



Department of
Environmental
Conservation

Permeable Reactive Barriers (PRB) Project Roadmap

REMOVING LEGACY NITROGEN FROM GROUNDWATER ON LONG
ISLAND WITH PERMEABLE REACTIVE BARRIERS:
A ROADMAP TO PROJECT PLANNING AND IMPLEMENTATION

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Executive Summary

This guide is designed to assist communities in the decision-making process of siting, designing, and installing a Permeable Reactive Barrier (PRB). By better understanding where elevated levels of legacy nitrogen may be present in your community's groundwater, you can begin to identify potential locations that could be suitable for PRB installations, as well as decide which type of PRB is appropriate. Utilizing best practices in the decision-making process will maximize the effectiveness of a PRB and minimize the chance of unintended impacts.

Overview of PRBs

- PRBs have been shown to effectively remove groundwater nitrate but must be properly sited, designed, installed, and monitored to avoid potentially harmful secondary impacts such as methane or sulfide production, and/or the release of dissolved metals at harmful levels.
- Treatment of nitrogen already in groundwater (i.e., legacy nitrogen) should never substitute treatment at the source (e.g., by installation of Innovative Alternate On-site Wastewater Treatment Systems or by connecting to sewage treatment plants).
- Initial site identification and evaluation can be completed with limited professional assistance. The correct design of a PRB requires a licensed design professional to conduct a comprehensive site evaluation that includes the characterization of groundwater chemistry and hydraulics and the drafting of a feasibility report.
- The [Suffolk County Subwatersheds Wastewater Plan](#) (2020) and the [Nassau County Nine Key Element Plan for Nitrogen](#) (2022) are helpful tools for initial site identification and evaluation.
- Choice of the PRB type and design will depend on the concentration of nitrate, velocity of groundwater, depth of plume, and logistical/site access considerations.
- Two types of PRBs are described here: woodchip-filled trenches and carbon injection wells. Woodchip trenches are generally limited to intercept groundwater to depths of less than 20 feet or with specialized trench and fill equipment to 40 feet. Injection of liquid carbon, such as vegetable oils, can be made to depths greater than 40 feet.
- Woodchips in a subsurface environment can generally supply the carbon required to remove nitrogen for more than 10 years; liquid carbon supplied by an injection well lasts for a shorter period, and therefore may require periodic maintenance injections after the initial injection. Liquid carbon injections may consequently be useful for the treatment of a known, discrete nitrate plume.

Overview of this Document

- This document is intended for town and municipal officials as well as others in non-governmental organizations who are exploring options to remediate or prevent nitrogen pollution in local lakes, estuaries, and embayments.
- It is designed to give an overview of how to evaluate if legacy nitrogen from groundwater may be impacting freshwater and saline waterbodies (Chapter 2); the types of groundwater remediation that may be available for remediation of groundwater nitrogen (Chapter 3); a roadmap to site, design, and install a PRB, as well as the required permitting and monitoring of PRB performance once installation has been completed (Chapter 4).

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Chapter 1: Introduction

Nitrogen is the leading cause of water quality deterioration in Long Island's fresh and marine waters, as well as the groundwater. The main source of nitrogen on Long Island is wastewater such as effluent from sewage treatment plants, septic systems, and cesspools, with additional input from fertilizer and atmospheric deposition.

Effluent from on-site wastewater systems (i.e., cesspools and septic systems) enters the groundwater, which ultimately reaches surface waters such as rivers or streams. Groundwater can also directly flow into estuaries or other coastal embayments. Excess nutrients, including nitrogen, can stimulate algal growth including harmful algal blooms in surface waters, which can lead to anoxia/hypoxia, and shellfish and finfish kills. Excess nitrogen also degrades marine habitats—such as seagrass beds that provide nurseries for juvenile fish and saltmarshes that provide protection against flooding from storm surges to many coastal communities. In addition to its ecological effects, nitrogen contaminates the aquifer, which is the sole source of drinking water on Long Island.

When a community wants to know if there is legacy nitrogen in their groundwater, a basic assessment is needed that includes a few key pieces of information. One factor includes understanding the upstream sources of nitrogen to a waterbody. The larger the number of sources, the more likely the groundwater has elevated levels. Nitrogen sources can be past and current practices, including the use of cesspools and septic systems, that have resulted in the accumulation of nitrogen in groundwater and soil. This is known as legacy nitrogen¹. Given that groundwater travel times toward surface waterbodies can range from years to decades, legacy nitrogen will continue to be in the groundwater system even after its sources have been addressed. Another factor to consider is the residence time of the waterbody receiving the groundwater. The residence time is how long water stays within a waterbody before being flushed out into open waters, such as the Atlantic Ocean. A longer residence time can lead to nitrogen remaining in the waterbodies longer, increasing the chances for hypoxia and fishkills.

Successfully addressing the nitrogen problem is not a matter of choosing one approach over competing ones. A strategic and coordinated plan using multiple approaches is recommended to address both ongoing sources of nitrogen in the environment and legacy nitrogen in groundwater.

The first step in remediation is to prevent pollution at the source. There are multiple initiatives to address Long Island's nitrogen pollution that are mainly guided by New York State Department of Environmental Conservation's (DEC) [Long Island Nitrogen Action Plan \(LINAP\)](#), the [Suffolk County Subwatersheds Wastewater Plan \(SWP\) 2020](#), and the [Nassau County Nine Key Element Watershed Plan for Nitrogen \(2022\)](#). LINAP is the overarching strategic plan to address nitrogen in Nassau and Suffolk counties and supports the two county plans. The *Suffolk County SWP* and *Nassau County Nine Key Element Plan* inventory sources of nitrogen pollution across their respective watersheds and model loading rates into nearby waterbodies. The plans also establish reduction targets and implementation priorities. These plans are currently being implemented and include initiatives and incentives to address nitrogen at the source, such as connecting homes and businesses currently on cesspools or inadequate septic systems to sewers or replacing them with Innovative/Alternative On-site Wastewater Treatment Systems (I/A OWTs) in areas that are unlikely to be sewered in the foreseeable future. However, discontinuing the use of cesspools and septic tanks will not address the issues associated with nitrogen already in groundwater. The time it takes the legacy nitrogen to reach the ocean (called travel time) varies with short travel times (less than two years) in areas close to the shore and longer travel times (multiple decades or even hundreds of years) further inland. While a community is working on eliminating current sources of nitrogen from discharging to groundwater, they may also want to address legacy nitrogen to mitigate nitrogen pollution of surface waterbodies. To do this, a community may consider using permeable reactive barriers (PRBs) to treat nitrogen (specifically, nitrate or nitrite) before the groundwater discharges to the surface water.

¹ Legacy nitrogen is sometimes used to refer to nitrogen contributed to groundwater from a prior land use; e.g., nitrogen in groundwater derived from fertilizer used at a farm would be referred to as legacy nitrogen if the farm had been converted to residential housing, whereas groundwater nitrogen from present land use (i.e. the residential housing) that replaced the farm would not be included as legacy nitrogen, regardless of how long ago the conversion occurred. In this document, the term legacy nitrogen refers more broadly to all nitrogen in groundwater from current and prior land use.

Some quantity of legacy nitrogen likely exists in most of Long Island's groundwater; however, simply because groundwater contains nitrogen does not mean it presents an ecological problem. This guide is designed to help communities determine if elevated levels of legacy nitrogen are present in their groundwater that could negatively impact surface waterbodies downstream, identify locations suitable for the installation of a PRB, assess the feasibility of different PRB approaches, and provide guidance on best practices to gather the information and data needed in the decision-making process toward a PRB installation that maximizes effectiveness and minimizes the risks of unintended impacts. A PRB may not be the best solution for every situation and a municipality should work with licensed professionals to determine the best solution for the municipality's situation.

Chapter 2: Resources to Identify Areas of Legacy Nitrogen

Substantial work has been done to evaluate the status and future risks related to nitrogen in groundwater. The *SWP*, accessible at [suffolkcountyny.gov](https://www.suffolkcountyny.gov), which models nitrogen loading from land use, also models nitrogen in the groundwater and contains information on 191 subwatersheds across Suffolk County. The *SWP* includes simulation nitrogen concentrations in the shallow glacial aquifer at the subwatershed scale considering existing land-use data from 2016 and wastewater management (Figure 1). This information is useful when considering a PRB installation. While the actual distribution of legacy nitrogen may differ considerably from the simulated distribution, the maps can help identify potential hotspots of legacy nitrogen—but it should be noted that the data do not account for historic land uses.

As part of *LINAP*, a Solute Transport Model Study is under development that looks at nitrogen in groundwater and includes inputs from historical nitrogen sources, such as agriculture and wastewater. This legacy nitrogen in groundwater is contributing to the nitrogen load to surface waterbodies. The tool may allow more accurate forecasting where legacy nitrogen impacts may be greatest to surface waters, further improving legacy nitrogen risk assessments. The model is expected to be available publicly in 2025 for the Peconic Estuary Watershed and rolled out subsequently for the rest of Long Island, Brooklyn, and Queens.

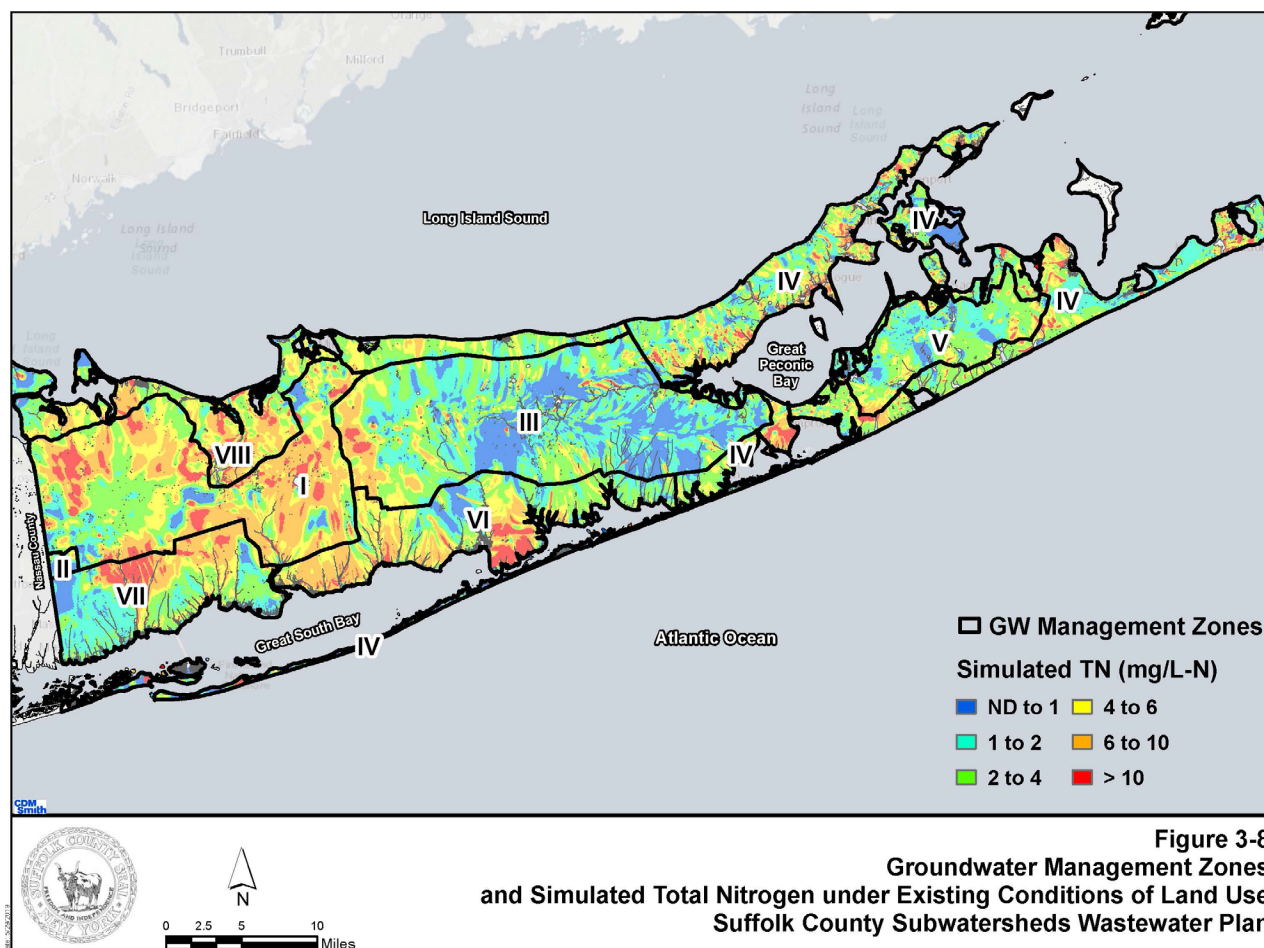


Figure 1. Simulated total nitrogen under existing conditions of land use (page 410 in the SWP).

Maps of 191 subwatersheds identified in the [SWP Appendices](#) are especially useful when identifying sites where legacy nitrogen is likely to present a problem. These maps give information on major sources of nitrogen within each watershed, groundwater travel times, the ecological sensitivity and water quality of the recipient waterbody, nitrogen reduction goals, and current land use. An example of the maps is shown in Figure 2. SWP Appendices contain similar information for all 191 subwatersheds. The information provided by those maps can help to screen for watersheds and locations within a watershed that are potentially suitable for the installation of a PRB.

Actual measurements of nitrogen from groundwater wells at different depths is available from the U.S. Geological Survey (USGS). The website is currently under construction and will contain water quality results from more than 2,000 wells sampled within the shallow aquifers in Nassau and Suffolk counties over the past 10 years (2014–2024). Appendix A contains a link to the USGS webpage with updates on database availability and instructions for data retrieval. Additional groundwater quality data, including concentrations of specific forms of nitrogen (i.e., nitrate, nitrite, and ammonium) in source water wells, can be obtained from Suffolk County

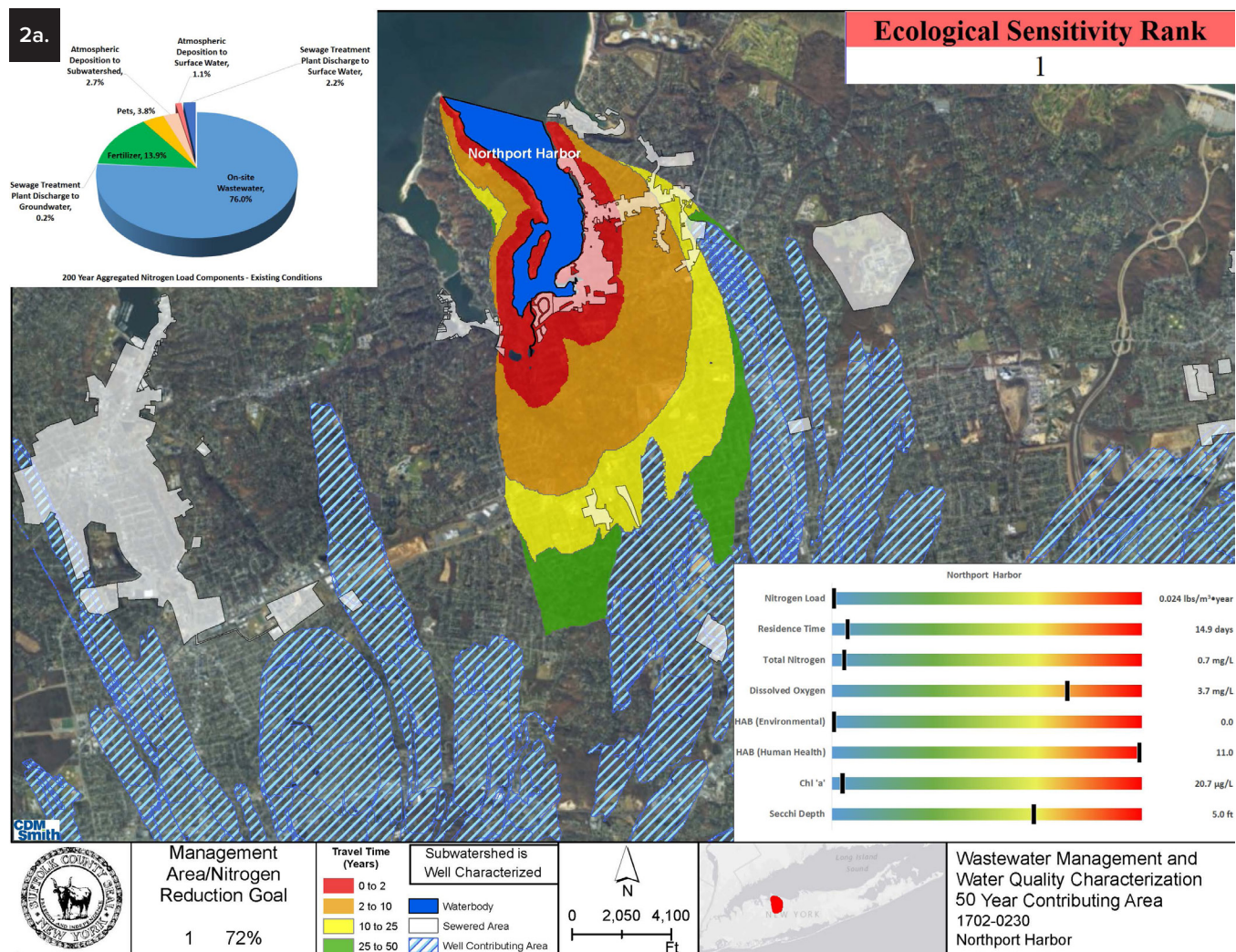
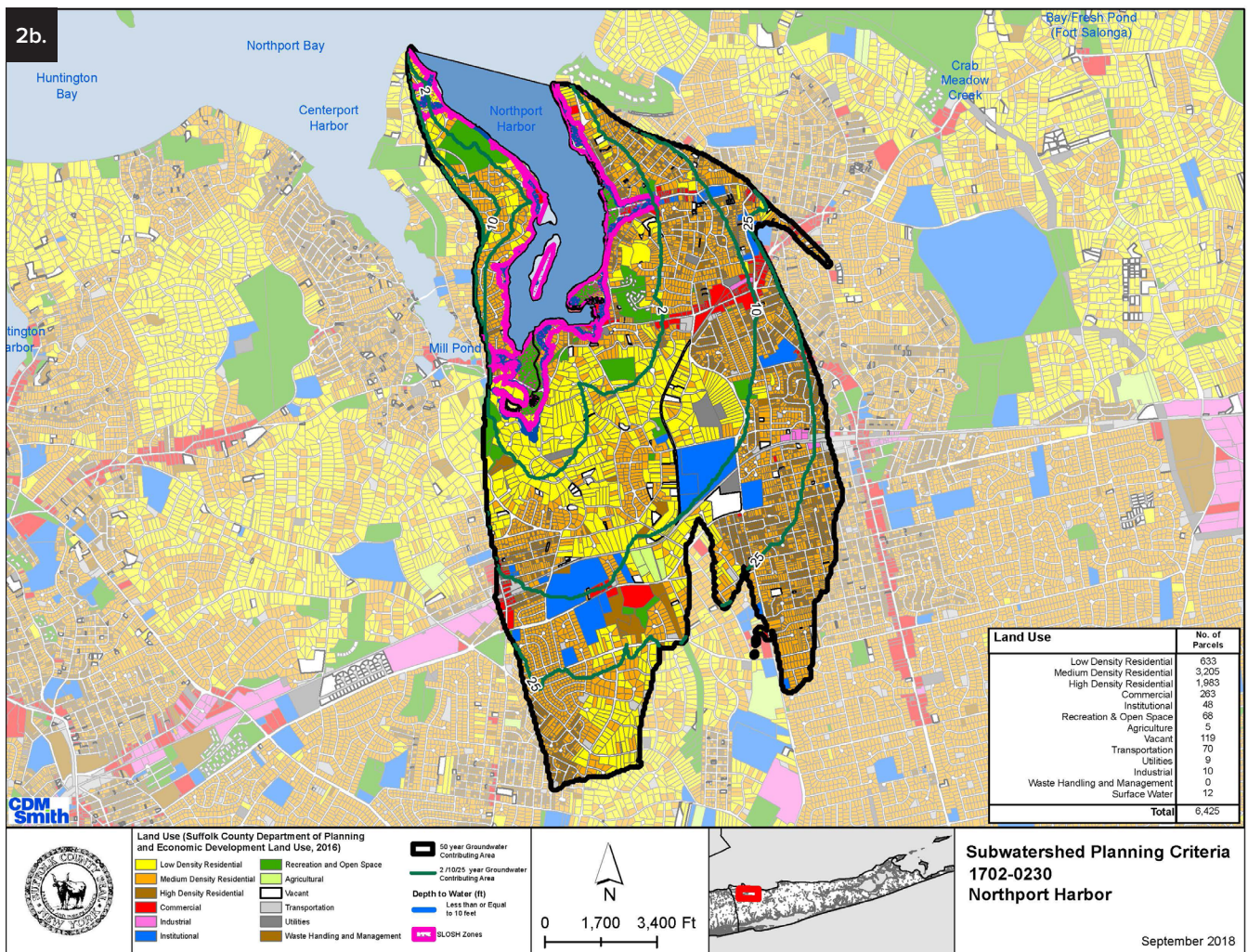


Figure 2. Figures from the Suffolk County SWP Appendix D that can be used to assess if a nitrogen problem is likely to exist within a specific subwatershed. a: Map of Northport Harbor with simulated groundwater travel times within the subwatershed and information on nitrogen load components, nitrogen reduction goals, water quality characteristics, and the ecological sensitivity rank (page 424 in the SWP Appendices).



b: Land use data from 2016 within the 2, 10, 25, and 50 year groundwater contributing areas of the subwatershed (page 618 in the SWP Appendices).

Department of Health Services, Suffolk County Water Authority, and other water purveyors through New York State’s Freedom of Information Law requests.

Although there are a number of publicly available sources with data relevant to assess groundwater nitrogen concentrations at the subwatershed scale, the data represents measurements from specific wells or broad estimates based on modelling. At the scale required to situate a groundwater remediation technology, the distribution of groundwater nitrogen can be spatially and temporally variable. Therefore, collecting samples from groundwater wells over a seasonal cycle is required to characterize a groundwater nitrogen plume at prospective installation sites. Best practices of site characterization procedures are outlined in Chapter 4.

Chapter 3: Types of Permeable Reactive Barriers to Address a Legacy Nitrogen Problem

PRBs are one available management strategy to remove excess nitrogen through denitrification from the groundwater before the nitrogen has the potential to enter the surface waters.

If properly located and designed, PRBs can be an effective technology to address legacy nitrogen in groundwater. PRBs are passive systems that are installed underground. They are relatively simple to implement, require minimal maintenance, and can be as cost-effective as other mitigation options. PRBs provide a carbon source to stimulate native soil microbes to convert nitrogen in the form of nitrate or nitrite into dinitrogen gas. The carbon source (reactive media in either solid or liquid form) is placed within the groundwater flow path using various installation methods.

Groundwater flow and the distribution of legacy nitrogen can vary substantially within a watershed and PRBs must be designed to account for site-

specific conditions. Furthermore, legacy nitrogen can be present as nitrate/nitrite (oxidized form) or as ammonia (reduced form). Denitrifying PRBs are only capable of removing nitrate and nitrite. If a PRB is not properly situated, designed, installed, or maintained, it can be ineffective at removing nitrogen, result in the alteration of local natural groundwater flow, and/or result in the formation and release of unintended secondary by-products, including methane gas, sulfide gas, and/or dissolved metals. These unintended by-products can create public health concerns and negative environmental impacts.

There are two major types of PRBs (Figure 4). In trench-type PRBs, soil is excavated and backfilled with solid reactive media (e.g., woodchips). In carbon injection PRBs, the carbon source is pumped into the subsurface using injection wells.



Figure 3. Iron staining in a streambed caused by the oxidation of dissolved iron.

Source: <https://phys.org/news/2009-12-drainage-abandoned.html>.

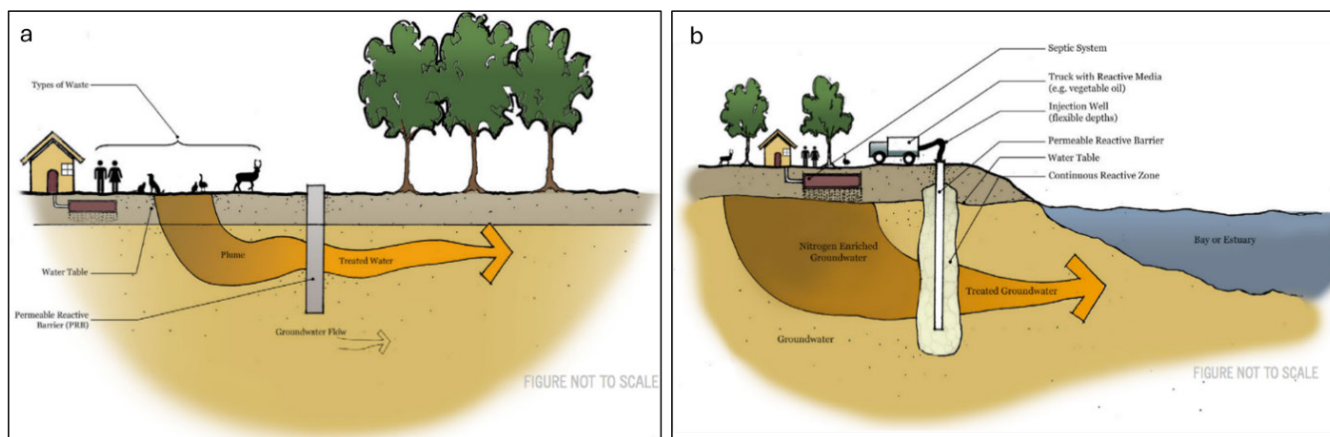


Figure 4. Diagrams of a trench-type PRB (a) and an injection well PRB (b).

Source: <https://capecodgreenguide.wordpress.com/permeable-reactive-barrier/1>.

3.1 Trench-Type PRBs

A common PRB installation method is trenching and backfilling with the reactive media. The depth of trenching is typically limited to approximately 40 feet below ground, which is generally the maximal depth accessible by trenching equipment. For shallow trenches (e.g., those less than 20 feet in depth), PRBs can be installed using conventional excavation equipment such as excavators, shoring boxes, and dewatering systems. When deeper trenches are required, a technique known as one-pass trenching can be used. The one-pass trenching operation cuts a precise trench and simultaneously backfills it with the reactive media using a delivery box that extends to the bottom of the trench. Since this operation does not leave an open trench, there is less risk for collapsing trench sidewalls. It is important to note that one-pass trenching involves specialized trenching equipment, making this technique often cost-effective for deeper trenches (i.e., 20–40 feet) or where soil is too unstable to allow trenching by an excavator.

Woodchips are commonly used as the reactive media when constructing trench PRBs for denitrification. Woodchips provide an inexpensive and readily available carbon source to create anoxic conditions conducive for denitrification. Woodchip-based PRBs can be expected to be effective for over a decade (Robertson et al. 2000, Long et al. 2011) and require minimal maintenance, but should only be installed at locations where the influx of legacy nitrogen by groundwater flow is not expected to significantly decline over this time span. Once a woodchip-based PRB is placed in the subsurface, it can be difficult and expensive to make alterations or remove the reactive

PRB media. A design professional will work with the municipality to select the best reactive PRB media composition, PRB dimensions, and PRB placement for the site.

Periodically sampling the groundwater allows the performance of the PRB to be monitored over time. Once the amount of carbon being gradually released from the woodchip-based PRB falls below the concentration needed to effectively treat the nitrogen in groundwater, there are methods that can rejuvenate the PRB. This could involve carbon substrate injections (see Chapter 3.2) to “refresh” the woodchips and the amount of carbon being slowly released (ITRC, 2011).



Figure 5. Woodchip PRB installation using conventional trenching equipment.

Source: [*Technical Protocol for Enhanced Anaerobic Bioremediation Using Permeable Mulch Biowalls and Bioreactors \(clu-in.org\).*](#)



Figure 6. Picture of a deep trencher, which may be needed for PRBs installed between 20 feet and 40 feet below land surface.

Source: [*Technical Protocol for Enhanced Anaerobic Bioremediation Using Permeable Mulch Biowalls and Bioreactors \(clu-in.org\).*](#)

3.2 Injection Well PRBs

PRBs can also be created using subsurface injections. Under the injection approach, a soluble or semi-soluble carbon substrate² (e.g., emulsified vegetable oil [EVO]) is injected in a series of wells to promote denitrification within the groundwater prior to entering surface waterbodies. The amendment distributed into the subsurface adheres to the aquifer sediment and gradually releases carbon, forming an anaerobic treatment zone. The residence time of the groundwater within the PRB is controlled by the groundwater velocity and the size of the injected amendment zone along the direction of groundwater flow.

The injections must be performed to achieve sufficient distribution through the reaction zone while still maintaining the permeability of the reactive barrier to allow groundwater to flow through the treatment zone. Injection wells are typically aligned in a row perpendicular to the direction of groundwater flow and screened throughout the depth and width of the contaminant plume. Sometimes multiple lines of wells are used. Amendment is injected through these injection wells until the target injection volumes are achieved. To verify the injection radius, groundwater screening can be performed using temporary or permanent well points during injection activities. The type of field screening method used to determine the radius of influence of the injection varies based on the type of amendment used.

Injected carbon substrates generally last for less than three years. After the carbon substrate has depleted, reinjections can be performed to restore the PRB. A design professional will work with the municipality to select the best carbon source, injection well spacing, and the frequency of injections for the site.

Which PRB type is more feasible at a specified location depends on a variety of factors. Table 1 provides a summary of the site characteristics or considerations to contemplate when deciding which PRB type is more appropriate at a prospective site.

2 In this document the following terms are used interchangeably: carbon substrate, amendment, reactive media and reactive PRB media.

Table 1. PRB Groundwater Treatment Technology Comparison		
Considerations	Trench PRB	Injection PRB
Site access	Requires access to a larger area for trenching equipment	Can be installed where site access is more limited depending on the drill rig needed to install the injection points and perform injections, but areas with obstructing overhead utilities may not be suitable
Groundwater flow velocity	Suitable for all groundwater velocities	Caution using in high groundwater velocity areas (i.e., higher than 2 feet per day) to prevent injected amendment (e.g., emulsified vegetable oil or EVO) from being carried downgradient
Nitrate/nitrite	Concentrations are elevated and steady	Concentrations are elevated and steady
Depth of nitrate/nitrite contamination	Contamination shallower than 40 feet below ground surface	Can address contamination at any depth, including deeper than 40 feet below ground surface
Soil properties	Suitable for all sediment properties, but trench reactive media must be at least as permeable as the surrounding soil	Avoid soil composed of gravels and coarse sands with high permeability and little to no silts/clays because injected carbon source may not stay in place but be mobilized easily.
Land disturbance	Significant land disturbance due to earthwork required	Minimal land disturbance and earthwork required
Reactive media (i.e., amendment) selection	Reactive media choices are not limited by installation technology	Reactive media choices are limited to those that can be injected
Treatment duration	Suitable for longer project durations (i.e., nitrogen treatment longer than 5 years)	Suitable for short or longer project durations
Corrective measures	Once installed, it is difficult/costly to modify or remove	Number of injection wells, injection frequency, and volume and amendment composition can easily be modified



Figure 7. Emulsified Vegetable Oil Injection at Environmental Remediation Site.

Source: [Protocol for Enhanced In Situ Bioremediation Using Emulsified Edible Oil \(clu-in.org\)](#).

Chapter 4: Roadmap for Site Screening, Design, Installation, and Performance Monitoring of Permeable Reactive Barriers

The roadmap toward a PRB installation is a multi-step process to ensure that a location that is not suitable for a PRB installation can be eliminated early in the process, a PRB installation at a suitable site is feasible, and the PRB will be designed to maximize effectiveness and minimize environmental risks.

The roadmap for site screening, design, installation, and maintenance for PRB installation is outlined in Figure 8. The process may start with online site screening activities using web map application tools, followed by an initial site investigation and a feasibility assessment. The goal is to identify a location where there are elevated levels of legacy nitrogen in groundwater, if the hydro-geological conditions are, in principle, suitable for a PRB installation, and if a groundwater PRB technology is a

feasible mitigation approach to address the problem. During the comprehensive site investigation, a more detailed study is performed to confirm that the prospective site is suitable for PRB installation, determine which type of PRB installation method would be appropriate and cost-effective, and gather the information to assess the feasibility of a PRB installation. Considering the site-specific conditions, the feasibility report should include a comparison of the different PRB technologies and other mitigation options in terms of cost-benefits (i.e., cost per pound of nitrogen removed). The information collected during the comprehensive site investigation will also inform the final PRB design and associated permitting. This chapter ends with an overview of PRB installation considerations and guidance on performance monitoring.

	Goals	Possible deal breakers
➤ Step 1 Online Site Screening ➤ Step 2 Initial Site Investigation ➤ Step 3 Feasibility Assessment	✓ Identification of a potentially suitable site that warrants further investigation during the comprehensive site characterization ✓ Preliminary assessment of cost-benefits against alternative mitigation options	➤ Property owner doesn't agree to PRB installation ➤ Historic or archaeological regulations prohibit installation ➤ Structures (above or below ground) interfere with prospective PRB installation ➤ No elevated nitrate in groundwater ➤ Other mitigation option are likely more effective
➤ Step 4 Comprehensive Site Characterization ➤ Step 5 Feasibility Study	✓ Data collection to confirm that the site is suitable and inform PRB design ✓ Assessment of cost-benefits against alternative mitigation options	➤ Geologic or hydrological conditions that may result in an ineffective PRB or a PRB that has negative environmental or human health impacts ➤ Cost-benefits analyses indicates a PRB installation is not feasible and/or other options are likely more cost-effective (cost per pounds of N removed)
➤ Step 6 PRB Design ➤ Step 7 Permitting ➤ Step 8 PRB Installation	✓ PRB design report that includes details on the selected PRB type, dimensions, placement, media composition, installation costs, and nitrogen load reductions.	➤ Necessary permits cannot be obtained
➤ Step 9 Performance Monitoring	✓ Confirmation of system effectiveness and cost-benefits	

Figure 8. Steps toward a successful PRB implementation to address a legacy nitrogen problem.

4.1. Step 1: Online Site Screening

In the online site screening step, use web map application tools to initially assess whether a location may be suitable for a PRB installation. After identifying a site where legacy nitrogen is likely to cause a problem in downstream receptors (e.g., surface waters and/or public or private drinking water supply wells), individual property parcels of land have to be identified that may overlie that impacted groundwater. For each identified parcel, the following tasks should be completed to assess if an initial site investigation can or should be performed.

4.1.1. Identify Land Ownership of Selected Location(s)

Once a possible site is identified, permission for the initial and comprehensive site investigations, the potential PRB installation, and performance monitoring must be granted from the party who owns the property, whether it be a public or private entity.

The owner of the land is provided on county tax maps. Refer to the parcel tax maps:

- Nassau County tax map link: <https://lrv.nassaucountyny.gov/> (If the link is broken, internet search on “Nassau County Land Records Viewer.”)
- Suffolk County tax map link: <https://gisapps.suffolkcountyny.gov/rptmviewer/>. (If the link is broken, internet search on “Suffolk County ArcGIS Web Application.”)
- *Deal Breaker:* If the owner declines to grant permission, there is no need to move on to the initial site investigation. If possible, identify a new site and start the assessment from the beginning.

4.1.2. Identify All Structures on the Property

Review aerial photos (e.g., Google Maps) and, if available, review maps and property surveys to check what structures or utilities are on the proposed site above and below ground. Ensure that there are no structures or utilities (e.g., overhead power lines) that would interfere with the construction or are located where a PRB would be placed. If a structure exists on or in proximity to the potential PRB location, it

may interfere with the installation or at least require additional considerations during design (e.g., utility relocation).

- *Deal Breaker:* Trench-and-fill PRBs cannot be installed under a building or within 15 feet of a structure. If a structure or utility lines (water, electricity, or natural gas) are interfering with the proposed PRB location, an injection well PRB might still be an option if reactive media can be injected in a sloped manner. However, belowground structures downstream of a PRB can constitute a health and safety concern as gases (e.g., methane or hydrogen sulfide) can be present within the redox recovery zone (see 4.1.4.). If a PRB interferes with existing structures or utility lines or is in close proximity to subsurface structures so that there are risks related to health and safety, there is no need to move on to the initial site investigation. If possible, identify a new site and start the assessment from the beginning.

4.1.3. Find Out if There are Significant Environmental, Cultural, or Historical Restrictions

The following are common sources of information about environmental, cultural, and historical restrictions. There may also be local sources that can provide additional information.

- Refer to the Cultural Resource Information System for cultural, or historically significant areas that may have restrictions at <https://cris.parks.ny.gov/>. (If the link is broken, internet search on “NY Parks Cultural Resource Information System.”)
- DEC Environmental Resource Mapper for significant environmental restrictions at <https://gisservices.dec.ny.gov/gis/erm/> (If the link is broken, internet search on “NYS DEC Environmental Resource Mapper.”)
- Historic Sanborn maps can help get more accurate historical information for the site. The New York Public Library Digital Collections has an extensive list of Sanborn Maps which can be found at <https://digitalcollections.nypl.org/collections/atlas-of-new-york-city/#/?tab=navigation&roots=30593990-bc6a-0132-4f30-58d385a7bbd0/721227b0-c5f7-012f-c979->

[58d385a7bc34](#). (If the link is broken, internet search on “NY Public Library Digital Collection Atlases of New York.”)

- County Health Departments or Building Departments may have historic records of subsurface structures.
- *Deal Breaker:* A PRB cannot be installed if any significant environmental, cultural, or historical restrictions exist at the site that will be harmed or disturbed during the installation of the PRB. If there are any significant restrictions that prohibit the installation of a PRB, there is no need to move on to the initial site investigation. If possible, identify a new site and start the assessment from the beginning.

These online analyses may indicate that permits to install sampling wells and potentially a PRB at the prospective site may be required by local, state, or federal regulatory agencies. Sites adjacent to fresh water or tidal wetlands may require permit reviews by DEC or local town agencies; sites with historic or cultural value may require review by the New York State Historic Preservation Office within New York State Parks, Recreation and Historic Preservation. Since these reviews often take time to complete, it is recommended to start the application process for the required reviews once a feasibility assessment (Section 4.3) has determined that the project should proceed to a comprehensive site characterization (Section 4.4).

4.1.4. Find Out if There are Public or Private Drinking Water Supply Wells in Close Proximity of the Envisioned PRB Site

Given the modification of groundwater chemistry by a PRB, great care should be taken that there are no public or private drinking water supply wells within close proximity that could be affected by the envisioned PRB. The redox recovery zone should be at least 60–100 days of groundwater travel time. For example, if the groundwater velocity is 2 feet per day, the PRB would need to be installed 120–200 feet upgradient of any drinking water supply wells. If the presence of drinking water supply wells is unknown, a municipality should contact the county’s health department to determine if drinking water supply wells exist within the redox recovery zone.

- *Deal Breaker:* A PRB cannot be installed if public or private wells are within the redox recovery zone of a PRB.

4.1.5. Estimate the Depth to Groundwater

Depth to groundwater at a specified location can be determined using the USGS Long Island Depth to Water Viewer at <https://ny.water.usgs.gov/maps/li-dtw/>. (If the link is broken, internet search on “USGS Long Island Depth to Groundwater and Hydrologic Conditions Viewer.”)

- *Deal Breaker:* A woodchip-based PRB is not a viable option if the depth to groundwater is greater than 40 feet below grade. In this case, consider an injection well PRB.

4.1.6. Estimate Groundwater Flow Direction and Velocity

A PRB must be placed approximately perpendicular to the predominant groundwater flow direction to be effective. The volume of woodchip or carbon fluid will be determined so that there is sufficient reactive PRB media to remove legacy nitrogen once oxygen becomes depleted, but no more than necessary to minimize the risk of forming unintended by-products. Groundwater velocity determines how much water will be treated per unit of time and thus is a critical parameter that determines the optimal thickness and feasibility of a trench-type PRB. If groundwater velocities are high (greater than 2 feet per day) and/or the ambient soil is composed of gravel and coarse sands and little to no silts/clays, the injected amendment may be carried downgradient and the site may not be suitable for an injection PRB. Groundwater flow direction and velocity at a site are two of the most important parameters determined during the comprehensive site investigation, but first approximations of horizontal hydraulic gradient and soil hydraulic conductivity to estimate flow direction and velocity can be derived using USGS and the U.S. Department of Agriculture (USDA) web map applications, respectively. Details on how to derive the necessary information is given in Appendix B.

- *Deal Breaker:* If the PRB cannot be placed perpendicular to the likely groundwater flow direction at the site, a PRB is not viable and there is no need to move on to the initial site investigation. If groundwater velocities and soil composition are not suitable for the injection amendment, an injection PRB is not viable.

4.2. Step 2: Initial Site Investigation

If a site seems suitable for a PRB installation based on the information gathered during the online site screening, the next step is to conduct an initial site investigation to decide if it makes sense to conduct a comprehensive site investigation. The following field tasks should be completed during the initial site investigation:

4.2.1. Confirm Adequate Area is Available and the Proximity to Downgradient Receptors

Conduct a site visit and confirm that adequate area is available and accessible for the installation and construction of a PRB. Confirm distances to property lines, wells, wetlands, or other structures identified in the online site screening. For example, make sure that sufficient space is available to work with machinery used for an installation, e.g., trenching machinery or a Geoprobe® to install groundwater wells. A subsurface utility mark-out should be ordered to locate any subsurface structures, such as gas or water lines, septic tanks, electrical cables, etc. Assistance for obtaining a mark-out can be found at <https://newyork-811.com>. (If link is broken, internet search on "New York 811"). Additional mark-outs are recommended for private subsurface structures.

- *Deal Breaker:* A PRB is not a feasible solution if there is not enough area available for the construction of a PRB, the site is not accessible for machinery needed for installation, utility lines or subsurface structures would interfere with an installation and cannot be easily relocated, or there are health and safety concerns in relation to belowground structures downstream.

4.2.2. Measure Depth to Groundwater and Characterize Groundwater Quality

To confirm that there is a legacy nitrogen problem and assess whether nitrate and nitrite are the dominant forms of nitrogen pollution at the site, at least three temporary groundwater sampling wells should be installed approximately parallel to the envisioned PRB. The sampling wells will be used to measure depth to groundwater and collect groundwater samples from multiple depths, covering

the approximate width and depth of the envisioned PRB. Sample collection during the initial site visit may be completed with a manual or powered auger for shallow wells. Deeper sampling may require a professional using direct push drilling technologies. Sites with hard soil or cobble would require a sonic drill rig or other specialized equipment. These approaches are generally more expensive than conventional drilling methods and should be reviewed carefully by a design professional. Samples collected for analytical work should be analyzed by a New York State Environmental Laboratory Approval Program (ELAP) accredited laboratory to determine concentrations of nitrate, nitrite, ammonia, and dissolved organic nitrogen (e.g., TKN-ammonia).

- *Deal Breaker:* If nitrate and nitrite are not the dominant forms of groundwater nitrogen or nitrate, and nitrite pollution is very localized (e.g., most samples do not have elevated nitrate and nitrite concentrations), a PRB is not a viable option.

4.3. Step 3: Feasibility Assessment

Up to this point, the site assessment has not necessitated any large expenditures. The search for publicly available information requires multiple hours on various websites; additionally, preliminary sampling may require expenses for a sample collection and certified analysis. Otherwise, no services requiring professional licenses or certifications are needed. However, the steps which follow the initial site investigation require licensed professionals (e.g., engineers and installers) and possibly heavy equipment. Therefore, the completion of the initial site investigation is a good time to review the information gathered for the site and assess the feasibility of a PRB installation. Beyond single factor “deal-breakers” described above, all factors impinging on the decision to move toward a comprehensive site characterization should be considered. The feasibility assessment may be used as the basis for the narrative of grant applications to fund the work that will need to be conducted during the comprehensive site characterization.

Based on the expected groundwater velocity at a prospective site and the assumption that the nitrate and nitrite concentrations measured during the initial site investigation are representative for the PRB location, the nitrogen removal potential of a PRB with some envisioned dimensions can be estimated as described in Appendix C.

The actual cost of a PRB installation will not be known until a design professional completes the project design; however, during the feasibility assessment, a cost estimate can be obtained from a design professional and/or installers to derive a cost per pound of nitrate/nitrite removed over the expected life of the system. This estimate would then allow comparison with other mitigation approaches based on published information (e.g., SWP, 2020, p. 260). Under no circumstances should PRBs be used as an alternative to treatment of nitrogen at the source (i.e., connection to a sewer or installation of a nitrogen-removing I/A OWTs).

4.4. Step 4: Comprehensive Site Characterization

If the feasibility assessment indicates that a PRB is practicable, the next step is a comprehensive site characterization to assess if the suitability of the prospective PRB site can be further confirmed during site visits and on-site measurements. During the comprehensive site characterization, the hydrological setting and groundwater nitrogen plume will be characterized in more detail. Based on the data collected during the comprehensive site characterization, the end product is a feasibility report and then a design report stamped by a professional engineer, which includes details about the PRB design and placement.

Appendix D provides detailed information on field tasks that have to be completed during the comprehensive site characterization. These should be considered by the project hydrogeologist and/or engineer when preparing the drilling work plan.

A clear conceptual site model should emerge from the comprehensive site characterization regarding groundwater elevations, groundwater flow direction and velocity, the distribution of nitrogen concentrations in groundwater, and the presence of any confining layers (e.g., a clay layer in the continuous core, peat/bog/meadow mat, etc.).

Confining layers can influence groundwater flow and knowing the depth and thickness of the confining layer, in addition to the depth to groundwater, helps to make the decision on PRB type and placement. In general, confining layers of the aquifer should not be pierced by a PRB, unless it is documented that the layer is discontinuous and the installation of the PRB would not adversely impact groundwater beneath the confining layer.

- *Deal Breaker:* If a PRB would intersect a confining layer of the aquifer, a PRB is not a viable solution, unless it is documented that the layer is discontinuous and installation of the PRB would not adversely impact groundwater beneath the confining layer.

The data collected during the comprehensive site characterization will enable consultants and design engineers to create a feasibility report with details on the PRB type, its dimensions and placement, reactive PRB media composition, installation costs, and nitrogen load reductions. In some cases, design professionals may decide that to properly design the PRB, additional monitoring wells and longer-term monitoring are necessary to further assess site characteristics.

- *Deal Breaker:* If the comprehensive site characterization reveals strong variations in groundwater velocities and nitrate and nitrite concentrations (e.g., localized plumes of nitrate and nitrite) along the envisioned PRB or over time, a PRB may not be suitable at the site.

4.5. Step 5: Feasibility Report

The data collected during the comprehensive site characterization will allow for informed decision-making when selecting which type of PRB (woodchip-based or carbon injection) is the appropriate approach to address the legacy nitrogen problem at the site. The choice will depend on the site's accessibility, the hydro-geological conditions, depth and distribution of the nitrogen plume, and the expected duration contaminated groundwater will flow through the PRB. Major considerations are summarized in Table 1.

Based on the expected nitrogen load reductions and implementation costs, a cost-benefit analysis should be conducted in which the cost spent per pound of nitrogen removed is estimated. Woodchip-based PRBs can be expected to be functional for at least 10 years (Robertson et al. 2000, Long et al. 2011). For carbon injection PRBs, the costs of repeated injection should be included in the cost-benefit analyses. The feasibility report should compare the effectiveness and feasibility of the proposed approach with other mitigation approaches that could address the legacy nitrogen problem at the site.

4.6. Step 6: PRB Design

A design report, prepared by the design professional, should include details on the selected PRB type, dimensions, placement, reactive media composition, installation costs, and nitrogen load reductions. This report should include drawings and specifications to guide the installation.

4.6.1. Trench-Type Woodchip-Based PRB Design

Trench-type woodchip-based PRBs may be a feasible approach if legacy nitrogen is present less than 40 feet below grade. Woodchip-based PRBs require minimal maintenance. Trench-type configurations are the most common type of woodchip-based PRBs, but other configurations are possible. For example, woodchip column arrays with PRB material that's augured into multiple rows may be a good alternative where site access or utilities prevent the mobilization or operation of trenching equipment or where deeper treatment is desired. Funnel and gate PRBs direct groundwater toward a treatment zone. This can be achieved by creating subsurface funnels with sheeting or other means. Since water velocities in the reactive PRB media are significantly increased by this method, the thickness of the PRB must be increased accordingly.

A design professional will work with the municipality to select the best reactive PRB media arrangement and composition, dimensions (width, depth, and thickness of a woodchip-based barrier) and placement for the site.

Based on nitrate and nitrite data, depth to groundwater measurements, and the presence or absence of confining layers, the design professional will recommend the depth horizon that should be treated. It is typically more effective and cost-efficient to build a PRB that is wide, rather than narrow and deep (Robertson et al. 2005), but the aim is to intercept groundwater at the depths with the highest nitrate and nitrite concentrations and to ensure that the PRB design does not adversely impact the local groundwater flow field.

Locally available woodchips are preferred over commercial woodchips that are non-native to Long Island, not only to minimize transportation costs but also because such commercial woodchips may have been sterilized, treated with pesticides, or conversely, may contain the eggs, larvae, spores, adults, or even seeds of invasive species that could get locally

released. The design professional shall then certify that the woodchips used are virgin material that has not been treated with creosote, chromated copper arsenate, or pentachlorophenol. The certification statement should read, *"To the best of the design professional's knowledge and belief, the woodchips material being used is Certified Clean and not contaminated pursuant to any applicable standards."* In certifying the woodchips, the design professional shall identify the steps taken to validate conformance with this requirement. Check with your local permitting agency/agencies to see if any additional certification information or language is required.

If the woodchips are obtained from a commercial processing facility, the name and location of the processing facility shall be provided. The composition of the PRB media has to be considered and optimized for site-specific conditions. The addition of pea gravel (typical in a 1:2 volumetric mixture of pea gravel and woodchips) avoids clogging over time and ensures that the PRB matrix will remain at least as permeable as the surrounding soil—otherwise, water will flow around the PRB media and the PRB would be ineffective. Pea gravel also lowers the risks of subsidence over time. Laboratory tests should be conducted to confirm that there are no contaminants in the aggregate material.

The choice of PRB thickness is probably the most important design feature to ensure that the system will function properly. The thickness should be chosen so that nitrate and nitrite are removed, but great care must be taken to not overtreat groundwater. A too-thick PRB would increase the risk of unintended by-product formation, such as sulfide and methane, and the release of such by-products to downgradient environments or the atmosphere. The nitrate removal potential of woodchip PRB media varies between wood type (e.g., hardwood versus softwood), woodchip age and size, and the amount of inert aggregate mixed into the media. More information on woodchip placement options and woodchip type selection are given in Appendix E.

4.6.2. Injection Well PRB Design

Carbon injection wells may be a feasible approach and may be particularly helpful if site access prevents the mobilization of trenching equipment or if the nitrogen plume is at a depth that cannot be accessed by trenchers. In a carbon injection PRB, a source of carbon is pumped through multiple injection wells. The PRB media distributed into the ground adheres to the soil particles and gradually releases carbon,

forming an anaerobic treatment zone that endures for up to three years. EVO typically lasts longer as a source of carbon than other carbon sources such as molasses, corn syrup, or other simple sugars. The design will need to consider the following PRB components:

Select Carbon Amendment: Available carbon sources include both “fast release” carbon sources that are readily soluble, such as feed-grade or food-grade molasses or corn syrup, and “slow release” carbon sources that are only slightly soluble and dissolve slowly over time, such as food-grade EVO or cheese whey. Fast release carbon sources are inexpensive and easy to inject, but require frequent maintenance injections (monthly to quarterly, depending on the groundwater velocity and injection volume) and tend to migrate readily. Slow-release carbon sources cost more but can significantly decrease the frequency of injections (typically last one–three years in fast-moving groundwater). There are several commercially available proprietary carbon sources available that are tailored to the environmental remediation industry. A design professional will work with the municipality to select the best carbon source for the site. Desired criteria for the carbon source include:

- Effectiveness in achieving denitrification
- Minimal effects on hydraulic conductivity
- Minimal ability to migrate
- Non-toxic
- Mild color

More details on carbon source criteria are given in Appendix F.

Estimate Radius of Influence: The design professional will conduct a test to determine the radius of the reactive PRB media once it is in the groundwater. This is done to ensure that the reactive PRB media from each well overlaps sufficiently to treat legacy nitrogen.

Select Delivery Configuration: Injection wells are typically installed along a center line, or along two parallel center lines slightly offset. These center lines are oriented roughly perpendicular to groundwater flow. Injections can be performed either via permanent or temporary injection wells that are

placed in either two alternating rows or are spaced closer together within the same row to provide a safety factor and minimal overlap to the conceptual injection radius of influence. More information on the carbon injection procedure and amendment dosing are given in Appendix E.

4.7. Step 7: PRB Project Permitting

The design professional will evaluate the design to determine what permits and/or work plans, if any, may be necessary prior to construction (e.g., well installation drilling permits, wetland permits, underground injection control (UIC) permits, erosion and sediment control plans, community air monitoring plan, etc.). Consult with the permitting agencies to ensure the design is permissible.

Here are common permitting activities to anticipate:

- **SEQR Environmental Review:** [New York's State Environmental Quality Review Act \(SEQR\)](#). If the link is broken internet search on "NYS SEQR.") requires all state and local government agencies to consider environmental impacts in the decision-making process at the earliest possible time. Once the PRB design and engineering report is complete, the municipality should initiate the SEQR review for the project, as outlined in 6 NYCRR Part 617, by filling out and submitting an Environmental Assessment Form.³ SEQR laws require that all local, regional, and state government agencies complete an environmental review of projects that have the potential to adversely impact the environment. Any potential wetland impacts will likely be covered within the SEQR review. All PRBs involve the placement or injection of reactive media directly into groundwater, which changes the hydrology and geochemistry of the groundwater. A properly designed and placed PRB will minimize the risk of any undesired outcomes. The lead agency will provide a SEQR determination and indicate whether any additional actions (e.g., environmental impact statement, public hearings) are needed on the proposed action.

³ Department of Environmental Conservation (DEC) State Environmental Quality Review Act (SEQR) <https://dec.ny.gov/regulatory/permits-licenses/seqr>

- **Wetlands Permit:** If the project site is within a wetlands setback, coordinate with the U.S. Army Corps of Engineers, DEC, or local authorities regarding necessary permits.
- **Erosion and Sediment Control Plans:** Before commencing construction activity, the owner or operator of a construction project that will involve soil disturbance of one or more acres must obtain coverage under the State Pollutant Discharge Elimination System (SPDES) General Permit for Stormwater Discharges from Construction Activity.
- **UIC “Authorized by Rule”:** EPA has program requirements for permitting underground injection of diesel fuels in hydraulic fracturing to ensure protection of underground sources of drinking water (USDWs). Visit the webpage [Protecting Underground Sources of Drinking Water from Underground Injection \(UIC\) | US EPA](#) to learn more about project permitting requirements.
- **Drinking Water Source:** Contact the public water purveyor for the area the PRB will be located or the county health department to determine if a permit is needed.
- *Deal Breaker:* If the necessary permits cannot be granted, then the PRB cannot be installed.

4.8. Step 8: PRB Installation

The PRB installation method should be determined in collaboration with the design professional and installation contractor. Appropriate construction work plans should be prepared and permits obtained. Below are some considerations for the municipality to discuss with the design professional and contractor in preparation for a PRB installation.

Installation Work Plans

An installation work plan, regardless of the type of PRB chosen, should be developed that describes the means/methods for installation and required permits or other regulatory-driven activities, such as erosion and sediment control, dust suppression, site control/access, etc. Health and safety are paramount, and work should be done under a project health and safety plan. Further woodchip PRB installation considerations and injection well PRB considerations are given in Appendix E and Appendix F, respectively.

4.9. Step 9: PRB Performance Monitoring

Following installation, nitrogen removal performance of the PRB should be monitored in accordance with a long-term monitoring plan and a Quality Assurance Project Plan (QAPP) to (1) ensure the PRB is functioning properly both in terms of nitrogen removal and hydraulically, (2) track formation and fate/transport of any secondary by-products, and (3) identify when carbon (woodchips or injection well fluids) replenishment is needed. The monitoring plan should include a QAPP to ensure sample collection methods and analysis conform with stated quality standards. Templates for drafting a QAPP are available from the US EPA and NYS DEC at:

<https://www.epa.gov/quality/guidance-quality-assurance-project-plans-epa-qag-5>

https://dec.ny.gov/docs/water_pdf/qapptemplate721.pdf

Monitoring wells should be installed at varying distances upgradient and downgradient from the PRB. Many of these wells will have already been installed during the site investigation and characterization phases.

PRBs should be sampled at least quarterly during the first year after installation and annually thereafter. During each sampling occasion, the direction of groundwater flow at the site and through the PRB should be assessed to evaluate if the PRB is clogging and/or adversely impacted by changes in the groundwater flow direction. Groundwater samples should be collected from all upstream and downstream transect wells to assess nitrate and nitrite removal; confirm that the conditions for biological remediation are maintained; and evaluate the magnitude, fate, and transport of secondary by-products, if present. Recommended parameters for analysis include nitrate, nitrite, ammonia, dissolved organic nitrogen (e.g., TKN-ammonia), total organic carbon (TOC), dissolved iron, and methane. If samples from downstream wells show diminishing or little nitrate/nitrite removal or high or increasing levels of methane or dissolved iron, the design professional should be contacted to assess viable solutions to remedy the problem(s). During each sampling occasion, the direction of groundwater flow at the site and through the PRB should be assessed to evaluate if the PRB is clogging and/or adversely impacted by changes in the groundwater flow direction.

Both trench-type and injection well PRBs may require carbon replenishment at some future date. This point in time can be determined when TOC concentrations within or downgradient of the PRB begin to decrease to a point that nitrate concentrations increase, possibly reaching as high as the nitrate concentrations measured upgradient of the PRB. At this point, it is clear that the carbon source is no longer generating sufficient carbon to denitrify the nitrate and nitrite. The plan to replenish the carbon should then be implemented.

Chapter 5: Summary

To address the nitrogen problem in New York State and, specifically, on Long Island, a multipronged approach is needed. First and foremost, ongoing and future nitrogen release to groundwater must be reduced. Many initiatives are underway to address nitrogen pollution at the source.

The installation of denitrifying PRBs can be a feasible and cost-effective option to help address legacy nitrogen. Without treatment, nitrate enriched groundwater will continue to seep into surface waters in the coming years and decades. PRBs must be strategically placed and correctly designed to be effective. This document gives guidance on how to identify suitable locations, best practices for site characterization to inform PRB design, permitting, and recommendations for construction and performance monitoring. By putting together this information, it is the hope that municipalities will consider PRBs as one tool in the toolbox when addressing the nitrogen problem in their community and benefit from a more streamlined process from PRB site screening to implementation.

Appendix A

Obtaining Groundwater Nitrogen Concentration Data From USGS Website

At the time of publishing this guidance document, USGS's Water Data for the Nation (WDFN) website is under development. The website will allow users to view and download groundwater quality and field sample data. For more information and instructions on how to download data visit <https://waterdata.usgs.gov/blog/wdfn-access-discrete-data/>.

Appendix B

Estimating Groundwater Velocity Using Web Map Applications and Field Measurements

Knowledge of the groundwater velocity at a prospective PRB site is critical for PRB design and feasibility assessment. If the linear groundwater velocity is very low (less than 0.5 feet day⁻¹) the volume of water that would be treated will be small and a PRB would not be a cost-effective means of treating nitrogen, unless groundwater nitrate concentrations are very high. The thickness of a trench-type PRB should be chosen so that there is sufficient reactive PRB media to remove legacy nitrogen once oxygen becomes depleted, but not too thick as this would increase the risk of unintended by-product formation.

Groundwater direction and velocities based on soil characteristics and hydraulic conditions from web map applications should be viewed as rough first estimates. The local conditions may be different and more complex and must be characterized on-site through groundwater level monitoring and/or injection testing.

The linear groundwater velocity is controlled by the soil's hydraulic conductivity, the horizontal hydraulic gradient, and the soil porosity at a given site. Use the following equation to calculate the linear groundwater velocity:

$$\text{linear groundwater velocity (feet per day)} = \frac{\text{soil hydraulic conductivity (feet per day)} \times \text{horizontal hydraulic gradient (feet per foot)}}{\text{effective porosity } (\phi)}$$

- **Soil Hydraulic Conductivity:** Hydraulic conductivity controls the groundwater velocities along a hydraulic gradient. Therefore, the hydraulic conductivity of the soil (in combination with the hydraulic gradient and soil effective porosity, outlined below) at the site will allow an estimate of how much water will be treated by a PRB. A rough estimate of hydraulic conductivity of soil at the potential PRB site can be obtained using the USDA Web Soil Survey web application, but it will need to be measured directly for proper design of an installation during the comprehensive site characterization.

Follow these steps to estimate the hydraulic conductivity at the specified site:

Go to <https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm> (If the link is broken, internet search on “USDA Web Soil Survey”) and click the green Start WWS button. On the map, zoom into the region of interest. Choose a scale of less than 1:20,000. Draw a box of the area of interest that includes the prospective PRB site using the AOI tool(s). Navigate to the Soil Data Explorer tab and click on Soil Properties and Qualities tab. Click on Soil Physical Properties then select Saturated Hydraulic Conductivity (Ksat), Standard Classes. Once selected, under advance options, select the following:

Aggregation Method	Weighted Average
Component Percent Cutoff	Leave blank
Tie-break Rule	Fastest
Interpret Nulls as Zero	Cannot be selected – leave blank
Layer Options (Horizon Aggregation Method)	All Layers (Weighted Average)

Once the advance options are selected as above, click on View Rating. The map now displays polygons that represent areas with similar hydraulic conductivities. Determine the Map Unit Symbol of the area in which the PRB is going to be located. The hydraulic conductivity rating for that area is displayed in the table below the map and is given in micrometers per second. Convert from micrometer per second to feet per day by multiplying by 0.283.

- **Horizontal Hydraulic Gradient:** USGS web map application “Long Island Depth to Water and Hydrologic Conditions Viewer” is located at <https://ny.water.usgs.gov/maps/li-gc/> and displays the “depth to water” in 2016. (If the link is broken, internet search on “USGS Long Island Depth to Water and Hydrologic Conditions Viewer.”) A data layer “surface of the water-table aquifer” can be added in the application to visualize lines of equal water-table altitudes. To add this layer, click on the dark blue layer box at the top right-hand corner of the screen and a “Data layers” pop up will open. Click on the Hydrologic Conditions 2016 group, and then click on the Surface of the water-table aquifer layer to view the layer on the screen. The direction of flow will be

approximately perpendicular to lines of equal water-table altitude. Close to the shore (within approximately 500 feet), groundwater flow can be expected to flow perpendicular to the shoreline. The horizontal hydraulic gradient across the potential PRB site can be estimated by dividing the difference in water-table elevation by the horizontal distance between two points, which can be determined with the application's "measure" tool.

- **Porosity:** Porosity is the pore space volume, i.e., the fraction of pore space that is occupied by water under water-saturated conditions. This parameter is needed to determine linear groundwater velocities. Porosity includes both mobile pore space and immobile pore space. Mobile pore space (e.g. "effective porosity") is a pore space that actively transports groundwater and drives groundwater velocity. Immobile porosity does not transport groundwater, but acts as a reservoir (sink) for contamination due to diffusion, which impacts the overall groundwater treatment timeframes (including the time it takes clean groundwater from a PRB to reach a downgradient receptor). Total porosity (mobile plus immobile) is determined by weight loss after drying a known volume of water-saturated soil. The fraction of mobile and immobile porosities may be determined from lab tests or through the injection test. If porosity data is not available, use a range of values of 0.15–0.30—which is a typical effective porosity value range of sandy soil.

After the comprehensive site characterization, a more accurate estimate of the groundwater velocity and flow direction at the site will be estimated. Groundwater velocities and flow direction at the site can be either directly derived from tracer injection tests or calculated using the equation above.

Appendix C

Estimating Nitrogen Removal Potential of a PRB

Based on the expected groundwater velocity at a prospective site, the volume of water that passes through a PRB can be estimated by:

$$\text{Volume treated (L feet}^{-2} \text{ year}^{-1}) = \text{Linear groundwater velocity (feet day}^{-1}) \times \text{porosity} \times 28.3 \text{ L feet}^{-3} \times 365.25 \text{ days year}^{-1}$$

For example, if the groundwater velocity is 2 feet day⁻¹ and assuming a porosity of 0.30, the volume treated per foot² cross section of the PRB per year would be 6,615 LFT.

Assuming that all nitrogen that passes through the PRB is removed, the nitrogen removal per foot² of PRB cross-section per year can be calculated as:

$$\text{N removal (pounds feet}^{-2} \text{ year}^{-1}) = \text{Volume treated (L feet}^{-2} \text{ year}^{-1}) \times \text{nitrogen concentration (mg-N L}^{-1}) \times (453,593 \text{ mg/pounds}^{-1})$$

For the above example, and if the nitrogen concentration is expected to be 10 mg L⁻¹, the N removal per foot² per year would be 0.146 pounds.

Thus, a 100-feet-wide and 20-feet-deep PRB would remove 292 pounds of N year⁻¹. For context, a typical septic system in the US releases 4.6- 13.6 pounds of N per year (EPA, 2002).

Appendix D

Typical Field Tasks for Comprehensive Site Characterization

Field Task	Description of Task	What Task Helps Determine
Installation of shallow groundwater-level monitoring wells (alternatively, tracer injection test, see below)	At least three groundwater-level monitoring wells, ideally at least 100 feet apart, should be installed at the site. Wells should be arranged in a triangle in accessible areas that provide the best coverage possible for determining local hydrologic and water-quality conditions. Wells should be: • Screened approximately 5–10 feet below the anticipated annual mean water table elevation, • Installed by an auger or using a direct-push drilling method or equivalent, • Constructed typically of two-inch inner diameter polyvinylchloride (PVC) tubes with a five-foot-long (1.5-m) well screen or equivalent, and • Surveyed using common horizontal and vertical datums. Differential leveling should be used to determine the elevation of the top of each well casing with respect to a nearby location with a known vertical datum (e.g., NAVD 88). The depth to groundwater measurements should be related to this mark.	• Groundwater flow directions • Horizontal hydraulic gradients • Groundwater velocity (once soil hydraulic conductivity is known) • Shallow water quality

Field Task	Description of Task	What Task Helps Determine
Tracer injection test minimum requirements, full injection test plan to be developed by engineer (alternatively: installation of shallow groundwater-level monitoring wells, see above)	Installation of 1) at least one injection well with neat cement seal, 2) at least three monitoring wells located within the intended radius of influence of the injection, and 3) at least three downgradient monitoring wells (vertical clusters preferred) located ~15 days, 30 days, and 60 days hydraulically downgradient. A single injection of a soluble carbon source (at least 10–15 feet radius) and a conservative tracer such as bromide, fluorescein, or rhodamine is the minimum requirement, and the project engineer will prepare a project-specific injection test plan. During injection: Continuous (every 0.5–1 hour) monitoring of groundwater wells within the anticipated region of injection for the tracer itself for the duration of the injection. The injection pressure must be carefully monitored for evidence of soil fracturing. Post-Injection monitoring: Sampling frequency and duration of test, well configurations, etc., within the region of injection and downgradient wells should be determined by the design professional based upon their general understanding of the local hydrogeology using conventional methods (e.g., hydraulic gradient, conductivity, etc.). In addition to soluble carbon and the conservative tracer, the following parameters should be analyzed: methane (CH₄), hydrogen sulfide (H₂S), iron (Fe), manganese (Mn), arsenic, chromium, pH, oxygen-reduction potential, dissolved oxygen, alkalinity, nitrogen-series, and TOC.	• Groundwater flow direction and velocity using the conservative tracer • Hydraulic conductivity, total porosity, mobile porosity, and secondary porosity (e.g., dead pore space), groundwater velocity • Assessment of changes in groundwater quality after the injection of an organic carbon source

Field Task	Description of Task	What Task Helps Determine
Installation of a water quality monitoring profile well transect	Install at least one well transect, consisting of at least four temporary wells, situated parallel and upgradient to the envisioned PRB location. The distance between wells will be chosen by the professional but should typically not exceed 25 feet. Wells should be situated in accessible areas that provide the best possible coverage for determining water conditions at the envisioned PRB location and may be used as injection wells during PRB implementation. It is recommended: • To use one-inch (2.5-cm) inner diameter polyvinylchloride (PVC) casing fitted with a five-foot-long (1.5-m) well screen or equivalent at the bottom. • Wells should be driven down at least five feet below the envisioned depth of the PRB. After being sampled, wells should be retracted and samples should be collected in approximately five-foot intervals until the screened portion has reached the top layer of the aquifer. Wells can remain at this depth for later sampling. • Once nitrate and nitrite profile data are available, “permanent” monitoring wells should be installed, screened at the depth where the PRB will be situated and where the highest nitrate and nitrite concentrations were found. • Wells should be kept in place for at least one additional set of samples that should be collected within a six-month period to characterize temporal variability of nitrate and nitrite concentrations.	• Depth profiles are snapshots of water quality along a transect just upgradient of the envisioned PRB • Time series of water quality at the center of the envisioned depth of the PRB
Collection of continuous soil cores	At least three continuous cores of the native soil should be collected at the site when a water quality monitoring profile well transect is installed. Soil cores should be collected along the potential PRB at each terminal end and in the middle of the PRB. The cores should be collected at the anticipated center of the PRB and extend from the soil surface to at least 10 feet below the envisioned depth of the PRB. Cores should be logged on site. Representative layers should be subsampled for sedimentological analysis.	• Native soil characteristics, including hydraulic conductivity, porosity, and grain-size composition for all apparently different sediment layers • Check if a confining layer is present
Measurement of water table height	Measure the groundwater level at least twice during approximate seasonal high (spring) and low (end of summer) water table heights in all wells at the site. This includes shallow wells, well clusters, and any other pre-existing or installed wells. It can also be useful to assess groundwater levels after heavy precipitation events or events related to any artificial irrigation at the site. If tidal influence is expected, water table fluctuation should be monitored for at least 14 days with autonomous water level loggers. Ideally, two loggers are deployed perpendicular to the PRB at different distances from the shoreline and one logger is deployed in the tidally influenced surface water downstream of the prospective PRB.	• Groundwater flow rates and velocities • Tide-driven variations in water table height

Field Task	Description of Task	What Task Helps Determine
Collection of water quality samples from well transects	After the initial sampling of depth profiles and once wells are situated at the desired depth, samples from all wells should be collected at least twice during a six-month period. Take readings for the following parameters in the field: dissolved oxygen, oxidation-reduction potential, pH, temperature, and specific conductance. Collect samples for analytical work in the laboratory and determine the following parameters: nitrate, nitrite, ammonia, dissolved organic nitrogen (e.g., TKN-ammonia), and dissolved organic carbon. Samples should be sent to an ELAP certified lab for analyses.	• Nitrate concentrations • Other nitrogen species concentrations • Overall groundwater quality at the site; assess if other contaminants are present
Slug tests	Slug tests can be used to determine the hydraulic conductivity of intact soil. They are performed by adding or removing water quickly from a single groundwater well and measuring the change in water level over time. While the soil's hydraulic conductivity is also determined from soil boring samples and tracer tests, slug tests can be useful to assess if there is any pronounced heterogeneity in soil hydraulic conductivity at the site. Slug tests should be done for at least three wells in the middle and at the terminal ends of the prospective PRB location.	• Hydraulic conductivity • Transmissivity

Field Task	Description of Task	What Task Helps Determine
Offshore porewater survey <i>*Optional for shallow PRBs close to the shore</i>	Contrasts in temperature and conductivity between surface water and marine porewater downstream of a PRB site can inform about magnitude and distribution of groundwater discharge. At the shoreline, the inland vertical groundwater profile becomes horizontal—therefore, analyses of porewater samples collected at similar depths along transects perpendicular to the shoreline can give insights on the vertical distribution of groundwater nitrogen upstream. Porewater should be sampled 50–60 cm below the sediment surface and temperature and conductivity should be measured immediately. Alternatively, a direct-push subsurface probe that measures conductivity/salinity and temperature can be used to measure conductivity and temperature directly in the sediment. The survey should provide the best coverage possible for determining local hydrologic and water-quality conditions, e.g., 2–3 offshore transects, 25–50 feet apart with 5 stations along each transect (10–20 feet apart). Measure the following parameters in porewater and surface water: • Conductivity and temperature; • Geochemical tracers that are known to be enriched in groundwater compared to seawater (e.g., ^{222}Rn) can also be used to identify areas of submarine groundwater discharge (SGD); • If conductivity/temperature readings or geochemical tracers indicate presence of submarine groundwater discharge, collect porewater samples for nitrogen series analysis; • GPS location of stations should be recorded with highest possible accuracy to allow revisiting locations after a PRB has been installed; and • Groundwater seepage rates measured at stations with significant SGD and elevated nitrate, or both, as indicated by the porewater survey, can be useful to further constrain hot-spots of nitrogen inputs to a bay and inform PRB placement.	• Assess whether and at what rate groundwater with elevated nitrate concentration is discharging into surface water • Approximate vertical distribution of nitrogen in groundwater upstream • Provides baseline data of site conditions prior to PRB installation that can be compared with post-installation conditions

Appendix E

Woodchip PRB Installation Considerations

- **Amendment Handling Considerations**

- PRB Media Preparation: Local, untreated wood should be used in all cases. Hardwood (e.g., oak, maple, cherry), softwood (e.g., pine), as well as woodchip mixtures can be used. Woodchip size should be >1 cm to reduce the risk of clogging. The source of woodchips should be known and certified by the design professional to avoid inadvertently placing wood that contains potential groundwater contaminants into the ground (e.g., wood containing chromated copper arsenate or other chemicals). To place woodchips at the desired depth within the water-saturated soil, they should be soaked in water for multiple days before deployment to reduce their buoyancy.
- Woodchip PRB Media Mixing: Pea gravel should be mixed with woodchips (typically 1 part pea gravel per 2 parts woodchips by volume). The pea gravel will simplify woodchip placement in the water-saturated zone, maintain PRB media permeability, and reduce the chance of subsidence. Wooden frames with biodegradable fiber netting can be prefilled with woodchips-pea gravel mixtures, which simplifies the placement of PRB media (Figure 9). Multiple frames can be vertically stacked to achieve treatment over the targeted depth horizon.

- **Installation Considerations**

- Trenching Equipment: The selection of the most appropriate trenching equipment will typically depend on the installation depth of the PRB, the thickness of the PRB, and site access. Shallow PRBs can be installed using traditional backhoes, with the type and size of backhoe depending on site access and the dimensions of the PRB. Long installations (e.g., over 200 feet) can be done by continuous “one-pass” trenching. Deep installations (e.g., greater than 20 feet) will require either “benching,” which uses a traditional backhoe, or the use of a specialized deep trencher. Deep trenchers can reach depths of 40–45 feet below land surface. This continuous and/or deep equipment is highly specialized and mobilization/demobilization can be expensive. Dewatering (i.e., pumping water and lowering the groundwater level before adding PRB) can help in the woodchip placement process.
- Vertical Woodchip Columns: The woodchip media can be arranged in an array of vertical columns by using a hollow stem auger (~10–12” ID) and can be driven down with a Geoprobe® (Figure 10). This allows for PRB installations at sites that cannot be accessed with larger machinery. The auger should be capped at the bottom so that the interior of the auger stays dry until the desired depth is reached. The cap can then be hammered out and woodchip media can be poured in quickly, ensuring woodchip and pea gravel reach the bottom of the column as a mixture rather than the bottom being dominated by the aggregate that sinks faster through water. The distance between woodchip columns and column rows should not be much larger than 3 feet to establish a coherent nitrogen removing barrier
- Amount of Woodchip Media: The amount of woodchip media placed in the subsurface (i.e., thickness of a woodchip trench or number of rows in a column array) must be chosen so that the residence time is sufficiently long to

remove most of the incoming nitrate but minimizing the risk of creating unintended secondary by-products. Providing more organic carbon than necessary can result in the formation of undesired secondary by-products, including methane. The optimal PRB thickness depends on many parameters, including groundwater velocities, nitrate concentrations, and the expected nitrate removal rates. Groundwater temperatures in the shallow aquifer on Long Island are typically around 14 °C. For this temperature, nitrate removal rates around 3.5 mg N L⁻¹ d⁻¹ have been reported for aged hardwood (Cameron & Schipper, 2010; Graffam, et al., 2020). The design professional will decide on the thickness of a woodchip trench based on the data collected during the site characterization but, as a first approximation, the optimal thickness can be calculated as: PRB thickness (ft) = groundwater velocity (ft day⁻¹) x groundwater NO_x concentration (mg N L⁻¹) / 3.5 mg N L⁻¹ day⁻¹.

- For example, at a groundwater velocity of 1 ft day⁻¹ and a groundwater nitrate concentration of 7 mg N L⁻¹, the optimal thickness of a PRB would be 2 feet. If woodchips are placed in an array of vertical columns, the same PRB media volume that would be needed for a trench should be distributed among multiple staggered rows of columns.

- **Additional Considerations:**

- Maintenance: Performance of woodchip-based PRBs should be monitored by regular sampling of multiple upstream and downstream wells following installation. Woodchips are expected to promote nitrate removal for at least 10 years. Woodchip-based installation can be “rejuvenated” by carbon injections if PRB performance monitoring indicates insufficient or strongly declined nitrate removal.

- **Site Management During and Following Installation**

- Erosion/sediment control and dust suppression are important to address during and following PRB installation. The

trenching soil should be characterized and disposed of accordingly. Clean soil can be left on-site/graded. If the soil/sediment is contaminated, it would require proper characterization and off-site disposal in accordance with local, State, and federal regulations. Disposal of personal protective equipment and any other waste generated from PRB installation activities will be required.

- **As-Built Survey**

- A final PRB as-built survey should be conducted to record the final dimensions and location of the PRB. The PRB should be marked out with metallic utility tape at the top so that it can be located in the future, if needed. The site surface features should be properly restored.



Figure 9. Example of a trench-type and woodchip column array PRB installation using pre-filled frames placed in the subsurface using a traditional backhoe. Photo credit: CCWT.



Figure 10. Image of Geoprobe. Photo credit: Geoprobe.

Appendix F

Injection Well PRB Installation Considerations

- **Amendment Handling Considerations**

- Amendment Handling: Amendments are generally purchased in totes and need to be stored in a protected location until used. An example of an injection system with EOS totes is shown in Figure 12. Generally, concentrated amendment is delivered from the manufacturer and requires on-site dilution, so a water source will be necessary.

- **Installation Considerations**

- Injection Wells: Temporary injection wells are generally installed using direct-push technology (DPT). Permanent wells may be installed using DPT, a hollow-stem auger, or similar methods. The contractor will be required to select appropriate equipment, monitoring, and control devices (e.g., pressure gauges, flow meters, totalizers, ball valves) suitable for the intended injection operation conditions. While temporary well points may be appropriate or required for some sites, permanent injection wells installed with a proper well seal are generally superior at ensuring the injected reagent is delivered properly to the subsurface and are preferred over temporary wells. Permanent injection wells also streamline future injection efforts and make the permanent injection well method more cost-beneficial in the long term. An example of an injection system is shown in Figures 11–13.
- Injection Sequencing: The design professional should evaluate the native soil and groundwater conditions and calculate the safe injection pressure for those conditions. The safe injection pressure can be tested during an injection and/or pilot test.
- Injection Flowrate: The total injection time, which drives the cost of labor, is dependent on the injection flowrate. Design professionals should design the injection system to achieve the maximum

safe injection rate (non-fracturing) for the project. Where practical, multiple or all injection wells should be injected simultaneously. The water supply should be designed to achieve a minimum flow rate corresponding to the maximum safe injection rate. Centrifugal booster pumps may be required when potable water is provided by tank(s).

- Amount of Carbon Media: The amount of carbon injected into the subsurface must be chosen so that the residence time of water in the amended zone is sufficiently long to remove most of the incoming nitrate while minimizing the risk of creating unintended secondary by-products. Providing more organic carbon than necessary can result in the formation of undesired by-products, including methane. Typically, the goal is to enrich the aquifer with 20–40 mg/L of TOC above background concentrations. The choice of carbon media, target dilution concentration, the volume of injected fluid, and the injection well spacing, depend on local site characteristics including soil properties (hydraulic conductivity, total porosity, mobile porosity, and secondary porosity) and groundwater velocity. The design professional will make those decisions based on data collected during the site characterization. As a first approximation, the amount of amendment needed per injection location can be calculated as $V_i = \pi \times r^2 \times d \times n_e$, where r is the target radius of influence of the injection, d is the depth of the target treatment zone, and n_e is the effective porosity of the aquifer (or “mobile” porosity).

- For example, to establish an amendment zone with a 10 feet radius and 10 feet in height, 3,760 gallons of a 1% EOS100 amendment (containing 85% EVO [U.S. Soybean oil]) would need to be injected per injection location, considering an effective porosity of 0.16 (i.e., 50% of a primary porosity of 0.32). Injections should overlap to some degree to minimize

the amount of groundwater flowing through the barrier that would not pass through reactive media. In the example above, if injections overlapped by 50% of the radius, injection wells should be spaced every 15 feet. The semi-soluble oil in EOS100 will be retained in the soil as it is injected. Therefore, the actual injection radius of the EVO will be smaller/lower than the overall injection radius of the fluid. The retention rate is site-specific, typically driven by soil type, and can be determined during an injection test.

- **Additional Considerations**

- Maintenance: PRB performance should be monitored by regular sampling of upstream and downstream wells following carbon injections. Carbon injections are expected to promote nitrate removal for 1–3 years. Injection well amendments should be replenished if PRB performance monitoring indicates insufficient or strongly declined nitrate removal. The amount of carbon in follow-up injections should be tailored to maintain treatment efficiency while minimizing by-product formation that can be caused by overtreating a nitrate plume.

- **Site Management During and Following Installation**

- Disposal of drill cuttings from injection well installation, personal protective equipment, amendment totes, and any other waste generated from PRB installation activities will be required. Minimal site restoration

is anticipated following completion of the PRB installation activities as the injection wells will remain in place.

- **As-Built Survey**

- A final as-built survey of the permanent injection wells or the temporary injections should be conducted to record the final locations of the injection points. The PRB should be marked out with metallic utility tape at the top so that it can be located in the future, if needed. The site surface features should be properly restored

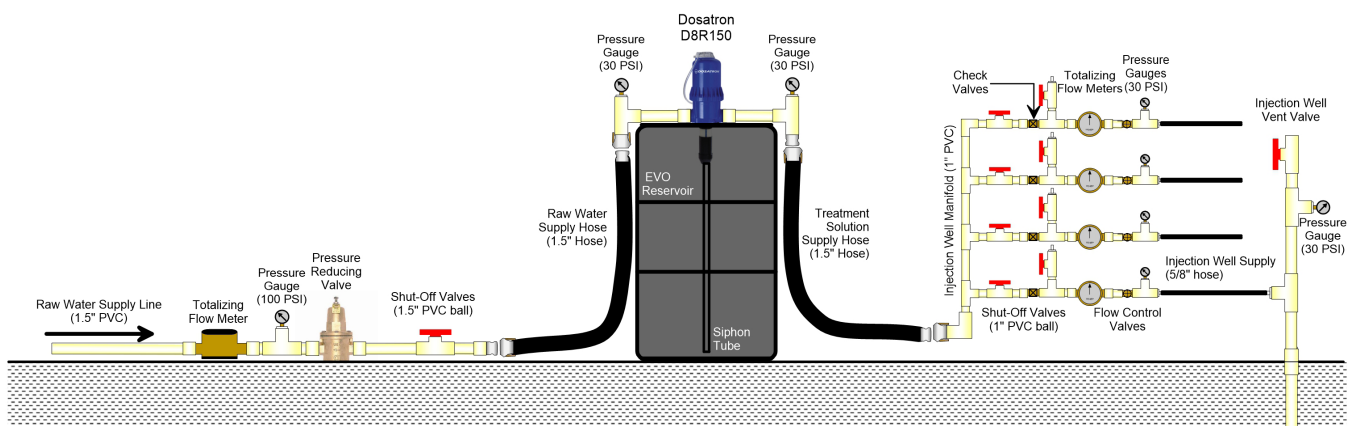


Figure 11. Typical amendment injection system setup. Photo credit: CDM Smith.



Figure 12. Example of an injection setup with EOS totes. Photo courtesy of Redox Tech.



Figure 13. Example of an injection manifold. Injection system design should maximize injection flow rate in an effort to minimize labor costs. Source: [Protocol for Enhanced In Situ Bioremediation Using Emulsified Edible Oil \(clu-in.org\)](https://clu-in.org/).

Appendix G

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