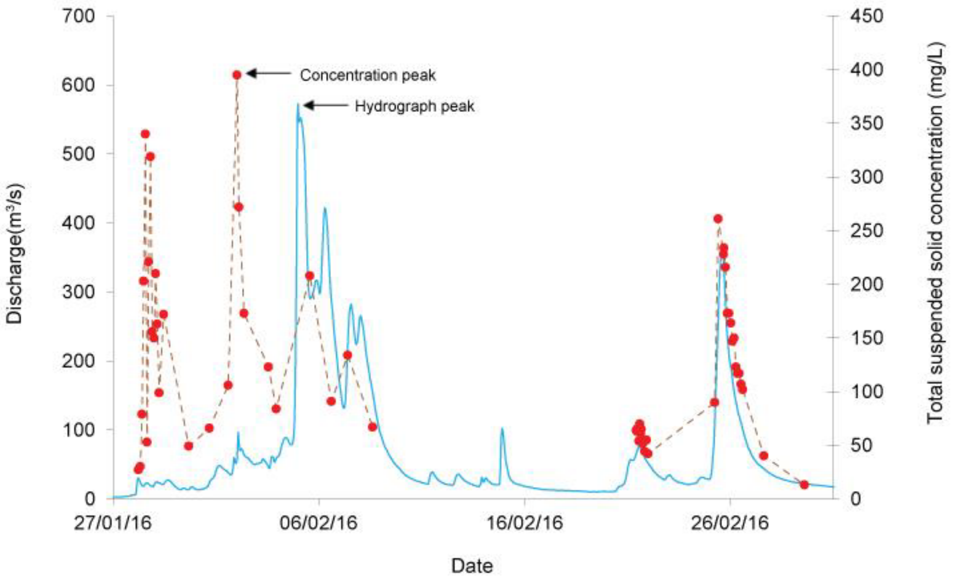


Figure 4: Example hydrograph showing the concentration of total suspended solids (dotted line) against discharge (blue line) during flow events. The red dots indicate the date samples were collected. Source: DES (2018).

3.2 Nitrogen forms

Nitrogen is present in water in various chemical forms (Figure 5). Total nitrogen is separated into particulate nitrogen and total dissolved nitrogen (TDN). Total dissolved nitrogen is defined as all nitrogen being able to pass through a 0.45 µm filter and can be divided into dissolved organic nitrogen (DON), which includes amino acids, urea, uric acids, purine, and pyrimidines (Kadlec and Wallace 2008), and DIN, which includes ammonium (NH_4^+), nitrite (NO_2^-), and nitrate (NO_3^-). Dissolved oxidised nitrogen (NO_x) includes NO_2^-, NO_3^-, and gaseous forms such as nitric oxide (NO), nitrous oxide (N_2O), and dinitrogen gas (N_2). The sum of particulate nitrogen, DON, and NH_4^+ is defined as Total Kjeldahl nitrogen (TKN), which becomes Total dissolved Kjeldahl nitrogen (DKN) when filtered at 0.45 µm. Total ammonia nitrogen (TAN) includes both ammonia (NH_3) and NH_4^+ formed via the protonation of NH_3.

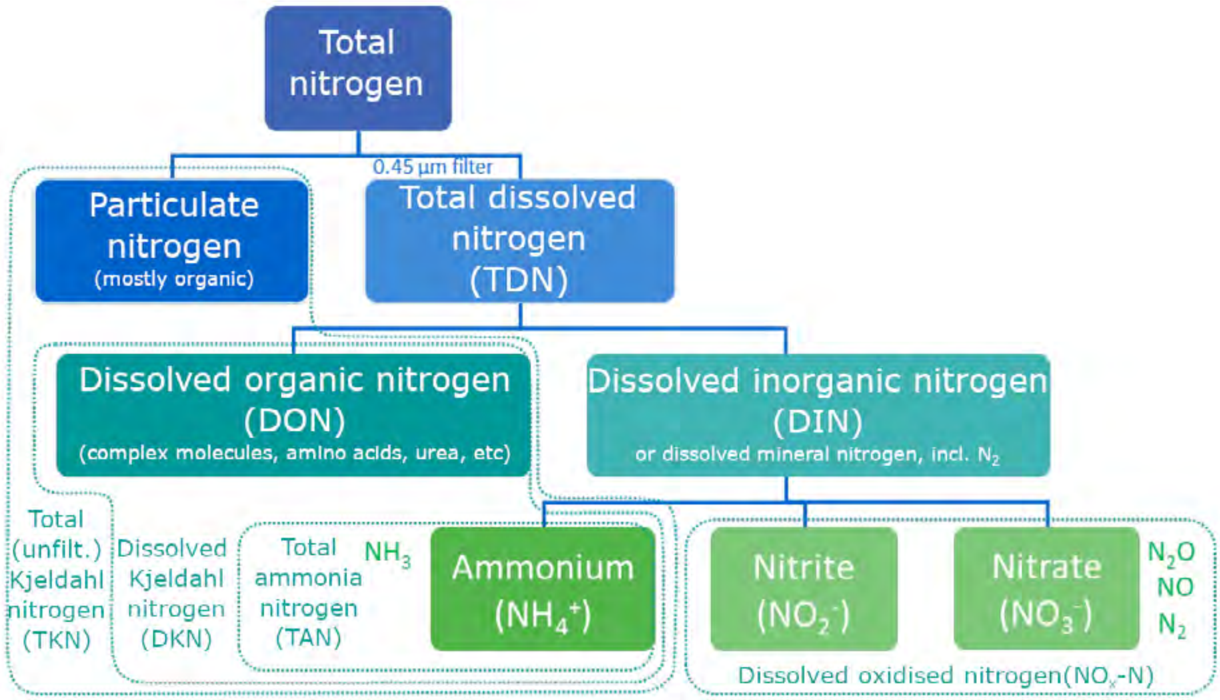


Figure 5: Overview of nitrogen forms in water samples, including gaseous forms (i.e. N_2O, NO, N_2 NH_3). Dissolved oxidised nitrogen (NO_X) predominantly comprises nitrate, with nitrite concentrations generally negligible. Modified after Cheesman *et al.* (2020)

Nitrogen cycling in VWT systems includes both nitrogen converting and nitrogen removal processes (Table 1). Nitrogen converting (from one chemical form to another) results in no net reduction in excess nitrogen in the water, whereas nitrogen removal processes result in the conversion of dissolved nitrogen to either a gaseous form, lost to the atmosphere, or to an increase in biomass which can be physically removed or buried as accumulated organic matter (Vymazal 2007). Refer to nitrogen processes (DES 2021b) for more information.

Among these processes, denitrification is considered the main permanent nitrogen removal mechanism in mature VWT systems (Vymazal 2007). Denitrification is the microbially mediated conversion of oxidised components of DIN (i.e., NO_3^- and NO_2^-) to gaseous nitrogen forms (i.e., NO, N_2O and N_2) (Rivett *et al.* 2008). Denitrifying microbes use oxidised nitrogen forms as a terminal electron acceptor in the absence of oxygen to metabolise organic matter (Groffman and Rosi-Marshall 2012). As anaerobic organisms require an anoxic (i.e., no free oxygen) environment they are often found in buried sediments or soils of VWT systems. It is important to understand the key nitrogen removal processes occurring in VWT systems when designing a monitoring program as this can inform the nitrogen form(s) to monitor.

Table 1 Nitrogen conversion/deposition and removal processes in vegetated water treatment systems, modified after Vymazal (2007) and DES (2021b).

Conversion and deposition processes	Transformation	Environmental conditions
Ammonification	Organic nitrogen ⇢ NH_3	Anoxic/aerobic
Nitrification	NH_4^+ ⇢ NO_2^- ⇢ NO_3^-	Aerobic
Dissimilatory nitrate reduction to ammonium	NO_3^- ⇢ NO_2^- ⇢ NH_4^+	Anoxic
Fixation	N_2 ⇢ NH_3	Anoxic
Sedimentation	-	-
Removal process	**Transformation**	**Environmental conditions**
Volatilisation	NH_3 (aq) ⇢ NH_3 (g)	Aerobic
Denitrification	NO_3^- ⇢ NO_2^- ⇢ NO ⇢ N_2O ⇢ N_2	Anoxic
ANAMMOX (anaerobic ammonium oxidation)	NH_3 + NO_2^- ⇢ N_2	Anoxic
Ammonia adsorption	-	-
Non-permanent removal		
Organic nitrogen burial	-	-
Plant/microbial uptake	NH_4^+, NO_2^-, NO_3^- ⇢ organic N	Anoxic/aerobic

4 Project budget

After defining the purpose of the monitoring project, it is necessary to review the project budget and resources available to allocate costs for the monitoring program and assess any budgetary limitations.

The key costs in a monitoring program include:

- The monitoring structures (i.e., gauging stations, piezometer network, etc).
- The monitoring strategy which will determine the purchasing of monitoring instruments and research consumables to perform surface water discharge quantification and sampling, and, if groundwater is present, groundwater discharge quantification and sampling, as well as the monitoring frequency.
- Salary for trained staff to perform the installation, utilisation and maintenance of the monitoring structures and devices, as well as the collection of samples and their freight to the laboratory facilities for analysis.
- Laboratory analysis costs.
- Salary for qualified staff to perform the data analysis for the nitrogen reduction quantification and report writing.

Existing resources, such as staff or landholder time should also be considered as an in-kind contribution.

The total cost will depend on the type and intensity of monitoring conducted, equipment used, purpose (level of accuracy required) and the site (i.e., accessibility). There can be trade-offs between equipment costs and salary costs, with automated sampling equipment providing a significant upfront cost, potentially offset in the future by salary savings.

5 Conceptual model

Developing a conceptual model of the VWT system is highly recommended when designing the monitoring program. This document promotes a mass balance approach to calculate the nitrogen reduction in a VWT system and a conceptual model can illustrate the elements to be considered in the mass balance to ensure these elements are factored into the monitoring program. The conceptual model should include (Von Sperling *et al.* 2020):

- All inputs and outputs of water and nitrogen to the VWT system.
- Temporal and spatial variability in water and pollutant inputs into the VWT system.
- The boundary of the VWT system under dry and wet conditions to inform the boundary of where the mass balance will be applied.
- Key monitoring locations to capture information on water and nitrogen to inform the mass balance.
- The processes likely to be occurring in the VWT system.

A desktop assessment, together with a site inspection, is needed to understand the site. A design should have been undertaken during the planning and design of the VWT system (Figure 6) and can form the template for the conceptual model. Although it is worth revisiting the original design when planning the monitoring program, as the site conditions may have changed. The model or map should define the inputs, outputs, removal processes, inlet/outlet structures, the system boundary (boundary of VWT system and its catchment), surrounding land-use, features that could influence water flow or nitrogen inputs (i.e., ag-pipe drainage, irrigation systems) and access. Conceptual models of nitrogen processes (Figure 2) in treatment wetlands and vegetated drains can help in understanding the inputs, outputs and removal processes occurring at the site.

The site hydrology should have been determined during the design of the VWT system and is critical to understanding the VWT system's inflow and outflow points during baseflow (i.e., any groundwater influence) and various flow events. Most VWT systems in Queensland will experience significant hydrological changes annually and across years due to wet and dry seasons and climatic cycles. This should be factored into the design of the monitoring. Furthermore, there can be significant changes in vegetation and hence potential nitrogen processes over time as the VWT system matures or is impacted by flood events or weeds. This has implications for monitoring and interpretation of results and should be planned upfront.

NOTE

Preliminary sampling may be needed to help design the monitoring program, including testing assumptions. Once the monitoring program is underway and data interpreted, the monitoring program should be reviewed and adapted to ensure it is meeting the purpose and budget.

The design of the monitoring program will determine the development of the monitoring strategy and the realisation of monitoring structures.

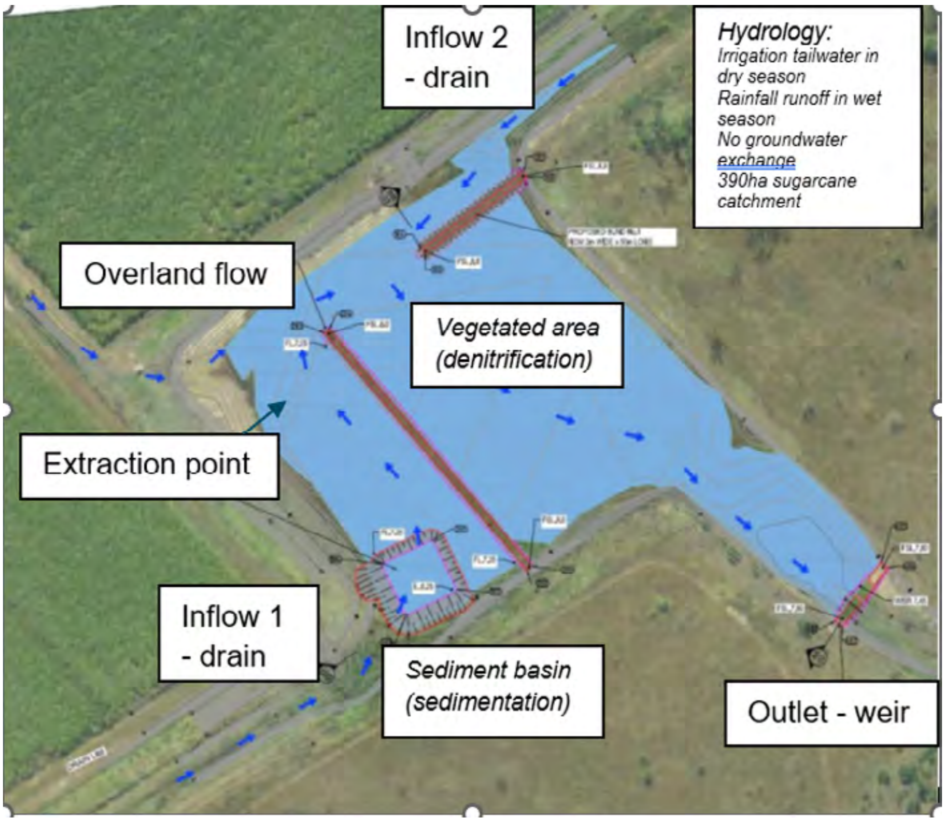


Figure 6: Site diagram showing inlet and outlet points and key features of a treatment wetland. Source: Modified from BBIFMAC (2020).

6 Monitoring program

Once the purpose of the monitoring has been defined and a budget allocated, the monitoring program can be designed.

6.1 Monitoring strategy

6.1.1 Monitoring duration

The monitoring duration depends on the purpose of the monitoring project, project budget and the flow regime(s). For example, some projects have monitored flooding periods to quantify the nitrogen reduction of treatment wetlands during a 6-day flow event (Adame *et al.* 2019) or throughout the entire hydrograph during a water-year (Hoffmann *et al.* 2019). Other studies have investigated the nitrogen reduction of vegetated drains under steady-state conditions during a 3-month dry season (Pierobon *et al.* 2013) or throughout the entire hydrograph during a water-year (Vymazal and Březinová 2018).

A longer monitoring duration (multiple years) will enable the assessment of variation across years, and this can increase confidence in results in Queensland's variable climate. Long term monitoring is also needed for recently constructed VWT systems as nitrogen reduction can change as vegetation establishes and the VWT system matures (Kavehei *et al.* 2021b). The monitoring duration will influence the monitoring frequency; ideally, higher frequencies are needed for shorter monitoring durations.

6.1.2 Monitoring frequency

The monitoring frequency is the time interval between two consecutive sampling events. Obtaining continuous discharge datasets (30-60 minutes, or more frequently depending on the site and project purpose) from continuous monitoring or rating curves obtained from direct monitoring is always recommended for surface water discharge monitoring.

The frequency of surface water sampling will vary depending on the purpose of the monitoring project and the flow regime, as well as the available budget and equipment that could allow for continuous monitoring. For example, some projects aim to monitor the baseflow, while others target flow events. The Queensland Government developed a water Monitoring and Sampling Manual (DES 2018) with sampling frequency recommendations.

Baseflow monitoring

For baseflow monitoring, samples should be collected long enough after an event to ensure that only baseflow water is monitored and not the tail of flow events. Samples should be collected at least once a month, but a weekly or bi-weekly collection is recommended if the project budget allows it.

Event-based monitoring

For flow event monitoring, the recommendation is to collect samples throughout the hydrograph from as many flow events as possible, prioritising the first flushes of the year. Thomson *et al.* (2012) suggest that for the Great Barrier Reef region, a minimum of six samples may be enough to produce an accurate nitrogen loading estimation.

Water-year monitoring

For water-year monitoring a mix of baseflow and event-based monitoring is recommended according to the different stages of the hydrograph, with at least monthly monitoring during the dry season and event-based monitoring during flow events in the wet season.

If groundwater is present at the VWT system site, it is recommended to replicate the baseflow monitoring frequency for groundwater discharge monitoring and groundwater sampling. For event-based monitoring, it is recommended to perform water table level measurements and groundwater sampling once for each of the flow events monitored. It is recommended that groundwater discharge monitoring and groundwater sampling for water-year monitoring is a mix of baseflow and flow event monitoring. Therefore, site inspections should be planned at least monthly during the dry season and event-based monitoring for each flow event in the wet season.

6.1.3 Monitoring methods

In this document, monitoring methods are divided into four classes: direct monitoring, indirect monitoring, continuous monitoring, and automated monitoring.

Direct monitoring

Direct monitoring is the in-situ measurement of parameters. Direct monitoring datasets have high accuracy if the monitoring devices are calibrated regularly, and measurements are collected according to standard procedures.

Indirect monitoring

Indirect monitoring is an extrapolation of time series from in-situ direct measurements. Indirect monitoring datasets have intermediate accuracy because time series are extrapolated from a relatively small number of measurements. Indirect monitoring also includes models or databases. In this case, the accuracy of the datasets will be lower because they may be based on data that are not collected in-situ.

Continuous monitoring

Continuous monitoring is the in-situ measurements of parameters, often at 30-60 minutes frequency, although the frequency will depend on the site conditions and project purpose. Continuous monitoring datasets have high accuracy because they provide continuous time series of data collected in-situ.

Automated monitoring

Automated monitoring is the collection of multiple water samples using automated samplers. Automated monitoring has high accuracy because it allows the collection of water samples multiple times a day, according to a specific sampling frequency.

6.1.4 Monitoring scheme

The monitoring scheme can be fixed (i.e., a specific weekday and time at a specific frequency) or random (i.e., any time of the day of the week at a specific frequency). Zamyadi *et al.* (2007) have systematically examined different nitrogen loading calculation methods in combination with varying sampling schemes, and they have found that fixed sampling schemes (i.e., fixed time span between sampling events) are associated with lower errors than random schemes (i.e., random time span between sampling events).

6.2 Monitoring structures

Monitoring structures need to be installed for data collection at the inlet(s) and outlet(s) of a VWT system to quantify surface water and groundwater discharge rates, and nitrogen concentrations.

6.2.1 Gauging stations

A gauging station should be located on a suitable section of a watercourse equipped with water level measuring devices to measure the flow depth or surface water discharge with direct, indirect and continuous monitoring, and are often the site of surface water sampling (including automated monitoring). Sites used for gauging should be in a straight and uniform stretch of the watercourse with a constant gradient, ideally with smooth banks and permanent basement material such as rock and no obstacles protruding from the water surface. The gauging station should also be located far from any flow disturbances (i.e., discharge points and pumping stations) because they can generate turbulence that affects the flow depth and the water velocity measurements. Narrow cross-sections in drains/ watercourses can be selected for ease of measurement, while access to the gauging station should always be easy and safe.

Gauging stations can be used at the inlet and outlet of vegetated drains (Han *et al.* 2019; Pierobon *et al.* 2013) (Figure 7) and treatment wetlands with or without distinct inlet and outlet structures. These treatment wetlands will often have drains forming inlet and outlet points (Figure 8), in which gauging stations could be installed. It is always recommended to install a water gauge at a gauging station and take manual reading of the flow depth at each site inspection. Flow depth at gauging stations can be also logged continuously with pressure transducers from points of known elevation, while surface water discharge monitoring is performed using current meters (Stone *et al.* 2003) or V-notch weirs and Parshall flumes (if the site is suitable for their installation).

Figure 7: Detail of a gauging station to collect water level measurements using a water gauge and discharge measurements with a current meter Source: (Errico *et al.* 2019).

Figure 8: Drain forming the inlet to a treatment wetland.

6.2.2 Inlet and outlet structures

Treatment wetlands are sometimes designed with inlet and outlet structures (Bruun *et al.* 2016; Groh *et al.* 2015; Hoffmann *et al.* 2019) (Figure 9), from which it is possible to perform surface water discharge measurements using direct, indirect and continuous monitoring, as well as surface water sampling and automated monitoring. The inlet and outlet structures will be designed according to site-specific conditions [i.e., see Treatment wetland planning and design; Constructed Wetlands Manual (UN-HABITAT 2008)]. Inlet and outlet structures permit the monitoring of flow depth using pressure transducers and surface water discharge using volumetric techniques and flow meters.

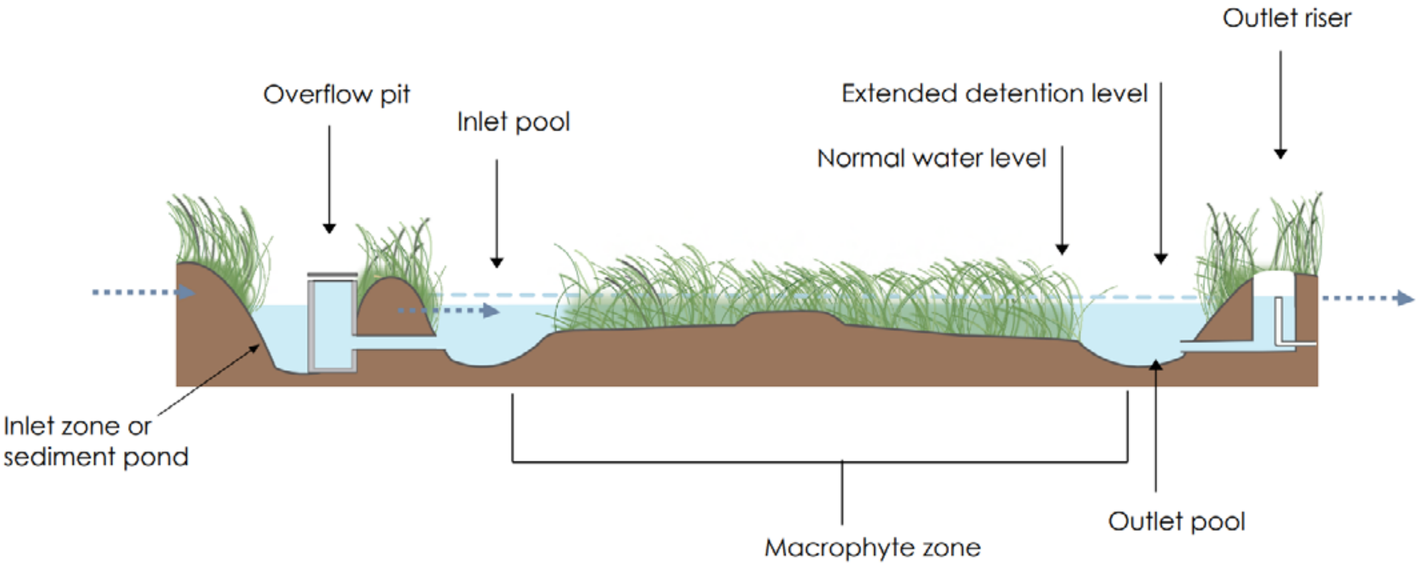


Figure 9: Diagram showing potential inlet and outlet structures in a treatment wetland. Source: WBD (2022).

6.2.3 Piezometer monitoring network

A piezometer monitoring network is used to perform groundwater discharge measurements and groundwater sampling at a VWT system if groundwater infiltration/exfiltration occurs. The monitoring network permits direct monitoring of groundwater, which includes the measurement of water table levels to calculate the hydraulic gradient, collection of samples for aquifer characterisation (i.e., porosity) and the performance of tests to determine the hydraulic conductivity (i.e., tracer tests).

Piezometers can be installed manually or using drilling rigs. A cluster of piezometers can be installed to understand groundwater movement and interaction with the VWT system. At least three triangulated monitoring piezometers are required to determine the direction of groundwater flow (TRCA 2016), but more may be necessary depending on the project scale and purpose.

Piezometers can be PVC pipes capped at the bottom with a filtering bottom section (Wegscheidl *et al.* 2021) (Figure 10). They should be surrounded by fine gravel or coarse sand to increase hydraulic conductivity and facilitate water sampling. The length of the piezometers and the filtering section depend on the depth of the water table. In Australia, any installation of piezometers greater than 6 m must be done by a licenced water bore driller. Please refer to the Minimum construction requirements for water bores in Australia (NUDLC 2012) for technical information. Additionally, approval for bore construction may be required [Bore construction and approvals | Business Queensland QGOV (2023a)].

After installing the piezometer monitoring network, it is necessary to perform a topographic survey (can be conducted via drone) of the top of the casing to express the height of the water table measurements of each piezometer in metres above sea level [Australian Height Datum (AHD)] which will be the height to reference.

The design of the groundwater monitoring network will be site and project specific (purpose and budget). Detailed information on groundwater monitoring networks is provided in Optimal Groundwater Monitoring Network Design (Abdeh-Kolahchi 2007). For information on the drilling and installation of the monitoring network, please refer to Groundwater Sampling and Analysis – A Field Guide (Sundaram *et al.* 2009).

Figure 10: Groundwater monitoring piezometers installed to monitor groundwater flow through a bioreactor wall.

7 Discharge monitoring

The calculation of nitrogen loading to quantify nitrogen reduction requires measuring the discharge at the inlet and outlet of a VWT system. Although the description below refers to the simple example of only one inlet and one outlet, where there is more than one inlet or outlet the cumulative flow at all inlets and outlets should be monitored.

The discharge at the outlet of a system (Figure 11) seeing no change in storage can be described in Eq. 1, similar to (TRCA 2016):

$$S_{out} = S_{in} + G_{in} - G_{ex} + P - ET \qquad \text{Eq. 1}$$

Where S_{out} and S_{in} are the surface water discharge measured at the outlet and inlet, respectively, and include both channel flow and runoff, G_{in} is the groundwater infiltration (i.e., entering the VWT system) between the inlet and the outlet of the VWT system, G_{ex} is the groundwater exfiltration (exiting), defined as the surface water leaving the VWT system between the inlet and the outlet of the VWT system and recharging the surrounding groundwater system, P is the precipitation on the surface of the water treatment system, and ET is the evapotranspiration from the surface area of the VWT system.

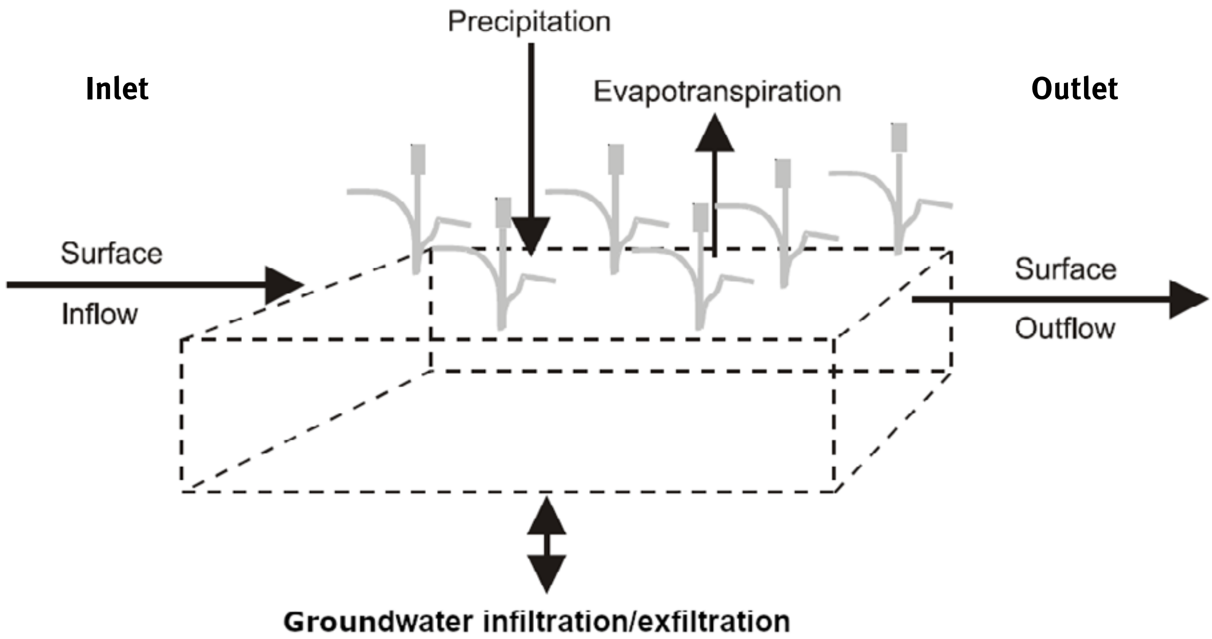


Figure 11: Diagram showing the dependence of the surface outflow (S_{out}) at a vegetated water treatment system on surface inflow (S_{in}) precipitation (P), evapotranspiration (ET) and groundwater infiltration/exfiltration (G_{in} and G_{ex}). Source: modified after (Yu and Fassman 1998).

The terms G_{in} and G_{ex} depend on the surface water-groundwater interaction type that defines infiltration/exfiltration processes. Please refer to Interaction of Ground Water and Surface Water in Different Landscapes (Winter 2000) for a classification of the types of surface water-groundwater interaction.

Note that Eq. 1 and Figure 11 are simplistic representations of a water balance in VWT systems and can be modified depending on the site and project purpose. Storage in VWT systems will usually change temporarily during flow events and the water balance represented in Eq.1 will be different during baseflow vs flow events, where the proportion of groundwater infiltration/exfiltration, precipitation and evapotranspiration will vary. The outlet of a treatment wetland may have a control structure to achieve design retention time by temporarily increasing storage. Therefore Eq.1 is intended to be applied to an entire flow event to understand the total volume of water passing through a VWT system during the event, using total inflow and outflow volume over the event (including the tail of the hydrograph when flow returns to baseline conditions).

7.1 Groundwater discharge

The occurrence of groundwater infiltration/exfiltration processes at a VWT system site should be assessed before its design and construction because groundwater interaction will affect the design and monitoring and in turn the monitoring project budget. Even if groundwater is present at a site, it might not necessarily be interacting with the VWT system, which could be perched and/or have an impervious clay layer preventing water exchange.

The occurrence of groundwater infiltration/exfiltration can be assessed in unconfined aquifers that are hydraulically connected with a VWT system (i.e., the bottom of the VWT system is not lined or impermeable). If groundwater infiltration/exfiltration is absent or negligible, the parameters to monitor according to Eq. 1 will be only S_{out}, S_{in}, P and ET. If groundwater infiltration or exfiltration are significant, groundwater discharge needs to be assessed.

Groundwater discharge can be estimated with direct monitoring by investigating groundwater characteristics (depth of water table, groundwater flow direction, hydraulic gradients and velocity), as well as the intrinsic parameters of the aquifer (saturated hydraulic conductivity, porosity, and cross-sectional area of the aquifer) (Davidsson *et al.* 2000; Kalbus *et al.* 2006). Groundwater characteristics and intrinsic parameters of the aquifer can be used to develop groundwater models to quantify infiltration/exfiltration processes. However, modelling approaches for quantifying groundwater infiltration/exfiltration in VWT systems are beyond the scope of this document, and is being investigated elsewhere [see Queensland Water Modelling Network (DES 2023a)].

Indirect monitoring using incremental gauging (Banerjee and Ganguly 2023; Kalbus *et al.* 2006) is also possible. There are inherent challenges and limitations in accurately assessing the extent of the groundwater 'catchment' and the groundwater infiltration and exfiltration under the varying conditions found in the field. These limitations must be considered when interpreting results.

7.1.1 Direct monitoring

Groundwater discharge (Q_g, m^3 d^{-1}) is calculated using Darcy's law (Darcy 1856) as:

$$Q_g = K\, i\, A_{aq} \qquad \text{Eq. 2}$$

K is the hydraulic conductivity, i is the hydraulic gradient calculated measuring water table levels, and A_{aq} is the cross-sectional area of the aquifer that can be quantified from field data collected during the installation of the piezometer monitoring network. Groundwater discharge is calculated by quantifying the terms in Eq. 2.

Water table level, groundwater flow pattern, and hydraulic gradient

Water table levels in the piezometer monitoring network are collected at each site inspection using dipmeters. Pressure transducers may be installed in strategic piezometers (i.e., located at the highest hydraulic head) for continuous monitoring of the water table level and groundwater temperature. The collection of groundwater levels allows contour line maps to be prepared indicating the groundwater flow direction.

The hydraulic gradient is calculated from the water table levels, and describes the slope of the water table, that is, the change in water table level per unit of distance along the direction of maximum head decrease. The hydraulic gradient can be calculated after measuring the water table level difference and distance between piezometers.

If it is not possible to measure hydraulic conductivity directly, values can be derived from another formulation of Darcy's law (Darcy 1856):

$$K = \frac{v * \varphi}{i} \qquad \text{Eq. 3}$$

v is the groundwater velocity, and *Φ* is the aquifer effective porosity.

If Eq. 2 and Eq. 3 are combined, a new equation is obtained:

$$Q_g = v * \varphi * A \qquad \text{Eq. 4}$$

Groundwater velocity can be estimated by tracer tests in VWT systems. A tracer test involves introducing a conservative tracer into a piezometer and monitoring the concentration of the tracer at time intervals (i.e., minutes or hours) with a logger or by grab sampling the time the tracer takes to reach a downgradient piezometer.

Because groundwater velocities are usually small, the piezometers must be close together to obtain results in a reasonable period. Furthermore, the flow direction should be precisely known (i.e., extrapolated from a contour line map); otherwise, the tracer plume may miss the downgradient piezometer. The groundwater velocity can be calculated from the tracer breakthrough curve (Figure 22) and the distance between the piezometers. Please refer to Groundwater (Freeze and Cherry 1979) for technical information on performing tracer tests in piezometers.

Porosity

Porosity is the number of voids within a given material and can be determined using bulk density and a water displacement test on a sediment sample of the aquifer. Please refer to Groundwater (Freeze and Cherry 1979) for technical information on performing porosity tests on soil/sediment samples.

Hydraulic conductivity

Hydraulic conductivity can be measured in core samples (i.e., permeameter test) or performing in-situ aquifer characterisation tests (i.e., slug tests and pumping tests).

Permeameter laboratory tests are performed on aquifer sediment core samples collected from the monitoring site enclosed between two porous plates in a tube. There are two permeameter tests: constant-head and falling-head tests. They can yield horizontal and vertical hydraulic conductivity values calculated from the head difference, time, tube, and sample geometry (Freeze and Cherry 1979; Todd and Mays 2004).

Slug tests are based on introducing/removing a known volume of water into/from a piezometer, and as the water level recovers, the head is measured as a function of time (Butler 2019). Slug tests are quick and easy with inexpensive equipment, providing point hydraulic conductivity measurements.

Pumping tests require a groundwater bore and at least one observation groundwater bore/piezometer in the capture zone. The first bore is pumped at a constant rate, and the second bore/piezometer's drawdown is measured as a time function. The hydraulic properties of the aquifer are determined using equations described in several pumping method equations (Chow 1952; Cooper and Jacob 1946; Moench 1995; Neuman 1975; Theis 1935).

7.1.2 Indirect monitoring

Incremental gauging

Incremental gauging is a technique to determine groundwater discharge (infiltration or exfiltration) by measuring the difference between the discharges measured at the inlet and outlet of a VWT system:

- Infiltration is occurring if the discharge decreases between the inlet and outlet ($S_{out} < S_{in}$).
- Exfiltration is occurring if the discharge increases between the inlet and outlet ($S_{out} > S_{in}$).

Incremental gauging should be performed when there is no rainfall, so that the precipitation (term *P* in Eq.1) equals zero. In this case, the only term that needs to be quantified is evapotranspiration (term *ET* in Eq.1). Incremental gauging can be measured at gauging stations with current meters, V-notch weirs and Parshall flumes in vegetated drains or treatment wetlands without inlet and outlet structures (Blume and Van Meerveld 2015; Mencio *et al.* 2014; Tazioli 2011). Incremental gauging can also be measured with flow meters in treatment wetlands with inlet and outlet structures. Incremental gauging can be employed without installing a groundwater monitoring network. However, aquifer characterisation and collection of groundwater samples will not be possible if a groundwater monitoring network is not installed. Therefore, it is recommended to install at least one piezometer on each side of the VWT system.

7.2 Surface water discharge

Discharge measurements at the inlet and outlet of a VWT system are necessary to calculate the terms S_{in} and S_{out} of Eq.1.

Surface water discharge can be monitored directly, indirectly or continuously. Direct Monitoring includes current meter, volumetric technique and floating spheres measurements performed at gauging stations installed in vegetated drains or treatment wetlands with or without inlet and outlet structures. Indirect monitoring involves extrapolating long term discharge data using rating curves. Continuous monitoring is performed using pressure transducers, V-notch weirs and Parshall flumes at gauging stations installed in vegetated drains or treatment wetlands or with pressure transducers and flow meters for treatment wetlands with inlet and outlet structures. Please refer to the Monitoring and Sampling Manual (DES 2018) for more information on surface water discharge measurements.

7.2.1 Direct monitoring

Current meters

Current meters are devices that use a velocity-area method at gauging stations in watercourses to calculate the surface water discharge (USDIBR 2001) as:

$$Q_s = v \times A_{cs} \quad \text{Eq. 5}$$

v is the surface water velocity, and A_{cs} the cross-sectional area of the measured watercourse.

Propeller, electromagnetic, and doppler current meters (Figure 12) can measure water velocity at a gauging stations in a watercourse. Please refer to the Water Measurement Manual (USDIBR 2001) for more information about the instruments' sensitivity and specific operating needs.

Current meters are relatively easy and fast to use, and propeller current meters have been used extensively in vegetated drain studies (Errico *et al.* 2018; Kavehei and Adame 2021).

Figure 12: Types of current meters: a) propeller current meter (www.valeport.co.uk/products/model-002-flowmeter/), b) electromagnetic current meter (flowmeterhire.com/open-channel-flowmeter/801-electro-magnetic-current-meter), and c) doppler current meter (hoskin.ca/product/acoustic-doppler-current-meter).

Before starting the data collection at the gauging station, it is critical to clean the cross-section of the watercourse from obstructions (i.e., rocks, logs, algae) to allow a homogenous flow distribution. The cross-section is then evenly divided into multiple subsections across the entire width (Figure 13). The spacing will depend on the width of the watercourse, and flow depth is measured at each subsection, where multiple vertical velocity measurements are performed (if the depth allows it) with a current meter (Figure 14). The velocities and flow depth measurements compute the total volume of water flowing through the cross-section during a specific time interval (USGS 2018). Once measurements are collected, the discharge can be calculated with spreadsheets and software. Please refer to Water Monitoring Standardisation Technical Committee Part 4 (BOM 2022) for a description of data analysis methods. Multiple discharge and flow depth measurements at gauging stations enable rating curves to be developed (Figure 15).

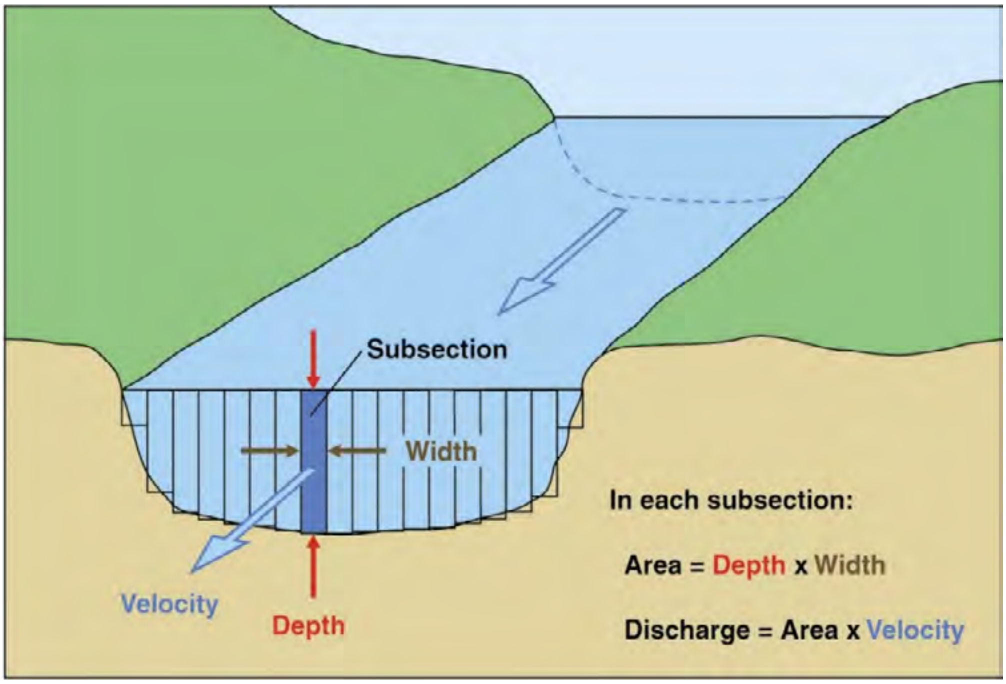


Figure 13: Illustration showing a channel cross section and how discharge can be calculated. Source: USGS (2018).

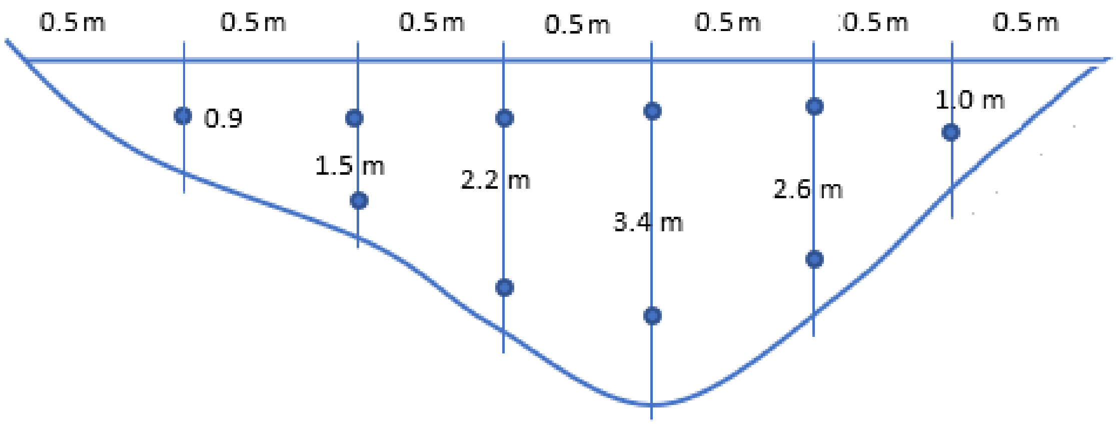


Figure 14: Water course cross-section divided into evenly divided subsections. Flow depth is measured at each subsection, and multiple vertical velocity measurements are performed using a current meter.

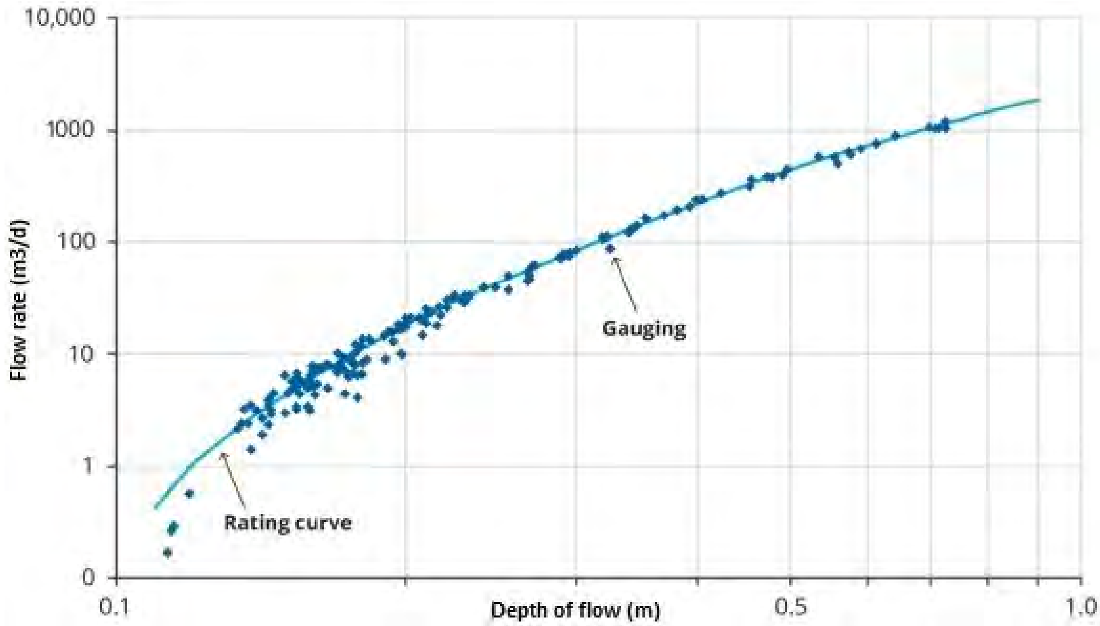


Figure 15: Rating curve relating depth of flow and discharge in a river, modified after Jain and Singh (2003).

Volumetric technique

The volumetric technique measures the time using a stopwatch to fill a container of known volume. This method is fast, replicable and measures the discharge at a point in time. However, volumetric measurements can be performed only under suitable conditions, such as when the flow is diverted into a relatively small channel or pipe, which enables the collection of the whole flow. For this reason, volumetric measurements might not be appropriate for vegetated drains but could be used in treatment wetlands equipped with inlet and outlet structures in low flow conditions. Multiple discharge measurements with the volumetric technique and flow depth measurement at the inlet and outlet structures of VWT systems enable rating curves to be developed.

Floating spheres

A cheaper, less accurate technique to estimate surface water discharge can be achieved using floating spheres, such as oranges (Adame *et al.* 2010). This technique requires measuring the distance between the inlet and the outlet. The flow velocity can be calculated as the ratio between the distance and the time the spheres take to move from the inlet (where they are released) to the outlet. The discharge at the outlet can be measured by multiplying the velocity for the cross-sectional surface area of the outlet of the VWT system. It is recommended to release multiple numbered spheres at regular intervals and measure the time they take to reach the outlet. The average time calculated based on their arrival will provide the average velocity. Multiple discharge measurements with the floating spheres technique and flow depth measurement at the inlet and outlet structures of VWT systems enable rating curves to be developed.

This method has a low accuracy because it is not based on a direct discharge measurement and could be influenced by external factors (i.e., wind, vegetation). However, it can be utilised for investigations with a low project budget.

This method can only be used when groundwater infiltration/exfiltration does not occur and the VWT system does not have vegetation growing across the system, which would entrap the floating spheres.

7.2.2 Indirect monitoring

Rating curves

Rating curves relate discharge and flow depth measured at different discharge rates (DES 2018; USDIBR 2001). Rating curves enable the discharge to be extrapolated when measurements are unavailable over the entire range of observed stages (Figure 15).

7.2.3 Continuous monitoring

Pressure transducers

Pressure transducers are devices that log water pressure continuously. Pressure measurements can be converted into flow depth. The water pressure needs to be compensated with barometric pressure. Therefore, when monitoring flow depth, it is necessary to monitor atmospheric pressure too. Regional barometric data can be used too, but it is always preferable to monitor barometric pressure with a logger at the site to enable more accurate site-specific measurements.

Flow meters

Flow meters are instruments used to measure the amount of liquid moving through a pipe. They are used in treatment wetlands with inlet and outlet structures.

Water flow meters can be mechanical or electromagnetic (Figure 16) and can log discharges continuously.

Mechanical flow meters have moving parts like propellers or rotors that measure the discharge and have been used in treatment wetlands (Lee *et al.* 2020; Scholz *et al.* 2007). However, mechanical flow meters are subject to vegetation blockage and require regular calibration.

Electromagnetic flowmeters have also been used in treatment wetlands (Bruun *et al.* 2016; Hoffmann *et al.* 2019), and unlike mechanical flow meters, they have the advantage of not experiencing blockages and might be a better solution for monitoring discharges in VWT systems.

Mechanical and electromagnetic flow meters may be a cost-effective option. However, they require a power source (i.e., battery and solar panel), a data logger, and regular maintenance, which could raise the monitoring cost.

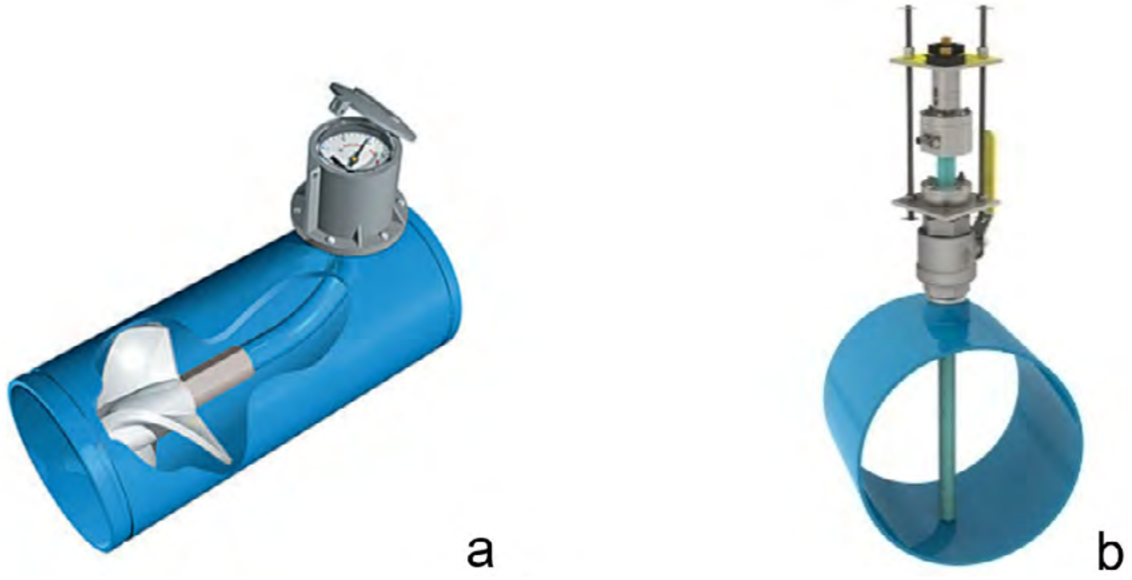


Figure 16: Different flow meter models: a) mechanical flow meter and b) electromagnetic flow meter. Source: www.mccrometer.com.

V-notch weirs and Parshall flumes

V-notch weirs (Figure 17) are used at the inlet and outlet of VWT systems and are placed to obstruct open channel flow and allow water to flow over the notch. Flumes (Figure 18) do not obstruct the flow and allow the flow through the throat. V-notch weirs and flumes require continuous monitoring of the flow depth with pressure transducers to quantify surface water discharge.

V-notch weirs and pressure transducers have been deployed to monitor vegetated drains and treatment wetlands (Groh *et al.* 2015; Han *et al.* 2019; Holland *et al.* 2004).

Please refer to the Water Measurement Manual (USDIBR 2001) for the technical information on the installation and data analysis of V-notch weirs and Parshall flumes.

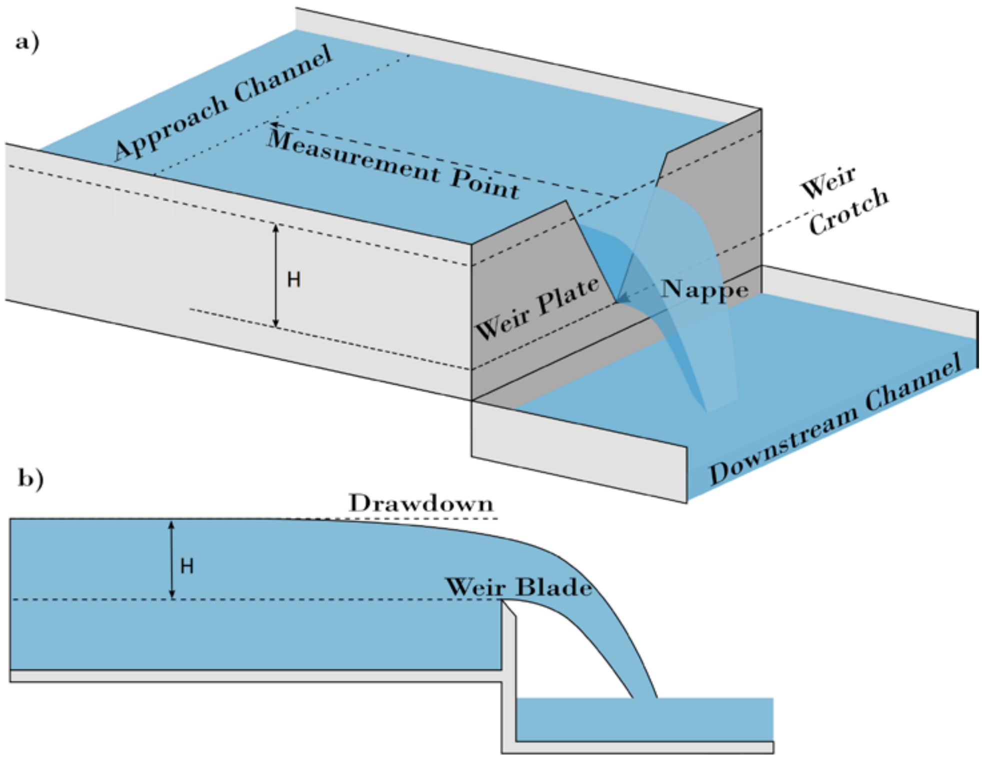


Figure 17: a) Schematic of the V-notch weir. b) Cross section of the V-notch weir along its long axis. Modified after Gould et al. (2021).

Figure 18: Flume installed on a sugarcane farm to monitor surface water discharge entering a treatment system.

7.3 Precipitation

Precipitation measurements are necessary to calculate the term *P* in Eq.1, and they can be obtained with continuous or indirect monitoring.

7.3.1 Continuous monitoring

Precipitation is generally monitored continuously, with weather stations monitoring other ancillary parameters, too (i.e., atmospheric temperature).

7.3.2 Indirect monitoring

Alternatively, daily weather data can be downloaded from the Australian Bureau of Meteorology weather station directory (BOM 2023b) if the study site is near monitoring stations belonging to the Bureau of Meteorology's network.

7.4 Evapotranspiration

Evapotranspiration (*ET* in Eq. 1) is a process that removes liquid water from an area due to evaporation to the atmosphere and vegetation transpiration. Evapotranspiration measurements can be obtained with direct, continuous, and indirect monitoring.

7.4.1 Direct monitoring

Pan reading

Evaporation can be measured directly using evaporation pans. An evaporation pan holds water during observations to determine the evaporation quantity at a given location. Evaporation pans are of varying sizes and shapes, the most used being circular or square. Evaporation pans can be automated with pressure transducers to measure the water level and are installed near a weather station. Evaporation pans provide daily evaporation data.

7.4.2 Continuous monitoring

Evapotranspiration sensors

Evapotranspiration can be continuously measured using sophisticated and expensive sensors (Fratini *et al.* 2023; Griessbaum *et al.* 2023).

7.4.3 Indirect monitoring

Models and databases

Daily evapotranspiration can be calculated from meteorological data using the FAO Penman–Monteith method (Allen et al. 1998) or using the evaporation model described by McJannet et al. (2008) and Wallace et al. (2015), which requires daily weather data. Daily evapotranspiration data can also be downloaded from the Agricultural Services directory (BOM 2023a) or the Queensland Government SILO website (QGOV 2023b).

8 Water quality monitoring

Quantifying nitrogen reduction in VWT systems requires sampling water entering the system and water leaving the system. This involves surface water sampling, and groundwater sampling, if groundwater infiltration/exfiltration occurs.

Depending on the nitrogen form(s) being investigated (Figure 5), water samples may require filtering in the field (0.45 µm) within 24 hr from collection. After collection, water samples must be stored in plastic bottles, refrigerated at 4 °C, and shipped to laboratory facilities to be analysed within 24 hr and determine the concentration of the targeted nitrogen form(s). Alternatively, samples can be frozen and analysed within 1 month from the collection (DEHP 2009).

8.1 Groundwater sampling

Groundwater samples should be collected from the piezometer monitoring network (Figure 19) where groundwater infiltration/exfiltration occurs in a VWT system. Before sampling, piezometers must be purged of water by pumping until dry or until removing 2-3 times the water volume (Sundaram *et al.* 2009), allowing the piezometer time to refill.

Figure 19: Groundwater sampling using a water pump in a piezometer.

8.1.1 Direct monitoring

Manual/electric pump

Groundwater sampling from piezometers is performed using manual or electric pumps. The pump brings water to the surface where it can be collected in bottles. The Monitoring and Sampling Manual (DES 2018) and Groundwater sampling and analysis (Sundaram et.al., 2009) provide detailed information on groundwater sampling equipment and techniques.

8.2 Surface water sampling

Water sampling in VWT systems needs to be performed at the inlet and the outlet to quantify the nitrogen reduction and can be manual or automated. The Monitoring and Sampling Manual (DES 2018) recommends the methodologies for direct monitoring, automated monitoring, or continuous monitoring.

8.2.1 Direct monitoring

Grab sampling with a sampling pole or container

Grab sampling allows the collection of discrete samples and should occur without disturbing the substrate to avoid affecting the representativeness of the water sample. In VWT systems, it can be performed using an extendable sampling pole so that a sample can be collected in the middle of the waterbody without disturbing the sediment (Figure 20). Containers attached to ropes can also be used in some situations.

Figure 20: Using an extendable pole to collect water samples in a wetland.

Grab sampling with manual/electric pumps

Grab sampling can also be performed with manual/electric pumps in treatment wetland inlet and outlet structures if these are present. Grab sampling is performed for baseflow, event-based and water-year monitoring according to the frequency established for the monitoring strategy.

8.2.2 Automated monitoring

Automated samplers

Automated monitoring allows the collection of discrete or composite samples multiple times daily and can save labour and enable sample collection during events when access may be limited. It generally uses automated water samplers (i.e., ISCO samplers) that can also be refrigerated and deployed at gauging stations or inlet and outlet structures of VWT systems. Automated samplers may be more expensive (i.e., higher capital cost relative to grab sampling) and need a power supply and connection to a data logger and trained technicians for the installation. Water sample retrieval should occur within a few hours after collection if the automated samplers are not refrigerated. Automated monitoring is performed for event-based monitoring and water-year monitoring according to the frequency established for the monitoring strategy.

8.2.3 Continuous monitoring

NO_3^-/NO_2^-/NH_4^+ probes

An alternative to collecting grab sampling can be continuous monitoring of NO_3^-, NO_2^- or NH_4^+ using probes (Figure 21). These probes can be deployed at the inlet or outlet structures or gauging stations of VWT systems. Despite being expensive, these probes avoid collecting and analysing multiple water samples and using research consumables. However, grab samples should be collected regularly to check the probe reading against laboratory-analysed samples.

They can be used for baseflow monitoring, event-based monitoring and water-year monitoring and to calculate an accurate nitrogen balance. The combination of time series of physico-chemical parameters together with nitrate and ammonium data have been used to provide estimates of total nitrogen (Zhuang *et al.* 2022).

Figure 21: A nitrate probe set up to monitor catchment water quality. Inset shows a close-up of the nitrate probe with a screen to protect it from debris.

8.3 Nitrogen chemical analyses

Water samples should be analysed in National Association of Testing Authorities (NATA) accredited laboratories for the targeted nitrogen form(s). The APHA (current version) analytical methods specified in Table 2 are one of the recommended methods.

Table 2: Nitrogen forms monitored in water treatment system studies, analytical APHA methods and codes for chemical analysis.

Analyte		Analytical method	APHA code	Filtered
DIN	NO_3	Colorimetric	4500-NO_3 Part E 1992	0.45 µm
		Ion chromatography	4110 Part B 1992	
	NO_2^-	Colorimetric procedure	4500-NO_2 Part B 1992	
		Ion chromatography	4110 Part B 1992	
	NH_3 or NH_4^+	Phenate colorimetric	4500-NH_3 Parts F,G or H, 1992	
		Ammonia selective electrode	4500-NH_3 Part D or E, 1992	
DON	-	Difference: TDN – DIN	-	-
TDN	DIN + DON	persulfate/UV digestion	4500-N Part B	0.45 µm
		persulfate digestion	4500-N Part C	
		combustion catalysis	4500-N Part E	
TN	TDN + particulate nitrogen	persulfate/UV digestion	4500-N Part B	-
particulate N	-	persulfate digestion	4500-N Part C	-
		combustion catalysis	4500-N Part E	
		Difference: TN – TDN or	-	
		Difference: TKN – DKN	-	
TKN	DON + NH_3 + particulate nitrogen	macro-Kjeldahl	4500-N_{org} Part B	-
		semi-micro Kjeldahl	4500-N_{org} Part C	
		block digestion method	4500-N_{org} Part D	
DKN	DON + NH_3	macro-Kjeldahl	4500-N_{org} Part B	0.45 µm
		semi-micro-Kjeldahl	4500-N_{org} Part C	
		block digestion method	4500-N_{org} Part D	
TAN	NH_3 + NH_4^+	Phenate colorimetric	4500-NH_3 Parts F,G or H, 1992	0.45 µm
Please refer to nitrogen forms for an explanation of the acronyms used for the analyses				

8.4 Ancillary measurements

Ancillary measurements are defined as those parameters that are not required to calculate the nitrogen reduction in VWT systems but are usually monitored in research projects to provide additional information and context to assess nitrogen reduction and nitrogen processes. They include physico-chemical parameters and hydraulic residence time.

8.4.1 Physico-chemical parameters

Physico-chemical parameters can support the interpretation of the water quality data. They are not critical to assess nitrogen reduction, but as the majority of nitrogen in WTS is removed via denitrification (Kavehei *et al.* 2021b), they can be used to evaluate whether suitable conditions are occurring. Physico-chemical parameters include temperature, dissolved oxygen, and pH; the optimal range of these parameters for denitrification are summarised in Table 3.

Table 3: Optimal range of physico-chemical parameters for denitrification.

Parameter	Optimal denitrification range
Temperature	25 and 35 °C (Robertson *et al.* 2000)
Dissolved oxygen	< 2 mg L^{-1} (Robertson *et al.* 2000)
pH	5.5 and 8.0 (Rivett *et al.* 2008)

Temperature (°C) can significantly impact the growth and reproduction of microbes. At low temperatures, the metabolism and activity of nitrifying and denitrifying bacteria tend to reduce, which in turn influences the denitrification process (de Klein 2008). Consequently, VWT systems' performance at removing nitrogen depends on temperature, with higher reduction found at warmer temperatures (Chen *et al.* 2015; Kumwimba *et al.* 2017). Warmer temperatures can also impact ammonia volatilisation with an increase in emissions when the temperature rises (Ng and Gunaratne 2011).

Dissolved oxygen (mg L^{-1} or as %) refers to the volume of oxygen in the water. It is an essential parameter in VWT systems because it affects microbial activities and regulates biochemical processes such as nitrification and denitrification.

The pH measures the acidity or alkalinity of water, with a pH of 1 being strongly acidic, a pH of 7 being neutral, and a pH of 14 being strongly alkaline. The capability of VWT systems to remove nitrogen depends on pH, with the optimum pH range for denitrification between 5.5 and 8.0 (Rivett *et al.* 2008). A pH out of this range can impact the ability of denitrifiers to synthesise reductase enzymes to perform denitrification (Liu *et al.* 2014).

Physico-chemical parameters can be collected with direct monitoring using portable instruments and continuous monitoring using probes and data loggers. It is critical to regularly calibrate monitoring instruments before using/deploying them in the field to ensure the validity of the collected data. For additional information on collecting physico-chemical parameters, please refer to the Monitoring and Sampling Manual (DES 2018).

Direct monitoring

Physico-chemical parameters can be measured in grab samples with the same frequency adopted for surface water sampling and groundwater sampling. They are measured in-situ with portable sensors by immersing them in a subsample of the grab sample. It is not recommended to measure physico-chemical parameters from water samples collected during automated monitoring, as the measurement of their physico-chemical parameters would occur when the sample is retrieved from the automated sampler rather than when it was collected. Grab sampling will usually miss detecting diurnal variations in physico-chemical parameters.

Continuous monitoring

When performing continuous monitoring with loggers, probes or data loggers are recommended to monitor physico-chemical parameters continuously. These devices need to be installed at the inlet and outlet gauging stations or inlet and outlet structures.

8.4.2 Hydraulic residence time

The hydraulic residence time (HRT, hr or d) is the theoretical length of time water takes to flow from the inlet to the outlet of a water treatment system, and it is defined as:

$$HRT = \frac{V}{Q} \quad \text{Eq. 6}$$

Where V is the volume of water in the treatment system, and Q is the discharge measured at the outlet. Hydraulic residence time is inversely proportional to the discharge, and consequently, the lower the discharge, the longer the HRT. In vegetated drains and treatment wetlands, a longer HRT is expected to provide higher nitrogen reduction (Kumwimba *et al.* 2018; Yousaf *et al.* 2021) because it allows for more interaction between the nitrogen dissolved in the water and the sediments where denitrification occurs. Hydraulic residence time can be measured with direct monitoring using tracer tests or can be calculated with Eq. 6 using indirect monitoring with volume and discharge estimation.

Direct monitoring

Tracer tests

Tracer tests are performed to acquire information about the flow type in a VWT system. These tests use conservative tracers, which do not react with the water and its constituents and allow tracking of the water movement through the VWT system. A known quantity of a tracer is added at the inlet and then sampled at regular intervals at the outlet. The tracer mass recovery rate provides information about the reliability of the tracer test. The test can be acceptable if 80% of the tracer mass is recovered when sampling water at the outlet. Recovery or breakthrough curves are used at the end of the tracer test to calculate the tracer hydraulic residence time (τHRT), which defines the average time a tracer particle spends in the VWT system. The τHRT is the centroid of the breakthrough curve (Figure 22), and it is calculated using:

$$\tau HRT = \frac{\sum t_i * C_i * \Delta t_i}{\sum C_i * \Delta t_i} \qquad \text{Eq. 7}$$

t_i is the time (hr) at the i^{th} sample, C_i is the outlet tracer concentration (mg L^{-1}), and Δt_i is the time interval (hr) between samplings.

Differences between τHRT and the HRT indicate the existence of short-circuiting (being a route through the VWT system that does not meet the calculated retention times or contact with vegetation) or dead zones without water flow.

A literature review of the most utilised tracers used for tracer tests is available in Headley and Kadlec (2007). Those suitable to use in VWT systems have been summarised below.

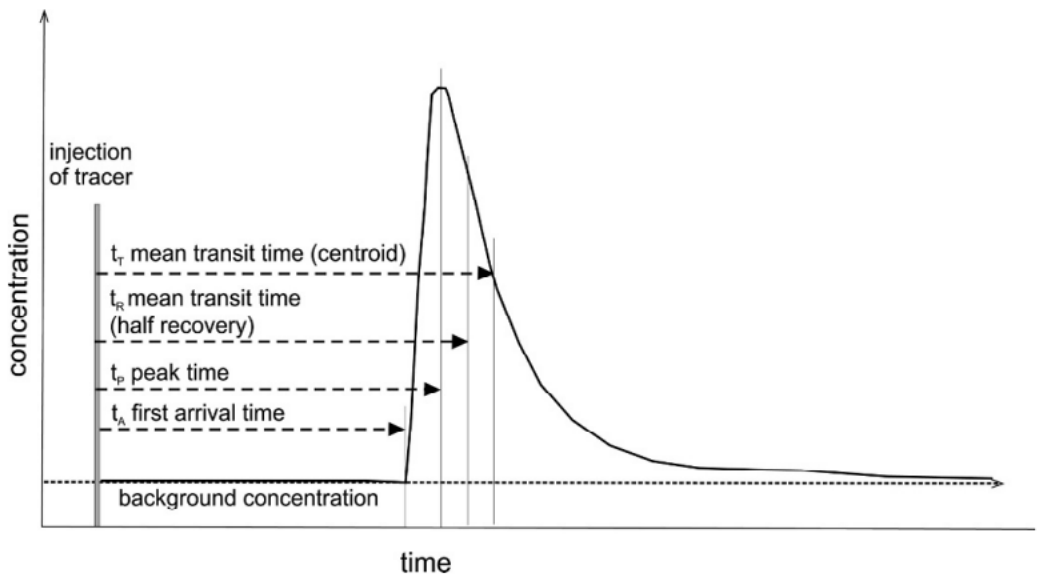


Figure 22: Definition of various times used for a hypothetical breakthrough curve. The first arrival time is defined by raising the tracer concentration above the background. The maximum concentration of the tracer defines peak time. Mean transit time (half recovery) is defined by the passage of 50% of tracer mass (background is subtracted). Median transit time (centroid) is defined by the centroid of the tracer (background is subtracted). Source: Vojtechovska *et al.* (2010).

Bromide and lithium are the most used tracers because of their relatively low cost and ease of analysis. They are typically added as sodium or potassium bromide or lithium chloride solutions and have yielded reliable results in numerous wetland studies (Bruun *et al.* 2016; Dierberg and DeBusk 2005; Lin *et al.* 2003). Both bromide and lithium are not subject to degradation but can be taken up by plants and other organisms (Whitmer *et al.* 2000). Lithium background concentrations are typically very low, but bromide may be present in natural waters at concentrations well above detection. Therefore, it is recommended to perform preliminary monitoring to assess the amount of background bromide concentration. Even if both bromide and lithium are relatively inexpensive, a significant amount of tracer might be required to achieve a significant peak and detection above background levels in large VWT systems. Bromide is typically analysed through ion chromatography, although less reliable portable probes can be used in the field. Lithium can be measured using atomic absorption spectrometry or inductively coupled plasma-optical emission spectrometry.

Rhodamine WT is a relatively cheap dye used when dissolved solids in the water are <600 mg L^{-1} and the pH >6. Preliminary monitoring is required to assess whether these conditions are met before the tracing test is performed. However, Rhodamine WT can be subject to biodegradation, photolysis and adsorption onto organic solids, detritus and some plastics (Dierberg and DeBusk 2005; Lin *et al.* 2003). For these reasons, it is recommended to apply rhodamine WT only at moderate to high initial concentrations in short-term tests (HRT <7 d) and in environments that are not highly organic, which would limit its use in established VWT systems. Collected samples should be stored in glass bottles and kept dark before analysis to prevent photo-degradation. Rhodamine WT is typically measured using fluorescence spectrophotometry (Simi and Mitchell 1999), but continuous logging probes can also be employed (Holland *et al.* 2004).

Sodium chloride is the cheapest tracer that can be employed for a tracing test, not only for its price but also because it can be easily monitored in the field using portable electrical conductivity instruments. However, high salt concentrations may negatively affect aquatic life and the VWT system's vegetation and performance. Additionally, the high concentrations required to create a significant spike in electrical conductivity can cause substantial density effects, with the heavy tracer impulse sinking to the bottom of the system, providing unrepresentative results (Chazarenc *et al.* 2003; Schmid *et al.* 2004).

Indirect monitoring

Volume and discharge estimation

The calculation of HRT requires measuring the discharge from the VWT system and the volume of water held in the system. The discharge can be measured using direct or continuous monitoring, while the volume calculation requires both bathymetric and topographic information.

The bathymetry should be surveyed in VWT systems at least once at the start of the monitoring program, although if there are significant changes in bathymetry during the monitoring due to sedimentation, erosion, or effects of flooding, then another survey is recommended. The survey can be undertaken in treatment wetlands at the end of the construction before the wetland is flooded to confirm the design volumes, or in vegetated drains when the drain is dry. There are various methods to survey bathymetry, including a multibeam sonar system (Montgomery *et al.* 2017), taped grid, auto-level, rotating level laser, pool-point radial survey, total station, and real-time kinematic (RTK) GPS. Please refer to Wetland Bathymetry and Mapping (Los Huertos and Smith 2013) for a description of these methods.

The cheapest way to obtain topographic information is to extrapolate them from topographic maps. Alternatively, topographic surveys of both vegetated drains and treatment wetlands can be performed with RTK GPS (Pugliese *et al.* 2020), LiDAR technology (Tanner *et al.* 2015; Tomer *et al.* 2013) or using digital elevation models from geotagged drone photographs (Levy and Johnson 2021; Villafañe *et al.* 2022). The information gathered with the bathymetric and topographic surveys can be managed in a GIS system and used to create a digital earth model (DEM) that enables an accurate volume calculation. Using a DEM along with flow depth data permits calculating the water volume in the VWT system and estimating its HRT.

9 Nitrogen reduction quantification

Nitrogen reduction can be calculated using a mass balance approach using information collected during the discharge and water quality monitoring (Figure 23). The calculation of nitrogen reduction is based on the targeted nitrogen form(s) (i.e., TN, TDN, DIN, NO_3^- etc.), depending on the purpose of the monitoring project and the project budget, as well as on the discharge measured at the inlet and the outlet of the VWT system.

There are two parameters to express the nitrogen reduction performance of VWT systems:

As outlined in limitations and assumptions, VWT systems are usually designed for a certain flow regime. During flooding, bypass and overbank flow events nitrogen reduction monitoring and estimation will have increased uncertainties and errors. The calculations described below are recommended when overbank flow does not occur, otherwise the total load of nitrogen passing through a VWT system cannot be measured.

- Removal rate which is a standardised quantitative parameter that enables the comparison of VWT systems and expresses the mass of nitrogen removed per unit surface area per unit of time.
- Loading reduction which is the total mass of nitrogen removed in a unit of time which is usually used when discussing a VWT system's contribution to catchment nitrogen load reduction or cost-effectiveness analyses.

The choice of parameter will depend on the purpose of the monitoring project.

The mass balance approach relies on mass loads:

Load (g d^{-1}) = discharge ($m^3 d^{-1}$) x concentration (mg L^{-1} = g m^{-3})

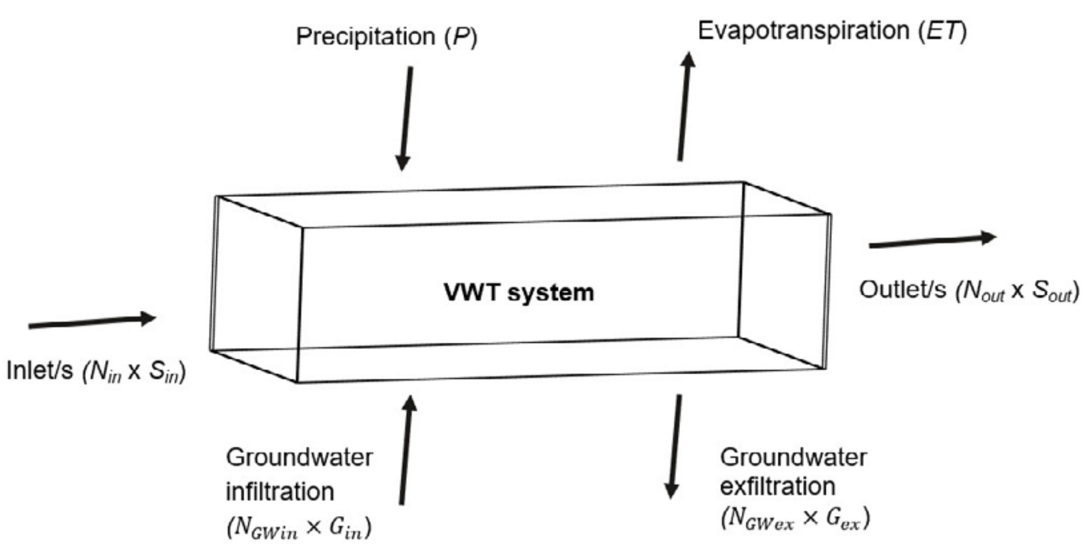


Figure 23: Illustration of the discharge (i.e., flow) and water quality monitoring (i.e., concentration) components of the monitoring program which are utilised to calculate nitrogen reduction.

9.1 Nitrogen removal rate

The nitrogen removal rate (NRR) should be expressed similarly to Kadlec *et al.* (2000) as the mass of nitrogen removed per unit of surface area and unit of time (g nitrogen m^{-2} d^{-1}). The calculation of the mass removal should be performed according to Dunne *et al.* (2015), as the difference between the product of discharge by nitrogen concentrations at the inlet and outlet, divided by the water treatment surface area:

$$NRR = \frac{(N_{in} \times S_{in}) - (N_{out} \times S_{out})}{A_{VWT}} \qquad \text{Eq. 8}$$

Where N_{in} and N_{out} are the concentrations (g nitrogen m^{-3} or mg nitrogen L^{-1}) of the targeted nitrogen form at the inlet and outlet, respectively, S_{in} and S_{out} are the discharges (m^3 d^{-1}) at the inlet and outlet, respectively, and A_{VWT} is the surface area (m^2) of the VWT system.

This formula needs to include all inflows and outflows and sources of N. Therefore, Eq.8 can only be used when the term *P* and *ET* of Eq. 1 are negligible and if groundwater infiltration/exfiltration do not occur (G_{in} and G_{ex} = 0). When groundwater infiltration occurs, and the terms *P* and *ET* are considered negligible, the NRR calculation needs to include the terms G_{in} of Eq. 1:

NOTE

The units can be modified depending on the purpose and site, provided all units in the calculation are applied consistently.

For example, discharge can be represented as m^3 s^{-1}, m^3 hr^{-1}, m^3 d^{-1} or ML $year^{-1}$, and concentration can be expressed as g nitrogen m^{-3} or mg nitrogen L^{-1}.

$$NRR = \frac{(N_{in} \times S_{in} + N_{GWin} \times G_{in}) - (N_{out} \times S_{out})}{A_{VWTS}} \qquad \text{Eq. 9}$$

Where N_{GWin} (g nitrogen m^{-3} or mg nitrogen L^{-1}) is the nitrogen concentration of groundwater entering the VWT system, and G_{in} is its discharge.

When groundwater exfiltration occurs, and the terms *P* and *ET* are considered negligible, the NRR calculation needs to include the terms G_{ex} of Eq. 1:

$$NRR = \frac{(N_{in} \times S_{in}) - (N_{out} \times S_{out} - N_{GWex} \times G_{ex})}{A_{VWTS}} \qquad \text{Eq. 10}$$

Where N_{GWex} (g nitrogen m^{-3} or mg nitrogen L^{-1}) is the nitrogen concentration of groundwater exiting the VWT system, and G_{ex} is its discharge.

When *P* or *ET* is significant these need to be added as water inputs or outputs, with negligible nitrogen concentrations.

9.2 Nitrogen loading reduction

The nitrogen loading reduction (NLR) should be calculated similarly to Dunne *et al.* (2015), as the difference between the product of daily discharges by daily nitrogen concentrations at the inlet and outlet per unit of time (kg nitrogen yr^{-1}):

$$NLR = (N_{in} \times Q_{in}) - (N_{out} \times Q_{out}) \qquad \text{Eq. 11}$$

This formula can be used when assuming that the term *P* and *ET* of Eq. 1 are negligible and if groundwater infiltration/exfiltration do not occur (G_{in} and G_{ex} = 0).

When groundwater infiltration occurs, and the terms *P* and *ET* are considered negligible, the NLR calculation needs to include the terms G_{in} of Eq. 1:

$$NLR = (N_{in} \times Q_{in} + N_{GWin} \times G_{in}) - (N_{out} \times Q_{out}) \quad \text{Eq. 12}$$

When groundwater exfiltration occurs, and the terms *P* and *ET* are considered negligible, the NLR calculation needs to include the terms G_{ex} of Eq. 1:

$$NLR = (N_{in} \times Q_{in}) - (N_{out} \times Q_{out} - N_{GWex} \times G_{ex}) \quad \text{Eq. 13}$$

When *P* or *ET* is significant these need to be added as water inputs or outputs, with negligible nitrogen concentrations.

10 Recommended monitoring programs

Three classes of monitoring (i.e., gold, silver, and bronze) for both vegetated drains and treatment wetlands are outlined in this document in Tables 4-9 to provide guidance. The choice of one class of standard will be dictated by the purpose of the monitoring project and the project budget, that will influence the design of the monitoring program. It is likely that a larger project budget will enable increased sampling duration and frequency, resulting in more accurate nitrogen removal quantification. Different levels of monitoring can be selected for different parameters depending on budget. However, this could change the overall accuracy of the monitoring. For this reason, in order to have the highest accuracy of the data, the gold standard is always recommended.

All classes allow the calculation of nitrogen reduction based on the mass balance approach and advise the parameters to monitor, the monitoring methods, and the monitoring devices/tests that should be used, ranked based on their accuracy, with one asterisk (*) corresponding to the lowest accuracy and three asterisks (***) to the highest. Multiple monitoring devices/tests may be possible for each parameter, but only one should be selected according to the project budget and specific site conditions.

Monitoring frequencies are specified for each flow regime, and the structures to perform the monitoring are also specified. However, this document does not provide information on the monitoring duration because it is project specific.

This document will not provide information regarding the accuracy of the data collected. Please refer to Guidance on Systematic Planning Using the Data Quality Objectives Process (USEPA 2006) for further information about the quality of the data collected and their analysis.

The Gold level represents the highest monitoring standard in this document and uses continuous, direct, and indirect monitoring methods. The monitoring frequency varies between 30-60 minutes (for continuous monitoring) and one week (for direct and indirect monitoring). Gold level monitoring for vegetated drains and treatment wetlands are in Table 4 and Table 5 respectively.

The Silver level represents the intermediate monitoring standard in this document and uses continuous, direct, indirect, and automated monitoring methods. The monitoring frequency varies between 30-60 minutes (for continuous monitoring) and one month (for direct, indirect, and automated monitoring). Silver level monitoring for vegetated drains and treatment wetlands are in Table 6 and Table 7, respectively.

The Bronze level represents the lowest monitoring standard and is considered less accurate than the other standards. It uses direct and indirect monitoring methods. The in-situ monitoring frequency is one month. Bronze level monitoring for vegetated drains and treatment wetlands are in Table 8 and Table 9, respectively.

10.1 Gold level (highest accuracy)

Table 4: Gold level monitoring for vegetated drains

Parameter	Monitoring method		Monitoring devices/tests	Monitoring device's accuracy	Monitoring frequency according to different flow regimes			Monitoring structure
					Baseflow	Event-based	Water-year	
Groundwater discharge	Direct monitoring	Water table level	Dipmeter and/ or Pressure transducers	***	Weekly 30-60 minutes for pressure transducers	When flow events occur 30-60 minutes for pressure transducers	Weekly and/or when flow events occur 30-60 minutes for pressure transducers	Piezometer monitoring network
		Contour line maps						
		Hydraulic gradient						
		Porosity	Water displacement test	***	Once	Once	Once	-
		Hydraulic conductivity	Permeameter	***	Once	Once	Once	-
			Slug test	***	Once	Once	Once	Piezometer monitoring network
			Pumping tests	***	Once	Once	Once	
	Indirect monitoring	Incremental gauging	Current meters	**	Weekly	Weekly	Weekly	Inlet and outlet gauging stations
			V-notch weirs or Parshall flumes + pressure transducers	***	30-60 minutes	30-60 minutes	30-60 minutes	
Surface water discharge	Continuous monitoring		V-notch weirs or Parshall flumes + pressure transducers	***	30-60 minutes	30-60 minutes	30-60 minutes	Inlet and outlet gauging stations
Precipitation rate	Continuous monitoring		Weather station	***	30-60 minutes	30-60 minutes	30-60 minutes	-
Evapotranspiration rate	Continuous monitoring		Evapotranspiration sensor	***	30-60 minutes	30-60 minutes	30-60 minutes	-
Groundwater quality (targeted nitrogen form concentration)	Direct monitoring		Manual/electric pump	***	Weekly	When flow events occur	Weekly and/or when flow events occur	Piezometer monitoring network
Surface water quality (targeted nitrogen form concentration)	Continuous monitoring		$NO_3^-/NO_2^-/NH_4^+$ probes	***	30-60 minutes	30-60 minutes	30-60 minutes	Inlet and outlet gauging stations
Physico-chemical parameters	Direct monitoring		Portable sensors	***	Weekly	When flow events occur	Weekly and/or when flow events occur	Inlet and outlet gauging stations
	Continuous monitoring		Data loggers or Probes	***	30-60 minutes	30-60 minutes	30-60 minutes	
Hydraulic residence time	Direct monitoring		Tracer tests	***	Twice (high and low discharge)	Twice (high and low discharge)	Twice (high and low discharge)	Inlet and outlet gauging stations

Table 5: Gold level monitoring for treatment wetlands

Parameter	Monitoring method		Monitoring devices/tests	Monitoring device's accuracy	Monitoring frequency according to different flow regimes			Monitoring structure
					Baseflow	Event-based	Water-year	
Groundwater discharge	Direct monitoring	Water table level	Dipmeter and/or Pressure transducers	***	Weekly 30-60 minutes for pressure transducers	When flow events occur 30-60 minutes for pressure transducers	Weekly and/or when flow events occur 30-60 minutes for pressure transducers	Piezometer monitoring network
		Contour line maps						
		Hydraulic gradient						
		Porosity	Water displacement test	***	Once	Once	Once	-
		Hydraulic conductivity	Permeameter	***	Once	Once	Once	-
			Slug test	***	Once	Once	Once	Piezometer monitoring network
			Pumping tests	***	Once	Once	Once	
	Indirect monitoring	Incremental gauging	Current meters	**	Weekly	Weekly	Weekly	Inlet and outlet gauging stations
			V-notch weirs or Parshall flumes + pressure transducers	***	30-60 minutes	30-60 minutes	30-60 minutes	
Surface water discharge	Continuous monitoring		Flow meters	***	30-60 minutes	30-60 minutes	30-60 minutes	Inlet and outlet structures
			V-notch weirs or Parshall flumes + pressure transducers	***	30-60 minutes	30-60 minutes	30-60 minutes	Inlet and outlet gauging stations
Precipitation rate	Continuous monitoring		Weather station	***	30-60 minutes	30-60 minutes	30-60 minutes	-
Evapotranspiration rate	Continuous monitoring		Evapotranspiration sensor	***	30-60 minutes	30-60 minutes	30-60 minutes	-
Groundwater quality (targeted nitrogen form concentration)	Direct monitoring		Manual/electric pump	***	Weekly	When flow events occur	Weekly and/or when flow events occur	Piezometer monitoring network
Surface water quality (targeted nitrogen form concentration)	Continuous monitoring		$NO_3^-/NO_2^-/NH_4^+$ probes	***	30-60 minutes	30-60 minutes	30-60 minutes	Inlet and outlet gauging stations or inlet and outlet structures
Physico-chemical parameters	Direct monitoring		Portable sensors	***	Weekly	When flow events occur	Weekly and/or when flow events occur	Inlet and outlet gauging stations or inlet and outlet structures
	Continuous monitoring		Data loggers or Probes	***	30-60 minutes	30-60 minutes	30-60 minutes	
Hydraulic residence time	Direct monitoring		Tracer tests	***	Twice (high and low discharge)	Twice (high and low discharge)	Twice (high and low discharge)	Inlet and outlet gauging stations or inlet and outlet structures

10.2 Silver level (intermediate)

Table 6: Silver level monitoring for vegetated drains

Parameter	Monitoring method		Monitoring devices/tests	Monitoring device's accuracy	Monitoring frequency according to different flow regimes			Monitoring structure
					Baseflow	Event-based	Water-year	
Groundwater discharge	Indirect monitoring	Incremental gauging	Current meters	**	Monthly	When flow events occur	Monthly and/ or when flow events occur	Inlet and outlet gauging stations
			V-notch weirs or Parshall flumes + pressure transducers	***	30-60 minutes	30-60 minutes	30-60 minutes	
Surface water discharge	Direct monitoring		Current meters + flow depth	**	Monthly	When flow events occur	Monthly and/ or when flow events occur	Inlet and outlet gauging stations
	Indirect monitoring		Rating curves	**	After data are collected	After data are collected	After data are collected	Inlet and outlet gauging stations
	Continuous monitoring		V-notch weirs or Parshall flumes + pressure transducers	***	30-60 minutes	30-60 minutes	30-60 minutes	Inlet and outlet gauging stations
Precipitation rate	Continuous monitoring		Weather station	***	30-60 minutes	30-60 minutes	30-60 minutes	-
Evapotranspiration rate	Direct monitoring		Evaporation pan	**	Daily data required	Daily data required	Daily data required	-
Groundwater quality (targeted nitrogen form concentration)	Direct monitoring		Manual/electric pump	***	Monthly	When flow events occur	Monthly and/ or when flow events occur	1 piezometer on each side of the vegetated drain
Surface water quality (targeted nitrogen form concentration)	Direct monitoring		Sampling pole or Manual/electric pump	***	Monthly	When flow events occur	Monthly and/ or when flow events occur	Inlet and outlet gauging stations
	Automated sampling		Automated sampler	***	Monthly	6 samples across the hydrograph when flow events occur	Monthly and/ or 6 samples across the hydrograph when flow events occur	
Physico-chemical parameters	Direct monitoring		Portable sensors	***	Monthly	When flow events occur	Monthly and/ or when flow events occur	Inlet and outlet gauging stations
	Continuous monitoring		Data loggers or Probes	***	30-60 minutes	30-60 minutes	30-60 minutes	
Hydraulic residence time	Indirect monitoring		Volume and discharge estimation	**	-	-	-	-

Table 7: Silver level monitoring for treatment wetlands

Parameter	Monitoring method		Monitoring devices/tests	Monitoring device's accuracy	Monitoring frequency according to different flow regimes			Monitoring structure
					Baseflow	Event-based	Water-year	
Groundwater discharge	Indirect monitoring	Incremental gauging	Current meters	**	Monthly	When flow events occur	Monthly and/ or when flow events occur	Inlet and outlet gauging stations
			V-notch weirs or Parshall flumes + pressure transducers	***	30-60 minutes	30-60 minutes	30-60 minutes	
Surface water discharge	Direct monitoring		Current meters + flow depth	**	Monthly	When flow events occur	Monthly and/ or when flow events occur	Inlet and outlet gauging stations
			Volumetric technique + flow depth	**	Monthly	When flow events occur	Monthly and/ or when flow events occur	
	Indirect monitoring		Rating curves	**	After data are collected	After data are collected	After data are collected	Inlet and outlet gauging stations or inlet and outlet structures
	Continuous monitoring		Flow meters	***	30-60 minutes	30-60 minutes	30-60 minutes	Inlet and outlet structures
			V-notch weirs or Parshall flumes + pressure transducers	***	30-60 minutes	30-60 minutes	30-60 minutes	Inlet and outlet gauging stations
Precipitation rate	Continuous monitoring		Weather station	***	30-60 minutes	30-60 minutes	30-60 minutes	-
Evapotranspiration rate	Direct monitoring		Evaporation pan	**	Daily data required	Daily data required	Daily data required	-
Groundwater quality (targeted nitrogen form concentration)	Direct monitoring		Manual/ electric pump	***	Monthly	When flow events occur	Monthly and/ or when flow events occur	1 piezometer on each side of the constructed wetland
Surface water quality (targeted nitrogen form concentration)	Direct monitoring		Sampling pole or Manual/ electric pump	***	Monthly	When flow events occur	Monthly and/ or when flow events occur	Inlet and outlet gauging stations or inlet and outlet structures
	Automated sampling		Automated sampler	***	Monthly	6 samples across the hydrograph when flow events occur	Monthly and/ or 6 samples across the hydrograph when flow events occur	
Physico-chemical parameters	Direct monitoring		Portable sensors	***	Monthly	When flow events occur	Monthly and/ or when flow events occur	Inlet and outlet gauging stations or inlet and outlet structures
	Continuous monitoring		Data loggers or Probes	***	30-60 minutes	30-60 minutes	30-60 minutes	
Hydraulic residence time	Indirect monitoring		Volume and discharge estimation	**	-	-	-	-

10.3 Bronze level (least accurate)

Table 8: Bronze level monitoring for vegetated drains

Parameter	Monitoring method		Monitoring devices/ tests	Monitoring devices accuracy	Monitoring frequency according to different flow regimes			Monitoring structure
					Baseflow	Event-based	Water-year	
Groundwater discharge	Indirect monitoring	Incremental gauging	Current meters	**	Monthly	When flow events occur	Monthly and/ or when a flow event occur	Inlet and outlet gauging stations
Surface water discharge	Direct monitoring		Floating spheres + flow depth	*	Monthly	When flow events occur	Monthly and/ or when a flow event occur	Inlet and outlet gauging stations
	Indirect monitoring		Rating curves	**	After data are collected	After data are collected	After data are collected	Inlet and outlet gauging stations
Precipitation rate	Indirect monitoring		Databases	*	Daily data required	Daily data required	Daily data required	-
Evapotranspiration rate	Indirect monitoring		Models	**	Daily data required	Daily data required	Daily data required	-
			Databases	*	Daily data required	Daily data required	Daily data required	
Groundwater quality (targeted nitrogen form concentration)	Direct monitoring		Manual/ electric pump	***	Monthly	When flow events occur	Monthly and/ or when a flow event occur	1 piezometer on each side of the vegetated drain
Surface water quality (targeted nitrogen form concentration)	Direct monitoring		Sampling pole or Manual electric pump	***	Monthly	When flow events occur	Monthly and/ or when a flow event occurt	Inlet and outlet gauging stations
Physico-chemical parameters	Direct monitoring		Portable sensors	***	Monthly	When flow events occur	Monthly and/ or when a flow event occur	Inlet and outlet gauging stations
Hydraulic residence time	Indirect monitoring		Volume and discharge estimation	**	-	-	-	-

Table 9: Bronze level monitoring for treatment wetlands

Parameter	Monitoring method		Monitoring devices/ tests	Monitoring devices accuracy	Monitoring frequency according to different flow regimes			Monitoring structure
					Baseflow	Event-based	Water-year	
Groundwater discharge	Indirect monitoring	Incremental gauging	Current meters	**	Monthly	When flow events occur	Monthly and/or when flow events occur	Inlet and outlet gauging stations
Surface water discharge	Direct monitoring		Floating spheres + flow depth	*	Monthly	When flow events occur	Monthly and/or when a flow event occurs	Inlet and outlet gauging stations
			Volumetric technique + flow depth	**	Monthly	When flow events occur	Monthly and/or when a flow event occurs	Inlet and outlet structures
	Indirect monitoring		Rating curves	**	After data are collected	After data are collected	After data are collected	Inlet and outlet gauging stations or inlet and outlet structures
Precipitation rate	Indirect monitoring		Databases	*	Daily data required	Daily data required	Daily data required	-
Evapotranspiration rate	Indirect monitoring		Models	**	Daily data required	Daily data required	Daily data required	-
			Databases	*	Daily data required	Daily data required	Daily data required	
Groundwater quality (targeted nitrogen form concentration)	Direct monitoring		Manual/electric pump	***	Monthly	When flow events occur	Monthly and/or when a flow event occurs	1 piezometer on each side of the constructed wetland
Surface water quality (targeted nitrogen form concentration)	Direct monitoring		Sampling pole or Manual/electric pump	***	Monthly	When flow events occur	Monthly and/or when a flow event occurs	Inlet and outlet gauging stations or inlet and outlet structures
Physico-chemical parameters	Direct monitoring		Portable sensors	***	Monthly	When flow events occur	Monthly and/or when a flow event occurs	Inlet and outlet gauging stations or inlet and outlet structures
Hydraulic residence time	Indirect monitoring		Volume and discharge estimation	**	-	-	-	-

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Appendix: Further information and links

Water sampling methods

DES (2018) Monitoring and Sampling Manual: environmental protection (water) policy.

Surface water monitoring

USDIBR (2001) Water Measurement Manual

USGS (2018) How Streamflow is measured

BOM (2022) Water Monitoring Standardisation Technical Committee Part 4

Installation of piezometers

QGOV (2023a) Bore construction and approvals | Business Queensland

NUDLC (2012) Minimum construction requirements for water bores in Australia

Groundwater monitoring

Abdeh-Kolahchi (2007) Optimal dynamic monitoring network design for reliable tracking of contaminant plumes in an aquifer system

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Construction of inlet and outlet structures

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