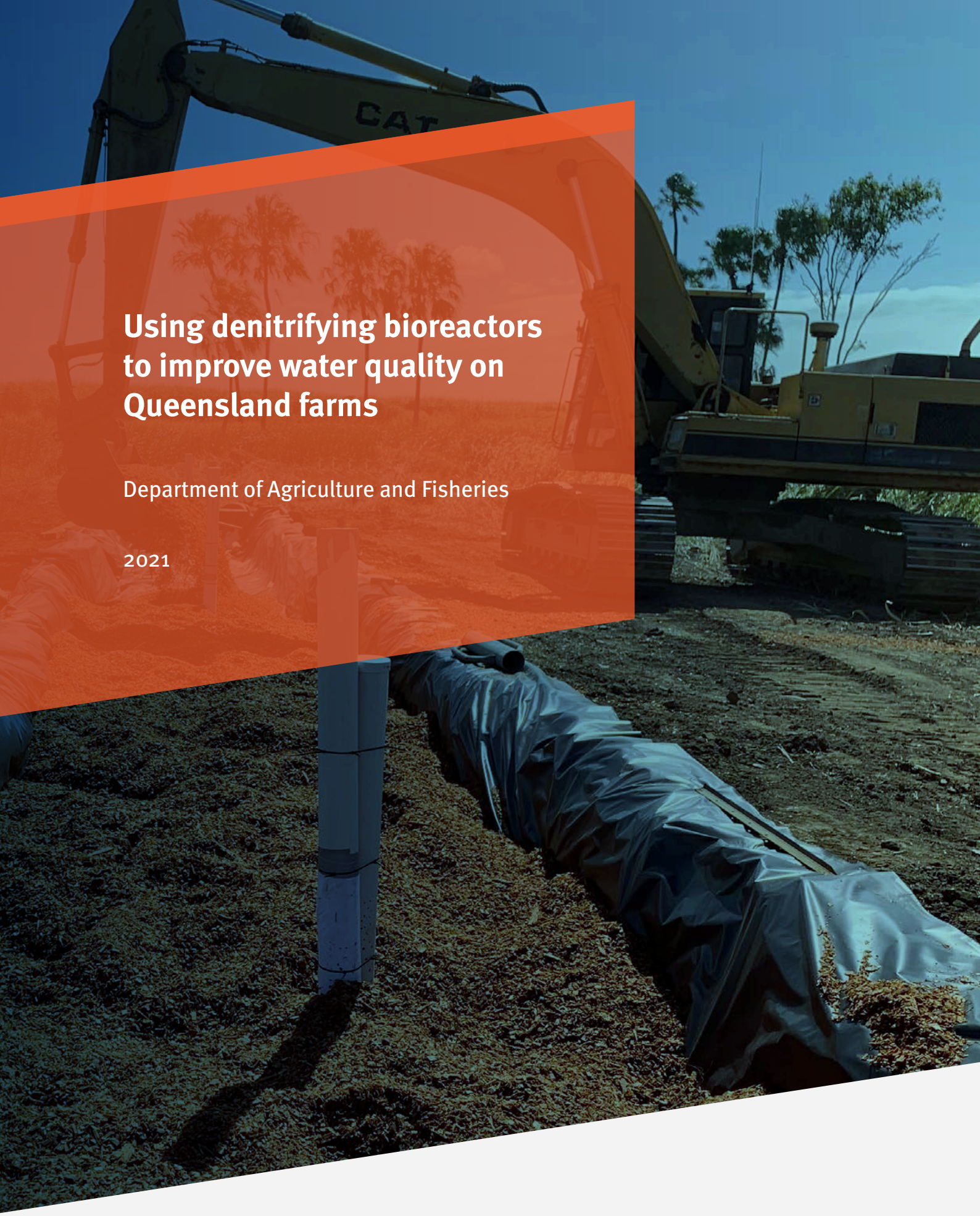

Using denitrifying bioreactors to improve water quality on Queensland farms

Department of Agriculture and Fisheries

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Queensland Government

This publication has been compiled by Carla Wegscheidl and Rhianna Robinson, Department of Agriculture and Fisheries (DAF) and Fabio Manca, Queensland University of Technology.

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Design & Artwork: Aussie Web Solutions

Purpose of this document

The purpose of this document is to provide guidance on the use of denitrifying bioreactors to improve water quality, specifically to remove nitrate from agricultural land uses in Queensland. Bioreactors are passive, relatively unobtrusive, low maintenance treatment systems that can fit within a farm without impacting production, or farm operations. However, they are not a cost-effective solution to improving water quality in all locations. Like any treatment system their suitability needs to be considered on a site-by-site basis, based on the landholder's objectives, water quality, water regime, position in the landscape and specific siting constraints. These guidelines aim to guide the reader through these key considerations to help determine if a bioreactor is suitable, and if so, how to design, construct and maintain one to maximise its nitrate removal performance.

This document collates and synthesises information from a range of bioreactor trials conducted in Queensland between 2015 and 2020, together with published literature on bioreactor research in other countries. The Queensland trials have predominantly been conducted on farms growing sugarcane and horticulture crops, as this is the dominant land use in coastal Queensland, contributing nitrate to coastal and marine ecosystems. Preliminary results from trials on aquaculture farms indicate that bioreactors can also be effective at removing nitrate from aquaculture wastewater. Therefore, these guidelines can also inform the use of bioreactors in intensively cultivated production systems, such as aquaculture, protected cropping systems (i.e. greenhouses) and nurseries. Please note, there is little or no published information on bioreactors specific to these production systems in Queensland.

The primary audience for these guidelines is extension officers, natural resource managers and land managers seeking to design, install and operate denitrifying bioreactors in agricultural areas. These guidelines are also relevant to researchers, industry groups, policy officers and natural resource managers seeking passive nitrogen removal techniques.

Information on treatment systems, including bioreactors, is available on the Queensland Government Wetland*Info* website wetlandinfo.des.qld.gov.au. Local Natural Resource Management groups and local government are contacts for relevant catchment planning and legislative requirements.

Scope and limitations

This document relates to denitrifying woodchip bioreactors in agricultural settings and is based on the most current bioreactor research in Queensland as of October 2020. Bioreactor research in Queensland has moved beyond the proof of concept, yet many gaps remain in understanding how bioreactors best operate across the range of Queensland's agricultural production systems and different climatic zones. Some information in these guidelines is based on trial results documented in reports, rather than peer-reviewed publications and the advice and recommendations may change as new research is conducted. Professional engineering advice should be sought for the design and construction of a bioreactor.

Foreword

Dr Laura Christianson (R) with Rhianna Robinson (author) at the International Bioreactor Forum

By Dr Laura Christianson
University of Illinois at Urbana-Champaign

Ernest Hemingway wrote, “Never write about a place until you’re away from it, because that gives you perspective.” Upon my arrival in beautiful Queensland in March 2020 for the International Bioreactor Forum, I was unconsciously looking for differences. Cropping systems, climate – what we call flip-flops. Many contrasts exist between Queensland and my research base in the US Midwest Corn Belt, but the similarities we share resonate much more.

Some of my favorite Queensland memories involve the farmers at the forefront of bioreactor technology. Our conversations during my visit – the ideas, questions, concerns, and eagerness – were strikingly similar to conversations I have with growers in my own backyard. No matter where you are, farmers with bioreactors tend to be innovators on multiple fronts, trialing new practices to improve many aspects of their farms including yield, soil health, wildlife and pollinator habitat, and water quality. They are proactively seeking solutions and are often enthusiastic voices for agriculture. Both in Queensland and the US, these growers open their farms and homes for demonstration days and research, none of which we could do without their generous and gracious participation.

The major driver for clean water in my backyard is the annual nutrient-induced hypoxic zone in the Gulf of Mexico, a very different environment from the outstanding and breathtaking Great Barrier Reef. Still, bioreactors link our two regions in terms of agriculture and water. In both places, we need solutions that support profitable and sustainable food production as well as the wise management of our natural resources. Denitrifying woodchip bioreactors have proven to meet these needs in practice across cropping systems and climates.

While bioreactors are many things – cost effective, low maintenance, relatively practical – they are not a silver bullet. They are best viewed as part of a suite of integrated practices, designed to synergistically address both agricultural production and environmental goals. Queensland’s climate, with massive rainfall events, will require agricultural conservation solutions beyond bioreactors to meet water quality goals for the Great Barrier Reef and South-East Queensland. Bioreactor research must continue to investigate performance in diverse Queensland production systems and climates. It remains equally important to honestly seek and evaluate all best practices for water quality.

This significant bioreactor guidance document collates results from bioreactor trials in Queensland, combined with published international research to provide comprehensive direction spanning bioreactor design, construction and management. This document is pioneering work for our field, a valuable resource for farmers, field staff or natural resource managers interested in using bioreactors in sustainable food production. Returning to the Hemingway quote, I’m thankful for the perspective on my own work provided by visiting Queensland, and I look forward to the future of bioreactor innovations adapted to Queensland’s unique environment.

Contents

How to use these guidelines

There are six parts to the document:

Part 1 Introduction to bioreactors: provides background information on bioreactors, nitrogen removal performance and research gaps.

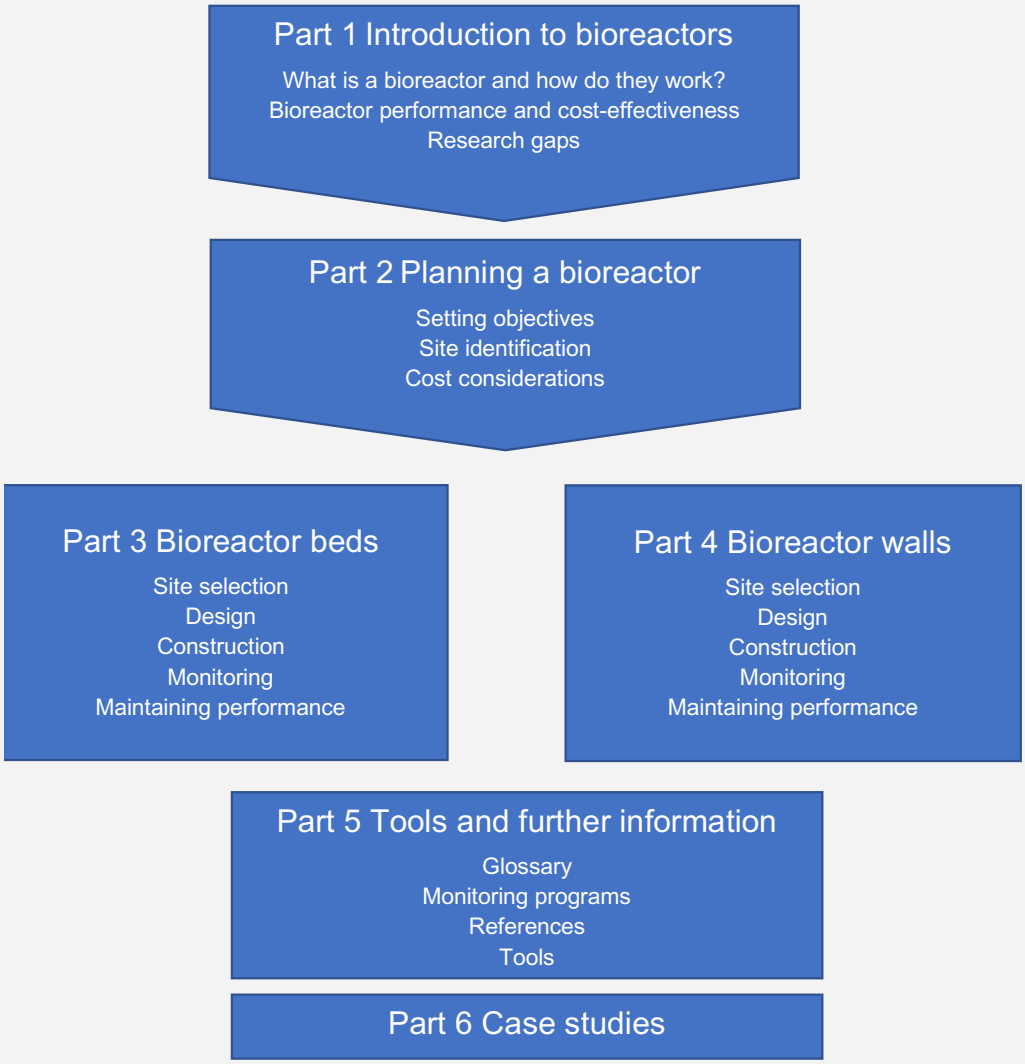
Part 2 Planning a bioreactor: outlines what to consider before commencing a bioreactor project.

Part 3 Bioreactor beds: details site selection, design, construction, monitoring and maintaining performance of bioreactor beds.

Part 4 Bioreactor walls: details site selection, design, construction, monitoring and maintaining performance of bioreactor walls.

Part 5 Tools and information: includes a glossary, monitoring programs, references, factsheets and further information.

Part 6 Case studies: describes different bioreactors constructed in Queensland.



PART 1:

Introduction to bioreactors

Part 1: Introduction to bioreactors

1.1 Background

1.1.1 Nitrogen forms

Nitrogen is a common and essential element that exists naturally in the environment in variable quantities, forms and pools. Complex nitrogen interactions and cycling between plants, animals, soil, water and air are continuous and are a part of the building blocks of life. Basic knowledge of nitrogen forms and the nitrogen cycle is useful to understand how bioreactors can work to improve water quality in agricultural production systems.

Nitrogen in water and soil can be categorised as two main forms, inorganic nitrogen and organic nitrogen. Inorganic nitrogen is also referred to as mineral nitrogen. It is comprised mainly of nitrate and ammonium, but may also include small quantities of nitrite and dissolved gases. Organic nitrogen refers to organic nitrogen which can take many forms, including amino acids, nucleic acids, proteins and urea.

The most common form of nitrogen in the environment is dinitrogen gas. This comprises roughly 78% of earth's atmosphere (Field 2004). Water generally contains dinitrogen in solution. Despite the abundance, the dinitrogen molecule requires a significant amount of energy for organisms to use because it necessitates breaking a triple covalent chemical bond. Over 90% of the nitrogen in soil is in an organic form that is not generally available to plants. Organic nitrogen must first be converted into either soluble organic compounds, or inorganic forms such as nitrate, nitrite and ammonium.

Nitrate, nitrite and ammonium are classified as inorganic nitrogen, a form of nitrogen more available for plants to use. Nitrate and nitrite are negatively charged, soluble in water and can readily leach below the plant root zone. Ammonium is positively charged and is bound in the negatively charged soil, providing plants with more opportunity for nutrient uptake.

In soil science the concentrations of nitrate, nitrite and ammonium are generally expressed as nitrate-nitrogen, nitrite-nitrogen, and ammonium-nitrogen, meaning that only the weight of the nitrogen atoms is considered rather than the entire weight of the molecules. For example, the molecular weight of nitrate will consider 1 nitrogen atom + 3 oxygen atoms, whereas nitrate-nitrogen will only consider the weight of the nitrogen atom.

Nitrogen is often the primary element of interest when investigating bioreactors for water quality improvement. Therefore, the figures expressed in these guidelines refer to nitrate-nitrogen. The guidelines use the abbreviated form for nitrate, nitrite and ammonium, whose concentrations will be referred in the nitrogen form (mg N L^{-1} or g N m^{-3}).

1.1.2 Nitrogen use and losses in agriculture

In agriculture, the application of synthetic nitrogenous fertilisers provides ammonium and nitrate to crops, or pastures to increase yield and quality, support rapid early growth, enhance root development, and increase uptake of other key nutrients. Nitrogen can also enter agricultural systems with application of manures, or nitrogen fixation by plants (e.g. legumes) or microbes. Nutrients not taken up by plants can be lost to the surrounding environment via leaching, volatilisation, run-off or denitrification (Figure 1.1).

Leaching is more prevalent in coarse or free-draining soils and in scenarios with large amounts of rainfall and/or irrigation. Excess nitrate can lead to the over enrichment of waters and cause adverse imbalances in aquatic ecosystems, known as eutrophication (Walter et al. 2016).

Declining water quality in Queensland's coastal and marine ecosystems has driven efforts to develop and promote fertiliser and crop best management practices to reduce the potential for off-farm nitrogen transport. Best management practices such as matching fertilisers to crop requirements, and timing of application and application techniques to minimise loss to the environment can significantly reduce the risk of nitrogen loss. These are essential for improving water quality in sensitive, high-value aquatic ecosystems, such as the Great Barrier Reef and Moreton Bay. It is acknowledged that other management actions, such as treatment systems and floodplain restoration, are required to complement best management practices to achieve water quality targets set for the Great Barrier Reef in Queensland (Waterhouse et al. 2017). This highlights the need for treatment system options that particularly target nitrogen, that are cost-effective, simple and will enable sustainable agricultural production.

Eutrophication occurs where excess nutrients make their way into inland and coastal waters, allowing increased growth of algae. As the algae decay, they deplete the oxygen content of the water and aquatic animals can die in large numbers.

WetlandInfo 2020 https://wetlandinfo.des.qld.gov.au/wetlands/management/pressures/lacustrine-palustrine-threats/nutrients/state.html

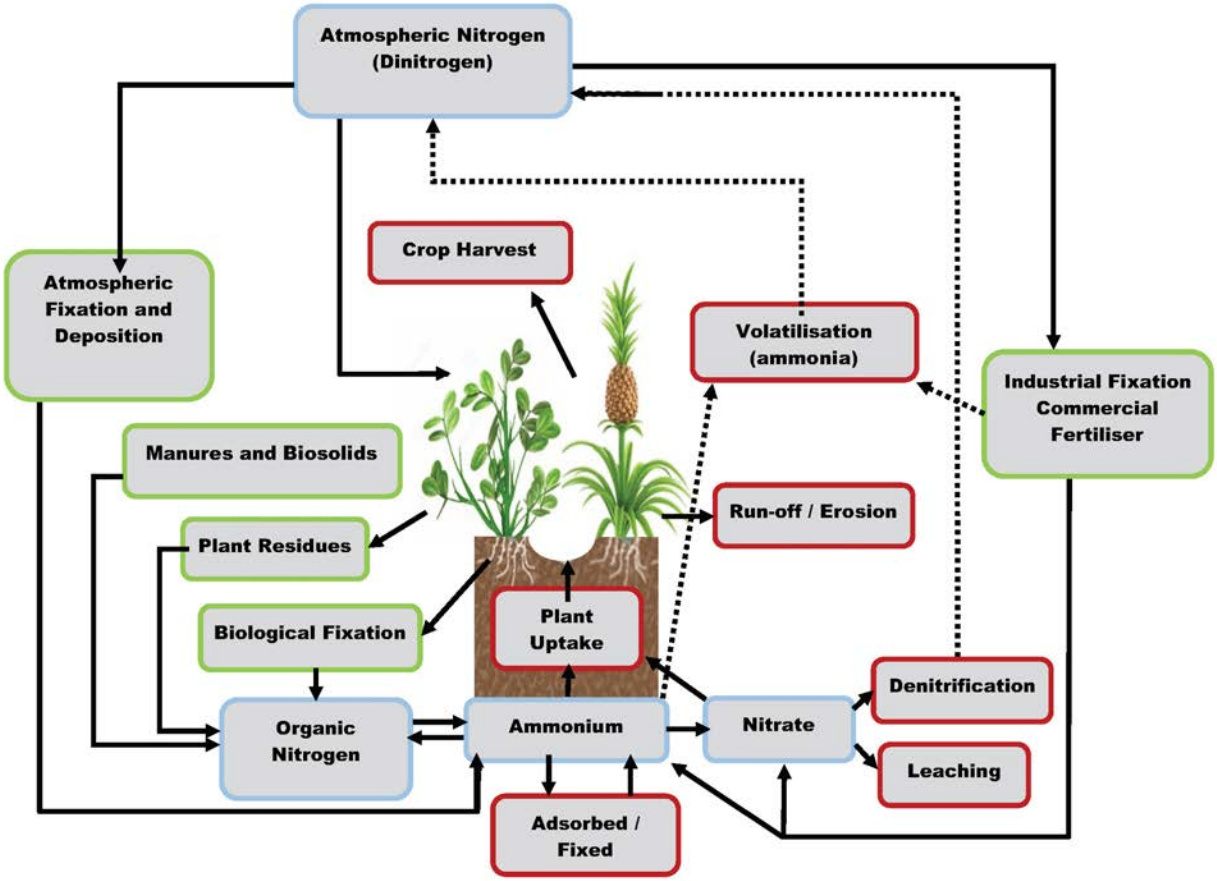


Figure 1.1 Illustration showing the cycling of nitrogen in an agricultural production environment, highlighting inputs to soil (green boxes), losses from soil (red boxes) and components (blue boxes). Dotted lines indicate losses to the atmosphere.

1.1.3 Potential use of bioreactors

Denitrifying bioreactors have been identified as one potential option to specifically target and transform nitrate to dinitrogen gas in a relatively cheap, effective and simple 'edge of field' system. They have been successfully used in the United States of America, Canada and New Zealand to mitigate nitrate loss from agricultural land uses. Bioreactors are referred to as an edge of field system, as they can be situated adjacent to a farming operation without affecting production, or other farm practices (Figure 1.2). Bioreactors have the potential to remove nitrate from both point source, and non-point source discharge, making them suitable for a variety of landscapes and farming systems.

Point-source vs non-point source

Pollutant discharge to the environment can be point source or, non-point source. A point source discharge enters a waterway from an easily identified location, such as a pipe from a sewage treatment plant, aquaculture farm or ag-pipe.

Non-point source or diffuse discharge has multiple pathways of entry to waterways and can include surface and sub-surface losses from crops, pastures and urban areas.

www.environment.des.qld.gov.au/management/water/pollution

Figure 1.2 Bioreactor wall (i.e. under green buckets) installed downslope of a pineapple crop in South-East Queensland.

1.2 What is a bioreactor?

Bioreactors are organic-matter (e.g. woodchip) filled systems designed to enhance the natural process of denitrification for the removal of nitrate from water (Christianson & Schipper 2016). Bioreactors are a relatively inexpensive, simple and passive treatment system option for removing nitrate from both surface water run-off and shallow groundwater (Figure 1.3).

Denitrification is a natural biological process. It occurs in wetlands and saturated soils where nitrate is reduced to non-reactive dinitrogen gas through a diverse group of denitrifying bacteria under anaerobic conditions (Christianson et al. 2012), which progressively synthesize enzymes for the conversion (Figure 1.4). Woodchip bioreactors enhance this natural process where the carbon source behaves as an electron donor to the nitrogen oxides facilitated by denitrifying bacteria during their respiration (Christianson et al. 2012).

Factors listed below influence rates of denitrification in bioreactors (Partheeban et al. 2014) and will be explored further in these guidelines:

- carbon source and its age
- temperature
- pH
- dissolved oxygen concentrations
- influent nitrate concentration
- hydraulic residence time.

A bioreactor is defined as a vessel designed and produced to provide an effective environment for enzymes or cells to transform biochemicals into products (Erikson 2011).

Common names include denitrifying bioreactor, woodchip bioreactor, denitrifying wall, denitrifying bed, bioreactor wall and bioreactor bed.

Throughout this document these terms may be used interchangeably. Other names less commonly used for these structures include biofilters, bioremediation detention beds, bioremediation trench, groundwater bioremediation trenches, reactive diches, permeable reactive barriers and woodchip filters.

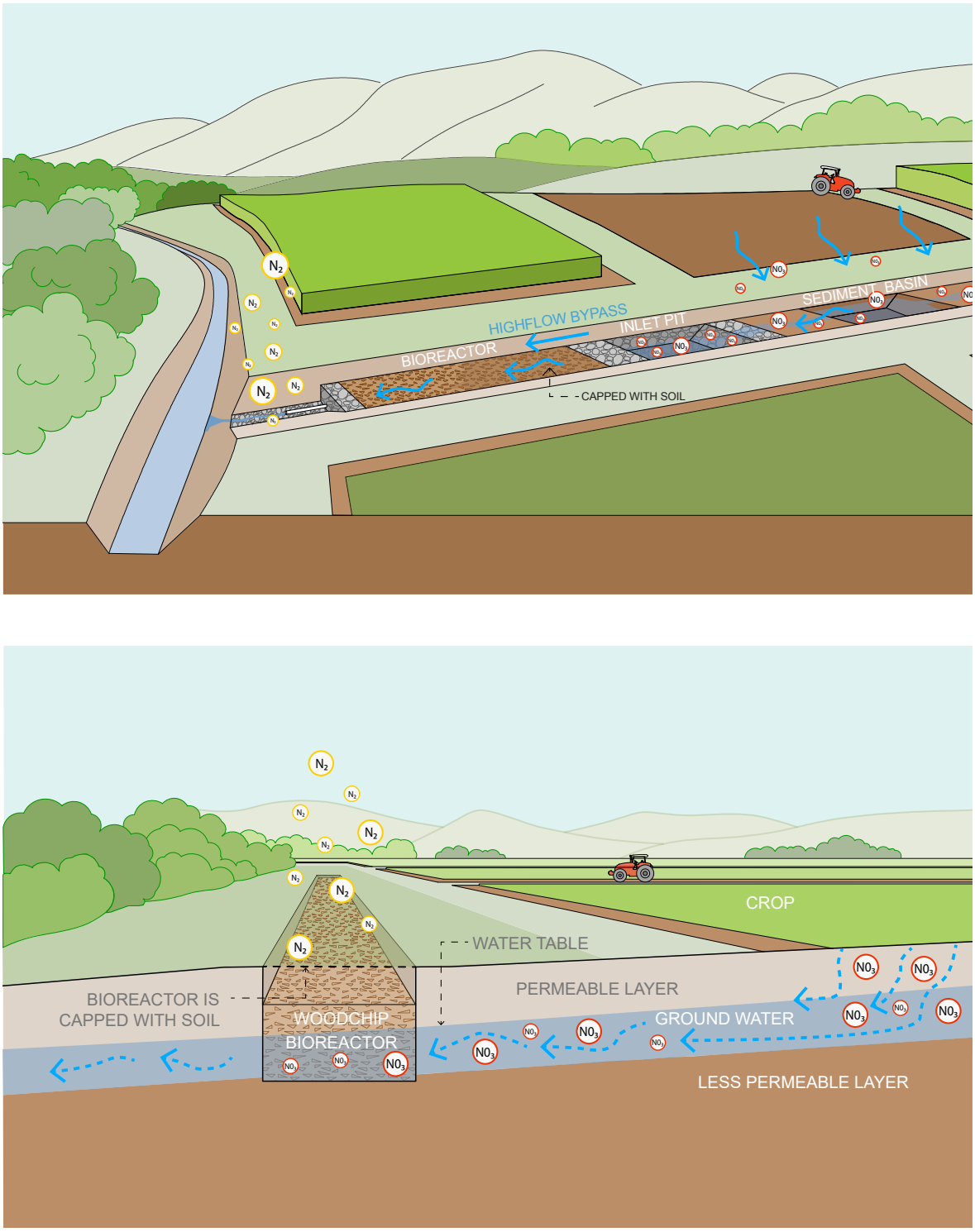


Figure 1.3 Bioreactors in an agricultural production landscape. Top image shows a bioreactor bed, image below is a bioreactor wall

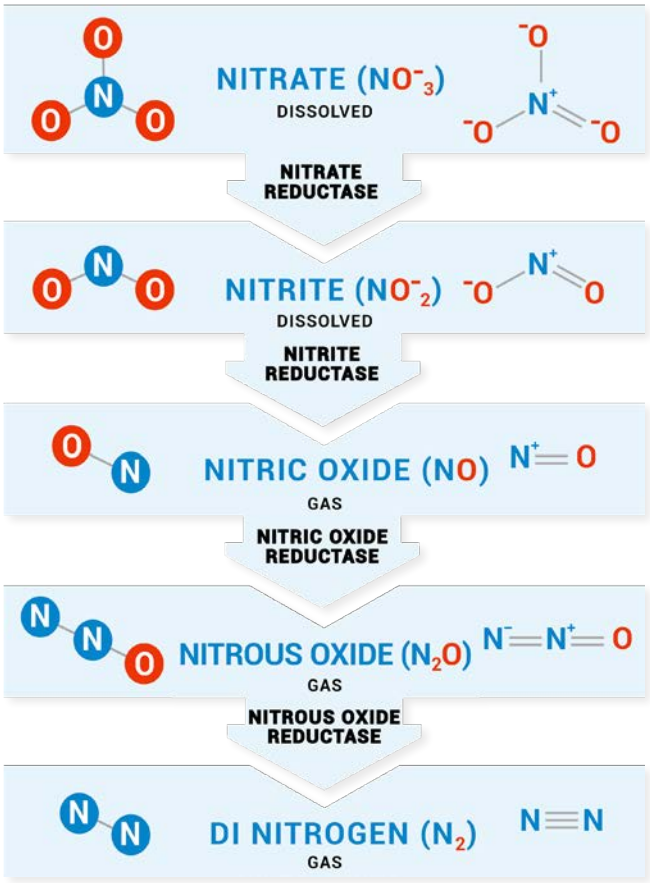


Figure 1.4 Denitrification is performed by microbes under low oxygen conditions. The microbes progressively convert nitrate to dinitrogen gas using the sequential synthetization of enzymes.

Denitrifying bioreactors have applications in a variety of settings and have predominantly been used for water quality improvement in wastewater treatment systems and in agricultural production systems. These guidelines refer to and describe bioreactors used in agricultural production settings, including field crops, aquaculture and protected cropping systems (i.e. greenhouses). However, it is important to note that the term bioreactor can also refer to other treatment systems such as Membrane Bio-Reactors which are used in municipal wastewater treatment. Bioreactors in this context have a different design, purpose and function and are not relevant for this document.

1.3 How do bioreactors work?

As mentioned above, bioreactors improve water quality by reducing nitrate in surface run-off or groundwater into the inert dinitrogen gas, a microbial process called denitrification. A combination of specific physiochemical attributes is needed to enable the microbes to proliferate and perform denitrification.

1.3.1 Attributes required for denitrification in bioreactors

1.3.1.1 Microbes

Denitrification is a natural microbial process driven by a vast community of denitrifying microbes under low oxygen (anaerobic or anoxic) conditions. There are a variety of microbes responsible for nitrate removal in woodchip bioreactors (Jang et al. 2019), which are naturally occurring in the environment. Denitrifying microbes naturally inoculate agricultural bioreactors and do not need to be introduced or 'seeded' once the bioreactor has been constructed. The microbes that carry out this process are commonly present in large numbers and are mostly facultative heterotrophic anaerobic bacteria, which obtain their energy and carbon from the oxidation of organic compounds (Rivett et al. 2008). For the denitrification process to continuously occur, the microbes require a relatively stable environment, a carbon source, low dissolved oxygen concentrations, suitable pH, an environment free from harmful chemicals and a relatively consistent supply of nitrate.

1.3.1.2 Carbon source

There are several factors to consider when selecting the carbon source for bioreactors. The material needs to have a high hydraulic conductivity, high carbon to nitrogen ratio, be readily available and have low deleterious effects when subject to low oxygen conditions (Robertson et al. 2000). Woodchips often meet these criteria, they are inexpensive,

readily available and have a high carbon to nitrogen ratio that ranges from approximately 30:1 to 300:1 (Gibert et al. 2008). For these reasons, woodchips are a commonly used carbon source in bioreactors (Figure 1.5). The size of the woodchips should be between 10-50 mm with at least half of the woodchip with a particle size ›13 mm (Christianson et al. 2010). This is particularly important for bioreactor walls to ensure they have a greater hydraulic conductivity than the surrounding soil, and to facilitate water flow through the system and not around it. Crop residues, such as corn cobs, rice husks and wheat straw have been tested in laboratory trials to investigate their performance, as a potentially cheap, readily available source of carbon on farms. While these carbon sources achieved very high rates of nitrate removal in laboratory studies, information from field studies is limited. These alternative carbon sources are likely to degrade much faster than woodchip and require more frequent replenishment (Schipper et al. 2010), especially under climates characterised by high temperatures.

To date studies have not measured major differences in performance between hardwood and softwood chips (Addy et al. 2016). Hardwood is more likely than softwood to reduce pH and increase dissolved organic carbon concentration, particularly in the initial phases of the bioreactor (Manca et al. 2020a). This can cause unwanted side effects such as:

- incomplete denitrification under low pH conditions which may increase the risk of pollution swapping. Low pH inhibits the production of nitrous oxide reductase enzymes of anaerobic microbes, with a consequent increase in nitrous oxide production (Dalal et al. 2003; Weymann et al. 2008).
- increased amount of dissolved organic carbon entering waterways, which can reduce dissolved oxygen levels in receiving waterways (Schipper et al. 2010).

It is unknown whether hardwood has other benefits, such as greater longevity, that could outweigh these potential issues.

Figure 1.5 Spreading woodchip in a bioreactor bed.

The life span of a bioreactor is strongly influenced by the carbon source and its rate of degradation. International studies indicate a 10-20 year life span for bioreactors (Schipper et al. 2010). Due to higher temperatures and more rapid degradation of the woodchip, the life span of a woodchip bioreactor in Queensland is likely to be less. There have been no long-term studies of bioreactors in Queensland to quantify longevity, however, research trials in the Lower Burdekin investigated woodchip degradation after 12-18 months and showed that the average potential longevity was between 16 and 35 years based on the rate of degradation monitored (although this was only a short trial) (Manca et al. 2020b). A longer, three-year trial of a bioreactor wall in South-East Queensland indicates a lifespan of 10-12 years.

Woodchips do not degrade evenly within the bioreactor as degradation depends on the wetting and drying regime. The more frequent the alternation between saturated and unsaturated conditions, the more intense the degradation. The Lower Burdekin trials showed that the middle section of the bioreactor, subject to the most wetting and drying, degraded the fastest. Over time, woodchips that remain saturated for most of the time (i.e. deeper in the bioreactor) retain a higher proportion of their carbon than those at the saturated/unsaturated interface of a bioreactor (Moorman et al. 2010). Therefore, the life span of the bioreactor will depend on how regularly the bioreactor is saturated and unsaturated, the type of carbon substrate used and the environmental conditions. As the bioreactor ages, water flow (i.e. hydraulic conductivity) through the bioreactor could be impacted from woodchips deteriorating and fine particles accumulating, causing either short-circuiting of flow, or complete blocking.

At the end of the presumed 10-12 year life, the woodchip can be replaced, inlet and outlet cleaned out and gravel replaced, essentially refurbishing the bioreactor. This should cost significantly less than the initial construction.

1.3.1.3 Temperature

Temperature plays an important role in the performance of bioreactors. Denitrification can occur in a wide range of temperatures, between 2 and 50 °C (Robertson et al. 2000, Jang et al. 2019). However, systems that experience relatively warmer temperatures have higher nitrate removal rates than systems in cooler temperatures, with optimum temperatures for denitrification ranging between 25 and 35 °C (Robertson et al. 2000, Jang et al. 2019).

1.3.1.4 pH

pH refers to the concentration of hydrogen ions in the water solution. The type of carbon source can influence the pH of water (Partheeban et al. 2014) and the South-East Queensland bioreactor wall trial confirmed that hardwood produces a lower pH compared to softwood (Manca et al. 2020a). However, the pH in a bioreactor is not constant over time, with lowest values observed during the start-up phase, following installation, as observed in field experiments (Cameron and Schipper 2010). In general, the optimal pH range for denitrifying microorganisms is between 5.5 and 8.0 (Rivett et al. 2008).

1.3.1.5 Dissolved oxygen

Dissolved oxygen in water is influenced by temperature, organic matter and salinity (Mesner and Geiger 2010). Cooler water will tend to have a higher concentration (e.g. mg L^{-1}) of dissolved oxygen while warmer, eutrophic waters will typically have a lower concentration. Healthy water should generally have dissolved oxygen concentrations above 6.5-8.0 mg L^{-1} or a saturation of between 80 to 120%.

For denitrification to occur, dissolved oxygen saturation should be no more than 10% with concentrations close to, or at, anaerobic conditions being the most desirable (Robertson 2010). Generally, when dissolved oxygen levels are very low (in combination with appropriate temperatures and pH) complete denitrification to dinitrogen gas can occur.

It will take at least an hour of saturated conditions for dissolved oxygen levels to decrease sufficiently (i.e. <2 mg L^{-1}) for denitrification to occur (Robertson 2010). Therefore water will need to remain within the bioreactor long enough for the dissolved oxygen levels to decrease sufficiently for denitrification.

What is the difference between anoxic and anaerobic?

Anoxic refers to an environment depleted of dissolved oxygen.

Anaerobic relates to an absence of free oxygen. In soil science it is when free oxygen is deficient and reducing processes are dominant (i.e. reducing nitrates to nitrogen gas), such as in waterlogged soil.

State of NSW (2017)

1.3.1.6 Influent nitrate concentration

The presence of dissolved nitrate in water intercepted by a woodchip bioreactor is a prerequisite for denitrification to occur. However, the enzymatic processes associated with denitrification are generally found to be not limited by nitrate at levels above ~0.5 mg L^{-1} (Schipper et al. 2010, Halaburka et al. 2017). That means the rate of denitrification is determined by the abiotic conditions of the bioreactor (i.e. temperature, salinity, organic matter source etc.) rather than the concentration of nitrate, until the nitrate concentration falls below the limiting value.

Nitrate limitation in a bioreactor occurs when the nitrate is completely consumed and there is enough carbon to potentially support additional denitrification.

Bioreactors are generally nitrate limited when the effluent nitrate concentration is less than 0.5 mg N L^{-1} (Addy et al. 2016).

Under nitrate-limited conditions, pollution swapping may occur leading to undesirable by-products (Lepine et al. 2016).

1.3.1.7 Hydraulic residence time

Hydraulic residence time is the length of time water takes to travel through the bioreactor. It is relevant in both walls and beds. Hydraulic residence time is important as the microbes require time to interact with the nitrate in the water to begin the conversion of nitrate to dinitrogen gas. The length of time required for this process depends on numerous factors described above (microbes present, temperature, available carbon, pH, dissolved oxygen), but most importantly the concentration of nitrate entering the bioreactor and the desired concentration of nitrate leaving the bioreactor. Generally, the longer water is in the bioreactor, the more nitrate will be removed.

1.3.2 Potential pollution swapping

Bioreactors have the potential to improve water quality, however, there can be deleterious side effects when bioreactors are not correctly designed and/or incorrectly located in the landscape.

1.3.2.1 Nitrous Oxide

Nitrous oxide is a potent greenhouse gas (Department of the Environment and Energy 2017) that can potentially be produced by bioreactors if denitrification is not complete. Acidic conditions can significantly control the production of nitrous oxide, as low pH can inhibit the production of nitrous oxide reductase enzymes, with a consequent increase in nitrous oxide emissions (Chapuis-Lardy et al. 2007). High dissolved oxygen can also encourage the production of nitrous oxide, especially under fluctuating dissolved oxygen conditions that often occur in the field (Robertson 2010).

Covering bioreactors with a soil cap can reduce nitrous oxide emissions by providing another opportunity for the gas to be reduced and transformed before being released into the atmosphere (Christianson et al. 2013a). Further information can be found in the 'Nitrous oxide emissions from bioreactors, crops and waterways' fact sheet (Part 5).

1.3.2.2 Dissolved oxygen

Bioreactors are designed to create a low oxygen environment to facilitate denitrification. As a result, bioreactor effluent often has a low dissolved oxygen concentration. This can be an issue for bioreactor beds which flow directly into environmentally sensitive waterways or wetlands, where the low oxygen water could impact fish or invertebrates dependent on high dissolved oxygen levels. The potential impact will depend on the volume of water leaving the bioreactor relative to the size of the receiving waterway and can be managed by siting the bioreactor further away from the waterways, or installing structures, such as riffles, to oxygenate the water.

1.3.2.3 Sulphate reduction

Sulphate reduction, leading to hydrogen sulphide production, methane production and iron reduction can occur in bioreactors (Christianson and Schipper 2016) if they are not designed and operated correctly. Sulphate reduction usually occurs when water stagnates within the bioreactor or under excessively long hydraulic residence times, leading to nitrate-limited conditions (Lepine et al. 2016). This is due to other reducing processes occurring once nitrate has been removed through denitrification.

1.4 Types of bioreactors

There are two main types of denitrifying bioreactors used in agricultural settings, bioreactor beds and bioreactor walls (Figure 1.6). Each bioreactor type is designed to suit the characteristics of the landscape, water movement at the site and the specific source of the nitrate. Bioreactor beds generally treat surface water run-off or sub-surface drainage, and bioreactor walls treat groundwater.

Water movement relevant to bioreactors

Surface run-off is defined as the movement of water on the surface of the soil, or other surface, that was not able to permeate through it.

Sub-surface drainage is water that has permeated through the soil profile and entered an underground drainage network, such as ag-pipe. It also refers to water that has passed through the soil profile and has been subsequently returned to the surface in a creek, or drainage line.

Groundwater is defined as the water that has entered the soil profile and leached beyond the root zone into a saturated aquifer.

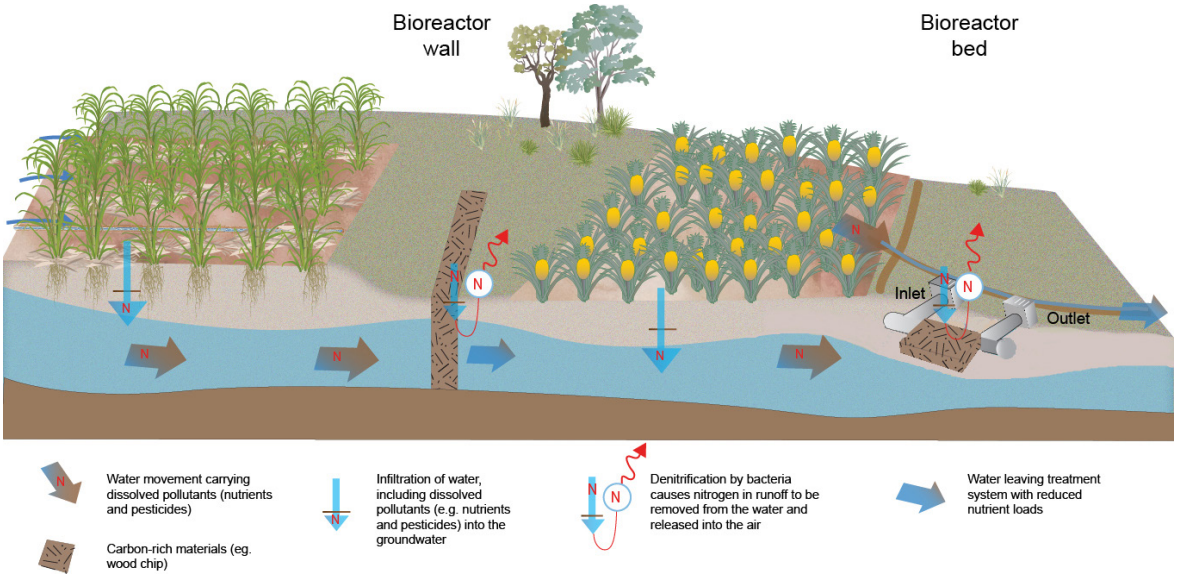


Figure 1.6 Illustration of a bioreactor wall and bioreactor bed in an agricultural production landscape. Source: WetlandInfo 2020

1.4.1 Bioreactor beds

Bioreactor beds are engineered structures filled with a carbon source that can be installed:

- within an existing drain network, often referred to as in-line bioreactors
- to receive diverted water from a drainage system, often referred to as off-line bioreactors
- to sub-surface drainage from agricultural pipes, referred to as ag-line bioreactors.

In-line, off-line and ag-line bioreactors operate similarly, receiving water at an inlet structure and discharging water via an outlet structure. They all require a system for bypassing flow in large flow events to avoid a backup of water that could impact the adjoining production area. The width, length and depth of bioreactors beds are designed based on the characteristics of the landscape, existing drainage systems, excavation equipment and available land. More information about bioreactor beds, site selection and construction guidance is provided in Part 3.

1.4.1.1 In-line bioreactor bed

In-line bioreactor beds are systems installed within an existing drain or pathway of water. The bioreactor can be installed below the base or floor (invert) of the drain, so that the cross-sectional profile of the drain remains the same (Figure 1.7). Bioreactors have also been installed above the floor of the drain with the woodchip encased in rock to

prevent scour (Figure 1.8). Bioreactors installed below the floor of the drain have the following advantages:

- likely to be more effective at removing nitrate due to a quicker reduction in dissolved oxygen concentrations and the maintenance of favourable conditions for denitrification
- do not impede flows within the drain as they are located below the floor of the drain
- bioreactors installed with a soil cap are less likely to produce nitrous oxide (Christianson et al. 2013a).

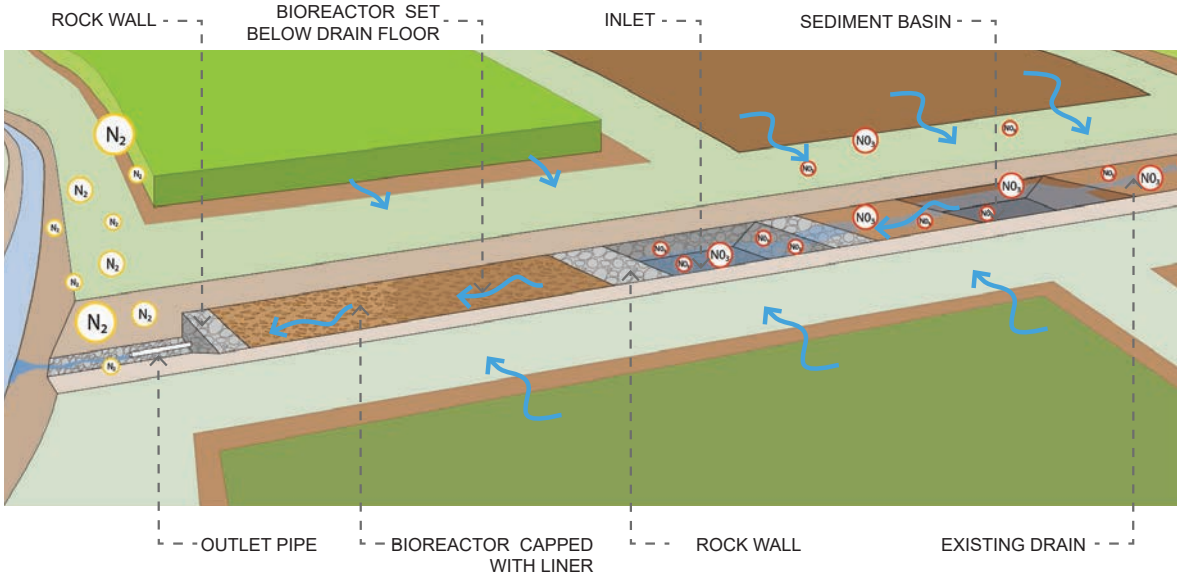


Figure 1.7 In-line bioreactor bed, below the floor of the drain.

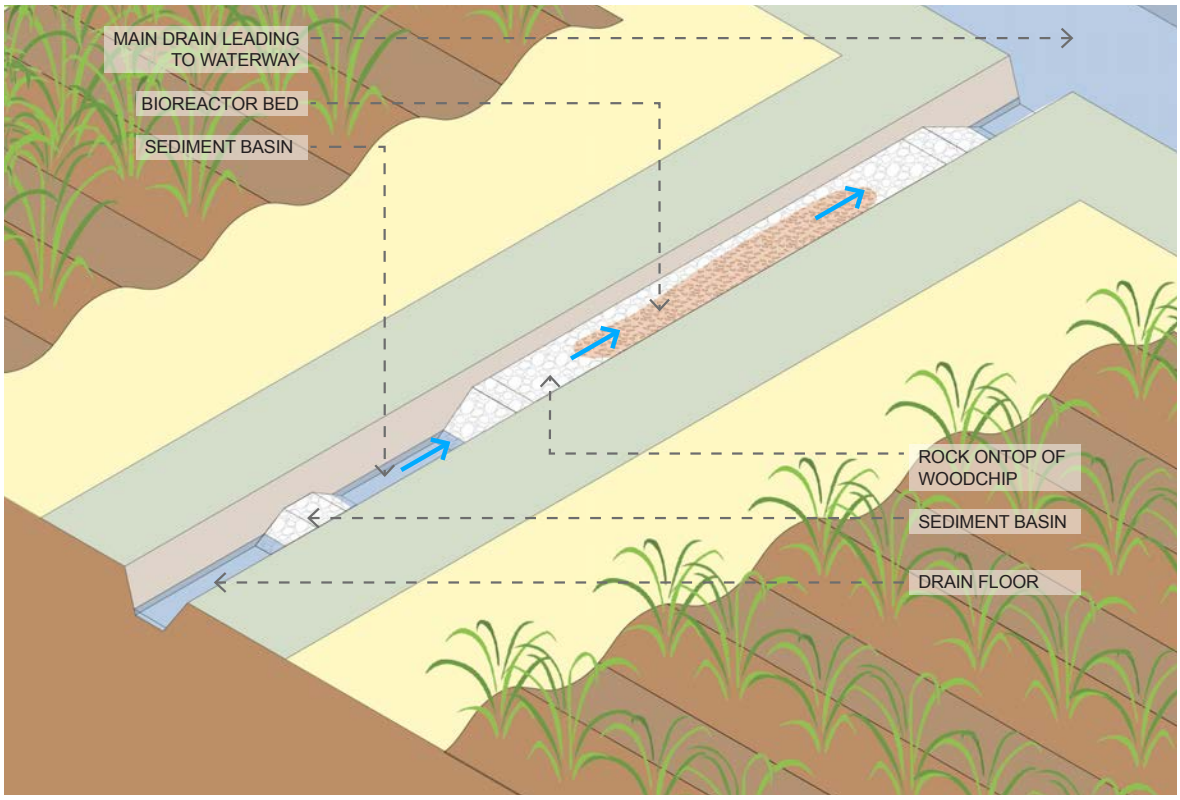


Figure 1.8 In-line bioreactor bed, above the floor of the drain.

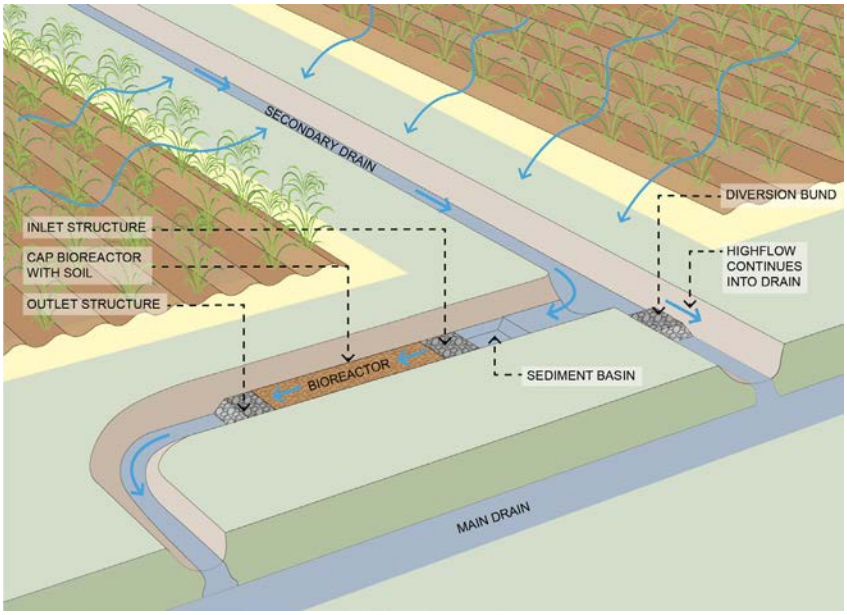


Figure 1.9 Off-line bioreactor bed, illustrating water diverted from a drain into the bioreactor.

1.4.1.2 Off-line bioreactor bed

Off-line bioreactor beds are different to in-line bioreactors in that a proportion of surface water is diverted from a main drain, or pipe into the bioreactor. The rest of the water bypasses the bioreactor (Figure 1.9). A small weir in the main drain or a Y-junction pipe is often used to direct water into the bioreactor.

1.4.1.3 Ag-line bioreactor bed

Bioreactor beds can also be installed to receive sub-surface water from an ag-pipe, or tile drain. These systems are connected to an existing ag-pipe, usually via an inlet pit, or Y-junction with a pipe into the woodchip and overflow pipe for excess water. After flowing through the woodchip, water is discharged via an outlet pit and pipe (Figure 1.10). The bioreactor bed should be installed below the level of the ag-pipe to enable passive flow through the bioreactor.

Some innovative adaptations on this design have been trialled in Queensland, whereby woodchip was placed around the ag-line so that the water flowed through the woodchip before entering the ag-pipe. The nitrate removal performance of this design has not been verified so this design is not promoted in the guidelines, but it highlights the ability to adapt standard designs to suit the site.

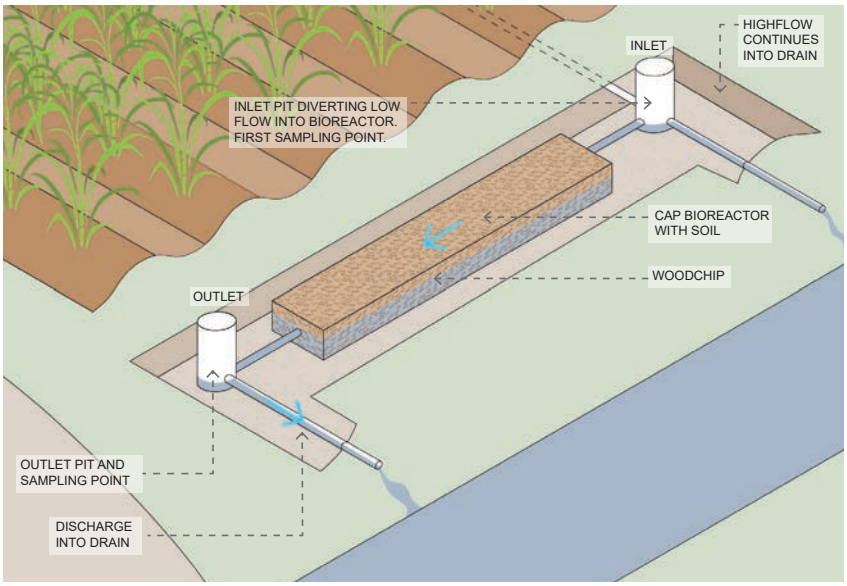


Figure 1.10 Ag-line bioreactor bed, illustrating water flows from an existing ag-pipe under the crop, into the bioreactor bed.

1.4.2 Bioreactor walls

Denitrifying bioreactor walls are shallow, trench-like excavations filled with a carbon source that are designed to intercept shallow groundwater flows (Figure 1.11). They target nitrate that has entered the soil profile and leached beyond the root zone into the groundwater. Bioreactor walls require a specific set of natural landscape characteristics including:

- shallow groundwater (1-3 meters)
- permeable soil, where possible overlying less permeable subsoil (e.g. aquitard or aquiclude)
- sufficient hydrogeological gradient that drives groundwater movement from the field through the bioreactor wall.

Bioreactor walls are typically installed perpendicular to the direction of groundwater flow and often parallel to the receiving waterway. The width, length and depth of bioreactor walls are based on the characteristics of the landscape, excavation equipment and available land. Part 4 has more information on bioreactor wall site selection, design and construction.

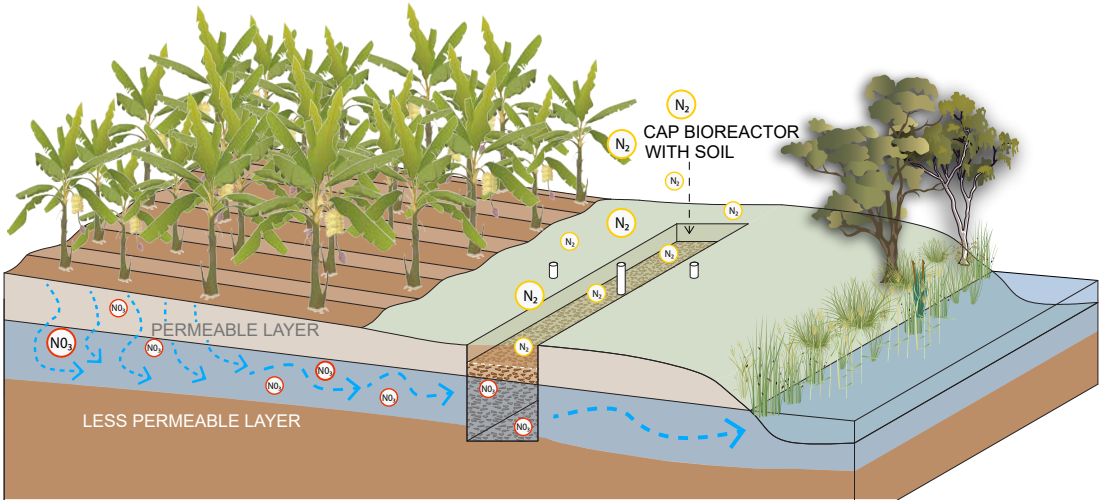


Figure 1.11 Bioreactor wall showing how the woodchip intercepts the shallow groundwater.

1.5 Efficiency of bioreactors in removing pollutants

1.5.1 Bioreactor performance metrics

Bioreactor performance can be assessed in different ways. The most commonly used metrics are nitrate removal efficiency and nitrate removal rate (Table 1.1). Each metric applies to a specified period for example a day, a flow event, or a year. The accuracy of the metrics is influenced by the number and frequency of samples analysed and flow measurements taken, as these values are obtained at points in time. Nitrate is the form of nitrogen used to calculate bioreactor performance in this document. The method of analysing performance can be modified for other forms of nitrogen depending on the objective of the project and all the consistent nitrogen species will need to be analysed.

Table 1.1. Bioreactor performance metrics and their calculation.

Metric	Calculation	Units
Nitrate removal efficiency	$NRE = \frac{[NO_{3in}^-] - [NO_{3out}^-]}{[NO_{3in}^-]} * 100$	% OR mg N L^{-1}
Nitrate removal rate	$NRR = \frac{[NO_{3in}^-] - [NO_{3out}^-]}{V_{sat}} * Q$	g N m^{-3} d^{-1}

NRE = Nitrate removal efficiency
NRR = Nitrate removal rate
$[NO_3\text{-}_{in}]$ = Influent nitrate concentration
$[NO_3\text{-}_{out}]$ = Effluent nitrate concentration
V_{sat} = Saturated volume of woodchip in the bioreactor
Q = Surface water or groundwater flow rate in the bioreactor

Nitrate removal efficiency provides information on the decrease in nitrate concentration as water flows through the bioreactor (i.e. difference between influent and effluent nitrate concentration). It indicates whether nitrate was removed in the bioreactor. It does not take into account the water treated by the bioreactor, nor the volume of bioreactor in which the nitrate reduction occurred, therefore it is not useful for assessing overall nitrate load reduction in a bioreactor and it cannot be used to compare the performance of different bioreactors.

The calculation of nitrate removal rate is a preferred metric for understanding bioreactor performance in peer reviewed publications to enable comparison between bioreactors in different contexts. The calculation of nitrate removal rate (NRR, g N m^{-3} d^{-1}) normalises the performance of a bioreactor as mass of nitrate removed per unit volume of bioreactor substrate (woodchip) per unit of time, according to Addy et al. (2016) and Schipper et al. (2010).

The performance of bioreactors depends primarily on the concentration of nitrate in the influent and the hydraulic residence time of water in the bioreactor. The hydraulic residence time is determined by the inflow rate and the dimensions of the bioreactor. In the Queensland bioreactor trials, nitrate concentrations usually declined at a linear rate until it reached a value below which denitrification could not effectively occur, most likely due to nitrate limitation (Figure 1.12). For instance, bioreactor performance increases with hydraulic residence time until the limiting nitrate concentration is reached. At hydraulic residence times beyond this point performance does not increase.

The linear decline is defined as the nitrate concentration decline rate and is determined mostly by temperature and the state of the woodchips (Cheesman et al. 2020). In north Queensland conditions the nitrate concentration decline rate is approximately 0.8 mg N L^{-1} hr^{-1} (Cheesman 2020), based on trial results to date.

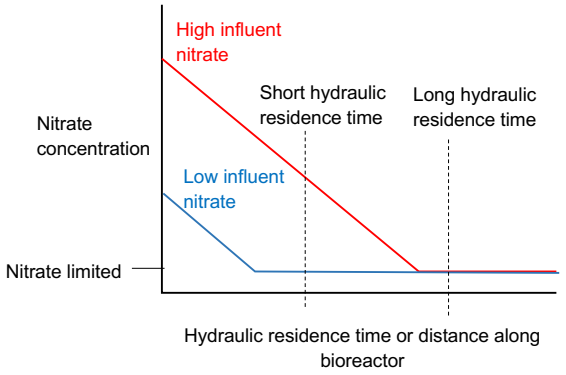


Figure 1.12 Illustration of the change in nitrate concentration within a bioreactor and the variation in the nitrate concentration decline rate depending on influent nitrate concentrations.

1.5.2 Bioreactor nitrate removal performance - global

Denitrifying woodchip bioreactors have been trialled in Canada, United Kingdom, United States of America, New Zealand and more recently in Australia. The first bioreactor studies were performed over 20 years ago in Canada to treat tile drainage (ag-line bioreactor beds) (Blowes et al. 1994; Robertson and Cherry 1995) and in New Zealand to treat livestock effluent leachate (bioreactor walls) (Schipper & Vojvodic-Vukovic 1998; Schipper & Vojvodic-Vukovic 2001).

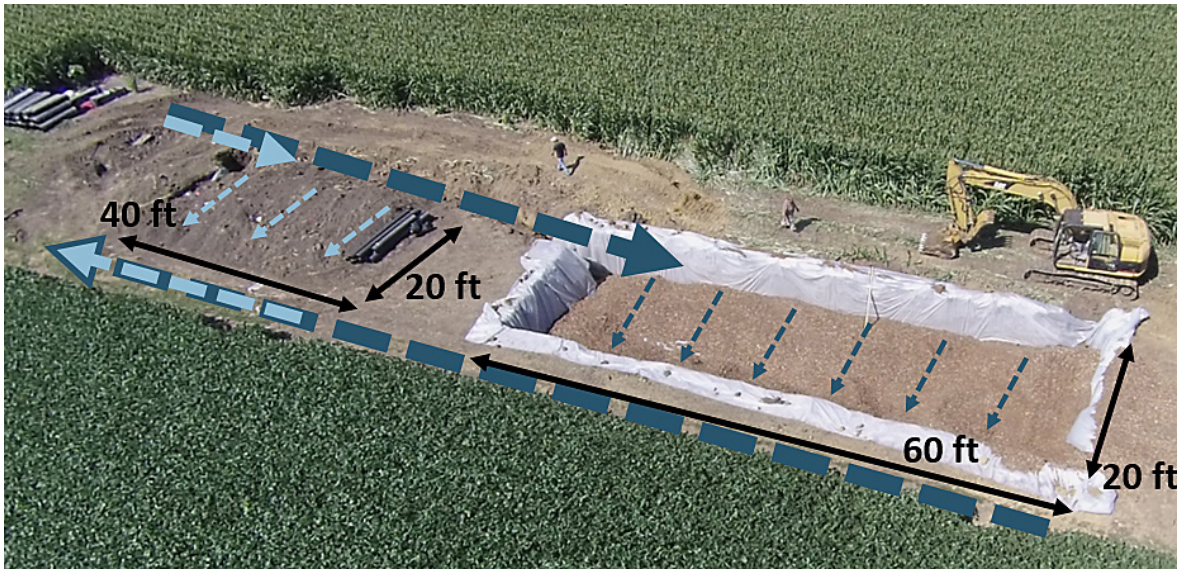


Figure 1.13 Bioreactor bed installed in Illinois, USA. Source: Illinois Drainage Research and Outreach program.

Bioreactors have been trialled in both laboratory and field-based scenarios. Field-based scenarios provide a practical insight into how systems perform in real world applications. Laboratory bioreactors have the advantage of completing the same simulated experiments in a controlled environment (i.e. control of temperature, pH, nitrate inflow concentrations, and hydraulic residence time).

Figure 1.14 Bioreactor bed in New Zealand. Source: Louis Schipper.

The nitrate removal rate of bioreactor beds can range from 0.07 to 44 g N m^{-3} d^{-1} where the volume is the saturated volume of the bed (Schipper et al. 2010; Addy et al. 2016). The variation is typically driven by operating temperature, where warmer temperatures produce higher nitrate removal rates. Additionally, influent nitrate concentration is a driver of removal rate and nitrate-limited systems produce lower nitrate removal rates.

The nitrate removal rate in bioreactor walls are generally lower than bioreactor beds, ranging from 0.6 – 12.7 g N m^{-3} d^{-1} (Schipper et al. 2010; Addy et al. 2016). The lower removal rates in comparison to beds can be attributed to many factors, such as a lower volume of water treated; potential mixing of soil with the carbon substrate (with consequent reduced hydraulic conductivity); and nitrate limitation. Nitrate limitation in walls generally occurs due to extended hydraulic residence time.

In 2015, the United States Department of Agriculture, Natural Resources Conservation Service released a conservation practice standard for denitrifying bioreactors (USDA-NRCS 2015). This outlines the key design criteria required for bioreactors to achieve expected performance as a conservation practice to improve water quality in areas with tile-drained crops. This practice standard has defined clear targets for bioreactor performance based on research of laboratory and field-based systems in the United States of America and is a testament to the validity of bioreactors as a treatment system option for removing nitrate.

1.5.3 Bioreactor nitrate removal performance - Queensland

Approximately 30 trial bioreactors were installed and monitored in Queensland between 2015 to 2020. These bioreactors were designed, and monitored, to allow for comparison of their performance and key parameters that influence performance. Bioreactor bed trials showed a nitrate removal efficiency of around 40% (percentage reduction in nitrate concentration from the inlet to the outlet) in those beds with a relatively short hydraulic residence time (1.5 – 3 hr) and higher (over 80%) reduction in nitrate concentrations in beds with a longer hydraulic residence time. Therefore, a longer hydraulic residence time can result in a greater nitrate removal efficiency, however it usually results in less water being treated by the bioreactor, which influences the overall amount of nitrate removed. This highlights the need to calculate the size of a bioreactor bed according to the hydraulic retention time needed to achieve the desired nitrate reduction for a given flow regime (refer section 3.3).

Nitrate removal rate varied considerably between bioreactor bed trials (on irrigated and rain-fed sugarcane farms) with reported average nitrate removal rate of between 0.08 g N m^{-3} d^{-1} to 3.4 g N m^{-3} d^{-1}. Bioreactor walls installed in South-East Queensland (rain-fed horticultural crop) had average nitrate removal rates of 2.0 and 1.6 g N m^{-3} d^{-1} for softwood and hardwood woodchips respectively (Manca et al. 2020a).

The trials in Queensland have highlighted three main factors that influence bioreactor performance:

- nitrate concentrations in the influent water
- timing, duration and volume of influent flow
- blockages or other factors influencing flow into and through the bioreactor.

Trials of bioreactors installed downslope of cane farms in the Wet Tropics Region of Far North Queensland (Figure 1.15)

commonly received large volumes of water in high run-off events with diluted nitrate. For example, trials in the Russell River catchment had influent mean concentrations of 0.5 mg N L^{-1} (Cheesman et al. 2020). Conversely, run-off from irrigated cane blocks in some parts of the Lower Burdekin region (Figure 1.16) had more consistent influent nitrate concentrations averaging 4.4 mg N L^{-1} (Manca et al. 2020b).

Figure 1.15 Bioreactor beds installed downslope of cane farms in the Wet Tropics region. Photo on left shows in-line bioreactor bed above the floor of the drain. Photo on right shows in-line bioreactor bed below the floor of the drain.

Figure 1.16 Off-line bioreactor bed installed downslope of an irrigated cane block in the Lower Burdekin.

1.5.4 Cost-effectiveness for nitrate removal

Denitrifying bioreactors can be a cost-effective method for reducing nitrate losses from agriculture and aquaculture production systems (Christianson et al. 2013b, Lepine et al. 2018). Cost-effectiveness metrics are used to enable comparison of different water quality improvement initiatives such as treatment systems, or agronomic practice change, and are presented as the cost of removing a given quantity of a pollutant (e.g. $ kg^{-1} N).

Christianson et al. (2013b) demonstrated that the cost-effectiveness of bioreactors in removing nitrate from agricultural run-off is comparable to treatment wetlands and controlled drainage and is significantly more cost-effective than some agronomic practices such as cover cropping and crop rotation. They reported costs in the order of US$ 3 to remove one kilogram of nitrogen per year (note the cost-effectiveness methodology is different to that used by Schipper et al. (2010) and DAF (2020) below). Schipper et al. (2010) estimated the cost of nitrate removal in a bioreactor to be between US$ 2.39 and $15.17 to remove a kilogram of nitrogen. These cost-effectiveness calculations are based on bioreactors installed in temperate climates in the United States of America and Canada receiving relatively consistent nitrate concentrations and having a relatively long, 20 to 40 year lifespan.

Trials of denitrifying bioreactors on sugarcane and horticultural farms in Queensland indicate they might have a shorter lifespan (10-12 years) than bioreactors in more temperate climates. This, together with the lower and more variable influent nitrate concentrations reported in Queensland trials to date, indicate that bioreactors in Queensland are likely to be less cost-effective than those reported in Schipper et al. (2010) and Christianson et al. (2013b).

A cost-effectiveness analysis conducted using results from a trial bioreactor bed in the Lower Burdekin region aimed to assess the cost per kilogram of nitrate removed by denitrifying bioreactor beds (DAF 2020). The bioreactor bed had relatively consistent influent nitrate concentrations (averaging 4.4 mg N L^{-1}) and an average nitrate removal rate of 3.4 g N m^{-3} d^{-1} (as measured in the trial). The analysis looked at all potential costs involved in installing and maintaining a bioreactor bed and concluded that well sited and designed bioreactor beds treating run-off from an irrigated sugarcane crop in the Lower Burdekin region would likely remove nitrate at a cost of A$108 per kg nitrate removed, based on the following assumptions (DAF 2020):

- average nitrate removal rate of 3.4 g N m^{-3} d^{-1}
- 100 m^3 bioreactor receiving run-off for 250 days per year
- planning and design costs totalling $9000
- 10-year lifespan with regular maintenance (costing around $1000 each year) and
- 33% decrease in nitrate removal performance after the first year then remaining constant throughout the rest of the lifespan.

This analysis included planning, design and maintenance costs. But if the installation costs alone were used (like the cost-effectiveness analysis reported in Schipper et al. 2010) as mentioned above, the cost-effectiveness of the bioreactor would be around A$87 per kg nitrate removed.

International studies have reported a decline in nitrate removal performance after the first year (Addy et al. 2016, Robertson 2010). However this reduction in performance has not been quantified in Queensland trials. Bioreactor trials in Queensland have only been monitored for one or two years, so the treatment performance and maintenance costs over the lifetime of the bioreactor can only be assumed.

The main factors influencing cost-effectiveness of bioreactors in Queensland include:

- Nitrate concentrations: bioreactors receiving consistently higher nitrate concentrations in the influent water are generally more cost-effective than those receiving consistently low nitrate concentrations, as they can remove more nitrate.
- Well positioned bioreactors: intercepting and treating water for more days of the year, are considerably more cost-effective than those with intermittent flow.
- Size of bioreactor beds: larger bioreactor beds are more cost-effective than smaller bioreactor beds due to economies of scale (this is not as relevant for walls).
- Maintenance: maintaining bioreactor performance throughout the lifetime of the structure through regular maintenance, including woodchip replacement.

1.5.5 Removal of other pollutants

Pesticides

Some laboratory studies have found that woodchip bioreactors have the potential to also reduce the concentrations of some pesticides and antibiotics. One example is atrazine, a herbicide used to prevent pre-emergence of broadleaf weeds, commonly used to control weeds in sugarcane crops. Atrazine detected in laboratory and field woodchip bioreactors did not adversely impact the denitrification performance of the systems and reductions in concentrations between the inlet and outlet were observed (Ilhan et al. 2011, Ranaivoson et al. 2019). Ranaivoson et al. (2019) found

that metabolites (i.e. break down products) of atrazine were not detected at the outlet, suggesting that reductions have occurred through adsorption rather than degradation (Trapp et al. 2001), unless complete degradation occurred.

Denitrifying bioreactors in Queensland may also serve as an atrazine adsorption tool as well as a nitrate mitigation strategy. A sub-set of pesticides monitored in bioreactor beds in the Lower Burdekin region showed a reduction from the inlet to the outlet of the bioreactor (Manca et al. 2020b). These included the herbicides atrazine, ametryn, metolachlor, simazine and tebuthiuron and the insecticide imidacloprid. It should be noted that some of the pesticides detected were not applied to the sugarcane crop and likely entered the drainage system via irrigation water.

The long-term effect of continual atrazine (or other pesticide) adsorption within bioreactors has not been studied, nor the combination of different agrichemicals and their by-products.

1.5.6 Potential additives to bioreactors

1.5.6.1 Soluble carbon source

Trials have investigated dosing bioreactors with a soluble carbon source, such as methanol and sodium acetate, to increase the microbially available carbon during periods of high nitrate loading, to maximise nitrate removal whilst minimising unwanted side-effects (Rivas et al. 2019; Roser et al. 2018). The effectiveness of ethanol-enhanced woodchip treatment systems has been tested with aquaculture wastewater and achieved >95% removal efficiency (Lepine et al. 2016). Carbon dosing could be investigated in Queensland production systems with high influent nitrate concentrations, such as aquaculture farms and protected cropping (i.e. greenhouse) systems.

1.5.6.2 Biochar

Biochar as a soil amendment is well-established to reduce the mobility of nitrogen and phosphorous in addition to improved cation exchange capacity, water retention and microbial growth (Bock et al. 2015). Adding biochar to woodchip bioreactors has been investigated to help bind nutrients and pesticides. Studies showed that the addition of biochar could result in increased denitrification performance as well as adsorption of phosphorus and some pesticides (Bock et al. 2015; Ashoori et al. 2019; Berger et al. 2019). Further research is required to better understand the hydraulic residence time and permeability trade-offs, cost-effectiveness, performance and any leaching or by-products associated with the use of biochar in woodchip bioreactors (Coleman et al. 2019).

1.6 Knowledge gaps and research needs

Since 2015, bioreactor trials have significantly enhanced understanding of the efficacy of bioreactors in a few different climatic regions and production systems in Queensland. These trials demonstrated that bioreactors do remove nitrates from agricultural run-off and leachate. Now the proof of concept has been established, research needs to focus on enhancing the cost-effectiveness of bioreactors through site selection, design adaptations and adjusting variables to increase pollutant removal in different production systems and regions.

Future research in Queensland needs to include:

- How to prioritise bioreactor sites using information on nitrate hotspots and hydrology?
- How to scale-up bioreactors to increase their effectiveness at a catchment scale?
- How can nitrate removal performance be maximised?
- How effective are bioreactors at removing other pollutants such as pesticides, or phosphorus?
- How do different variables interact to impact efficacy of pollutant removal, including temperature and the chemical and physical characteristics of the influent water?
- What are the negative impacts of bioreactors? Do these outweigh water quality benefits? How can negative impacts be mitigated?
- What designs are best for specific site conditions?
- How can bioreactors be designed to maximise interception and treatment of short, high volume run-off events characteristic of Queensland's coastal farming systems?
- How effective are other carbon sources such as farm residues (e.g. cane trash)?
- How effective are additives, such as methanol?
- What impact do wetting and drying regimes have on bioreactor effectiveness and longevity?
- What is the lifespan of woodchip in the tropical Queensland climate?

There is a need for both field and laboratory research to address these questions, with more field trials in different regions and production systems in Queensland. Trials on an aquaculture farm in North Queensland show that bioreactors may be useful for treating aquaculture waste water. This technology could potentially enable expansion of aquaculture where there are strict regulations limiting nitrogen discharge to waterways. There is scope to investigate using bioreactors in other intensive food production environments. Each production system has unique challenges and design adaptations required and therefore trials will be required to identify the best design features in these different applications.

PART 2:

Planning a bioreactor

Part 2: Planning a Bioreactor

Steps to planning a bioreactor

1. Setting objectives (2.1)
2. Site identification to select possible sites for a bioreactor bed or wall (2.2)
3. Identify possible approvals required (2.3)
4. Calculate potential costs and confirm sufficient budget available (2.4)
5. Detailed site investigation for bioreactor bed (3.2) or bioreactor wall (4.2)
6. Design bioreactor bed (3.3) or bioreactor wall (4.3)

2.1 Setting objectives

2.1.1 Broad project objective

The first step in planning any on-ground works is to determine the objectives of the project, i.e. what is the purpose of doing on-ground works? The funding available for the works and the priorities of the landowner and the individuals or organisation/s initiating the project will have a significant influence on the objectives. For example, a university wishing to conduct a research trial will have a different objective to a landowner wanting to reduce nitrate leaving their farm. These guidelines detail two distinct broad objectives, noting that some projects often have elements of both:

- research: project aimed at investigating a defined question, such as nitrate removal performance of a bioreactor
- non-research: on-farm project aimed at maximising nitrate removal.

2.1.2 Priority catchment issues to address

Specific project objectives should be defined through developing a whole-of-system understanding of the site and surrounding landscape, by identifying:

- components (e.g. soil, production features)
- processes (e.g. hydrology and hygrogeology)
- values (e.g. nutrient cycling, habitat)
- drivers (e.g. landowner goals, planning, funding)
- threats (e.g. pollutants).

A structured 'Walking the Landscape' process involving stakeholders and landowners, can assist in developing this catchment understanding. It can help to identify the priority issues to address and the interventions, such as treatment systems, that may be suitable in different parts of the catchment. 'Walking the Landscape' is a systematic process which integrates existing data with expert knowledge through hands-on workshops to create a common understanding amongst stakeholders. More information is available on *WetlandInfo* wetlandinfo.des.qld.gov.au/wetlands/ecology/landscape/.

Alternatively, a review of relevant Natural Resource Management plans, water quality improvement plans and water quality monitoring results can be used to identify water quality priorities in the area of interest. Each catchment, or sub-catchment, will have specific water quality priorities, which can be determined through catchment or Great Barrier Reef water quality improvement plans. The Reef Plan website (www.reefplan.qld.gov.au/), Healthy Land and Water (hlw.org.au/) or your local Natural Resource Management body (www.nrmrq.org.au/find-your-regional-group/) has relevant information. Different agricultural land uses will have a propensity for different pollutant losses – for instance nitrate losses from sugarcane production systems is a priority in the Great Barrier Reef catchment.

2.1.3 Landowner priorities

It is critical to engage the landowner while setting project objectives to ensure the project meets their priorities and expectations. A farm planning and mapping process can help discuss catchment priorities and individual landowner goals and expectations.

2.1.4 Whole of farm approach to improving water quality

A whole of farm approach to improve water quality should adopt an integrated suite of practices including:

- agronomic best management practices
- prevention measures (e.g. buffers, vegetated drains, riparian vegetation)
- treatment systems (e.g. bioreactors, treatment wetlands).

Bioreactors and other treatment systems are designed to work in conjunction with agronomic best management practices to achieve the best water quality outcomes. They are not a substitute for good farming practice, as the treatment system will not function effectively if there are large losses of sediment, nutrients and/or chemicals from the production area. In the case of in-line or off-line bioreactor beds, excess sediment run-off from the production area can rapidly smother the inlet of bioreactor beds, reducing their capacity to accept and treat surface run-off.

Check out WetlandInfo for information on a range of treatment systems:

wetlandinfo.des.qld.gov.au/wetlands/management/treatment-systems/for-agriculture/

This combined approach of using treatment systems together with agronomic best management practices and prevention measures is called a treatment train. A treatment train works by preventing or minimising pollutants leaving the production area, through best management practices, then intercepting or treating run-off, or leaching, through one, or more, treatment systems.

Treatment systems commonly used to improve water quality in agricultural settings include treatment wetlands, sediment basins and bioreactors. Each system is designed to enhance removal of specific pollutants and each have their unique requirements and limitations. Pollutants are generally removed from water in this sequence:

1. coarse-medium sediments, through the physical process of sedimentation
2. fine sediments and particulate nutrients, through filtration and adsorption
3. soluble particles (nutrients and pesticides), through biological and chemical processes of denitrification, degradation, transformation, adsorption and absorption.

Denitrifying bioreactors operate at the third step, through the biological process of denitrification. As such they can require other treatment systems upstream of the bioreactor, to reduce the loads of other pollutants in the water before it enters the bioreactor, such as sediment basins and vegetated drains upstream of bioreactor beds.

The advantage of bioreactors over many other treatment systems, is that they are relatively cheap, passive and low maintenance and can fit within existing farm infrastructure (drains or headlands) without impacting farm operations. Like any treatment system they are not suitable in every location and need to be considered on a site-by-site basis, according to the landowner's objectives, water quality, water regime, position in the landscape and specific siting constraints.

Checklist before proceeding to preliminary site identification

- ☐ the landholder agrees to investigating a site for a bioreactor
- ☐ the objective-setting process of a project identifies nitrate as a water quality priority
- ☐ the bioreactor would be part of a treatment train or whole of farm approach to water quality improvement
- ☐ there are no landscape features limiting the use of treatment systems.

2.2 Preliminary site identification

When assessing possible sites for a bioreactor, it is important to understand the farm in the context of the broader landscape and the farm operations. The process conducted while setting the project objectives (section 2.1) should have identified the broader landscape within which the farm sits and some of the characteristics of the farm. An understanding of the soil, landscape, hydrology/hydrogeology and farm management practices are required to understand potential pollutant loss pathways and to determine which, if any, parts of the farm may be suitable for a bioreactor (Table 2.1).

Table 2.1 Characteristics of the farm to be investigated during the site assessment

Components and processes	Characteristics to investigate during the site assessment
Soils	• soil type and soil profile • potential acid sulphate soils • other soil constraints e.g. sodic soils or soils with existing high denitrification potential
Landscape	• slope of the land / topography • natural areas (wetlands, creeks, native vegetation) • catchment and sub-catchment size
Hydrology/ hydrogeology	• water flow (direction, amount) and extent of inundation during rain events, irrigation events and flood events • waterlogging or areas where water ponds • drainage lines and waterways and presence of water during wet season and dry season • groundwater levels (if known) or presence of groundwater bores • presence of sub-surface drainage such as ag-pipe
Farm management practices	• unproductive and unused parts of the farm, or any areas earmarked for treatment systems or restoration • landowner's plans for expanding or reconfiguring paddocks • farm access points and how regularly tracks or headlands are used by vehicles and machinery • nutrient management practices, including how often fertiliser applied, surface or sub-surface application and if Best Management Practices are adopted • irrigation management (if relevant) including source of irrigation water, frequency of irrigation, irrigation volumes, volume of run-off, tailwater capture and reuse.

The specific site requirements for bioreactor beds and bioreactor walls needs to be understood (Table 2.2). This process may identify a few sites for further investigation (Figure 2.1). Potential sites can proceed to the detailed site investigation and design phase for bioreactor beds (part 3) and walls (part 4). In some cases, there may be no locations on the farm deemed suitable for a bioreactor and another type of treatment system could be considered.

Information on soils can be sourced from the landowner, online Government mapping resources (e.g. Queensland Spatial Catalogue - QSpatial http://qldspatial.information.qld.gov.au) or via local agronomists. Similarly, landowners, Local Government Authorities, or natural resource management officers and QSpatial are sources for information on the landscape within and surrounding the property. Hydrological/hydrogeological information may also be available via the landowner, QSpatial, or the local water management authorities.

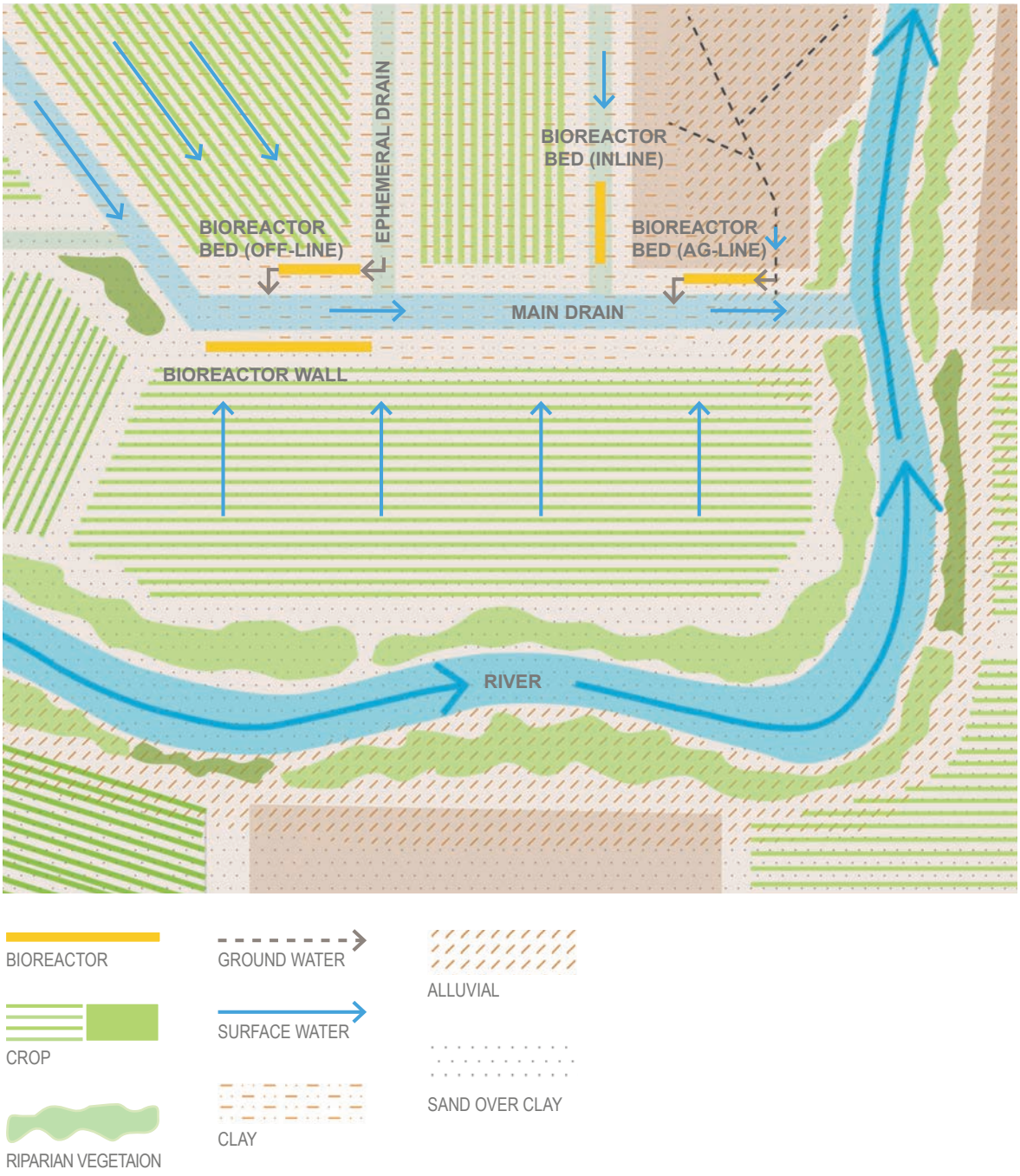


Figure 2.1 Example farm map showing possible locations for bioreactors on a farm.

Table 2.2 Site specific requirements for bioreactor beds and walls

Site characteristic	Bioreactor bed	Bioreactor wall
Water regime	Regular surface water flow via rain, or irrigation, or groundwater ingress into drains or via ag-pipe, so that woodchip is saturated regularly throughout the year.	Moderately high groundwater level (i.e. within a metre of the surface) during the wet season, or rain events, so that the woodchip intercepts groundwater.
Suitable soil type	No specific soil type.	Sandy / sandy loam topsoil less than 3 m depth ideally underlain by less permeable clay or rock layer.
Position relative to production area	Point at which water leaves the production area, either within (in-line) or adjacent (off-line) to a drainage line conveying run-off from the production area and prior to entry to a larger drain or natural waterway. Alternatively, if crop is drained via ag-pipe, a point along, or at the end of the ag-pipe, can be a suitable location for a bioreactor bed. If there is a risk of low dissolved oxygen concentrations in the effluent impacting sensitive aquatic species, it is best to situate the outlet pipe (from the bioreactor bed) at least 10 m upstream from any natural waterways.	Locate along a headland, or vacant area of land at the downslope end of the production area, such as between the crop and drain/waterway. Bioreactor walls are often parallel to a water course.
Topography	A site where sufficient hydraulic head can be obtained to facilitate water movement through the woodchip. Usually achieved via a slight topographic gradient, or by situating the bioreactor where the outlet can be lower than the inlet, (e.g. outlet discharges into a larger drain allowing the outlet height to be set lower than the inlet, without being flooded). Steep sites should be avoided as this can increase the risk of sediment transport, and flow through the bioreactor may be too quick, i.e. short residence time.	Site where groundwater flows, or is likely to flow, from beneath the crop to a drain or waterway. **Note:** a slope may indicate groundwater flow paths, but groundwater often flows differently to surface water.
Other site characteristics	Sites that avoid disturbance of existing riparian or native vegetation. Avoid areas used by vehicles or machinery.	Sites that avoid disturbance of existing riparian or native vegetation. Headlands receiving light traffic may be suitable.

2.3 Identify relevant approvals and legislation

Depending on the location and design of the bioreactor, the construction may trigger approvals. Legislative requirements may be triggered by, but are not limited to, structures in mapped watercourses (barriers to fish passage); works within trigger areas of wetlands of ecological significance; and disturbance of remnant vegetation. The programs, planning and legislation page on the WetlandInfo website outlines different approvals and legislation that may be relevant wetlandinfo.des.qld.gov.au/wetlands/management/legislation-update/. The legislative requirements, including the cost and time to receive approval may influence site selection. Approvals should be sought prior to, or during the design phase of the project.

Contact the relevant Local Government Authority before any construction to understand any locally relevant planning requirements. Most bioreactor projects are classified as general farm work and require limited, to no approvals.

It is recommended that local Traditional Owners are engaged to ensure no sites or items of cultural significance are disturbed during excavation. It is also important to ensure there are no underground utilities (i.e. power cables, water pipes, gas pipes) that may be impacted during construction. Dial before you dig should be used to identify underground utilities www.1100.com.au/.

2.4 Cost considerations

2.4.1 Cost of bioreactors

When planning and designing a bioreactor, costs need to be considered. The overall cost will be determined by location of the site and size of the bioreactor and access to equipment, labour and materials. Throughout the life of a bioreactor there will be a range of up front and ongoing costs. There are economies of scale, whereby larger bioreactors are less expensive per cubic metre than smaller bioreactors, because some costs (e.g. planning, design, excavator haulage) are the same regardless of the size of the bioreactor.

Upfront costs

- planning, including site selection
- design, including costs to engage specialists
- approvals
- haulage cost for excavator
- excavator and driver
- woodchip and delivery costs
- rock and gravel (for bioreactor beds) and delivery costs
- gabion baskets and sleepers (for bioreactor beds), star pickets, pipes
- liner and sealant, disposables
- labour for constructing the bioreactor and design oversight.

On-going costs

- maintenance costs, including vegetation removal around bioreactor, cleaning out sediment, replacing woodchip or gravel
- monitoring, including labour, sample collection and analysis
- opportunity cost, i.e. foregone production if land was taken out of production for the bioreactor.

As many of the on-going costs will be borne by the landowner, it is vital to discuss these upfront, and obtain agreement with the landowner prior to installing a bioreactor.

2.4.2 Calculating costs

To ensure there is sufficient budget to adequately plan, design, install, maintain and monitor the bioreactor, costs need to be estimated up front. To calculate the total cost of the bioreactor the total present value cost (TPVC) should be used. This is calculated by adding together the total upfront costs with the estimated future or on-going costs (refer Section 2.4.1) over the life of the bioreactor, discounted to present value (Equation 1).

$$TPVC = upfront\ cost + sum\ of\ dicounted\ future\ costs \qquad \text{(Equation 1)}$$

Future and on-going costs are discounted to the present value so that all costs (upfront and future) are expressed in a common metric, their present value. A discount rate is used to calculate the present value of future costs and should be set by the project. This is usually based on interest rates, with discount rates of 3%, 5% or 7% commonly used. It is recommended to use several discount rates for comparison (Hasan and Smart 2020). Equation 2 discounts the cost of an item that will be incurred t years in the future (Hasan and Smart 2020).

$$PVC = \frac{\text{FVC}}{(1+r)^t} \qquad \text{(Equation 2)}$$

where PVC is present value cost ($),

FVC is future value cost (not inflation corrected) ($),

r is real discount rate (%), and

t is the number of time periods in the future that the cost will be incurred (years).

To enable comparison between treatment systems with different predicted lifespans it is recommended that the costs be annualised into the equivalent present value so that costs can be expressed in $/year as per Equation 3.

$$APVC = \frac{TPVC}{Annuity\ factor} \qquad \text{(Equation 3)}$$

where APVC is Annualised equivalent present value cost ($/yr), and

TPVC is total present value cost ($).

The annuity factor is given by:

$$Annuity\ Factor = \frac{1-(1+r)^{-T}}{\text{r}} \qquad \text{(Equation 4)}$$

where *r* is the real discount rate (%) and

T is the assumed lifetime of the bioreactor (years).

2.4.3 Calculating cost-effectiveness

Cost-effectiveness is used to compare different on-ground actions to improve water quality. It is calculated by dividing the total present value cost by the quantity of the target pollutant removed and is usually expressed as $ kg^{-1} of pollutant removed. The cost-effectiveness of a particular project is often required by funding bodies to enable them to compare the cost-effectiveness of different projects in achieving water quality improvement.

There are different approaches used to calculate cost-effectiveness of bioreactors, see Christianson et al. (2013b) and Lepine et al. (2018). One method for calculating cost-effectiveness, as used in the lower Burdekin bioreactor (section 1.5.4) and other bioreactor trials in Queensland (not yet published) is Equation 5 below (from Hasan and Smart 2020).

$$\text{CE} = \frac{\text{TPVC}}{TLR} \qquad \text{(Equation 5)}$$

where *CE* is the cost-effectiveness ($ kg^{-1} N)

TPVC is total present value cost ($), and

TLR is total load reduction (kg N). Note that in some cases the total load reduction can be discounted using the same discount rate as costs (*r*), particularly if investors place a higher value on the load reduction occurring sooner rather than later.

PART 3:

Bioreactor beds

Part 3: Bioreactor beds

3.1 Overview

In Queensland's intensive agricultural systems, fields are typically drained via open drains. The drains can often remove a mix of surface run-off and shallow groundwater. This drainage system is sometimes supplemented by subsurface ag-pipe drainage (also known as 'tile drains'), that maintain the water table below most of the crop root zone, discharging excess groundwater to an open drain.

Bioreactor beds can be installed within open drainage lines as an 'in-line' system, adjacent to drains as an 'off-line' system or connected to ag-pipe (section 1.4.1). The most suitable type of bioreactor bed will depend on the characteristics of the site, determined during the site investigation.

3.2 Site investigation

A detailed site investigation is required to determine the most appropriate site, type, design and size of potential bioreactor beds identified through the preliminary site identification (section 2.2). Three steps are involved in the detailed site investigation:

1. engage landholder and inspect site
2. determine water regime
3. identify presence of nitrate.

3.2.1 Engage landholder and inspect site

A site inspection and discussion with the landholder, or land manager, is essential to understand water movement on the farm, potential presence of nitrate, site suitability and constraints. Obtaining this information from the landholder will minimise the amount of preliminary monitoring required, saving time and money. Landholder support and input from the beginning and throughout the bioreactor project is critical to success, as is ensuring all parties are clear about the objective of the bioreactor project.

The site inspection and discussion with landholder should aim to determine:

- Location of potential bioreactor site relative to production areas, or other potential sources of nitrate.
- If there is a sufficient slope (or difference in head) from the inlet to the outlet of the proposed bioreactor bed to facilitate water movement through the woodchip (Figure 3.1). Having the outlet discharge into a deeper drain can also achieve the required hydraulic head.
- Machinery and vehicle access and use of the potential site, (e.g. is access available and will the proposed bioreactor bed impact or be impacted by farm operations).
- Sources of sediment such as farm tracks, gullies, or sediment loss during land preparation, as this will inform the design of sediment mitigation strategies.

Figure 3.1 Taking levels during the site investigation to determine if slope is sufficient.

3.2.2 Determine water regime

Understanding the water regime at the proposed bioreactor site is critical to determine the type, size and design of the bioreactor bed (Figure 3.2). The following information is required:

- rainfall pattern and magnitude
- water movement on the farm during low, medium and large rainfall events and irrigation events (where relevant)
- irrigation practices including irrigation schedule, water source, volume of run-off and flow rate (where relevant)
- water flow in the drain, or pipe, during different sized events
- water levels in the drain during the wet and dry seasons
- presence of any subsurface drainage (e.g. ag-pipes).

Water movement on the farm, water levels in drains, sub-surface drainage and irrigation practices (where relevant) may be obtained from the landholder. Rainfall pattern and magnitude may be obtained through:

- SILO www.longpaddock.qld.gov.au/silo/
- Bureau of Meteorology www.bom.gov.au
- landholder records.

Quantifying water flow in a drain or pipe, ideally during different sized events, is critical to determine sizing during the design stage (section 3.3.2). Information on water flow may be available from the landholder, or can be calculated through preliminary monitoring. Different methods for monitoring water flow are provided in section 5.3.

Figure 3.2 Investigating water regimes on different farms (left protected cropping/greenhouse system, right irrigated sugarcane).

3.2.3 Identify presence of nitrate

Understanding of nitrate concentrations in the water is essential to identify the most cost-effective location for a bioreactor bed and to calculate the size of the bioreactor bed (section 3.3.2).

For the proposed bioreactor bed site, the aim is to understand:

- average, or most likely nitrate concentrations (ideally at least 3 mg N L^{-1} for most of the time if the aim is cost-effective nitrate removal)
- the highest likely nitrate concentration.

The landowner may have water quality monitoring results from the farm to indicate nitrate concentrations at the proposed bioreactor bed site. If water quality monitoring results are not available, preliminary water quality monitoring should be conducted (section 5.2). Note section 5.2 provides recommendations for monitoring to maximise the success of the bioreactor bed. The sampling intensity and duration recommended can be altered depending on the project objectives, budget and timeframe.

Why is the influent nitrate concentration important?

It is recommended that bioreactor beds be located where the influent nitrate concentration is at least 3 mg N L^{-1} most of the time, for the following reason.

The USDA-NRCS (2015) conservation practice recommends to 'design the bioreactor (bed) hydraulic retention time for a minimum of 3 hours at the peak flow capacity'.

With a nitrate concentration decline rate of 0.8 mg L^{-1} hr^{-1}, as observed in north Queensland trials (section 1.5.1), approximately 2.4 mg N L^{-1} would be removed over three hours.

To minimise the risk of nitrate limitation (below 0.5 mg N L^{-1}) and potential pollutant swapping, a minimum influent nitrate concentration of at least 3 mg N L^{-1} is recommended.

Checklist before proceeding to bioreactor bed design

- ☐ Landholder has provided in-principle agreement to the bioreactor bed objective and site.
- ☐ Know water flow at bioreactor bed site (at least during average flow conditions).
- ☐ Know likely nitrate concentration at the site.
- ☐ Confirm there is suitable slope at the site, or the bioreactor inlets and outlets can be positioned to ensure water movement through woodchip.

3.3 Design

3.3.1 Design features

3.3.1.1 Design considerations

Bioreactor beds (Figure 3.3) generally have water control structures to manage the outflow, hydraulic residence time and bioreactor saturation. The trials in Queensland are gravity fed systems that rely on head pressure of water and gradient to push water through the system.

The choice of bioreactor bed type (in-line, off-line or ag-line as described in section 1.4.1) will depend on the drainage layout, presence of ag-pipe, flow regime, slope or site conditions to achieve sufficient hydraulic head and will need to be determined on a case-by-case basis. The design features will be influenced by the type of bioreactor bed and the specific site characteristics.

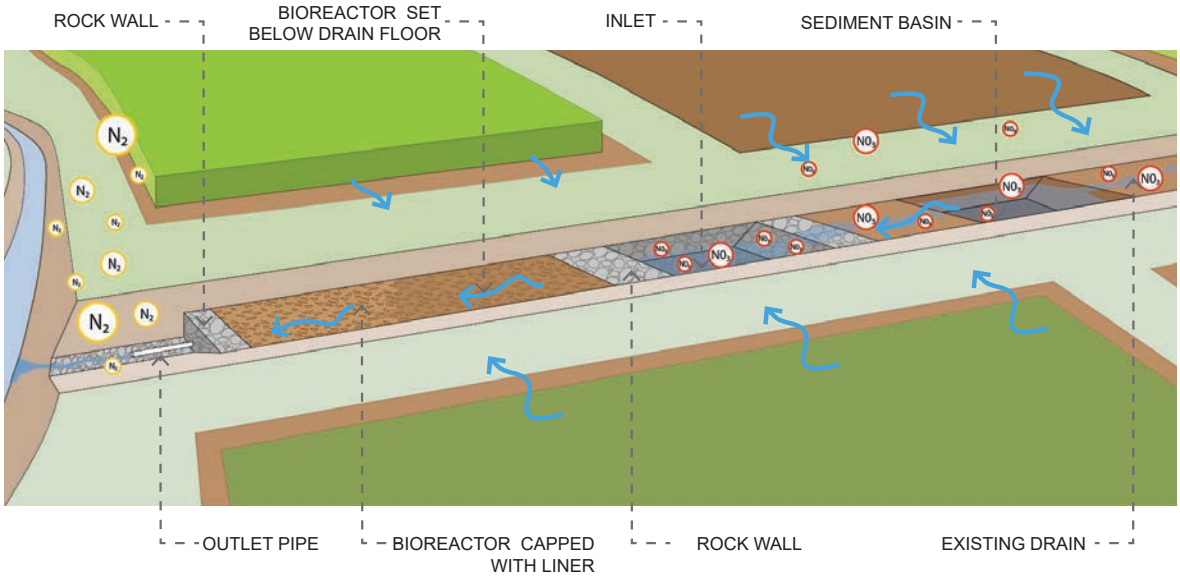


Figure 3.3 In-line bioreactor bed showing key design features including inlet, outlet and sediment trap. Note the bioreactor is capped with soil, with excess water flow over the top of the bioreactor.

3.3.1.2 Inlet structure

If the influent water enters the bioreactor via a single pipe, it is necessary to install a 'spreader'. This can be a perforated pipe, or series of pipes, that disperse the water evenly across the width of the bioreactor (Figure 3.4). This is to prevent the development of any preferential flow pathways and/or 'dead zones' within the woodchip to maximise performance.

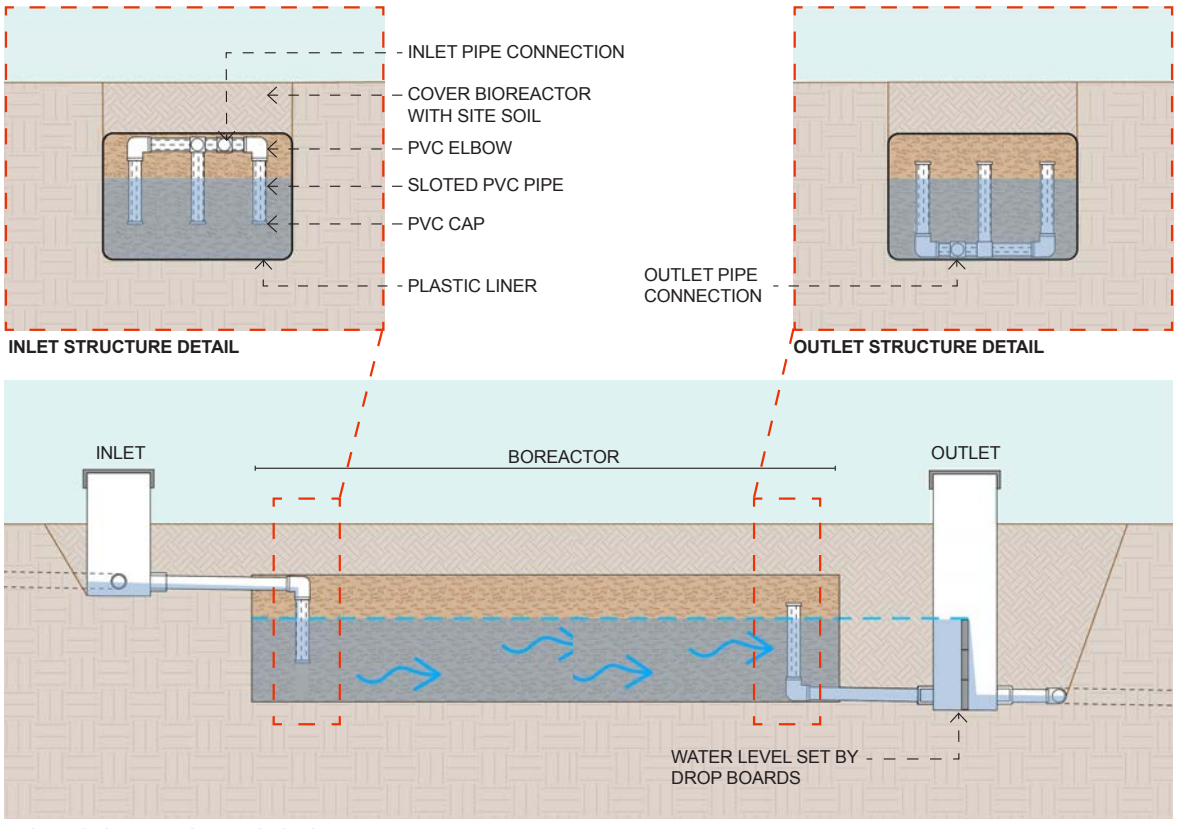


Figure 3.4 Detail of ag-line bioreactor bed.

3.3.1.3 Outlet structure

In production systems where relatively continuous flow occurs, for example protected cropping such as glasshouse systems, bioreactors can be designed to stay saturated by having the bioreactor outlet drainage point located at the top of the woodchip. For maintenance and safety, it is recommended that the outlet is designed to include an option to completely drain the system when required.

For most Queensland production systems, for example sugarcane and field-based horticultural crops, it is likely that flow is sporadic, and bioreactors will experience wet and dry periods. In this case, it is important to allow the bioreactor to freely drain by locating the outlet at the base of the bioreactor. If water cannot freely drain from the bioreactor the water can become stagnant and full denitrification can occur, leading to nitrate limitation which occurs when the effluent nitrate concentration is below 0.5 mg N L^{-1} (Addy et al. 2016). This can result in pollution swapping (section 1.3.2).

If outlet pipes are being used, there should be multiple outlets to minimise the risk of blockages (Figure 3.5). The diameter and number of pipes depends on the target hydraulic residence time. The outlets should be installed so that they can freely drain and not be submerged regularly, especially in instances where the flow rate of the bioreactor needs to be monitored. Valves on the outlet pipes, or other methods to adjust flow rate, should be considered, as this will provide an opportunity to adjust the hydraulic residence time.

Bioreactor beds located immediately upstream of environmentally sensitive waterways may require an additional structure downstream of the outlet (e.g. installing rock riffles) to oxygenate the effluent. This is to reduce the risk of low oxygen water from the bioreactor impacting the receiving waterway.

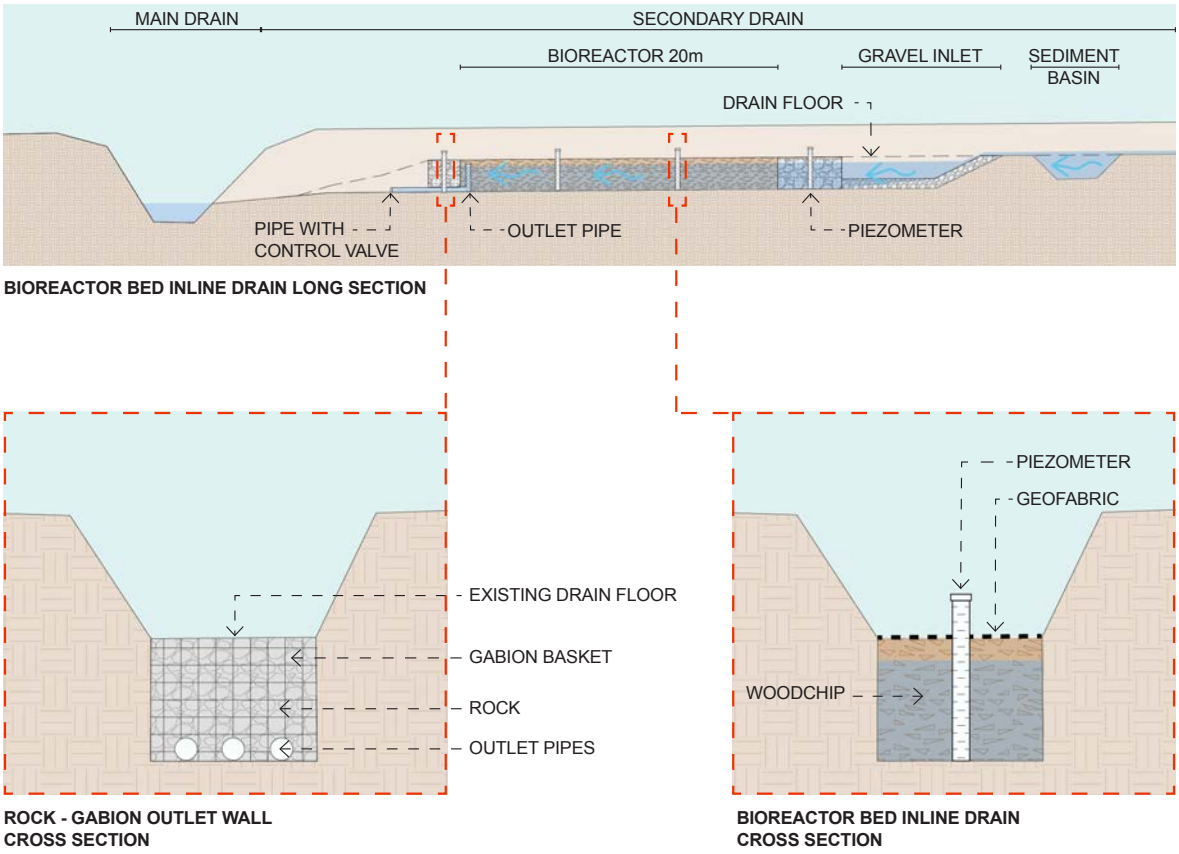


Figure 3.5 In-line bioreactor bed showing outlet pipes and monitoring piezometers.

3.3.1.4 Bypass

Bioreactor beds are generally not designed to receive all the run-off water, particularly during large rainfall or irrigation events, and therefore an overflow, or bypass to divert water around the system, is required. A bypass is important to prevent water backing up, causing damage to drainage networks, or damaging the crop, or bioreactor itself. Additionally, in drainage networks (irrigated or rainfall driven) flow will vary significantly and it is important to allow for peak flows to bypass the bioreactor.

For in-line bioreactors installed below the floor of the drain, excess water can flow over the top of the bioreactor. For in-line bioreactors above the floor of the drain, the design will have to ensure excess flow, beyond the capacity of the bioreactor, can be accommodated within the drain without water backing up or flooding adjacent production areas.

Off-line or ag-line bioreactors can have a Y-junction or inlet pit whereby excess water can be directed away from the bioreactor via a bypass pipe (Figure 3.6).

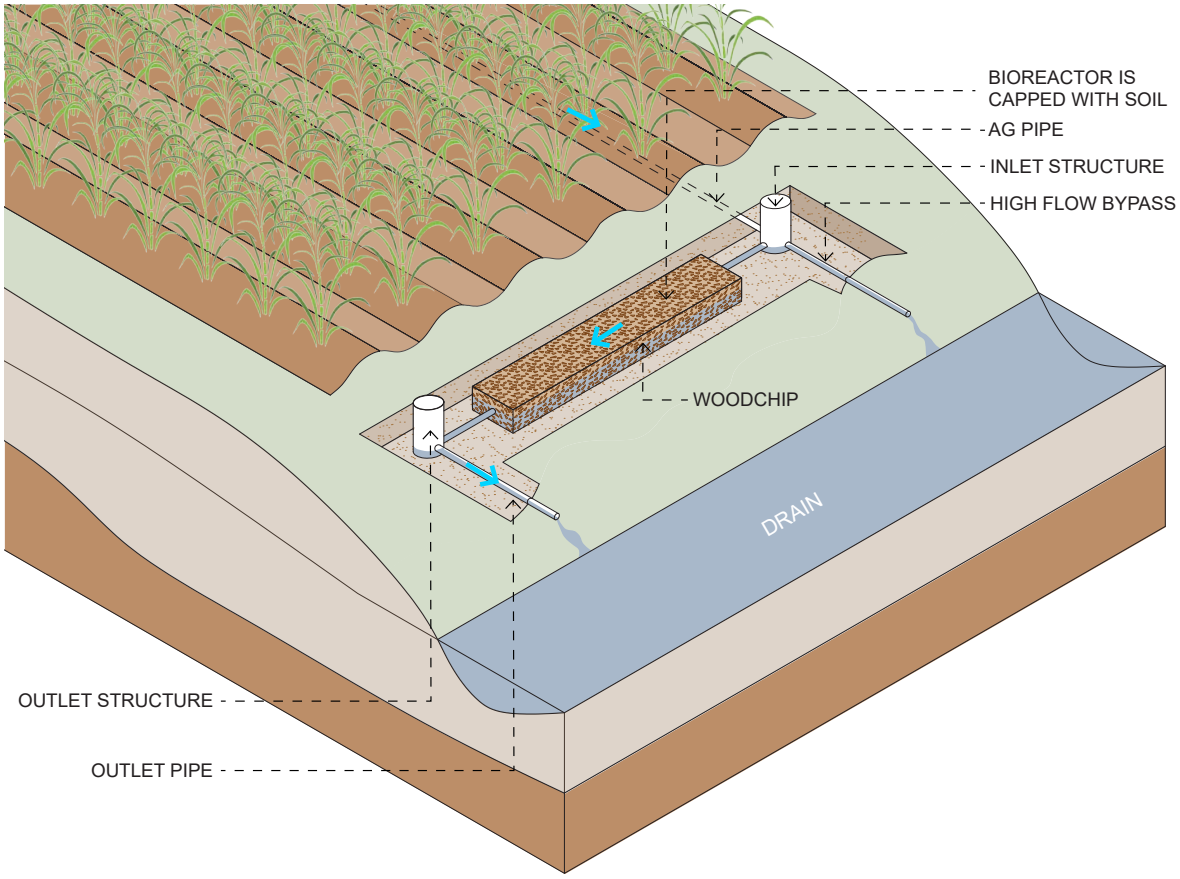


Figure 3.6 Ag-line bioreactor showing high-flow bypass.

3.3.1.5 Sediment basin

In most agricultural production systems, there will be a risk of sediment transport in surface water run-off. Slopes, light soils and bare, unvegetated areas have an increased likelihood of significant sediment movement. Where bioreactor beds intercept surface run-off, a sediment basin is required upstream of the bioreactor inlet to capture sediment and reduce the amount of sediment entering the bioreactor (Figure 3.5 and Figure 3.7). The design and sizing of the sediment basin depends on the size of the catchment, the flow rates and size of the transported sediment particles.

Equation 6 enables the surface area of a sediment trap to be calculated using the flow rate determined during the site investigation (section 3.2) and the rate at which a particular sediment type is deposited, known as the sediment settling velocity. Note that fine clay may never settle, especially if it is contained in sodic soil.

$$A = \frac{Q}{v_s} \qquad \text{(Equation 6)}$$

Where A is the surface area of the sediment basin (m^2), Q is the flow rate ($m^3\ sec^{-1}$) and v_s is the sediment settling velocity ($m\ sec^{-1}$). Table 3.1 provides sediment settling velocities for different particle sizes and should be selected based on what type of sediment is most likely to be found at the site.

Sediment basins are often recommended to be between 1.5 – 2.5 m depth to maximise sediment deposition and reduce frequency of maintenance. Shallower basins can be built if space is limited, however desilting will need to occur more frequently. Further information on the design of a sediment basin and other techniques for estimating the size of sediment basins can be found on WetlandInfo wetlandinfo.des.qld.gov.au/wetlands.

Table 3.1 Sediment settling velocities. Source: Pilgrim 2001 in DEEDI 2011 Wetland Management Handbook.

Classification of particle size range	Particle diameter (µm)	Settling velocity (v_s, m s^{-1})
Very coarse sand	2000	0.2
Coarse sand	1000	0.1
Medium sand	500	0.053
Fine sand	250	0.026
Very fine sand	125	0.011
Coarse silt	62	0.0026
Medium silt	31	0.0066
Fine silt	16	0.0018
Very fine silt	8	0.0004
Clay	4	0.00011

Figure 3.7 Sediment basin shown in the foreground with baffles to slow water velocity and enable sediment to settle before water flows into the bioreactor (beyond timber sleepers).

3.3.1.6 Monitoring equipment

The monitoring equipment required will depend on the objective of the project (section 2.1). If the bioreactor is installed on a farm for non-research purposes, the bioreactor bed will need at least two sampling points, one at the inlet and one at the outlet. These can be piezometers or alternatively samples can be collected from the drain, or pipe upstream of the inlet, and at the outlet of the bioreactor. An additional piezometer should be installed in the middle of the bioreactor, if bioreactor saturation is to be monitored to calculate nitrate removal rate (section 3.5.1).

If the bioreactor is installed for research purposes, such as to quantify nitrate reduction performance, multiple piezometers may be required at the inlet, outlet and within the woodchip zone (Figure 3.5 and 3.8). Multiple sampling points allow measurements of water depth, flow and nitrate concentration in different sections of the bioreactor. Additional piezometers can be installed to monitor the woodchip degradation. Woodchip can be placed in mesh bags within the piezometer. The mesh bags will hold the woodchip in place and will facilitate future sampling. A flume, automatic samplers and other monitoring equipment may be required for research projects. The type of monitoring equipment and its layout will depend on the objective of the research project.

Figure 3.8 Monitoring equipment set up at a research trial site, showing piezometers and automatic samplers.

3.3.2 Sizing a bioreactor bed

The size of a bioreactor bed (i.e. the volume of woodchip) can be estimated based on the water flow to be treated by the bioreactor and the hydraulic residence time required to reduce nitrate by a given concentration. The nitrate concentration of the water to be treated and water flow rate, determined during the site investigation (section 3.2), is required to calculate the woodchip volume.

The method outlined below is used for estimating the volume of woodchip and footprint of the bioreactor. As additional bioreactor trials are undertaken, and more research results become available, the methods of calculating bioreactor size might be updated. Therefore, the below method should be used as a guide only. The final design will often be constrained by other factors, including availability of land and funds for construction.

It is highly recommended that professional engineering advice is sought for the design and sizing of a bioreactor. The calculations below are theoretical and include implicit assumptions that should be considered.

Step 1 Set target water flow to be treated

In the USA, the USDA-NRCS (2015) sets different targets for bioreactor beds:

- Treat peak flow from a 10-yr, 24-hr drain flow event.
- Treat at least 15% of the peak flow from the drainage system.
- Treat at least 60% of the long-term average annual flow from the drainage system.

This is an example of the types of targets that can be used for designing bioreactor beds. Specific targets have not been set for Queensland and therefore each project site should set their own target based on local water quality targets, climatic conditions (especially intensity, frequency and duration of rainfall), crop type (irrigated or rain-fed), soil and water nitrate concentration. Table 3.2 provides some examples of target water flow (Qtarget $m^3 h^{-1}$) based on different flow rates and percentages of the flow to be treated. The target water flow is used in Step 3.

Table 3.2 Different target water flow rates based on flow rate at the site and percentage of flow to be treated.

Flow rate in drain or pipe ($m^3 h^{-1}$)	Percentage of flow to be treated (%)	Target water flow rate (Qtarget) ($m^3 h^{-1}$)
3.0	60	1.8
3.6	60	2.16
7.2	60	4.32
10	20	2.0
15	20	3.0

Step 2 Set target hydraulic residence time

The target hydraulic residence time (tHRT) can be calculated using the nitrate concentration of the water to be treated ($[NO_3\text{-}]_{in}$), the desired nitrate concentration leaving the bioreactor ($[NO_3\text{-}]_{out}$) and the nitrate concentration decline rate (NCDR) within the bioreactor substrate, using Equation 7.

$$tHRT = \frac{([NO_3^-]_{in} - [NO_3^-]_{out})}{NCDR} \qquad \text{(Equation 7)}$$

The nitrate concentration decline rate is defined as the amount of nitrate reduced per hour within the bioreactor. North Queensland trials indicate a generic nitrate concentration decline rate of approximately 0.8 mg N L^{-1} hr^{-1} (section 1.5.1). This rate can be used for the purpose of estimating bioreactor woodchip volume. See section 1.5.1 for more information and to determine if this generic nitrate concentration decline rate is suitable for the type of carbon substrate and field conditions (such as temperature) appropriate to the project site.

The nitrate concentration leaving the bioreactor will need to be decided for each site, depending on the water quality targets and site context. Different nitrate concentrations can be modelled in the equation to assess the influence of nitrate concentration on hydraulic residence time.

The tHRT should be at least three hours, to allow time for dissolved oxygen to reach suitable concentrations for denitrification (also consistent with the USDA – NRCS (2015) guidelines for bioreactors).

Step 3 Calculate saturated woodchip volume

Once the target water flow and hydraulic residence time is determined, it is possible to calculate the required saturated woodchip volume using equation 8 (Christianson et al. 2011; Metcalf and Eddy 2014):

$$V_{sat} = \frac{tHRT * Q_{target}}{\varphi} \qquad \text{(Equation 8)}$$

where v_{sat} (m^3) is the saturated woodchip volume, tHRT is the target hydraulic residence time (h), φ ($m^3 m^{-3}$) is the woodchip porosity, and Q_{target} ($m^3 h^{-1}$) is the target water flow.

Step 4 Calculate final bioreactor woodchip volume

The target hydraulic residence time will not necessarily correspond to the actual hydraulic residence time that is measured using tracing tests. Sometimes the actual hydraulic residence time can be shorter than the tHRT due to the presence of preferential short circuiting flow (Christianson et al. 2013b) or the presence of dead zones (Ghane et al. 2019), that reduce the effective woodchip volume able to remove nitrate.

For this reason, it is recommended to construct a bioreactor bed that is 20-30% bigger than the size of V_{sat} calculated using equation 8. The addition of flow-control valves on the outlet pipe will enable the flow rate to be adjusted to obtain the desired hydraulic residence time.

Woodchip porosity φ

Porosity can vary between different types of woodchip used in bioreactors and will influence the rate of water movement through the woodchip. Woodchips used in Queensland bioreactor trials have had porosities between 0.5 and 0.75 (Manca et al. 2020a, Cheesman et al. 2020). An average φ of 0.6 $m^3 m^{-3}$ is assumed for the purpose of the guidelines. For a more accurate calculation of bioreactor volume, it is recommended that the porosity be monitored for the type of woodchip to be used.

Example

A bioreactor bed is planned to be installed downslope of a paddock where the average run-off flow rate was 3 $m^3 h^{-1}$.

Step 1. After the site assessment the targeted bioreactor flow rate is set to be 60% of the average run-off flow rate (using Table 3.2) which provides a Q_{target} of 1.8 $m^3 h^{-1}$.

Step 2. The average nitrate concentration in the water to be treated is expected to be 12 mg N L^{-1} and based on local water quality targets, the aim of the bioreactor is to reduce nitrate by 50% to 6 mg N L^{-1}.

Using Equation 7 and the generic nitrate concentration decline rate of 0.8 mg N L^{-1} hr^{-1} a tHRT of 7.5 hours is considered to be sufficient to remove nitrate without inducing limiting conditions with consequent pollution swapping (Fenton et al. 2014; Schipper et al. 2010).

$$tHRT = \frac{12 - 6\ (mg\ N\ L^{-1})}{0.8\ (mg\ N\ L^{-1}\ h^{-1})}$$

Step 3. If a maximum saturation of the bioreactor is assumed, V_{sat} will equal the bioreactor volume. Assuming a woodchip porosity φ of 0.6 $m^3\ m^{-3}$ the final volume of the bioreactor can be calculated using equation 8:

$$V_{sat} = \frac{7.5\ (h) *\ 1.8\ (m^3 h^{-1})}{0.6\ (m^3\ m^{-3})}$$

Consequently, the bioreactor saturated woodchip volume will be 22.5 m^3.

Step 4. Allowing for an additional 30% of woodchip to account for changes in the actual hydraulic residence time the final bioreactor woodchip volume will be 29.25m^3

Table 3.3 provides examples of bioreactor volumes based on different nitrate reduction and water flow targets.

Table 3.3 Examples of bioreactor volumes based on different target water flow and nitrate reduction targets.

Nitrate reduction required from inlet to outlet	Target hydraulic residence time (tHRT)*	Target Water Flow (Qtarget)	Porosity (φ)	Saturated woodchip volume (vsat)	Total bioreactor volume (30% larger)
mg L^{-1}	hours	$m^3 h^{-1}$	L L^{-1}	m^3	**m^3**
2	3	1	0.6	5	**6.5**
5	6.25	1	0.6	10.42	**13.5**
2	3	3	0.6	15	**19.5**
5	6.25	3	0.6	31.25	**40.63**
2	3	5	0.6	25	**32.5**
5	6.25	5	0.6	52.08	**67.71**
2	3	10	0.6	50	**65**
5	6.25	10	0.6	104.2	**135.45**

* a minimum 3 hour target hydraulic residence time is recommended.

3.3.3 Dimensions of a bioreactor bed

Bioreactor dimensions should have a length to width ratio of approximately 10:1 (Christianson et al. 2013b). Table 3.4 displays some practical sizes using the 10:1 length to width ratios based on common excavator bucket widths. Narrower bioreactor beds are not recommended as they might be more prone to clogging from sediment. Depths greater than 1 m require engineered bank reinforcement and can increase the cost of construction.

Table 3.4 Potential bioreactor bed dimensions.

Length (m)	Width (m)	Depth (m)	Volume (m^3)	Ratio
8	0.8	1	6.4	10:1
10	1	1	10	10:1
12	1.2	1	14.4	10:1
15	1.5	1	22.5	10:1
20	2	1	40	10:1
25	2.5	1	62.5	10:1
30	3	1	90	10:1
60	3	1	180	20:1

3.4 Construction and establishment

3.4.1 Construction sequence

The following sequence of steps to construct a bioreactor aim to accelerate the construction process and minimise the length of time heavy machinery (i.e. excavator and woodchip transport truck) are on site.

3.4.1.1 Mark, trench and line

- Mark out the dimensions of the bioreactor bed and confirm the dimensions, inflow and outflow points and design with the landowner.
- Excavate a trench long enough for the woodchip zone, inlet and outlet structures and sediment basin (if needed). The base of the bioreactor should be sloped (0.4-0.5%) to permit complete draining of the woodchip after a flow event. A laser level should be used to slope the base.
- Line the base and sides with heavy duty builder's plastic or geofabric (Figure 3.9). It is recommended to line all bioreactors to minimise the exchange of water and soil in the woodchip zone. Lining with plastic is essential for a research project.

Equipment and material checklist

Consumables:

- ☐ plastic liner
- ☐ woodchip
- ☐ rock and gravel
- ☐ PVC pipes
- ☐ valves
- ☐ gabion baskets (if using)
- ☐ star pickets (if required)
- ☐ tape/sealant

Equipment:

- ☐ laser level
- ☐ excavator
- ☐ drill

Figure 3.9 Bioreactor bed showing liner and gabion basket.

3.4.1.2 Monitoring equipment (where required)

- Install monitoring piezometers. Monitoring piezometers can be PVC pipes capped at the bottom and slotted to form a filtering section at the base. The filtering section should cover not more than ¾ of the bioreactor bed's depth, to avoid potential cross contamination from the surface. The filtering sections of the monitoring piezometers may be wrapped with geofabric, to avoid entry of particles into the piezometer. However, geofabric can clog if sediment transport occurs, and the passage of water could be significantly hindered and affect representative sampling. Slotted agricultural drainage pipe has also been used to cover the piezometers.
- The diameter of the piezometers should be 50- 100 mm to permit rapid water sampling, and to install monitoring devices such as temperature and pressure loggers.
- Piezometers should be installed prior the installation of woodchip and gravel and be equidistant. Star pickets can be used to support them vertically.
- Extra piezometers can be installed to monitor the woodchip degradability. Woodchip can be placed in mesh bags and pushed in the piezometer. The mesh bags will hold the woodchip in place to facilitate future sampling.

3.4.1.3 Inlet and outlet structures

- Install inlet and outlet structures. Rock-filled gabion baskets can be used at the inlet and outlet to provide lateral support for the woodchip. Gabion baskets (Figure 3.9) are off-the-shelf products that can be easily assembled on-site, filled with large rocks and consequently provide a high hydraulic conductivity. If gabion baskets are not used, rocks should be placed at the inlet.
- To complement the sediment basin and further reduce sediment ingress into the woodchip, as well as to provide a porous media for the ingress of the water, a gravel pit (Figure 3.10) should be installed adjacent to the inlet rock gabion basket. This should be filled with washed gravel to prevent fine sediments entering the woodchip and decreasing hydraulic conductivity or causing blockages. The washed gravel particle size should be at least 25 mm, but 40-60 mm is preferable, to permit enough porosity and a rapid flow of water into the bioreactor.

Figure 3.10 Gravel inlet pit (foreground).

- It is NOT recommended to use geofabric at the inlet as it can create blockages due to fine particles or algal growth effectively sealing the geofabric.
- The outlet should consist of horizontal PVC pipes placed at the base of the bioreactor to facilitate complete draining of the woodchip. The number and diameter of pipes depends on the targeted flow rate, based on the site investigation and design (sections 3.2 and 3.3) and calculating this may require a hydraulic engineer. At least two outlet pipes are recommended to minimise the risk of blockages (Figure 3.11). The pipes can either be connected perpendicularly to another PVC pipe, or be separate from each other. It is critical to drill a filtering section on the

PVC pipe laying in the woodchip to permit water outflow. The outlet pipes can be equipped with valves, to regulate flow and consequently hydraulic residence time. The use of geofabric for the outlet pipes is not recommended as it might block and impact outflow.

- The horizontal outlet pipes can be passed through the liner and the gabion baskets. For research projects, special attention must be focussed on the area where the perforated liner (to permit the passage of the pipes) overlaps the gabion basket, as this area should be completely waterproof. The use of sealant is strongly recommended to prevent leaks around the outlet pipe, which can confound monitoring results.

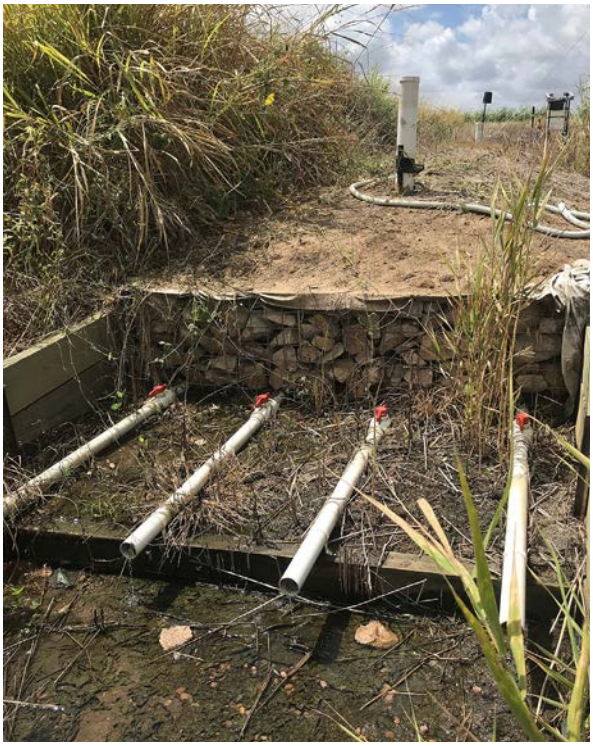


Figure 3.11 Outlet pipes.

3.4.1.4 Fill and seal

- Once the piezometers, inlet and outlet structures are installed, the woodchip can be placed in the trench between the inlet and outlet structures.
- The recommended carbon substrate is softwood woodchip, as it provides the same nitrate removal performance as a hardwood (Addy et al. 2016), but with lower impact on effluent water quality (dissolved organic carbon concentrations) and greenhouse gas emissions (Manca et al. 2020a). Consequently, the use of locally sourced soft woodchip is strongly encouraged. Although the particle size of the woodchip does not affect nitrate removal performance (Cameron and Schipper 2010) a 50% fraction of woodchip with a particle size >13 mm is recommended, as a smaller fraction can affect the hydraulic conductivity and be rapidly flushed or degraded (Christianson et al. 2010). For research projects it is recommended to sample some of the woodchip at the time of installation, to be tested for porosity and degradability.
- For research projects, the top of the bioreactor bed should be covered with the liner and sealed onto the existing liner to encase the woodchip.
- All bioreactors should be covered with at least 0.1 m of topsoil to minimize surface water flowing directly into the woodchip zone and to reduce nitrous oxide emissions (Christianson et al. 2013a).

3.4.1.5 Bypass and sediment basin

- A bypass is required to accommodate excess flow once the bioreactor is full of water. The bypass can run beside the bioreactor bed, or flow on top of the bioreactor. The location and geometry will depend on the design and site characteristics (3.3.1.4). Where flow velocities are high, the bypass should be lined with rock to prevent erosion.
- For in-line, or off-line bioreactor beds, a sediment basin(s) should be constructed upstream of the bioreactor bed inlet to trap coarse and medium sized sediments before they enter the bioreactor inlet, according to the size calculated during the design stage (section 3.3.1.5).

3.4.2 Establishment

Once constructed, denitrification should commence within days of nitrate entering the bioreactor. The microbes responsible for denitrification are naturally present in the environment therefore no 'seeding' of microbes is required. Some Queensland trial results indicate that when the bioreactor receives the first water after construction, or a prolonged dry period, it may take a few days to build the microbe population (Owen pers. comm).

Literature suggests it will take at least one hour of saturated conditions for dissolved oxygen levels to decrease sufficiently (i.e. <2 mg L^{-1}) for denitrification to occur (Robertson 2010). Once the woodchip is saturated and oxygen levels are depleted, denitrification should occur. Bioreactor performance is usually highest during the first year when the carbon is most readily available (Addy et al. 2016, Robertson 2010). Therefore, rates of nitrate removal during the first year might not be representative of the bioreactor's long-term performance.

3.5 Monitoring and analysis

3.5.1 Monitoring

The monitoring undertaken on a bioreactor bed (i.e. frequency and monitored parameters) (Table 3.5) will depend on the project objectives (section 2.1), i.e. whether it is a research project or for non-research purposes, and also the budget available. Some monitoring is recommended, even for non-research bioreactors, to check that the bioreactor bed is working to intercept water and reduce nitrate. The monitoring described in this section is for a bioreactor bed built on a farm to reduce nitrate for non-research purposes. A research project would likely have a larger budget for monitoring and water quality analyses and a more rigorous monitoring program, tailored to the research objectives. Refer to section 5.4 for information on more comprehensive monitoring for research projects aiming to quantity nitrate reduction performance of bioreactor beds.

Note the final monitoring program will be determined by specific project objectives and constraints including time, budget, resources and site access.

3.5.1.1 Monitoring non-research bioreactor bed

The available budget and the nitrate removal performance metrics required for the project (section 1.5.1) will influence the parameters to be assessed during monitoring and the sampling frequency.

If the budget for the monitoring is small and the project only requires information on nitrate removal efficiency, the following should be monitored:

- water quality (nitrate) of samples collected from the inlet/upstream and outlet/downstream of the bioreactor.

If the monitoring budget is larger, and the project requires information to calculate nitrate removal rate, the following should be monitored:

- water quality (nitrate) of samples from the inlet and outlet of the bioreactor
- water physical parameters (temperature, dissolved oxygen, and pH)
- water levels (from at least one piezometer installed in the centre of the bioreactor bed)
- flow rate.

Table 3.5 describes the method and frequency of sampling according to different budgets. Samples should be collected to coincide with rainfall or irrigation events and a range of possible influent nitrate concentrations, based on the specific conditions of the site.

Example 1 Irrigated crop

If the bioreactor bed is installed on a farm that is irrigated every three weeks, and each irrigation lasts for multiple days, an event-based approach can be used. The event-based approach consists of one sampling event for each irrigation. This would make it possible to assess the yearly removal performance of a bioreactor with around 34 samples, assuming three-weekly irrigation and two piezometers or sampling points (inlet and outlet).

Example 2 Rain-fed crop

If the bioreactor is installed on a farm that is rain-fed, samples can be collected monthly (if there is residual flow) or after significant rain events leading to surface run-off. In this case, it would be possible to assess the yearly removal performance of a bioreactor bed with around 24 samples, assuming two piezometers or sampling points.

If the budget is limited, the sampling regime can be further reduced to focus sampling on five rainfall or irrigation events following fertiliser application, plus a sampling event when there is less likelihood of nitrate losses. This will provide information on the range of likely influent nitrate concentrations and bioreactor performance under different conditions.

Table 3.5 Monitoring program for a bioreactor bed for non-research purposes

Budget	Measure	Purpose	Method	Frequency	Parameters quantified
Small budget	Water quality Nitrate	Determine the influent and effluent nitrate concentration	Water samples are collected either from the upslope and downslope drains or from the inlet and outlet pie-zometers	Event based: one sampling per irrigation event for irrigated farms. Monthly, or once during rain event for rain-fed farms. Or focus on five flow events following fertiliser application	Nitrate influent variability Nitrate removal efficiency
Larger budget	Water quality (nitrate) as described above PLUS				
	Water physical parameters Temperature Dissolved oxygen pH	Temperature, pH and dissolved oxygen are necessary to determine the suitability of internal conditions for denitrification	Water samples are collected from the inlet and outlet and analysed onsite using portable instruments	Event based: concurrently with sample collection outlined in row above	Nitrate influent variability Denitrification conditions Nitrate removal efficiency Nitrate removal rate
	Water level	Quantify woodchip saturation and hydraulic gradient	Measurements collected in each piezometer	Event based: concurrently with sample collection outlined in row 1	
	Flow rate	Determine the water flow rate at different water levels	Realisation of discharge rating curves that relate to the flow rate at the water level in the bioreactor bed at different water level stages (at least 3-4)	Event based: concurrently with sample collection outlined in row 1	

3.5.2 Nitrate removal calculation

The nitrate removal efficiency (NRE, %) of a bioreactor bed is calculated (according to Greenan et al. 2009) as:

$$NRE = \frac{[NO_{3in}^{-}] - [NO_{3out}^{-}]}{[NO_{3in}^{-}]} * 100 \qquad \text{(Equation 9)}$$

Where $NO_{3\text{-}in}$ and $NO_{3\text{-}out}$ [mg N L^{-1}] are the influent and effluent NO_{3}- concentrations, respectively.

The nitrate removal rate (NRR, g N m^{-3} d^{-1}) of a bioreactor bed is calculated like Warneke et al. (2011) as:

$$NRR = \frac{[NO_{3in}^{-}] - [NO_{3out}^{-}]}{V_{sat}} * Q \qquad \text{(Equation 10)}$$

Where $NO_{3\text{-}in}$ and $NO_{3\text{-}out}$ [g N m^{-3}] are the influent and effluent nitrate concentrations, respectively, Q (m^3 d^{-1}) is the flow rate measured at the outlet of the bioreactor bed, and V_{sat} (m^3) is the saturated woodchip volume.

3.6 Maintaining bioreactor performance

3.6.1 Maintenance

Maintenance of a bioreactor bed will involve:

- For in-line, or off-line bioreactor beds with sediment basins, regular sediment removal from the sediment basin will be required. The frequency will depend on the size of the basin and the amount of sediment entering the structure but will generally be biannually, or after flood events. Trash, leaves and grass may also accumulate in the sediment basin and should be removed to maintain capacity.
- Clearing the inlet structures biannually ,or after flood events. Anything growing in, or accumulating on the inlet, should be removed (e.g. grass, algae, leaves, sediment). For gravel inlets, if flooding of the inlet occurs, or if sediment accumulates in the inlet structure, the inlet may need to be cleaned out by removing and replacing gravel.
- Infrequent cleaning out of outlet structure (annually). The outlet structure should be monitored regularly to check for blockages and any blockages cleared. Grass, sediment build-up and debris should be kept clear of the outlets so that water can freely discharge from the bioreactor.
- Infrequent replacement of woodchips. The woodchips will gradually degrade over time and will need to be topped up, or replaced. The timing of replacement will depend on the material and environmental conditions such as temperature, wetting and drying regimes. Current information from Queensland trials suggests replacing woodchips after 10-12 years.

3.6.2 Limitations

Bioreactor beds will have limited capacity to cost-effectively remove nitrate in the following situations:

- If the catchment is dominated by erosive soils and/or there is a high risk of sediment movement.
- If there are steep sites (slope >20%).
- Areas with frequent, intense water flows (i.e. storms) as the bioreactor would be unlikely to treat a significant proportion of the run-off.
- If nitrate concentrations (in the water to be treated) are regularly below 3 mg N L^{-1}.
- If there are high groundwater levels, or sandy soils and the bioreactor is unlined, the water may disperse before it enters the bioreator and could not be treated.

3.6.3 Troubleshooting

Monitoring may identify operational and nitrate removal performance issues with denitrification beds. Table 3.6 can be used to identify possible issues and solutions.

Table 3.6 Possible issues with bioreactor beds and ways to solve them.

Issue	Likely causes	Investigation	Rectification
Not much water leaving bioreactor relative to flow upstream of bioreactor.	• Blockage either at the inlet, or the outlet, causing nearly all the water to flow around the bioreactor.	• Check for sediment, algae or debris in the inlet structure (e.g. inlet gravel or rock). • Check for any blockages in outlet pipe/s. • Pressure transducers installed in the monitoring piezometers may provide information about where the blockage occurred.	• Remove or replace inlet gravel, or rock. • Remove blockages at the outlet. • If the blockage occurs in the bioreactor, dig up and replace the woodchip.
Bioreactor not removing nitrate.	• Carbon source may be depleted. • Sampling regime may not be adequately capturing the same plug of water through the bioreactor due to variable influent nitrate. • Excessively fast hydraulic residence time. • The pH range and dissolved oxygen in the bioreactor might not be suitable for denitrification.	• Check carbon source has not degraded (look for subsidence or expose carbon source to check). • Monitor influent nitrate variability. • Perform tracing tests for hydraulic residence time. • Monitor pH and dissolved oxygen in the influent and effluent.	• Replace carbon source. • Design a monitoring regime to collect samples at the outlet with a delay that corresponds to the measured hydraulic residence time. • Identify if pH and dissolved oxygen are in the suitable ranges for denitrification. If not, amelioration may be required e.g. increase pH with the injection of an alkaline solution. • Increase hydraulic residence time by adjusting the outlet valves (if present) or install valves at the outlet.
Sediment trap is not working.	• Sediment trap is full, or not of sufficient capacity to remove sediment. • Sediment generation upstream is greater than expected.	• Check depth and capacity of sediment trap and the rate of sediment accumulation. • Check for source of sediment and identify what options are available to minimise sediment loss.	• Remove sediment, or enlarge sediment trap. • Implement sediment reduction practices upstream of bioreactor.
Rotten egg smell from bioreactor due to hydrogen sulphide production.	• Nitrate limited conditions. • Extended hydraulic residence time. • The bioreactor does not drain completely.	• Investigate whether nitrate limited conditions are due to nitrate influent variability or to extended hydraulic residence time. • Check for any blockages in the outlet of the bioreactor.	• Increase the outflow of the bioreactor to reduce the hydraulic residence time by opening any control valves. • Remove any blockages.
Ammonium concentrations increase within bioreactor.	• Likely occurrence of dissimilatory nitrate reduction to ammonium due to nitrate limited conditions and presence of high dissolved organic carbon.	• Monitor nitrate, ammonium and dissolved organic carbon in influent and effluent to identify if nitrate is limited and if ammonium concentrations are high.	• The risk of dissimilatory nitrate reduction to ammonium is low if sites are selected with consistent influent nitrate. If nitrate concentrations are seasonally low, flow can be directed around bioreactor during higher risk periods, if the generation of ammonium is a concern to downstream waterways.
Water discharging from bioreactor is tea coloured.	• Leaching of organic compounds (i.e. tannin) is generally harmless and occurs for a short time after bioreactor installation.	• Continue to monitor discharge over time and wait for the bioreactor to 'flush'. • Wash the woodchip before installation.	• If coloured discharge is a concern for the receiving environment, ensure there is a buffer between the bioreactor and any sensitive receiving environment.

PART 4:

Bioreactor Walls

Part 4: Bioreactor walls

4.1 Overview

In some parts of Queensland, intensive agricultural production systems occur on sandy soils with shallow groundwater. There is a risk of nitrate loss through the soil profile into the groundwater and subsequently into sensitive receiving waterbodies. Denitrifying walls can be used in these locations to intercept and treat shallow groundwater.

Compared to bioreactor beds, walls are relatively simple to construct, take up little space and have minimal maintenance requirements.

4.2 Site investigation

A detailed site investigation is required to determine the most appropriate site, design and size of a potential bioreactor wall. This site investigation follows the preliminary site identification (section 2.3) and follows four steps:

1. Engage landholder and inspect site.
2. Determine soil type and profile.
3. Determine groundwater level and flow.
4. Identify presence of nitrate.

4.2.1 Engage landholder and inspect site

A site inspection and discussion with the landholder, or land manager is essential to understand soil types, potential nitrate loss pathways from the production areas, site suitability and constraints. Obtaining this information from the landholder will minimise the amount of preliminary monitoring required, saving time and money. Landholder support and input from the beginning and throughout the bioreactor project is critical to success, as is ensuring all parties are clear about the objective of the bioreactor project. The landholder will likely have a preference for siting the bioreactor and therefore the design approach will need to balance nitrate removal performance with the area of available land.

The site inspection and discussion with landholder should aim to determine the:

- Location of potential bioreactor site relative to production areas or other potential sources of nitrate and the likelihood of nitrate leaching to shallow groundwater.
- Location of potential bioreactor site relative to drains or waterways.
- Soil types and areas of shallow groundwater.
- Machinery and vehicle access and use of the potential site (e.g. is access available and will the proposed bioreactor wall impact or be impacted by farm operations).
- Presence of any ag-pipes or other drainage infrastructure.

4.2.2 Determine soil type, profile and properties

The landholder may have soil maps of the farm to show the soil types and profile, or information on the potential presence and depth of a low permeability layer. It is also important to obtain information on soil properties such as hydraulic conductivity and drainable porosity. If information is not readily available soil sampling is recommended, as described in section 5.5.

4.2.3 Determine groundwater level and flow

Determining the groundwater level and flow is important to identify the most suitable location and orientation for an effective bioreactor wall, for the following reasons:

- Groundwater levels are necessary to identify the presence of shallow groundwater that a bioreactor wall could intercept. The range in groundwater levels is also important because this defines the groundwater seasonal variability in terms of maximum and minimum levels. The presence of shallow groundwater levels for most of the year will increase the effectiveness of a bioreactor wall and reduce the cost and complexity of construction, i.e. bioreactor walls installed at depths greater than two metres have additional construction challenges and costs (i.e. risk of trench collapse).

- Groundwater flow directions are important, so the bioreactor wall can be oriented perpendicular to the flow path to maximise the groundwater treatment, minimise impact on the groundwater flow pattern and minimise the likelihood of groundwater by passing the wall.

Groundwater information can be determined in multiple ways, depending on the project objective, budget and timeframes:

- At a catchment, or sub-catchment scale, using publicly available groundwater information.
- By installing piezometers to monitor groundwater level and flow at the site (section 5.5).
- The landholder may have information on groundwater levels at different times of the year and soil cores can be taken to investigate the presence of groundwater. Although relatively cheap and quick, this approach could result in a poorly performing bioreactor wall if it is not regularly receiving shallow groundwater, or if groundwater is bypassing the wall due to its orientation.
- Some bioreactor trials in Far North Queensland used electromagnetic soil mapping to help identify suitable locations for bioreactor walls, by identifying changes at depth. If electromagnetic soil mapping is an option, or if it has already been conducted at the site, it could provide useful information for siting a bioreactor wall.

4.2.4 Identify presence of nitrate

Understanding nitrate concentrations in the groundwater is important to identify the most cost-effective location for a bioreactor wall and to calculate the size of the wall (section 4.3.2). If the bioreactor is nitrate limited, defined as an effluent nitrogen concentration below 0.5 mg N L^{-1} (Addy et al. 2016), pollution swapping could occur (section 1.3.2), so the aim is to locate bioreactors where the nitrate concentrations are high enough to minimise the risk of nitrate limitation within the bioreactor. If nitrate concentrations are consistently low, other agronomic management practices or treatment system options may be a more cost-effective option than a bioreactor wall.

For the proposed bioreactor wall site, the aim is to understand:

- average or most likely nitrate concentrations (ideally greater than 5 mg N L^{-1} for most of the time)
- the highest likely nitrate concentration.

The landowner may have water quality monitoring results from the farm to indicate nitrate concentrations at the proposed bioreactor wall site. If water quality monitoring results are not available, preliminary water quality monitoring could be conducted (section 5.5). Note section 5.5 provides recommendations for monitoring to maximise the success of the bioreactor wall. The sampling intensity and duration recommended can be altered depending on the project objectives, budget and timeframe.

Why is the nitrate concentration important?

It is recommended to locate bioreactor walls where the influent nitrate concentration is at least 5 mg N L^{-1} most of the time, for the following reason.

For practical reasons, the width of a bioreactor wall should be the width of an excavator bucket. Using a narrow bucket (0.23 m) and relatively fast groundwater velocity of 1.1 m d^{-1} the hydraulic residence time would be five hours (as per equation 11 in 4.3.2).

With a nitrate concentration decline rate of 0.8 mg L^{-1} hr^{-1}, as observed in north Queensland trials (section 1.5.1), approximately 4 mg N L^{-1} would be removed over five hours.

To minimise the risk of nitrate limitation (below 0.5 mg N L^{-1}) and potential pollutant swapping, a minimum influent nitrate concentration of at least 5 mg N L^{-1} is recommended.

Checklist before proceeding to bioreactor wall design

- ☐ landholder has provided in-principle agreement to the bioreactor wall objective and site
- ☐ confirm presence of shallow groundwater for most of the year
- ☐ understand soil profile and preferably confirm location of low permeability layer
- ☐ know groundwater flow direction at bioreactor wall site
- ☐ know likely nitrate concentration at the site

4.3 Design

4.3.1 Design considerations

Before the installation, it is critical to determine the groundwater flow direction for the right orientation of the bioreactor wall. The bioreactor wall should be installed downslope of the crop, and perpendicular to the groundwater flow, to maximise the groundwater treatment and minimise the impact on the groundwater flow pattern and the likelihood of groundwater bypassing the bioreactor.

4.3.2 Sizing a bioreactor wall

In theory, the width of the bioreactor wall should be calculated to provide a hydraulic residence time of sufficient duration to reduce nitrate concentrations by a specified amount. However, in practice, the width of the bioreactor wall will be dictated by the possible widths of excavator buckets available, which in turn will influence the hydraulic residence time, as per Equation 11:

$$W_w = HRT * v \qquad \text{(Equation 11)}$$

Where Ww (m) is the wall width, HRT (d or hr) is the hydraulic residence time, and v (m d^{-1} or m hr^{-1}) is the groundwater velocity. The groundwater velocity can be calculated using Darcy's law (Darcy, 1856):

$$v = \frac{Ki}{\varphi_a} \qquad \text{(Equation 12)}$$

where v (m d^{-1}) is the groundwater velocity, K (m d^{-1}) is the hydraulic conductivity of the aquifer, i (m m^{-1}) is the hydraulic gradient (defined as a measure of the change in groundwater head over a given distance), and φ_a (m^3 m^{-3}) is the drainable porosity of the aquifer. This is calculated based on the information collected during the site investigation (section 4.2).

The required hydraulic residence time depends on the average nitrate concentration in the groundwater to be treated and can be estimated using a generic nitrate concentration decline rate of approximately 0.8 mg N L^{-1} hr^{-1} (Cheesman et al. 2020) as observed in North Queensland trials (section 1.5.1). See section 1.5.1 for more information and to determine if this generic nitrate concentration decline rate is suitable for the type of carbon substrate and field conditions (such as temperature) appropriate to the project site.

Once the suitable hydraulic residence time is identified it is possible to estimate the most suitable bioreactor width using Equation 11. Table 4.1 provides examples of bioreactor wall widths based on different nitrate reduction and groundwater velocity scenarios. It highlights that although the bioreactor widths can be calculated (using the above equations), in most cases standard excavator bucket widths will be sufficient to remove most, if not all, the nitrate in the groundwater.

The length of the bioreactor wall will be determined by the available funding, available land, area of upslope crop requiring treatment and extent of suitable site conditions (e.g. shallow groundwater).

Example

A bioreactor wall is proposed on a farm and the landholder has an excavator that can be equipped with buckets with different widths, which include 0.61 and 0.76 m. It would be installed downslope of a paddock where the average nitrate concentration in the groundwater is expected to be 12 mg N L^{-1}.

Using a nitrate concentration decline rate of 0.8 mg N L^{-1} hr^{-1}, a hydraulic residence time of 14 h (0.58 d) is considered to be sufficient to remove nitrate without inducing limiting conditions with consequent pollution swapping (Fenton et al. 2014, Schipper et al. 2010). During a preliminary study the average value of groundwater velocity was 1.1 m d^{-1}.

Using Equation 11 the bioreactor wall width (W_w) can be calculated as:

$$W_w = 0.58\ (d) * 1.1\ (m\ d^{-1})$$

Consequently, the final bioreactor wall width will be 0.64 m.

The more suitable digging bucket for the installation of the bioreactor wall will be the 0.61 m wide bucket.

Table 4.1 Examples of bioreactor wall widths under different nitrate reduction and groundwater velocity scenarios.

Average likely groundwater nitrate conc.	Nitrate reduction required	Hydraulic residence time (HRT)*	Average groundwater velocity	Bioreactor wall width
mg N L^{-1}	mg N L^{-1}	days	m d^{-1}	m
5	4	0.13	1.1	0.14
5	4	0.13	0.5	0.065
10	8	0.26	1.1	0.29
10	8	0.26	1.1	0.13
15	12	0.4	1.1	0.44
15	12	0.4	0.5	0.2

* Assuming a nitrate concentration decline rate of 0.8 mg N L^{-1} hr^{-1}

4.3.3 Design features

If a shallow, low permeability layer (aquitard/aquiclude) is present at the site, the base of the bioreactor wall needs to be set slightly within the low-permeability layer so that groundwater does not flow beneath the woodchip (Figure 4.1). The low-permeability layer must not be fully penetrated, otherwise the groundwater can bypass underneath the woodchip.

Bioreactor walls are often excavated in a rectangular cross-section (Figure 4.1). However, a V-shaped, trapezoidal or U-shaped cross-section (Figure 4.2) can be used if site conditions such as sandy, or saturated soils, or safety considerations, limit the ability to use vertical walls in the trench.

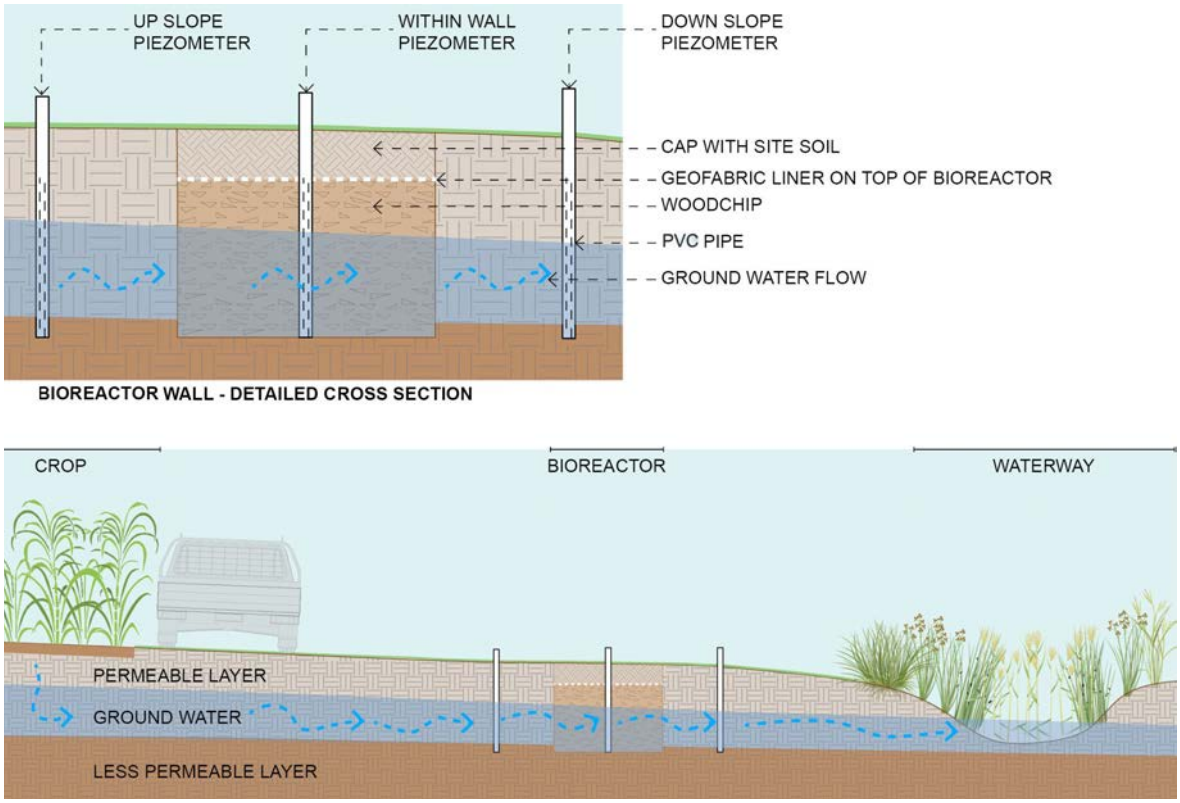


Figure 4.1 Design of a bioreactor wall showing base set slightly within the layer of low permeability and rectangular cross-section.

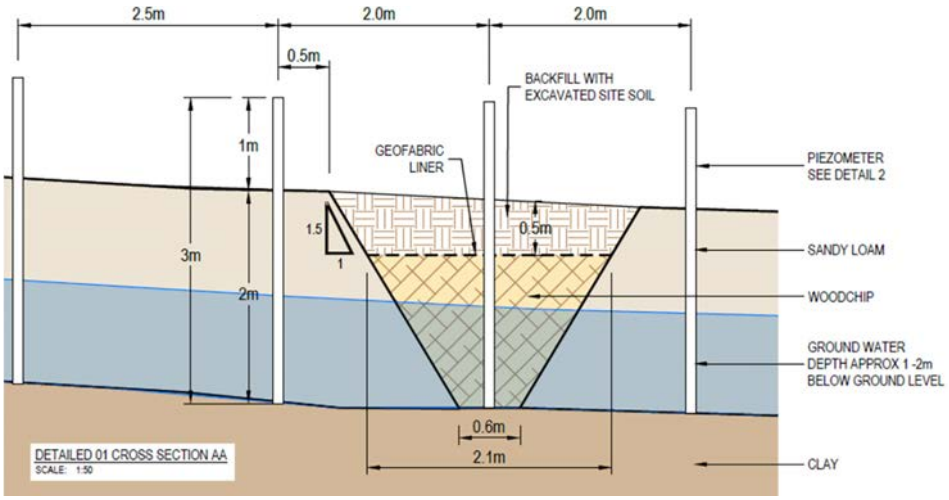


Figure 4.2 Cross-section plan of bioreactor wall designed in a V shape to accommodate site conditions (soft, sandy soil). Source: Wet Tropics Major Integrated project.

4.3.4 Monitoring equipment

The monitoring equipment required will depend on the objective of the project (section 2.1). It is designed to facilitate groundwater level measurement and sampling within the bioreactor wall and the surrounding aquifer, to quantify the saturation of the woodchip and aquifer as well as to assess the water quality.

If a bioreactor wall is installed on a farm for non-research purposes, it is recommended to install at least two piezometers, one upslope and one in the wall. Additional piezometers can be installed depending on budget and project objectives. The piezometers installed within the bioreactor wall should be in the centre of the wall and not too close to the bioreactor wall edges.

If the bioreactor is installed for research purposes, such as to quantify nitrate reduction performance, three transects of piezometers may be required (upslope, downslope and within the wall) with multiple (e.g. three or more) piezometers in each transect (Figure 4.3). Additional piezometers can be installed to monitor the woodchip degradation, or as injection wells to inject tracers (for a direct measurement of groundwater velocity), nitrogen (to evaluate the potential maximum nitrate removal) or other substances into the soil profile. The type of monitoring equipment and its layout will depend on the objective of the research project.

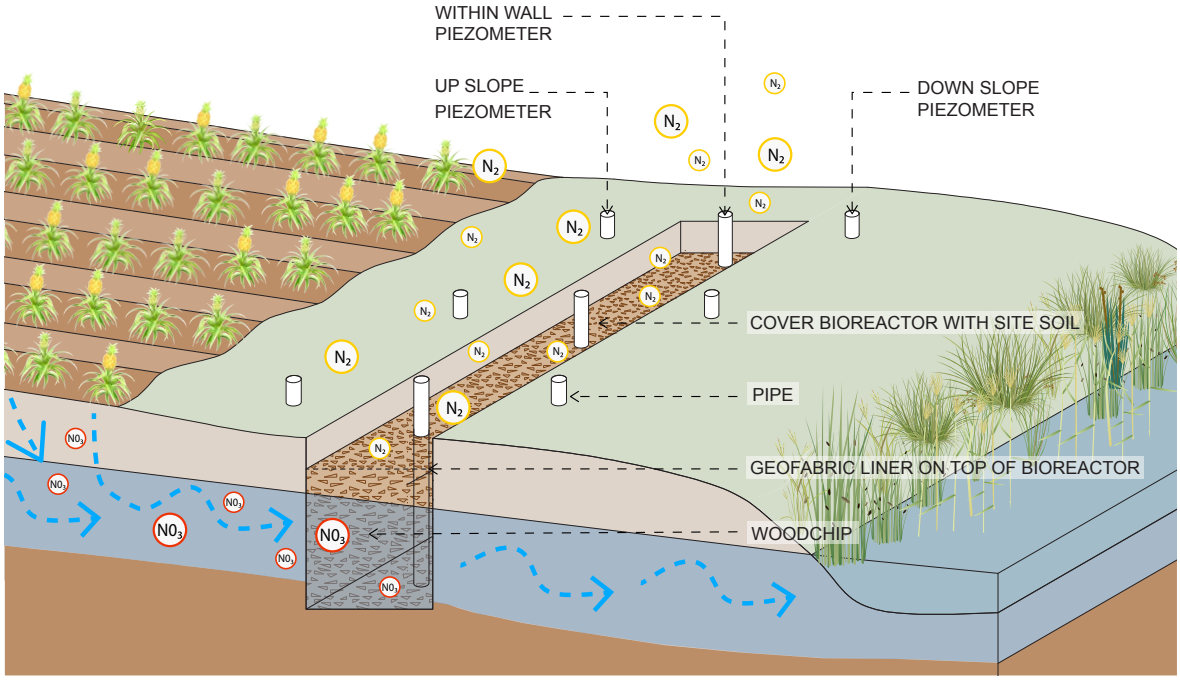


Figure 4.3 Potential monitoring equipment layout for a bioreactor wall for research purposes.

4.4 Construction and establishment

4.4.1 Construction sequence

4.4.1.1 Mark, trench and line

- The dimensions of the bioreactor wall should be marked on site and confirmed with the landowner before works commence.
- Excavate trench.
- Use a laser level to ensure that the floor of the bioreactor wall is level. This will help in avoiding preferential flow paths and/or ponding within the bioreactor.
- Stockpile topsoil for recapping.

4.4.1.2 Monitoring network

- Install piezometers (Figure 4.4). Monitoring piezometers can be PVC pipes capped at the bottom and slotted to form a filtering section at the base. The filtering section should cover not more than ¾ of the bioreactor wall's depth, to avoid potential cross contamination from the surface. The filtering sections of the monitoring piezometers may be wrapped with geofabric, to avoid entry of particles into the piezometer. However, geofabric can clog, and the passage of groundwater can be significantly hindered and affect representative sampling. Slotted agricultural drainage pipe has also been used to cover the piezometers.

Figure 4.4 Installing a bioreactor wall for a research trial with monitoring piezometers within the wall.

- Piezometers should be installed using a laser level, to make sure that their filtering section is at the same depth and to ensure that the water samples are representative of the same depth in the bioreactor wall and aquifer.
- Upslope and downslope piezometers can be installed (where required) in the aquifer using an automated, or hand auger. They should be surrounded by coarse sand, which increases hydraulic conductivity and facilitates groundwater transfer into the piezometers. Piezometers within the bioreactor wall should be installed before the woodchip is loaded and can be attached to star pickets to keep them vertical.

4.4.1.3 Fill and seal

- Once the piezometers are installed, the woodchip can be placed in the trench. A 50% fraction of woodchip with a particle size >13 mm is recommended, as a smaller fraction can affect the hydraulic conductivity and be rapidly flushed or degraded (Christianson et al. 2010). For research projects it is recommended to sample some of the woodchip at the time of installation, to be tested for porosity and degradability.
- Cover the woodchip with geofabric to prevent sedimentation and clogging of woodchip over time. This will also allow the woodchip to be exposed later in the project if desired. The use of geofabric is recommended because it also permits the quantification of subsidence after years of monitoring. The subsidence can be quantified using a soil corer, which will penetrate the soil cap, but not the geofabric. A plastic liner can be placed on the top of the wall if the project is for research purposes, to minimise the likelihood of cross-contamination from the surface during rain events. Alternatively, if the top of the bioreactor is not lined, a small piece of plastic lining could be placed around each piezometer directing surface water run-off away from the piezometer to avoid any surface water contamination of the piezometers.

- The liner should be covered by at least 0.2 m of topsoil, so that groundcover can establish on top of the bioreactor.
- Consider using a berm, or diversion bank in situations where a large volume of surface run-off flows across the site as this may damage the bioreactor through scouring and/or cause topsoil loss or deposition. This will also help prevent contamination of piezometers with surface waters.
- Establish grass, or low groundcovers, on the soil cap following construction. This will help in stabilising the site, reduce sediment loss and improve amenity for the landowner.
- Mark the area so it is easily located and heavy traffic over the area can be minimised.

4.4.2 Establishment

Once constructed, denitrification will commence within days of nitrate entering the bioreactor. Literature suggests it will take at least an hour of saturated conditions for dissolved oxygen levels to decrease sufficiently (i.e. <2 mg L^{-1}) for denitrification to occur (Robertson 2010). The actual time taken will depend on the oxygen concentration of the groundwater, as this can vary between sites. Once the woodchips are saturated and dissolved oxygen has reduced, denitrification should occur. Bioreactors often have increased performance during the first year when the carbon is most readily available (Addy et al. 2016, Robertson 2010).

4.5 Monitoring and analysis

4.5.1 Monitoring

The monitoring undertaken on a bioreactor wall (i.e. frequency and monitored parameters) (Table 4.2) will depend on the project objectives (section 2.1), i.e. whether it is a research project or for non-research purposes, and the budget available. Some monitoring is recommended, even for non-research bioreactors, to check that the bioreactor wall is working to intercept groundwater and reduce nitrate. The monitoring described in this section is for a bioreactor wall built on a farm for non-research purposes. A research project will likely have a larger budget for monitoring and water quality analyses and a more rigorous monitoring program, tailored to the research objectives. Refer to section 5.6 for information on more comprehensive monitoring for research projects aiming to quantity nitrate reduction performance of bioreactor walls.

4.5.1.1 Monitoring of a non-research bioreactor wall

The available budget and the nitrate removal performance metrics required for the project (section 1.5.1) will influence the parameters to be assessed during monitoring and the sampling frequency.

Note the final monitoring program will be determined by specific project objectives and constraints including time, budget, resources and site access.

If the budget for the monitoring is small and the project only requires information on nitrate removal efficiency, the following should be monitored:

- water quality (nitrate) of samples collected from the upslope and wall piezometers.

If the monitoring budget is larger and the project requires information to calculate nitrate removal rates, the following should be monitored:

- water quality (nitrate) of samples collected from the upslope and wall piezometers
- water physical parameters (temperature, dissolved oxygen, and pH)
- water levels in upslope and wall piezometers
- groundwater velocity.

Table 4.2 describes the method and frequency of sampling according to different budgets. Samples should be collected to coincide with rainfall, or irrigation events, and a range of possible influent nitrate concentrations, based on the specific conditions of the site.

Example 1 Irrigated crop

If the bioreactor wall is installed on a farm that is irrigated every 3 weeks, and each irrigation lasts for multiple days, an event-based approach can be used. The event-based approach consists of one sampling event for each irrigation, ideally at the last day of irrigation to increase the likelihood of a partially/fully saturated aquifer. This would make it possible to assess the yearly removal performance of a bioreactor wall with around 34 samples (assuming three-weekly irrigation and two piezometers).

Example 2 Rain-fed crop

If the bioreactor wall is installed on a farm that is rain-fed, samples can be collected monthly or after significant rain events (i.e. those that are likely to lead to leaching to groundwater). In this case, it would be possible to assess the yearly removal performance of a wall with 24 samples (if only two piezometers are sampled).

If the budget is limited, the sampling regime can be further reduced to focus sampling on five rainfall, or irrigation events, following fertiliser application, plus a sampling event when there is less likelihood of nitrate losses. This will provide information on the range of likely influent nitrate concentrations and bioreactor performance under different conditions.

Table 4.2 Monitoring program for bioreactor walls for non-research purposes with different budgets.

Budget	Measure	Purpose	Method	Frequency	Parameters quantified
Small budget	Water quality Nitrate	Determine the influent and effluent nitrate concentration and its variability over time	Water samples are collected from the piezometers	Event based: one sampling per irrigation event, for irrigated farms, at the last day of irrigation. Monthly, or once during rain event, for rain-fed farms.	Nitrate influent variability Nitrate removal efficiency
Larger budget	Water quality (nitrate) as described above PLUS				
	Water physical parameters Temperature Dissolved oxygen pH	Temperature, pH and dissolved oxygen are necessary to determine the suitability of internal conditions for denitrification	Water samples are collected from the monitoring piezometers and analysed onsite using portable instruments	Event based: concurrently with sample collection outlined in row above	Nitrate influent variability Denitrification conditions Nitrate removal efficiency Nitrate removal rate
	Water level	Quantify woodchip saturation and hydraulic gradient	Measurements collected in each piezometer	Event based: concurrently with sample collection outlined in row 1	
	Groundwater velocity	Quantify groundwater flow	Tracing tests	Once	

4.5.2 Nitrate removal calculation

The nitrate removal efficiency (NRE, %) for a bioreactor wall is calculated according to Greenan et al. (2009) as:

$$NRE = \frac{[NO_{3up}^{-}] - [NO_{3wall}^{-}]}{(NO_{3up}^{-})} * 100 \qquad \text{(Equation 13)}$$

Where NO_3-$_{up}$ and NO_3-$_{wall}$ [mg N L^{-1}] are the nitrate concentrations measured in the upslope and wall piezometers, respectively.

For a bioreactor wall the nitrate removal rate (NRR, g N m^{-3} d^{-1}) is calculated similar to Schipper and Vojvodić-Vuković (2000) as:

$$NRR = \frac{[[NO_{3in}^{-}] - [NO_{3wall}^{-}]] * v * A * \varphi_c}{V_{sat}} \qquad \text{(Equation 14)}$$

Where NO_3-$_{up}$ and NO_3-$_{wall}$ [g N m^{-3}] are the nitrate concentrations measured in the upslope and wall piezometers, respectively, v (m d^{-1}) is the groundwater velocity, A (m^2) is the saturated woodchip section transmitting groundwater, φ_c (m^3 m^{-3}) is the drainable porosity of the woodchip, and V_{sat} (m^3) is the saturated woodchip volume.

4.6 Maintaining bioreactor performance

4.6.1 Maintenance

Bioreactor walls require limited maintenance. The surface of the wall will need slashing and/or vegetation control like other access tracks, or headlands on a farm, and may need soil to be topped up if erosion, or subsidence occurs.

The carbon source will gradually degrade over time and subsidence may occur. The carbon source will eventually need to be replenished, or replaced. The timing of replacement will depend on the material and environmental conditions, such as temperature and wetting and drying regimes.

4.6.2 Limitations

Bioreactor walls will have limited capacity to cost-effectively remove pollutants in the following situations:

- Nitrate concentrations in the water to be treated are low (e.g. generally below 5 mg N L^{-1}). Bioreactors can be installed at sites with low nitrate concentrations for research purposes, however for cost-effective water quality improvement higher nitrate concentrations are recommended.
- Lack of, or minimal rain, for bioreactors downslope of rain-fed crop.

4.6.3 Troubleshooting

Monitoring may identify operational and nitrate removal performance issues with bioreactor walls. Table 4.3 can be used to identify possible issues and solutions.

Table 4.3 Possible issues with bioreactor walls and solutions.

Issue	Likely causes	Investigation	Rectification
Groundwater not flowing through bioreactor.	• The hydraulic conductivity of the wall is lower than the surrounding aquifer. This can occur if the woodchip is mixed with soil. • Groundwater bypassing the wall.	• Tracing tests. • Additional soil cores to establish groundwater flow pattern and if it is bypassing wall.	• Remove the mix of woodchip and soil and install only woodchip. • Ensure wall is installed into low permeability layer below.
Bioreactor not removing nitrate.	• Excessively fast hydraulic residence time. • The pH range and dissolved oxygen in the bioreactor might not be suitable for denitrification. • Nitrate below detectable limits.	• Monitor the influent nitrate variability. • Perform tracing tests. • Monitor nitrate, dissolved oxygen and pH in the upslope and in wall piezometers.	• Identify if pH and dissolved oxygen are in the suitable range for denitrification. If not, amelioration may be required.

PART 5:

Tools and further information

Part 5: Tools and further information

5.1 Glossary

Ag-pipe – agricultural pipe; perforated plastic pipe that is installed at depth to drain groundwater and lower the water table.

Anaerobic – absence of free oxygen.

Anoxic – environment that is greatly depleted in oxygen.

Aquiclude – a media characterized by a relatively low hydraulic conductivity able to limit groundwater flow (i.e. clay), that can underlie or overlie an aquifer.

Aquifer – a media that is characterized by a relatively high hydraulic conductivity able to permit groundwater flow (i.e. sand).

Aquitard – a media characterized by a relative hydraulic conductivity higher than an aquiclude, but lower than an aquifer able to permit a limited groundwater flow (i.e. silt).

Carbon source – in the case of denitrifying bioreactors, any high-carbon, low-nitrogen containing material (e.g. hard or soft woodchip).

Denitrification – the biological mediated conversion of nitrate to dinitrogen gas, via several intermediate nitrogen oxide products (nitrite, nitric oxide, and nitrous oxide).

Denitrifying bioreactor – an engineered structure to intercept water, which uses a carbon source (e.g. woodchip) and creates conditions with low, or no oxygen, to enhance the conversion of nitrate to dinitrogen gas via denitrification.

Denitrifying bioreactor bed – an engineered structure filled with a carbon source that can be installed within a drain or else installed to receive surface or sub-surface water from a drain or pipe.

Denitrifying bioreactor wall – a shallow trench perpendicular to the direction of groundwater flow filled with high-carbon substrate that intercepts shallow groundwater; often located adjacent to farm drains, stream networks, waterways etc.

Dissolved organic carbon – fraction of organic carbon able to pass through a filter with a pore size typically between 0.22 and 0.7 µm.

Groundwater – water contained in a saturated aquifer.

Inorganic nitrogen – nitrogen atoms that occur in inorganic compounds including nitrate, nitrite, and ammonium and dinitrogen gas.

Leachate – water passing through soil profile and in the process picking up pollutants, such as nitrate.

Organic nitrogen – nitrogen atoms that occur in organic compounds. These can take many forms including amino acids, nucleic acids, proteins and urea.

Piezometer – a small-diameter pipe used to measure the water level that is 'slotted' (has holes in it) at a particular depth.

Run-off – surface water flowing to a receiving water body, such as drain, waterway or wetland.

Tile drain – see ag-pipe.

Treatment systems – landscape features used to remove pollutants in surface water and groundwater.

Treatment train – a series of treatment systems combined with best management practices to remove pollutants from surface water or groundwater.

Treatment wetland – an engineered wetland system designed specifically to intercept and treat surface run-off, using natural wetland filtering and nutrient cycling processes to enhance pollutant removal.

Water table – the upper surface of the zone of saturation in an aquifer.

5.2 Preliminary monitoring for a bioreactor bed

A preliminary monitoring program to determine suitability for a bioreactor bed is outlined in Table 5.1. Note this program is designed to provide information to enable cost-effective bioreactor bed design. The final preliminary monitoring program will be dependent on project constraints (time, resources and budget).

Table 5.1 Preliminary monitoring program for identifying the most suitable site and design for a bioreactor bed.

Measure	Purpose	Method	Frequency
Slope	Determine if sufficient slope or head can be achieved.	Use of laser level to compare height at the proposed inlet vs outlet.	Once.
Water flow	Determine water flow for sizing the bioreactor bed.	Flume and pressure transducers installed in a drain located upslope of the location where the bioreactor is proposed. OR Container and timer method to assess flow from a pipe.	Monitor on 2-3 occasions during an average irrigation or rainfall event that will provide representative water flow information for the size of event the bioreactor is designed to intercept and treat.
Water quality, specifically nitrate, nitrite and ammonium	Determine the potential influent nitrogen and its variability over time, to design for the optimal hydraulic residence time.	Water samples are collected from the drain.	Monitor 2-3 irrigation and/or rainfall events following fertilising with one sample collected during each event. Monitor one event before or well after fertilising to understand variability.
Optional Water physical parameters: Temperature Dissolved oxygen pH Turbidity	Temperature, pH and dissolved oxygen are necessary to determine the suitability of environmental conditions for denitrification. Turbidity is necessary to determine potential sediment transport.	Water samples are collected from the drain and analysed on-site using portable instruments.	Monitor 1-2 times when irrigation and/or rainfall events are being monitored to determine water quality (above), ideally following fertilising (if feasible).

5.3 Measuring water flow

Three methods for determining water flow in the field are outlined in this section, although this doesn't preclude the use of other methods:

- container and timer method for flow from a pipe
- flume method for measuring flow in a smaller drain
- manning equation for estimating flow in a larger drain.

5.3.1 Container and timer method

The container and timer method (Figure 5.1) enables accurate measurement of water volume by filling a graduated container within a certain time frame. It is particularly suited to smaller flows, and flow in pipes.

The following process can be used to determine flow (L s^{-1}).

- Start filling the container and begin the timer at the same time. When the vessel has filled, stop the timer.
- Divide the litres in bucket by the time taken to fill bucket (in seconds). Repeat this process three times for more accurate estimation of the flow and take an average across all the recorded values.

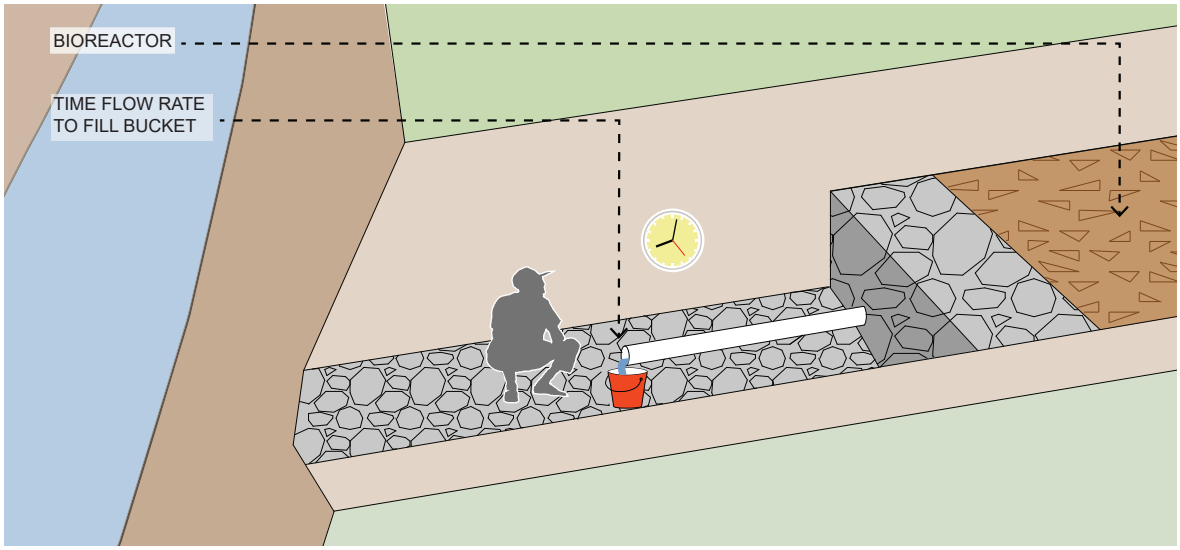


Figure 5.1 Container and timer method for calculating water flow from a pipe.

5.3.2 Flume

The flume method relies on a specific engineered flume installed within a drain. It is suited to smaller drains where the flume can be easily installed. Water flow is determined by measuring the water level at a single defined point in the flume and translating the level measurement into flow using a specific equation (dependent on the type of flume used).

5.3.3 Manning equation

The Manning equation can be used to estimate flow where other methods are not suitable. It requires uniform flow, so the section of drain to be assessed must have a constant bottom slope, constant hydraulic radius (i.e. channel size and shape) and constant surface roughness. Professional engineering advice is recommended.

5.4 Monitoring bioreactor bed for research purposes

This section provides a recommended monitoring program for a research trial in Queensland aimed at quantifying the nitrate reduction performance of a bioreactor bed. All bioreactor bed trials with this objective in Queensland are recommended to follow this monitoring program, for consistency and to enable comparison with existing bioreactor trials. This will further build knowledge of the suitability and performance of bioreactor beds in different agricultural production systems and locations in Queensland.

This monitoring program aims to assess if the bioreactor bed developed suitable conditions for denitrification and to quantify its nitrate removal and water treatment performance. It involves monitoring:

- water quality parameters (dissolved inorganic nitrogen, dissolved organic carbon)
- water physical parameters (temperature, dissolved oxygen and pH)
- water flow rate
- water depth/woodchip saturation
- hydraulic residence time
- potential woodchip degradation.

The monitoring methods and frequency are detailed in table 5.2. For example, if the bioreactor is installed on a farm that is irrigated every 2-3 weeks and each irrigation lasts for multiple days, a high frequency monitoring should be performed, collecting samples multiple times a day, each day. Alternatively, if the bioreactor bed is installed on a farm that is mostly rain-fed, multiple samples should be collected over the hydrograph throughout each rain event. This monitoring approach will quantify the nitrate influent variability, suitability of denitrification conditions, nitrate removal efficiency, nitrate removal rate, nitrate load reduction and hydraulic residence time.

When monitoring a denitrification bed, it is critical that the water sampling in the piezometers is undertaken starting from the outlet (usually characterized by lower nitrate concentrations) towards the inlet, to minimise cross contamination. High frequency monitoring (multiple times a day) is recommended for the five irrigation or rainfall events after nitrogen fertiliser application. An accurate estimate of the woodchip saturation can be measured by installing pressure transducers in all the piezometers.

Quantifying water flow rate (and consequently its volume) can be achieved using flumes. The flow rate can be measured at the outlet of the bioreactor bed as described in Section 5.3.

Bioreactor trials in Queensland have only been monitored for a short-term, negating the ability to quantify their long-term nitrate removal performance, longevity and maintenance requirements. For this reason, it is recommended to monitor the denitrification beds for at least five years and investigate the degradability of the woodchip installed in the bioreactors.

Table 5.2 Monitoring program for research projects aimed at quantifying the nitrate reduction performance of a bioreactor bed

Measure	Purpose	Method	Frequency	Parameters quantified
Rainfall	Determine the rainfall pattern and magnitude.	Installation of a rain gauge.	High frequency: hourly	Rainfall pattern Nitrate influent variability Denitrification conditions Nitrate removal efficiency Nitrate removal rate Nitrate load reduction Hydraulic residence time
Surface run-off volume	Determine the volume of run-off for the calculation of the water treatment capacity.	Flume and pressure transducers installed in a drain located upslope of the location where the bioreactor is installed.	High frequency: hourly monitoring during each irrigation and rainfall event.	
Water quality: Nitrate, nitrite and ammonium Dissolved organic carbon	Determine the influent nitrate and its variability over time to calculate the removal rate.	Water samples are collected from the piezometers.	High frequency: multiple times during each irrigation, and rainfall event with increased frequency following nitrogen fertiliser application.	
Water physical parameters: Temperature Dissolved oxygen pH	Temperature, pH and dissolved oxygen are necessary to determine the suitability of the internal conditions for denitrification.	Water samples are collected from the monitoring piezometers and analysed on-site using portable instruments.	High frequency: concurrently with sample collection outlined in row above.	
Woodchip saturation	Determine the saturated volume of the woodchip.	Water level measurements using a dipmeter, tape measure or pressure transducers.	High frequency: water level measurements are performed at each water sampling event. High frequency: hourly monitoring using pressure transducers.	
Hydraulic residence time	Determine the length of time water is in the bioreactor bed.	Bromide, saline or thermal tracing tests	Every 6 months	
Flow rate	Determine the flow rate.	Flume or Installation of a pressure transducer in the outlet piezometer and collect volumetric flow measurements at the outlet, at various woodchip saturation stages (at least four). A volumetric method (container and timer method as per section 5.3) can be used to determine flow. Discharge rating curves can then be produced with the coupled values of pressure and flow rate.	High frequency: hourly monitoring using flumes or pressure transducers. Discharge rating curves developed every 6 months.	
Rate of woodchip degradation (optional)	Determine potential longevity of the bioreactor	Remove some of the woodchips from the dedicated woodchip sampling piezometers (if used) and analyse for degradation.	Annually	Potential longevity

5.5 Preliminary monitoring for bioreactor walls

5.5.1 Soil sampling

Soil sampling should be performed in the area where the bioreactor wall is planned, to determine:

- soil type
- soil profile, to identify potential presence and depth of a low permeability layer (i.e. aquitard/aquiclude)
- soil properties, i.e. hydraulic conductivity and porosity.

The number of soil samples will depend on the proposed length of the wall, with at least two soil cores collected at each end and the central part of the future bioreactor wall. More samples should be collected for very long walls (e.g. aim for one sample for every 10 m of proposed wall). Soil samples should be collected to at least at the design depth of the bioreactor, to assess potential vertical variability in the soil profile. A soil coring rig, or small excavator, can be used to dig a small, excavated pit to conduct this assessment.

If possible, the hydraulic conductivity and porosity of the soil profile should be assessed to quantify the groundwater velocity to help size the bioreactor according to a designated hydraulic residence time (section 4.3.2).

5.5.2 Groundwater monitoring

Groundwater monitoring is desirable to assess the occurrence and duration of groundwater flow, groundwater level and nitrate concentrations over time. The occurrence of groundwater is related to the rainfall pattern and magnitude. Information on rainfall can be readily sourced from:

- SILO www.longpaddock.qld.gov.au/silo/
- Bureau of Meteorology www.bom.gov.au
- landholder records.

Irrigation frequency and magnitude can also influence groundwater and this information should be available from the landholder.

The preliminary groundwater monitoring (Table 5.3) should be performed by collecting water samples from monitoring piezometers (e.g. 50 mm PVC pipe installed where the soil samples were collected) as long as necessary in order to have confidence in the groundwater conditions, or as the budget allows. The number of piezometers can vary, depending on the size of the area of interest and the project budget. However, it is recommended to install at least four piezometers oriented perpendicular to the assumed groundwater flow direction. Water samples should at least assess groundwater levels, nitrate concentration, ammonium, pH, temperature and dissolved oxygen to help identify the potential occurrence of denitrification and presence of nitrate.

After the installation of the piezometers, a survey using a laser level is required to measure the altitude of the top of the casing of each piezometer. This is necessary for groundwater level data analysis (i.e. to develop contour line maps, ideally for both the wet and the dry season to show variability in groundwater levels). The groundwater flow direction can be assumed based on a slope. However, it is recommended to involve a hydrogeologist in the design of the monitoring network and for the groundwater flow direction assessment. The groundwater flow direction should be determined using groundwater contour line maps, using the groundwater levels measured during the preliminary monitoring.

The preliminary groundwater monitoring should be timed to follow significant rainfall or irrigation events. Rainfall and irrigation are considered significant when they are large enough for water to leach through into groundwater and generate groundwater flow.

Guidelines for water monitoring can be found in the Queensland Government Monitoring and Sampling Manual (State of Queensland 2018) www.environment.des.qld.gov.au/management/water/quality-guidelines/sampling-manual.

Table 5.3 Preliminary monitoring program for identifying the most suitable site for a bioreactor wall.

Measure	Purpose	Method	Frequency	Parameters quantified
Soil profile assessment	Determine whether the soil profile is suitable for installing a bioreactor, and the potential presence of a low permeability layer. Measurement of the hydraulic conductivity and porosity of the soil samples.	Soil corer/soil rig	On one occasion	Aquifer properties Groundwater flow direction Nitrate influent variability Denitrification conditions
Installation of piezometers	The installation of piezometers (at least 4) is recommended to monitor the occurrence of groundwater in response to rainfall and irrigation, as well as its quality and level fluctuation over time.	Installation of piezometers wrapped in geofabric in the location where the soil cores are extracted	On one occasion	
Survey with laser level	Determine the altitude of the top of the casing of the monitoring piezometers to develop water table contour maps.	Use of laser level/survey equipment	On one occasion	
Groundwater level	Measure the groundwater level from the top of the casing of the piezometers.	Use of dipmeter and pressure transducers	The groundwater level measurement in all the piezometers should be performed after each irrigation, and rainfall event as budget allows. Pressure transducers can be installed in some of the piezometers to monitor the groundwater level.	
Groundwater quality: Nitrate, nitrite, and ammonium	Determine the potential influent nitrate and its variability over time, to estimate the optimal hydraulic residence time and consequently to estimate the width of the wall.	Water samples are collected from all the piezometers.	Each irrigation, and rainfall event as budget allows, with increased frequency following fertilising.	
Groundwater physical parameters: Temperature Dissolved oxygen pH	Determine the suitability of environmental conditions for denitrification.	Water samples are collected from all the piezometers and analysed on-site using portable instruments.	Each irrigation, and rainfall event with increased frequency following fertilising, or as budget allows.	

5.6 Monitoring a bioreactor wall for research purposes

This section provides a recommended monitoring program for a research trial in Queensland aimed at quantifying the nitrate reduction performance of a bioreactor wall. All bioreactor wall trials with this objective in Queensland are recommended to follow this monitoring program, for consistency and to enable comparison with existing bioreactor trials. This will further build knowledge of the suitability and performance of bioreactor walls in different agricultural production systems and locations in Queensland.

This monitoring program aims to assess if the bioreactor wall developed suitable conditions for denitrification and to quantify its nitrate removal and water treatment performance. It involves monitoring:

- water quality (nitrate, nitrite, ammonium and dissolved organic carbon)
- water physical parameters (temperature, dissolved oxygen, and pH)
- woodchip saturation
- hydraulic residence time
- potential woodchip degradation.

Monitoring methods and frequency are detailed in table 5.4.

For example, if the bioreactor wall is installed on a farm that is irrigated every 2-3 weeks, and each irrigation lasts for multiple days, a high frequency monitoring program should be performed, collecting samples after each significant irrigation on a weekly basis. Alternatively, if the bioreactor wall is installed on a farm that is mostly rain-fed, samples should be collected following each significant rain event on a weekly basis. This monitoring approach will quantify the nitrate influent variability, suitability of denitrification conditions, nitrate removal efficiency, nitrate removal rate and hydraulic residence time.

Table 5.4 Monitoring program for research projects aimed at quantifying the nitrate reduction performance of a bioreactor wall.

Measure	Purpose	Method	Frequency	Parameters quantified
Rainfall	Determine the rainfall pattern and magnitude	Installation of a rain gauge	High frequency: hourly	Rainfall pattern Groundwater flow direction Nitrate influent variability Denitrification conditions Nitrate removal efficiency Nitrate removal rate Nitrate load reduction Hydraulic residence time
Groundwater level	Measure the groundwater level from the top of the case of the piezometers	Use of dipmeter and pressure transducers	High frequency: The groundwater level measurement in all the piezometers should be performed after each irrigation, and rainfall event on a weekly basis. Pressure transducers can be installed in some of the piezometers to monitor the groundwater level more often.	
Water quality: Nitrate, nitrite and ammonium Dissolved Organic carbon	Determine the influent nitrate and its variability over time to calculate the removal rate	Water samples are collected from the piezometers.	High frequency: Each irrigation, and rainfall	
Water physical parameters: Temperature Dissolved oxygen pH	Temperature, pH and dissolved oxygen are necessary to determine the suitability of the internal conditions for denitrification.	Water samples are collected from the monitoring piezometers and analysed on-site using portable instruments	High frequency: concurrently with sample collection outlined above	
Woodchip saturation	Determine the saturated volume of the woodchip	Water level measurements using a dipmeter or tape measure. Pressure transducers	High frequency: water level measurements are performed at each water sampling event. High frequency: hourly monitoring using pressure transducers.	
Rate of woodchip degradation (optional)	Determine potential longevity of the bioreactor	Remove some of the woodchips from the dedicated woodchip sampling piezometers (if used) and analyse for degradation.	Annually	

5.7 Further Information

Treatment system on-line toolkit

www.wetlandinfo.des.qld.gov.au/wetlands/

Factsheets

Bioreactor Factsheet

Nitrous oxide emissions from bioreactors, crops and waterways factsheet

5.8 References

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PART 6:

Case studies

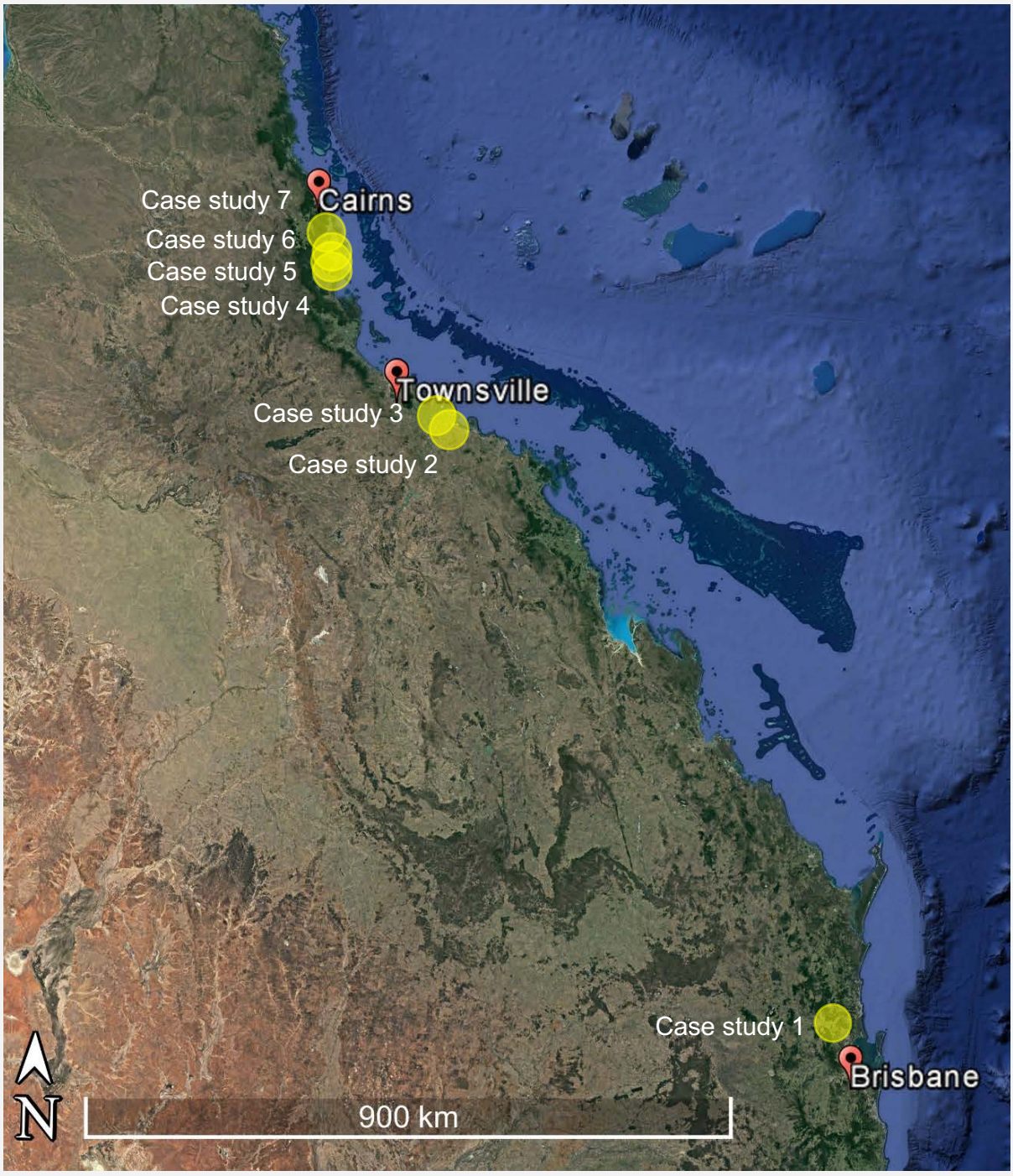

Figure 6.1 Locations of Queensland bioreactors featured in the case studies. Background image source: Google, n.d.

Case study 1: Bioreactor wall South-East Queensland

Project leader and partnerships	Department of Agriculture and Fisheries collaborating with Queensland University of Technology
Funding source	Department of Environment and Science (Resilient Rivers Initiative)
Project length	Two years (June 2017 – June 2019) of intensive monitoring completed Opportunity for continuation of monitoring
Region	South East Queensland (Glass House Mountains)
Production system	Pineapples
Date of installation	14th June 2017
Length of installation	Three working days for installation (two weeks including design and site selection)
Bioreactor type	Wall bioreactors (one softwood, one hardwood)
Project objective	Research trial to quantify nitrate removal performance.

Summary of the landscape

The two bioreactor walls were located downslope of a pineapple production system. They were located perpendicular to the slope and parallel to the adjoining waterway, with the intent of intercepting shallow groundwater and any nitrate leaching through the soil profile from the pineapple crop. One wall was filled with softwood chips and the other hardwood chips. The soil at the bioreactor site is a free draining kurosol and overlies a clay layer.

Average rainfall and temperature

The area has a humid subtropical environment with average daily temperatures ranging from 14.0°C to 25.8°C. During the monitoring period mean annual rainfall was approximately 800 mm per year.

Sizing and volume capacity

The walls were approximately 20 m long, 1 m deep, and 1.4 m wide. The final volume of the softwood and hardwood walls was 27.9 and 26.2 m^3 respectively.

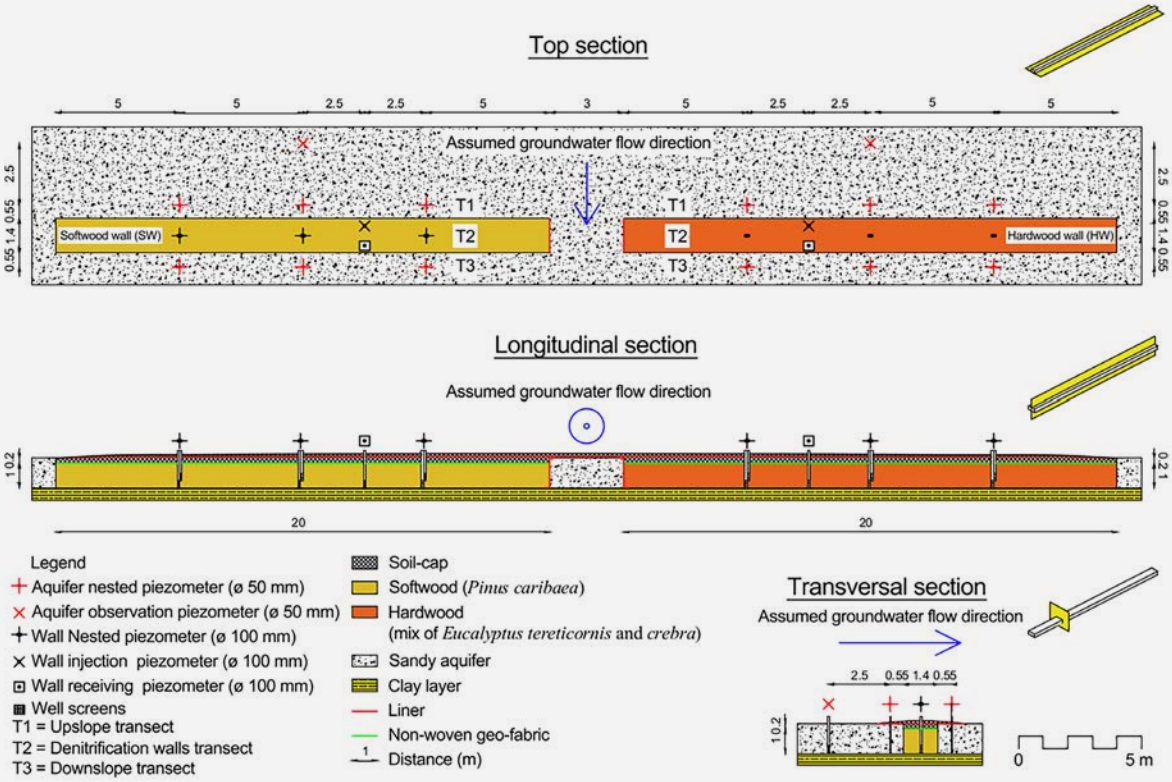

Figure 1 Design of the bioreactor walls showing transects. Source: QUT

Design features

Each bioreactor (Figure 1) is rectangular in cross-section and featured three transects of nested piezometers parallel to the wall, located up-gradient (T1), within (T2) and down-gradient (T3) of the wall. There are nested piezometers to intercept two regions of the aquifer and the bioreactors, set at 0.0-0.3 m and 0.3-0.6 above the clay layer.

Water source

The bioreactor receives shallow groundwater recharged by rainfall. The groundwater only flows intermittently during the year, with the majority of flow during the wetter summer months (November – April). The direction of shallow groundwater flow was at a 30-45° angle to the bioreactors.

Construction methods and materials

The bioreactor walls were constructed by digging two trenches perpendicular to the assumed groundwater flow direction (Figure 2). The bioreactor depth was determined by the underlying shallow clay layer and the width was determined by the excavator bucket dimensions. A three-metre gap was left between the two trenches and black plastic was placed on the sides of the soil bank to prevent water flowing between the two walls.

Figure 2 Construction of bioreactor walls.

PVC piezometers for water sampling were installed above, in the centre and below the trench at intervals along their lengths (Figure 3). The piezometers were prepared by drilling 5 mm perforations around the base of the pipe for a 0.5 m length to allow for water sampling. Piezometers were wrapped in a 2 mm geo-fabric, to avoid fine particles entering the piezometers. Three 100 mm PVC piezometers were installed and mesh bags filled with woodchips were placed in the piezometers to enable woodchips to be collected and analysed for degradation.

The bioreactors were filled with approximately 20 mm woodchips. The softwood used was *Pinus caribaea* and the hardwood was a mix of *Eucalyptus tereticornis* and *Eucalyptus crebra*. Geofabric was placed on top of the woodchips and both systems were covered with a 20 cm deep soil cap. A heavy-duty plastic liner was placed on top of the soil cap to prevent contamination of the walls with rain and surface run-off.

Manual gas sampling chambers were installed upslope, on top, and downslope of the bioreactors (six per bioreactor). Additional piezometers were installed up slope of each bioreactor, to extend the groundwater monitoring network.

Figure 3 Location of wall downslope of pineapple crop, showing layout of monitoring piezometers (green buckets).

Costs

The bioreactor walls cost approximately $50 m^{-3} based on machinery (hire, driver), woodchip (including delivery) and grass seeding.

Performance

100% removal efficiency in both bioreactor walls, likely due to nitrate limited conditions.

Softwood wall: 0.0-5.0 g N m^{-3} d^{-1} with an average of 2.0 g N m^{-3} d^{-1}.

Hardwood wall: 0.0-5.7 g N m^{-3} d^{-1} with an average of 1.6 g N m^{-3} d^{-1}.

Monitoring regime (intensity and frequency)

The bioreactor walls were monitored once a week (when saturated) for a period of 24 months. The following water quality parameters were analysed: nitrate, ammonium, dissolved organic carbon, dissolved oxygen, pH and temperature.

Water samples for dissolved greenhouse gas analysis were collected weekly for 18 months (nitrous oxide, carbon dioxide and methane).

Gas samples for greenhouse gas surface emissions (nitrous oxide, carbon dioxide, and methane) were monitored for a period of four months.

Saline tests were completed once the system was fully saturated.

Troubleshooting

The bioreactor was installed at a 30-45° angle to the direction of shallow groundwater flow which created bypass flow.

What would you do differently?

Pre-determine the hydrogeology of the landscape to determine the best location and design for the bioreactors.

For more information:

Manca, F., De Rosa, D., Reading, L. P., Rowlings, D. W., Scheer, C., Layden, I., Irvine-Brown, S., Schipper, L. A., and Grace, P. R. (2020). Nitrate removal and greenhouse gas production of woodchip denitrification walls under a humid subtropical climate. *Ecological Engineering* **156**, 1-10

Case study 2: Off-line bioreactor bed Lower Burdekin

Project leader and partnerships	Department of Agriculture and Fisheries collaborating with Queensland University of Technology
Funding source	Department of Environment and Science (Queensland Government Reef Water Quality Program)
Project length	One year (May 2019 – April 2020) of high-frequency monitoring completed.
Region	Burdekin (Ayr)
Production system	Sugarcane
Date of installation	May 2019
Length of installation	Five working days for installation (two weeks including design and site selection)
Bioreactor type	Modified off-line bed systems receiving water via large drainage pipe
Project objective	Research trial to quantify nitrate removal performance.

Summary of the landscape

The modified off-line bed style bioreactor received run-off from 25.7 ha sugar cane paddock divided in two irrigation sets. At the time of monitoring the upslope blocks consisted of 11 ha of plant cane and 14.7 ha of ratoon cane. The soil at the bioreactor site is a vertosol. The site slopes from the cane block to a low-lying ponded area, eventually leading to a drain/modified waterway. The site of the bioreactor is subject to flooding during large rainfall events due to the proximity to a large channel.

Average rainfall and temperature

The area can be classified as tropical savannah with maximum and minimum average annual temperatures of 29.4 °C and 18.7 °C, respectively, during 2010 to 2017. The mean annual rainfall during the same period was 834 mm.

Sizing and volume capacity

26 m long, 0.7 m deep, and 2.0 m wide. Approximately 37 m^3 (softwood woodchip).

Design features

The bioreactor (Figure 1) features a 600 mm 'T' pipe junction that diverts water into the bioreactor through a gravel inlet. Once the bioreactor has reached capacity excess water bypasses the bioreactor, via the pipe and inlet overflow, and flows into the low lying non-production area. The bioreactor has piezometers at inlet, outlet and within woodchips and woodchip analysis piezometers. The outlet consisted of a quad 50mm PVC outlet pipe, 1.5 m long that drains from the lowest point of the bioreactor.

Water source

The bioreactor received predominantly flood furrow irrigation run-off that is sourced from three bores combined with channel water (when required). The irrigation water is pumped and applied to the paddock through gated pipes located at the top of the field. Irrigation water flows down furrows between the cane rows. When irrigation run-off reaches the bottom of the furrows it enters a collection drain and is diverted under the road to the bioreactor. The bioreactor also receives run-off from rainfall events with larger volumes predominantly in the wet season (November – April).

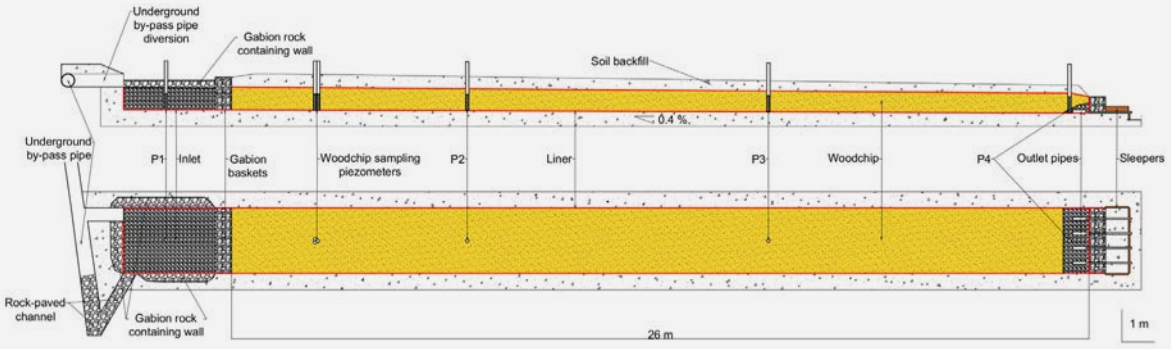

Figure 1 Design of the bioreactor bed in cross section (top) and plan (below) view, showing key design features. Source: QUT

Construction methods and materials

A 30 m long trench was excavated on a soil platform to permit the installation of the bioreactor bed and associated inlet structure. The trench on the soil platform was excavated at a shallow depth ranging from 0.7 m (near the inlet) and 0.4 m (near the outlet) to minimise the risk of outlet flooding.

A laser level was used to ensure that the trench bottom had a 0.4% slope (0.1 m height difference over 26 m between the inlet and outlet). Heavy-duty plastic liner was laid in the trench to create a waterproof seal to prevent ingress of surface and sub-surface water into the woodchip section of the bioreactor.

Four 100 mm (diameter) PVC piezometers were installed in the centre of the bioreactor at intervals along the length of the bioreactor. The first piezometer was positioned at the inlet (P1) to facilitate sampling of water entering the bioreactor and the fourth piezometer was at the outlet (P4) for monitoring water leaving the bioreactor. The piezometers were prepared by drilling 5 mm perforations around the base of the pipe for a 0.5 m length to allow for water flow. Piezometers were wrapped in a 2 mm geo-fabric, to avoid fine particles clogging the piezometers.

Figure 2 Bioreactor looking from the inlet toward the outlet, showing the rock gabion separating the inlet from the woodchip.

Figure 3 Completed bioreactor showing inlet structure with pipe from upslope cane block directing water into the inlet pit filled with washed river gravel (left). Excess flow bypasses the structure to a low-lying area on the right.

The inlet structure consisted of a trench filled with washed river gravel (diameter = 25 mm), with two stacked gabion baskets (2.0 m long, 0.5 m deep, and 0.5 m wide) filled with gabion rocks (diameter ≥75 mm) with a total volume of approximately 4.6 m^3 (Figure 2). A 600 mm underground pipe directed the water from the sugar cane block into the inlet of the bioreactor (Figure 3). A T-junction in the pipe enables excess run-off to bypass the bioreactor and discharge directly into the low-lying area through a rock-paved channel to minimise erosion.

The outlet of the bioreactor was constructed using four separate drilled 100 mm PVC pipes wrapped in geo-fabric connected with reduction sockets to four 50 mm PVC pipes, equipped with valves to regulate the outflow if necessary (Figure 4). The 50 mm PVC pipes passed through a gabion basket (2.0 m long, 0.5 m deep, and 0.5 m wide), placed to contain the woodchip. Hardwood sleepers were installed at the outlet to minimise erosion and soil collapse.

The trench was backfilled with softwood woodchips with a depth ranging from 0.7 m (at the inlet) to 0.6 m (at the outlet). More heavy-duty builder plastic was placed on the top of the woodchip with gaps and joins sealed with silicon to seal the woodchip section of the bioreactor before backfilling with soil.

Figure 4 Bioreactor outlet showing four outlet pipes.

Costs

	Total cost $	Bioreactor $/m^3
Excavator inc. driver and float	7056	191
Woodchip inc. delivery	1925	52
Pipes	151	
Inlet gravel	165	
Gabion basket and rock	1900	
Other miscellaneous (liner, pickets, sealer etc)	717	
Total Cost	$11,914.00	$352/m^3

Performance

Average influent nitrate concentration (mg N L^{-1})	4.4
Nitrate Removal Efficiency Average	44.90%
Nitrate Removal Efficiency Range	0.6 – 100%
Nitrate Removal Rate Average (g N m^{-3} d^{-1})	3.4
Nitrate Removal rate Range (g N m^{-3} d^{-1})	0.7 - 9.3
Hydraulic Residence Time (Hours)	2.3
Carbon Longevity Average (Years)	35.5

Monitoring regime (intensity and frequency)

High frequency monitoring conducted, with water samples analysed for the following water quality parameters: nitrate, ammonium, dissolved organic carbon, dissolved oxygen, temperature, and dissolved greenhouse gas analysis (nitrous oxide, carbon dioxide, and methane).

Two automated samplers were installed to collect samples every 6-8 hours from the inlet and the outlet. Four pressure transducers were placed in each of the piezometers within the denitrification bed to monitor both water temperature and pressure.

Troubleshooting

Inlet gravel blockages occurred. This was remediated by replacing the gravel and removing the sediment.

The bioreactor flooded during a large rainfall event, however the flooding did not damage the bioreactor.

What would you do differently?

Create a larger sediment settlement basin and situate the bioreactor higher in the landscape to avoid flooding and site access issues.

Case study 3: In-line bioreactor bed Lower Burdekin

Project leader and partnerships	Department of Agriculture and Fisheries collaborating with Queensland University of Technology
Funding source	Department of Environment and Science (Queensland Government Reef Water Quality Program)
Project length	One and a half years (October 2018 – April 2020) of event-based monitoring completed Opportunity for continuation of monitoring
Region	Burdekin (Ayr)
Production system	Sugarcane
Date of installation	15th October 2018
Length of installation	Three working days for installation (2 weeks including design and site selection)
Bioreactor type	In-line drain bioreactor bed, below the floor of a pre-existing drain
Project objective	Research trial to quantify nitrate removal performance.

Summary of the landscape

The bed style bioreactor was located down slope from a 2.1 ha sugar cane paddock divided in two irrigation sets. Sugar cane was planted in the upslope block in May 2019 and was fallow prior to planting. The soil at the bioreactor site is a Kandosol. The bioreactor is situated on a natural slope and is not prone to flooding. The existing drain flows into a larger drain at the base of the block.

Average rainfall and temperature

The area can be classified as tropical savannah with maximum and minimum average annual temperatures of 29.4 °C and 18.7 °C, respectively, during 2010 to 2017. The mean annual rainfall during the same period was 834 mm.

Sizing and volume capacity

22 m long, 0.6 m deep, and 1.1 m wide. Approximately 14.5m^3 (softwood woodchip).

Design features

The bioreactor (Figure 1) features a gravel inlet, spoon drain overflow, piezometers at inlet, outlet and within woodchips and woodchip analysis piezometers. The outlet consisted of a single 50mm PVC outlet pipe 25m long that drains from the lowest point of the bioreactor.

Water source

The bioreactor received predominantly flood furrow irrigation run-off. The irrigation water is sourced from channel water and is pumped from a drain and applied to the paddock through gated pipes located at the top of the field. Irrigation water flows down furrows between the cane rows. When irrigation run-off reaches the bottom of the furrows it enters a collection drain and irrigation ceases. Irrigation usually lasts for 6 to 12 hours. The bioreactor also receives run-off from rainfall events with larger volumes predominantly in the wet season (November – April).

Construction methods and materials

A 45 m trench was mechanically excavated to permit the installation of a denitrification bed and associated sediment basin, inlet structure and outlet. As the trench was excavated on a slope, the depth (from the surface) ranged from 0.0 to 1.6 m. A laser level was used to ensure the bottom of the trench had a 0.5% slope (0.1 m height difference between the inlet and outlet location over 22 m). Heavy-duty builder plastic liner was laid in the trench to create a waterproof seal around the woodchip, to prevent water ingress via the soil profile or from the surface.

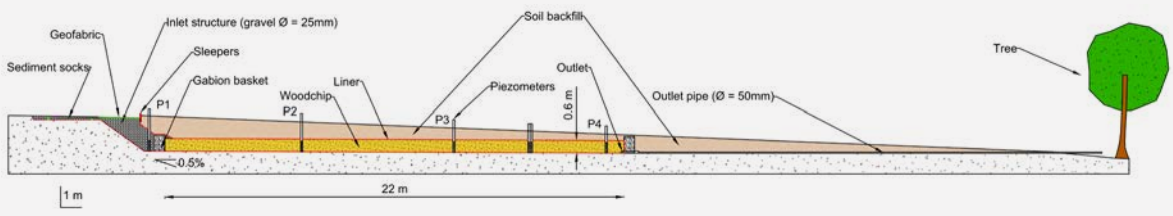

Figure 1 Design of the bioreactor bed showing key features. Source: QUT

Figure 2 Inlet structure showing washed river gravel and geofabric designed to capture fine sediment.

Four 100 mm (diameter) PVC piezometers for water sampling were installed in the centre of the bioreactor and at intervals along the length of the bioreactor. The first piezometer was positioned at the inlet (P1) to facilitate sampling of water entering the bioreactor and the fourth piezometer was at the outlet (P4) for monitoring water leaving the bioreactor. The piezometers were prepared by drilling 5 mm perforations around the base of the pipe for a 0.5 m length to allow for water sampling. Piezometers were wrapped in a 2 mm geo-fabric, to avoid fine particles entering the piezometers.

Figure 3 Bioreactor outlet showing single outlet pipe with valve to regulate flow, if required.

Three 100 mm piezometers were installed and mesh bags filled with woodchips were placed in the piezometers to enable woodchips to be collected and analysed for degradation.

The inlet structure (Figure 2) was constructed by excavating a funnel structure, which was sealed on the sides and at the bottom using heavy-duty plastic liner. A gabion basket (1.1 m long, 0.8 m deep, and 0.5 m wide) was placed to separate the inlet from the woodchip. The gabion basket was filled with rocks (diameter ≥75 mm). Washed river gravel (diameter = 25 mm) was positioned in the funnel inlet structure upslope of the gabion basket with a total volume of about 4.0 m^3. A sediment trap was installed upslope of the inlet structure to capture sediment in the run-off prior to entering the woodchip section of the bioreactor. The sediment trap was constructed using geo-fabric 'socks' filled with gravel and placed on the liner, perpendicular to the flow of the water. Additional gravel was placed on the top of the sediment socks to support water infiltration and sedimentation. An additional geo-fabric layer was placed on top of this gravel to prevent sediment build-up and to enable the geo-fabric to be readily replaced before each irrigation event.

The outlet of the bioreactor was a single, 25 m length of 50 mm PVC pipe connected perpendicularly to a pre-drilled 100 mm PVC pipe wrapped in geo-fabric. At the end of the 50 mm PVC pipe a valve was installed to adjust the outflow from the pipe if required (Figure 3). The 50 mm pipe passed through a gabion basket (1.1 m long, 0.8 m deep, and 0.5 m wide). The basket was installed to support the woodchip from moving downslope.

Figure 4 Bioreactor trench filled with woodchip, showing liner and piezometers.

The trench was backfilled with softwood woodchips (14.5 m^3) (Figure 4). Heavy-duty plastic liner was placed on the top of the woodchip and all gaps and joins sealed with plumbing sealant before backfilling with soil. A spoon drain (surface bypass drain) was constructed adjacent to the bioreactor to accommodate excess runoff and was paved with rock to minimise erosion.

Costs

	Item cost $	Cost $/m^3
Excavator inc. driver and float	3850	265
Woodchip inc. delivery	2000	137
Pipes	485	
Inlet gravel	313.5	
Laser level hire	375	
Materials (liner, sealant etc)	1326	
Total Cost	$8349	$575/m^3

Performance

Average influent nitrate concentration (mg N L^{-1})	1.3
Nitrate Removal Efficiency Average	84.30%
Nitrate Removal Efficiency Range	2.3 – 100%
Nitrate Removal Rate Average (g N m^{-3} d^{-1})	0.4
Nitrate Removal Rate Range (g N m^{-3} d^{-1})	0.0 – 1.8
Hydraulic Residence Time (Hours)	3.0 – 36.6
Carbon Longevity Average (Years)	16.3

Monitoring regime (intensity and frequency)

Event-based monitoring was conducted during each irrigation event. The following water quality parameters were analysed: nitrate, ammonium, dissolved organic carbon, dissolved oxygen, temperature, and dissolved greenhouse gas analysis (nitrous oxide, carbon dioxide, and methane).

Four pressure transducers were placed in each of the piezometers to monitor both water temperature and pressure.

Troubleshooting

Geofabric on the surface of the inlet structure needed to be replaced regularly after it became blocked with sediment.

There was a gradual reduction in hydraulic conductivity within bioreactor over time, leading to long hydraulic residence times. This may have been due to sediment entering woodchip or a blockage at the outlet.

What would you do differently?

Create a larger sediment settlement basin and use multiple outlet pipes to ensure the bioreactor can continue to operate in the event of a blockage. Avoid installing geofabric in the interior of the bioreactor.

Case study 4: In-line bioreactor bed Wet Tropics

Project leader and partnerships	Terrain NRM, Wet Tropics Major Integrated Project (WTMIP) collaborating with Australian Wetland Consulting (AWC)
Funding source	Department of Environment and Science (Queensland Government Reef Water Quality Program)
Project length	18 months of event-based monitoring
Region	Wet Tropics (Johnstone)
Production system	Sugarcane
Date of installation	21st September 2019
Length of installation	Three working days for installation
Bioreactor type	In-line bioreactor (above the invert/floor of the drain)
Project objective	Research trial to quantify nitrate removal performance.

Summary of the landscape

The bioreactor is at the bottom of foothills and receives both high flow from storm events and base flow from groundwater seepage from sugarcane paddocks and native vegetated hill side.

The bioreactor was placed onto the underlying clay layer at the base of a drain, occupying approximately 50% of the total drain depth. Base flow and low flow stormwater move through the bioreactor, with larger stormflows bypassing over the top.

Soil texture is a light clay (0 - 85 cm) over sandy clay loam (85 - 160 cm) over light clay (160 - 210 cm). Soil pH was acidic throughout (pH 4.9 - 5.6). The water table periodically drops to >210 cm depth during the dry season.

Average rainfall and temperature

The area is located in the Wet Tropics with maximum and minimum average annual temperatures of 28.1 °C and 19.1 °C, respectively. The mean annual rainfall is 3200 mm (long term average) (BoM, 2017).

Sizing and volume capacity

10 m long, 0.5 m deep, and 1.8 m wide. Approximately 10 m^3 (softwood woodchip).

Design features

Due to the lack of available space on the cane farm, this bioreactor was designed to be constructed within an existing drain. A collaborative design process with the farmer and local contractors resulted in a 'in-drain' bioreactor design (i.e. bioreactor built on top of the drain floor/invert) that occupied no more than 50% of the total height of the drain. This meant that base flow drainage water can move through the bioreactor (undergoing treatment), with large stormflows moving over the top. Given that the bioreactor will experience high flow rates during the wet season, a considerable amount of rock was needed to ensure a level of structural integrity (Figures 1 and 2).

Water source

Rainfall run-off and shallow groundwater, which flows most of the year.

Construction methods and materials

A large excavator was used to tidy and shape the pre-existing drain. Approximately 10 m^3 of softwood woodchip (particle size 20 mm) was placed between the inlet and outlet gabion rock baskets. The woodchip was encased with rocks that were held in place by mesh. Rocks were also used to create entry and exit 'ramps' to help secure the gabion baskets in periods of high flow.

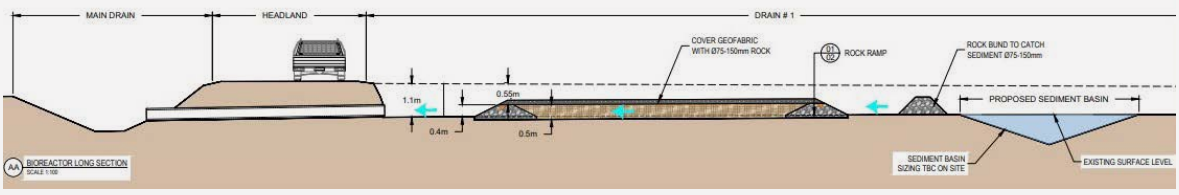

Figure 1 Cross section of in-line bioreactor bed. Source: WTMIP.

The walls of the drain were lined with geofabric.

Three 100 mm PVC piezometers were installed at the inlet, bioreactor centre and the outlet for monitoring. The piezometers were prepared by pre-drilling 5 mm perforations for a length of 30 cm at the base. The piezometers were held in place with star pickets and zip ties.

A 50 mm PVC piezometer was installed in the upslope paddock for ground water sampling.

Costs

Costs included woodchips, earth moving equipment, labour, geofabric, PVC pipe and other materials.

Performance

This system is currently being monitored and performance information is not yet publicly available.

Monitoring regime (intensity and frequency)

The bioreactor is monitored for temperature, pH, dissolved oxygen, total nitrogen, ammonia, nitrate and nitrite, total phosphorus, phosphate and redox potential.

Samples are collected as grab samples fortnightly and during other rainfall events and has been monitored since installation in September 2019. Water level monitoring is measured using a hobo diver and is collected at hourly intervals.

Troubleshooting

Wild pigs came on site during construction, causing damage and sediment loss.

The project team placed some left-over rock in the bottom of the drain to deter pigs and erected an electric fence to prevent future damage.

What would you do differently?

An important factor to consider when placing bioreactors within larger drains, is to ensure that the location (within the drain) is not on a corner, or an erosion prone area. Construction needs to be cognisant of high velocity water flow, such that it does not cut, or scour the banks around the bioreactor.

Figure 2 In-line bioreactor bed showing rock on top of woodchip zone for stability.

Case study 5: Ag-pipe bioreactor bed Wet Tropics

Project leader and partnerships	Terrain NRM, Wet Tropics Major Integrated Project (WTMIP) collaborating with Australian Wetland Consulting (AWC)
Funding source	Department of Environment and Science (Queensland Government Reef Water Quality Program)
Project length	18 months of monitoring
Region	Wet Tropics (Johnstone)
Production system	Sugarcane
Date of installation	14th August 2019
Length of installation	Two working days for installation
Bioreactor type	Ag-pipe surrounded by woodchip (novel system)
Project objective	Trial to investigate nitrate removal efficiency.

Summary of the landscape

The bioreactor is a novel system installed beneath a sugar cane farm in the wet tropics, 17m above sea level. The outlet enters a farm drainage network at bottom of surrounding foothills and receives both high flow from storm events and base flow from groundwater seepage from the sugarcane paddocks and native vegetated hill sides (Figure 1).

The soil is classified as a Ferosol to a depth of 1.8 m and overlays weathered basalt. The soil is structured and freely draining and the ag-pipe bioreactor was installed in a particularly wet area of the field to increase drainage. The ag-pipe was installed overlaying the less permeable basalt layer at approximately 1.5 – 1.8 m deep and the wood chip was placed around the outside of the pipe.

Average rainfall and temperature

The area is in the Wet Tropics region with maximum and minimum average annual temperatures of 28.1 °C and 19.1 °C, respectively. The mean annual rainfall is 3200 mm (long term average) (BoM, 2017).

Sizing and volume capacity

175 m long, 0.4 m deep, and 0.6 – 1.1 m wide. Approximately 80 m^3 (softwood woodchip).

Figure 1 Aerial image of ag-pipe bioreactor under construction, showing cane crop and drainage line into which the bioreactor outlets. Source: WTMIP

Design features

Due to the lack of available space within this cane farm, this bioreactor was designed to be constructed around an ag-pipe that was installed to address in paddock drainage issues. An idea came up during discussions with the landholders, to install woodchip around the sub-surface drainage pipe, as an alternative to sand which is traditionally used. If proven effective, this design could be a cost- effective way to install bioreactors, as they can be integrated into sub-surface drainage systems.

Water source

Shallow groundwater, which flows year-round.

Construction methods and materials

A 175 m long trench was excavated with a V bucket in the sugar cane paddock. The trench was backfilled with 20 mm softwood woodchips and the ag-pipe placed on top (Figure 2). At the outlets (Figure 3), PVC pipe was installed approximately 6 m long to ensure a good sampling point and to avoid any damage caused from traffic on the headland. More woodchip was placed on top of the ag pipe and then backfilled with soil.

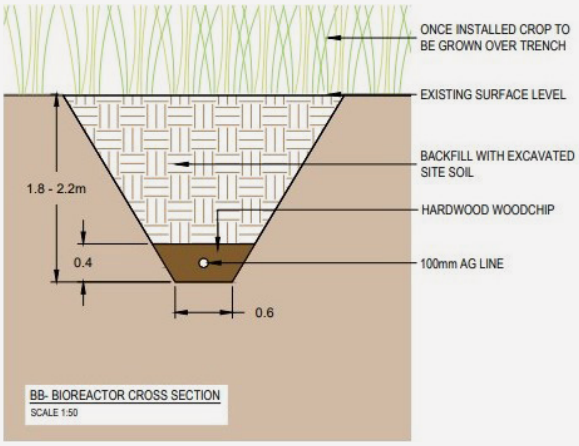

Figure 2 Cross-section plan of bioreactor showing V-shaped trench, woodchip and ag-pipe location. Source: WTMIP

Costs

Costs included woodchips, earth moving equipment, labour, ag-pipe, PVC pipe and other materials.

Performance

This system is currently being monitored and performance information is not yet publicly available.

Monitoring regime (intensity and frequency)

The bioreactor is monitored for temperature, pH, dissolved oxygen, total nitrogen, ammonia, nitrate and nitrite, conductivity, total phosphorus, phosphate and redox potential.

Samples are collected as grab samples fortnightly and during other rainfall events and has been monitored since installation in August 2019. The flow rate from the ag-pipe is calculated during monitoring.

Figure 3 Ag-pipe bioreactor outlet into drainage line. Source: WTMIP

Case study 6: Bioreactor beds for aquaculture wastewater, Wet Tropics

Project leader and partnerships	Mainstream Aquaculture collaborating with James Cook University
Funding source	Mainstream Aquaculture and Department of Industry Innovations Connection Grants (2019 & 2020)
Project length	Two and a half years (April 2019 – Aug 2021)
Region	Wet Tropics (Johnstone)
Production system	Land based aquaculture, Barramundi
Date of installation	23 July 2019
Length of installation	One week
Bioreactor type	Six parallel bioreactor beds
Project objective	Research trial to quantify nitrate removal performance and determine suitability on an aquaculture farm.

Summary of the landscape

The bioreactor beds are built on a level area between the aquaculture ponds and treatment wetlands.

Average rainfall and temperature

The area is in the Wet Tropics Region with a mean annual rainfall of 3283 mm. Maximum and minimum average annual temperatures are 28.1 °C and 19.3 °C respectively.

Sizing and volume capacity

Six parallel beds all approximately 10 m long, 1.8 m wide and 1.5 m deep.

Approximately 18 m^3 (softwood woodchip).

Design features

The system was originally designed to include a set of trickle-bed nitrification filters to intercept water coming from the aquaculture ponds and convert ammonia (excreted by fish) to nitrate. This water was then split into one of two header tanks that each feed into three woodchip bioreactor beds.

The header tanks enabled experimentation and testing of the impacts of flow, salinity and nitrogen load. This design gave the ability to run nitrate and carbon dosing experiments in three of the beds and keep the other beds as controls.

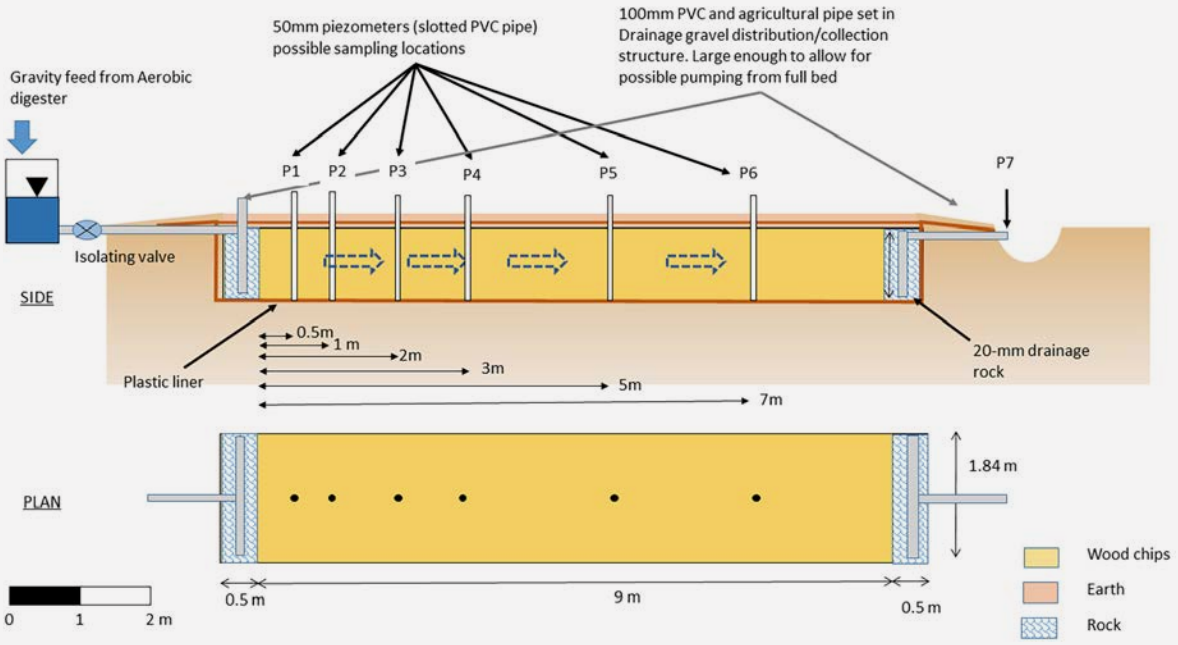

Figure 1 Design of individual woodchip bioreactor bed. Source: JCU

Each bioreactor bed was lined with 3 mm high density polyethylene (HDPE) lining, including a capping piece (Figure 1). This eliminated groundwater and rainwater contamination.

The header tanks ensure that all beds received the same hydraulic head, though each bed has a ball valve on each inlet allowing fine tuning of inflows and thus residence times. Each bed has six piezometers installed to allow for water sampling, with a standard ag pipe 'halo' installed into the gravel filters at both the inlet and outlet.

Water Source

Water is pumped into the system from an adjacent aquaculture pond (stocked with fish). Since January 2021, water has been sourced from an on-site hatchery. This water is treated with a mixed bed biofilm reactor (MBBR) to convert ammonia to nitrate, prior to entering the header tanks and bioreactor beds.

Construction methods and materials

The trenches for the bioreactor beds were excavated using a six-tonne excavator. They were then lined with HDPE liner. Piezometers were installed and the trenches were filled with approximately 20 mm softwood woodchip, sourced locally from timber mills. HDPE liner was then placed over the top of the woodchip (Figure 2).

Other tools and materials required for the build were a dumpy level for height measurements, shovels, rakes, wheelbarrows and a front-loading tractor.

Costs

Not applicable because the systems were over-engineered to provide an ongoing research capacity. The build costs are therefore not relevant to a commercial setting.

Performance

Nitrate removal rate: 9.4 to 13.1 g N m^{-3} day^{-1}

Monitoring regime (intensity and frequency)

The sampling regime involves:

- Monthly or fortnightly collection of samples from i) nitrification filters, ii) header tanks and iii) outlets
- Sampling of all piezometers when a significant change in salinity is observed in the influent water or when dosing experiments are conducted.

Grab samples analysed for dissolved inorganic nitrogen, dissolved organic nitrogen, total nitrogen and ammonium. Alongside grab samples, a probe is used to measure pH, temperature, dissolved oxygen and conductivity.

Troubleshooting

The water was originally sourced from an existing treatment wetland, which was found to have a large amount of organic matter that fouled the nitrification trickle filters. This was rectified by moving the inlet pump to a nearby production pond and bypassing the trickle filters. However, fish excrete ammonia and so nitrate was found to be limiting for bioreactor efficacy.

The system has since been modified to receive water from an onsite hatchery which employs a mixed bed biofilm reactor (MBBR) to convert ammonia to nitrate.

What would you do differently?

To effectively use bioreactor beds to treat aquaculture wastewater requires pre-treatment to convert ammonia to nitrate. Filtration to remove organic matter may also be required.

Figure 2: Woodchip bioreactor beds, showing equipment in the foreground used to add extra nitrate to test performance under different nitrate concentrations. Source: JCU

Case study 7: In-line bioreactor beds Wet Tropics

Project leader and partnerships	Jaragun EcoServices collaborating with James Cook University
Funding source	Department of Environment and Science (Queensland Government Reef Water Quality Program)
Project length	Three years (August 2017 – June 2020)
Region	Wet Tropics, Russell River Catchment (Babinda Swamp Drainage Area)
Production system	Sugarcane
Date of installation	Bioreactor 1: 29-30 Aug 2018, Bioreactor 2: 31 Aug- 1 Sep 2018
Length of installation	Four working days for installation (2 x bioreactors)
Bioreactor type	Twin in-line bioreactor beds (below floor/invert of drain)
Project objective	Research trial to quantify nitrate removal performance.

Summary of the landscape

Low elevation with minimal slope (<1.0%)

Babinda series (peat) and Hewitt series soils (sapric peat overlaying clay). Bioreactor design to fit into existing agricultural drain beds.

Average rainfall and temperature

Annual hydro monitoring period from November 2018 to March 2020. The mean annual rainfall was ~4358 mm (Lat. -17.35°S, Long. 145.95°E), with an average daily temperature of 28.7°C (Babinda, BOM Station No. 31004)

Sizing and volume capacity

20 m long, 0.88 m deep, and 0.99 m wide. Approximately 17.5 m^3 (hardwood woodchip).

Design features

Woodchip bioreactors were installed below existing drain beds with 0.2 m soil cover. Trenches were lined with geofabric, builders plastic then another layer of geofabric. Note: Plastic liner was included to enable accurate measurement of flow through the inlet and outlet of the bioreactor, which was needed to calculate the nitrogen removal rate.

Gabion rock baskets were installed at both ends of the bioreactor to hold the woodchip bed in place. The inlet included 100 mm diameter rock and had an angled rock face to help funnel water into the system. The outlet included 20 mm rock, with a 'halo' of agricultural drainage pipe installed into the rock wall to take water from the entire end drainage face into a 100mm outlet pipe. In high flows, excess water overtops the inlet and flows unimpeded through the drain.

Measuring equipment included two piezometers. A 50mm PVC piezometer was installed into the inlet gabion cage. An outlet piezometer was installed in the woodchip immediately upstream of the gabion rock cage.

Water source

Water in the agricultural drains originates from surface run-off from adjacent sugarcane paddocks and also from shallow groundwater.

Construction methods and materials

A hardwood woodchip mix was used (particle size approximately 50mm, predominantly *Eucalyptus tereticornis* sourced from Gympie, Queensland). The bioreactor beds were dug using an excavator, with a 0.9 m wide bucket (Figure 1).

Figure 1 Construction of the in-line bioreactor bed within an agricultural drain.

The woodchip was encased in plastic heavy duty liner (3mm thick) for the trial to restrict water entry into the bioreactor inlet and water exit via the outlet. The plastic was encased in geofabric to prevent possible puncture. Bentonite clay was used to create a seal around the outlet pipes and piezometers.

The bioreactor bed was capped with soil, dusted with cement and compacted to reduce in-stream erosion. The finished level was to the original drain height.

Costs

$6,653 per bioreactor.

The cost is based on estimates of future construction, using similar machinery, materials and project management needs as the trial. The amount excludes the additional costs of materials, equipment and labour for scientific assessment and monitoring purposes of the trial.

Performance

Average removal efficiency was 41% of nitrogen that entered the bioreactors, with the bioreactors intercepting 7.2% of the total annual nitrogen load in the drain. However, due to low loads, this resulted in a low performance, removing just 0.47 kg nitrogen with a removal rate of 0.07 g N m^{-3} day^{-1}.

Monitoring regime (intensity and frequency)

Water sampling was undertaken fortnightly, over 675 days between May 2018 to March 2020. Samples were analysed for total dissolved nitrogen and oxidised nitrogen. The capacity for denitrifying bioreactors to intercept and remove oxidised nitrogen was assessed by comparing concentrations of nitrogen in inlet and outlet water.

Additional daily composite samples were collected in one of the bioreactors via ISCO 3700. The additional sampling included short periods during the 'wet up period', after harvest to capture specific rain events, and periods of known high dissolved inorganic nitrogen loss.

When saturated, salt tracer tests were taken to calculate residence time within the bioreactor beds.

An in-line flow meter (Flomec DP490, Flomec, Sydney, Australia) was initially deployed to measure flow through the bioreactor bed. However, as the resolution was insufficient for the accuracy required, direct measurement of bed outflow was carried out.

Drain discharge was determined using continuous stage measurements and rating curves established using the channel cross-sectional area and occasional velocity measurements. Depth was measured using pressure transducers (CS451, Campbell Scientific, Logan, UT, USA) and recorded with solar-powered data loggers (CR300, Campbell Scientific, Logan, UT, USA). Site specific rating curves were determined by recording water velocity over 2-week deployments of a Doppler instrument (6527 Starflow QSD, Unidata O'Connor WA, Australia) and accurate surveys of the drain cross sectional area using a RTK GPS (Trimble R8 GNSS). Daily discharge was calculated by summing discharge over measured 5-minute intervals.

Troubleshooting

Construction issues included use of heavy machinery along the soft edges of the agricultural drains causing bank collapse. Further collapse was limited by the excavator straddling the drains for construction. Geofabric was applied to reduce additional collapse and left in-situ post construction to reduce future erosion (e.g. from rainfall). Pooling of groundwater in the drain was removed by pump.

Flow through the bioreactor slowed during the wet season, presumably due to clogging by algae, other biofilms and possible fine sediment. This problem self-rectified after completely drying out during the dry season. However, the issue quickly returned after fully rewetting.

What would you do differently?

Re-design of bioreactors to address the above issues, including potential for larger, more cost-effective bioreactors in locations that have continuous water flow.