Treatment of Legacy Nitrogen as a Compliance Option to Meet Chesapeake Bay TMDL Requirements

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1. Introduction

In 2010, the U.S. Environmental Protection Agency (EPA) established the largest and most comprehensive federal effort to date to limit the total amount of pollutants entering a waterbody. EPA's Chesapeake Bay Total Maximum Daily Load (TMDL) program established numeric nitrogen (N), phosphorus (P), and sediment reduction targets for six states and the District of Columbia in order to achieve Chesapeake Bay water quality standards. Chesapeake Bay jurisdictions are struggling to meet these reduction goals by the 2025 deadline established in the TMDL. Nitrogen goals are proving particularly difficult to meet. After decades of implementation, Chesapeake Bay jurisdictions must achieve an additional 43 million pounds of annual N reductions.

The states implement a variety of mandatory and voluntary programs to achieve nutrient and sediment reduction targets. Under the TMDL, most states assign numeric load limits (typically expressed as annual load limits) to two classes of permitted dischargers under the Clean Water Act (CWA): municipal and industrial wastewater treatment facilities ("point" sources) and municipal stormwater systems ("nonpoint" sources called MS4s or Municipal Separate Storm Sewer Systems). Both face regulatory compliance challenges. Municipal and industrial sources have spent billions of dollars retrofitting existing wastewater treatment systems to achieve levels of control near the limits of technology. While most existing point sources have met TMDL nutrient reduction requirements, future growth represents a critical regulatory compliance challenge. MS4s manage the collective urban runoff conveyed through municipal stormwater systems. MS4s implementing conventional urban stormwater control practices face continual growth and exceedingly high nutrient abatement costs, at least an order of magnitude higher ($/lb) than point sources and agricultural nonpoint sources (Van Houtven et al 2012). Though the details vary significantly across states, most Chesapeake Bay states allow these two classes of permittees a number of off-site compliance options (in the form of reductions not achieved at the site of the permitted discharge) through nutrient trading programs (Stephenson and Shabman 2017a).

To reduce agricultural nonpoint source loads, which are not currently subject to permitting, states largely rely on voluntary financial assistance programs. These programs provide land managers technical and financial assistance ("cost share") to reduce nutrient and sediment runoff from agricultural lands. Achieving the necessary agricultural reductions through these programs has proven difficult. Despite extensive efforts, more than three quarters of the remaining N reductions needed to achieve the TMDL must come from agriculture. Achieving the level of reduction needed has proven challenging given the voluntary nature of the program and limited state and federal budgets available for conservation cost share (Shortle et al 2012). Furthermore, water quality scientists have noted that there is limited evidence that implemented nonpoint source BMP practices have produced their intended instream reductions (Keisman et al. 2018).

Access to technically feasible, environmentally effective, and financially cost-effective compliance options is critical if point sources, MS4s, and state nonpoint source program managers are to achieve Chesapeake Bay TMDL goals. An overlooked, but potentially important, source of treatable loads, are legacy nutrients. Legacy nutrients result from excess input of anthropogenic nutrients and their subsequent accumulation and storage in soil, sediment, or groundwater. Legacy nutrients have been identified as an important impediment to achieving

Bay water quality goals (NRC 2011). By definition, these nutrient pools persist and influence biogeochemical processes beyond the duration of the initial nutrient application. Groundwater, for example, may be a significant source of legacy N, particularly in areas with a history of intensive livestock production (Easton et al. 2019: Greene et al 2005). Emergent groundwater discharged from springs also represents discrete, identifiable discharge points that could represent opportunities for possible treatment.

The objective of this paper is to evaluate the efficacy of treating legacy N as a TMDL compliance strategy for three potential classes of buyers of nutrient reductions: permitted point sources, MS4s, and state nonpoint source program managers. We compare denitrifying bioreactors, an innovative technology capable of removing legacy N from emergent groundwater, with conventional agricultural and urban nonpoint source removal technologies. Bioreactors are lined beds filled with an organic carbon substrate designed to convert soluble reactive inorganic N into inert di-nitrogen gases (Schipper et al., 2010; Bock et al., 2018). Though originally designed to treat N in agricultural runoff from artificially drained fields, bioreactors can be redesigned to treat emergent groundwater (springs) in areas with high nitrogen levels (Easton et al., 2019). We focus on N control technologies since N is widely recognized as the most difficult TMDL goal to achieve (Blankenship 2018). Nitrogen removal technologies are compared using a set of evaluative criteria relevant to the compliance objectives of the three classes of nutrient buyers. Although a dominant compliance alternative does not exist for any of the 3 classes of buyers, the analysis does find that treatment of legacy N with bioreactors offers a number of important advantages over conventional reduction technologies.

2. Compliance Needs of Buyers of Nutrient Reductions in the Chesapeake Bay Region

Each of the three classes of buyers of nutrient reductions have specific compliance objectives. Cost effectiveness is a key objective of any buyer. All three classes of buyers face limited budgets and are assumed to want to meet compliance obligations at the lowest possible cost (*ceteris paribus*). Buyers would consider not only the installation, operation, and maintenance costs of nutrient investments but also the transaction costs such as search, contracting/permitting, monitoring, and reporting costs of any given nutrient control alternative. Beyond these general financial objectives, each potential buyer of nutrient reductions in the Chesapeake Bay may have additional objectives and compliance needs.

Existing municipal and industrial wastewater treatment plants ("point" sources) face stringent nutrient concentration and mass load limitations (called wasteload allocation or WLA)in 5-year permits. Existing point sources have very little demand for off-site nutrient technologies since most face mandatory individual nutrient standards. In states such as Virginia and Maryland, there is limited ability to transfer these obligations to other sources (Stephenson and Shabman 2017c). Furthermore, generous capital grant programs have facilitated the upgrade to municipal wastewater systems and compliance with nutrient requirements. New and expanding point sources, however, face more challenging compliance obstacles. Most Bay states require any new and expanding point source to completely offset all new nutrient loads through nutrient reductions from existing point or nonpoint sources (zero net discharge). Given the stringency on existing regulatory requirements, existing sources are reluctant to provide long term offsets to new/expanding sources. How new and expanding sources can comply with Bay TMDL requirements is emerging as a major policy concern (Pipkin 2017). For perspective, a new treatment facility treating 1 mgd of wastewater with a limit of technology N control technology (3 mg/l total N) will need to offset approximately 9,100 pounds of N annually.[1]

For regulatory compliance, new and expanding point sources require secure, long-term nutrient offsets. Such sources must typically plan for wastewater treatment needs of capital investment projects with useful lives exceeding 20 years. Given the technical challenges of achieving zero nutrient discharge, these sources will need to secure long-term offsite offsets. The CWA, however, creates legal risks with securing third party offsets. Under the CWA, any offset must be included within the source's permit (e.g. there is no legal transfer of pollution control responsibility between an offset supplier and a regulated buyer under the CWA). Thus, regulated (permitted) sources have a preference for offset projects that are directly under their technical and legal control (Stephenson and Shabman 2017a).

Most Chesapeake Bay states have also recently extended numeric nutrient and sediment regulatory requirements to MS4s. While MS4s are not required to directly measure nutrient and sediment loads, states have developed procedures for estimating loads based on modeled nutrient losses from different land uses (eg. nutrient loss per acre of impervious surface, lawn, forest, etc). States then establish caps on nutrient/sediment loads generated by lands within the MS4s. MS4s can achieve compliance with these load limits by installing structural urban stormwater BMPs (bioretention, wet ponds, constructed wetlands, extended dry detention ponds, bioswales, etc), making land use changes (ex. increasing urban forest cover), and implementing urban stream restoration within their jurisdiction. States establish nutrient and sediment removal efficiencies of each technology (typically expressed as a % removal of land-based load estimate).

[1] A one mgd municipal wastewater treatment plant could treat the domestic waste of 15,000 to 20,000 people.

Most Bay states also grant MS4s flexibility to achieve compliance by purchasing nutrient reduction credits from sources outside their jurisdiction.

Like point sources, MS4s face long-term nutrient/sediment control obligations. MS4s' nutrient control requirements are established in 5 year, continuously renewable CWA permits. Given the gradual expansion of urban lands and the high costs of reducing urban nonpoint source loads, MS4 are finding it difficult to achieve and maintain reductions. Despite the challenges, MS4s have demonstrated a preference for implementing technologies within the jurisdictional boundaries of the MS4. Besides a possible preference for maintaining regulatory control over compliance, MS4s may have other reasons to invest in local nutrient control technologies. MS4s typically face multiple regulatory obligations. Besides Bay nutrient/sediment reduction requirements, most MS4s have locally impaired waterbodies within their jurisdictions. Common local urban water quality impairments include bacteria and aquatic life (with sediment typically identified as the chief stressor for aquatic life impairments). Many of the technologies available to the MS4 to reduce nutrients (listed above) will also provide some local water quality benefits for bacteria and aquatic life impairments. Furthermore, some of the technologies, such as riparian forested buffers and stream restoration may also provide more general benefits (aesthetics, habitat, recreation, etc) to the local community.

Finally, state water quality managers have multiple objectives when implementing programs to reduce agricultural nonpoint source loads. Like MS4s, state nonpoint source managers face multiple water quality challenges and many agricultural BMPs provide multiple benefits besides nutrient/sediment reductions to the Bay. In addition, the state may have preferences for technologies that provide more certainty in providing the intended service (nutrient reductions). The actual nutrient reduction performance of many nonpoint source technologies (BMPs) is subject to considerable uncertainty (Stephenson et al., 2018). Regulated parties may be unconcerned with actual service delivery if the government guarantees nutrient reduction credits derived from model estimates. State agencies, however, are more directly tasked with generating demonstrative water quality improvements. Thus, a government objective may include more demonstrative evidence that the nutrient reduction service is actually being delivered. Reduction technologies that provide a government buyer with more certainty are assumed to be preferred over technologies with less certainty in producing the desired service.

3. Evaluative Compliance Criteria and Alternatives for Buyers of Nutrient Reductions

We evaluate and compare the treatment of legacy N against a wide variety of conventional N control technologies available using evaluative criteria relevant to potential nutrient buyers. Buyers may purchase nutrient reductions through a number of different source control alternatives including agricultural BMPs, urban stormwater control practices, land conversion, and stream restoration. Denitrifying bioreactors designed to remove legacy N from emergent groundwater (springs) are added to these conventional alternatives. These possible alternatives are evaluated using criteria relevant to the objectives of the three groups of buyers including implementation costs, contracting costs (transaction costs), regulatory risks, and regulatory and nonregulatory "co-benefits". This section will first describe these criteria and corresponding indicators and then briefly describe the compliance alternatives available to buyers.

3.1 Evaluative Criteria and Indicators

Table 1 lists the criteria and indicators used to evaluate N reduction alternatives available for buyers of N reductions. The evaluative criteria were derived from possible buyer objectives identified above.

Implementation costs include construction and maintenance costs and are reported as the annual cost to remove a pound of N. Cost data is derived from a number of sources including published studies, permittee compliance reports, and estimated costs from the Chesapeake Bay Program (CBP). Nitrogen removed per year is estimated using approved methods from the CBP Chesapeake Assessment Scenario Tool (CAST) and the published literature. Cost and removal effectiveness are estimated using Virginia data.

Table 1: Criteria and Indicators for Evaluating Nitrogen Reduction Alternatives

Criteria	**Indicator**
Implementation Cost	Construction costs ($/N lb/yr) Operation and maintenance costs ($/N lb/yr)
Transaction/Contracting Costs	Number of contracts to offset 10,000 lbs/N/yr Typical Length of Typical Contract (years)
Buyer Control over Alternative	A 3rd party contract is required (yes, no)
Certainty in Control Performance	Qualitative assessment of whether N outcomes are estimated (modeled) or measured (monitored)
Regulatory Co-benefits	List of pollutants reduced by the alternative
Nonregulatory Co-benefits	Qualitative type of co-benefit (aesthetics, wildlife habitat, etc)

Transaction/contracting costs of claiming the N reduction from a particular control technology are an important, but poorly characterized, element of the overall cost effectiveness of a nutrient reduction alternative. Transaction costs are closely linked to both the duration and number of contracts necessary to secure a given level of N removal service (Deboe and Stephenson, 2016). Two indicators are used to reflect the relative magnitude of transaction costs for each N reduction alternative: the number of contracts needed to achieve an annual reduction of 10,000 pounds of N and the number of years of a N removal contract. The 10,000 lb/N/yr reduction benchmark is roughly equivalent to the N discharge in 1 mgd of point source discharge (with limits of technology N control). Data on contract duration is derived from assumptions about the useful life of the control technology from the CBP (CAST) and/or the published useful life of the N removal technology.

Other evaluative criteria include qualitative indicators of control over the N removal technology, certainty in N removal performance, and regulatory and nonregulatory co-benefits. As noted above, the option to actively own or manage a nutrient reduction alternative may be an important feature for some buyers of N removal services. Thus, alternatives that require the involvement of a third party provider are less preferable than a nutrient control alternative which the buyer can actively manage. A categorical indicator of whether a third party contract would be required element of an N removal alternative is represented as either a "yes" or "no".

The certainty of N removal outcomes is defined as the whether N removal outcomes are either "estimated" using models or some best professional judgment or "observed" using direct measurements/monitoring. The assumption is that measured outcomes provide the buyer with more assurance of N removal than modeled estimates (Stephenson and Shabman 2017b). Whether buyers demand demand "higher quality" (more certain) load reductions, however, is ambiguous. Buyers facing permit limits care primarily about regulatory compliance. A regulator-approved model estimate may be preferred since the load reduction (credit) would be known with certainty before installation and would remain constant over the approved life of the project. Measured outcomes would be variable over time and actual removal efficiency unknown at the time of installation. Currently, the CBP nutrient accounting system provides regulated parties no incentive to care about certainty of reductions. However, state agency nonpoint source managers of nutrient reductions may value certainty in N removal performance since the states are more directly responsible for achieving water quality outcomes.

Finally, any N reduction project may also provide ancillary benefits beyond N reduction. Regulatory co-benefits are defined as the list of regulated pollutants (besides N) that the control technology has been documented to reduce. Nonregulatory co-benefits include the list of other non-pollutant ecosystem services potentially provided by the alternative.

3.2. Nitrogen Control Alternatives Evaluated

Table 2 lists the N reduction alternatives evaluated. The list includes common agricultural and urban stormwater best management practices, stream restoration, and land conversion. These N reduction alternatives are common technologies being targeted for implementation by state and local water quality program managers (as defined by state watershed implementation plans). Each of these technologies is designed to target current nutrient sources.   Denitrifying bioreactors to target legacy N is added to this list as an innovative alternative.

Denitrifying bioreactors area technology that could be adapted and used to treat and remove legacy N stored in groundwater. Bioreactors remove N through heterotrophic denitrification. In conditions with sufficient levels of inorganic N (primarily nitrate), denitrifying microorganisms ubiquitously present in soils coupled with carbon sources under anaerobic conditions convert inorganic N (NO_3) into inert di-nitrogen gas (N_2). Denitrifying bioreactors are an established practice to treat runoff from artificially drained fields and are a recognized USDA-NRCS conservation practice (USDA-NRCS 2015), but have new research demonstrates their potential to treat legacy N (Easton et al 2019).

Table 2: Nitrogen Reduction Alternatives Available to Potential Buyers

Technology	Description
Denitrifying Spring Bioreactors	Treatment cells designed to remove legacy inorganic N from emergent groundwater.
Agricultural BMPs	
Cover Crops	Post harvest fall planting of ground cover to scavenge residual nutrients and reduce sediment losses. Additional credit given for early establishment.
Nutrient Mang (N-based).	Application of N at rates below standard recommendations.
Stream Fencing with grass or forested buffer	Excluding livestock from streams and riparian zones to reduce sediment and nutrient losses (assume 100’ buffer).
Urban Stormwater Practices	
Bioretention	Constructed infiltration areas to reduce stormwater flows and sequester N,P.
Wetponds	Permanent pools to treat/settle N, P, S in stormwater runoff.
Constructed Wetlands	Constructed wetlands designed to treat stormwater runoff.
Land Conversion	Conversion of high N, P, S land uses to permanent grass or forest cover.
Stream Restoration	Stabilizing and restoring degraded urban stream channels to reduce sediment/nutrient loss, facilitate N processing.

Legacy N originates from land application of imported nutrients (commercial fertilizer or manure) for agricultural production or urban lawn management. When the landscape is unable to assimilate all nutrient imports, excess N is either exported with runoff/streamflow or stored, often in groundwater. Nitrogen leached through soil into groundwater may take decades to eventually be discharged to surface waters. In the Chesapeake Bay region, the lag time for groundwater being discharged into surface water can range from less than a year to more than 50 years (Phillips and Lindsey 2003; Sanford and Pope 2007; Meals et al. 2010). Regions with high nitrate levels in groundwater are typically associated with areas of intensive animal livestock production (Greene et al 2005).

Bioreactors could be adapted to treat legacy N rich emergent groundwater (springs) by diverting a portion of spring water into an off-stream bioreactor, which would be returned back to the spring or stream after treatment (Easton et al 2019) (see Figure 1). Bioreactors are designed with water control devices that can regulate the flow of water into and out of the bioreactor. Identifiable influent and effluent points allow direct measurement and monitoring of N control performance through quantification of flow and monitoring of influent and effluent concentrations. Total N removal efficiency is highly dependent on the residence time of water in the bioreactor, which typically ranges from 3 to 8 hours (Christianson et al. 2013; Greenan et al. 2009; Lepine et al. 2016; Moorman et al. 2015; Coleman et al., 2018). Results on a pilot application of a spring in southwest VA (median influent nitrate concentration of 8.68 mg/l and a median flow of 26.9 m3/d) averaged 44% N reduction annually (approximately 0.1 kg/d or 36.5 kg/yr), and achieved reductions greater than 65% during the warmer summer months (Easton et al. 2019).

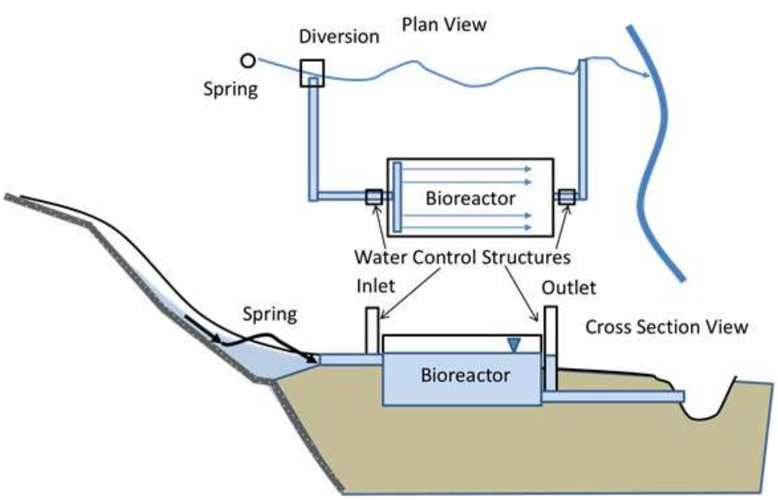

Figure 1: Bioreactor Application to a Spring

Spring bioreactors are compared to conventional N reducing agricultural BMPs including cover crops, enhanced nutrient management, and stream buffer/livestock exclusion (see Table 2). Bay states rely heavily on these practices to meet the Bay TMDL. However, given confidentiality concerns, little cost and performance data is available for agricultural nonpoint source BMPs. This analysis uses CBP program cost estimates and watershed model estimates from CAST to estimate the cost effectiveness of agricultural BMPs.

MS4 use a variety of practices to meet Chesapeake Bay requirements including bioretention areas, wet ponds, extended dry detention ponds, and urban stream restoration (as reported in individual MS4 permit compliance reports). Cost and outcome data for these practices was obtained from project level information reported by MS4s in annual compliance reports. Finally, Virginia has an active market for nutrient credits from land conversion projects (Stephenson and Shabman 2017a). Private nutrient bankers permanently convert agricultural land to grass or forest to receive "perpetual" nutrient credits. To date, the nutrient bankers sell P credits almost exclusively to land developers who offset impacts from land development, but these credits are also available to MS4s, point sources, and the state to purchase. Virginia DEQ has certified over 120 nutrient banks to date. Nutrient credit prices and nutrient bank information is used to describe the land conversion alternative.

4. Results: Comparison of Nitrogen Compliance Alternatives

The evaluative summary of N removal alternatives is shown in Table 3. Treatment of legacy N using bioreactors ranks high relative to other alternatives for many evaluative criteria. Prior research estimates that spring bioreactors can remove N for less than $5/lb/yr, lower than all the alternatives evaluated (Easton et al 2019). Agricultural BMPs are often cited as the low cost nutrient removal option (Van Houtven et al 2012). While lower than most other classes of removal alternatives, agricultural BMP per unit N removal costs are estimated to be 2 to 3 times greater than bioreactor costs (see Table 3).[2] Urban stormwater BMPs cost orders of magnitudes more than agricultural or bioreactor alternatives.

The bioreactor's low unit cost is driven largely by economies of scale. In areas with elevated N levels in groundwater, a single spring can discharge tens of thousands of pounds of N annually (Easton et al 2019). Springs continuously discharging groundwater with 6 to 8 mg/l nitrate is not uncommon. A single bioreactor treating 0.25 to 1 mgd of spring flow can remove between 1,500 and 12,000 N lbs/yr annually, assuming conservative removal efficiencies ranging from 30 to 50% (Easton et al 2019).

The high per treatment removal potential of bioreactors represent a significant opportunity to economize on transaction (contracting) costs. A potential buyer would only require a small number of bioreactors (with a possible minimum of one) to achieve a 10,000 lb/yr reduction or offset. Furthermore, these projects would provide long term (estimated 15 years) reductions per treatment (see Table 3). These two indicators suggest that bioreactors would also be one of the lowest cost options in terms of transaction costs as well. Agricultural BMPs such as cover crops and nutrient management generate relatively low reductions per acre (2 to 6 lbs/ac) in Virginia (Potomac-Shenandoah basin). Assuming that a typical contract would cover between 100 and 300 acres, between 6 to 52 separate contracts would be required to secure 10,000 lbs of reductions. Furthermore, these would have to be renewed as frequently as 1 to 3 years, requiring buyers to constantly manage large numbers of N reduction contracts for the length of the desired service change. Achieving 10,000 lbs of N reductions using urban stormwater BMPs is extremely challenging given the very small reduction achieve per project,

[2] Note, agricultural BMP costs should be considered low-end estimates since baselines were not part of these calculations. Most CBP states require agricultural sources to first meet baseline levels of N control before being credited for N reductions.

requiring hundreds of separate projects. Even securing 10,000 lbs of reduction through land conversion/retirement based nutrient credits would be challenging. The average land conversion nutrient bank generates 381 N credits (lbs/yr), with the 1st and 3rd quartile banks generating 101 and 532 credits respectively.[3]

Bioreactors offer buyers multiple potential contracting options. For instance, a buyer could secure reductions through leasing or purchase of small parcels adjacent to springs. This would allow the buyer to maintain control and management of the N reduction project. Similarly, they could contract with third party providers to supply N reductions. The only class of N reduction practices where third-party contracting is a general requirement would be agricultural BMPs (see Table 3). In these situations, the buyer of N reductions must contract with farmers/landowners to supply the reductions. Urban BMPs, stream restoration, and land retirement options would all allow the buyer to own and operate the N reduction technology.

Given the large, identifiable point of discharge, spring bioreactors present the only realistic alternative for quantifying N removal performance through direct measurement. Flow can be directly measured and influent and effluent concentrations can be sampled to estimate the net removal. All other alternatives rely on CBP-approved model estimates of nutrient load and N-removal efficiency. Thus, treatment of legacy N provides higher levels of certainty in terms of load reduction achieved than any evaluated alternative. As discussed above, whether buyers demand such certainty is unclear. Of course, the CBP may eventually develop default modeled estimates for treatment of legacy N using bioreactors. In that case, spring bioreactors would be equivalent to all other N removal alternatives.

[3] Nutrient bank credits must meet agricultural baselines, thus reducing the number of credits that can be claimed by land conversion.

Ancillary benefits represent the only evaluative criteria where spring bioreactors rank unambiguously below other alternatives. Spring bioreactors remove only N. While bioreactors could be designed to remove P and pesticides, emergent groundwater is typically low in dissolved P and pesticides. Most other N control practices simultaneously reduce P and sediment loads. Other BMPs (urban BMPs, stream fencing) may also reduce local pollutants such as bacteria. The joint pollutant reduction attributes of urban BMPs and stream restoration may be particularly relevant to MS4s with locally impaired waters. A smaller subset of practices also provide nonregulatory ancillary benefits to the buyer. Stream restoration, for example, improves aquatic habitat and aesthetics.

5. Discussion

This analysis provides support that bioreactors designed to remove legacy N from emergent groundwater offer nutrient buyers a viable alternative to conventional treatment practices. For new and expanding point sources, bioreactors are one of the few N offset options capable of reducing large quantities of N with a few treatments over an extended time period. Large N offsets can be achieved at costs lower than options. Bioreactors also offers multiple contracting options to point sources for securing the N reductions. Bioreactors, however, would not generally provide any P reductions and it is unclear whether monitored results would be preferred to modelled estimates.

MS4s buyer interest in bioreactors is less clear. To meet Bay TMDL requirements, MS4s spend millions of dollars installing urban stormwater BMPs and stream restoration projects. The cost and reduction data used in Table 3 are derived from projects installed by Virginia MS4s. As a class of alternatives, these projects are the highest cost alternative ($/lb/yr). Yet MS4s have largely avoided less expensive trading options (many of which involve technologies identified in

Table 2). This behavior suggests other objectives in addition to nutrient removal costs are important to MS4s. Other potential MS4 objectives include, but not limited to, control over N removal technology and regulatory/non-regulatory ancillary benefits. Depending on the objectives of MS4s, bioreactors may or may not offer any additional advantages over conventional N removal technologies.

Bioreactors offer state water quality managers responsible for Bay TMDL compliance several clear advantages. State nonpoint source managers have limited budgets and are struggling to solicit enough participation from agricultural producers to achieve nonpoint source reduction goals. Treatment of legacy N offers opportunities to achieve substantial reductions at low cost.

The ability to directly monitor and quantify outcomes from bioreactors represents a significant potential opportunity to provide greater certainty and assurance that the N removal service is being delivered. Modelled outcomes appear to consistently overestimate the effectiveness of conventional nonpoint source BMPs (Osmond et al 2012), so direct measurement of outcomes offers a potential means to improve the ambient response to N reduction investments. Yet, the CBP offers few incentives for buyers to care about the "quality" of the N removal service. The potential of water quality management programs to create incentives for both low cost implementation and high quality N abatement is an intriguing management challenge.

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Table 3: Evaluation of Nitrogen Reduction Alternatives

	Cost ($/lb/yr)		Contracting Costs					
Alternative	**Installation**	**O&M**	**# contracts to achieve 10,000 lb**	**Contract Duration (yrs)**	**3rd Party Contract Required**	**Certainty of Service**	**Regulatory Co-benefits**	**Other Co-benefits**
Spring Bioreactor	$1 to $5	<$1/lb/yr	1 to 30	15	No	Measured	None	None
Agricultural BMPs								
Cover Crops	$18	N/A	6 to 17	1-3 yrs	Yes	Modeled	P, S(ediment)	Minimal
Nutr. Mang.	$12	N/A	17 to 52	1-3 yrs	Yes	Modeled	P	None
Stream Fencing +								
Grass buffer	$5	$2.5	40 to 101	10 yrs	Yes	Modeled	P, S, Bacteria	Habitat
Forest buffer	$11	$2	34 to 86	75 yrs	Yes	Modeled		Habitat
Urban BMPs								
Bioretention	$388-$1408	$31-$113	277-1099	25	No	Modeled	P, S, Bacteria	Minimal
Wetpond	$126-$336	$16-$44	35-121	50	No	Modeled	P, S, Bacteria	Aesthetics,
Const. Wetland	$237-$714	$31-$93	35-121	50	No	Modeled	P, S, Bacteria	Habitat
Land Conversion	$69 to $104	N/A	19 to 99	Perpetual	No	Modeled	P, S, Bacteria	Habitat, Aesthetics
Stream Restoration	$308-$1893	$39-$236	122-275	5	No	Modeled	P, S	Habitat, Aesthetics