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When, Where, and How to Intervene? Tradeoffs Between Time and Costs in Coastal Nutrient Management

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Research Impact Statement: Shellfish are worth between 11-37¢ per animal harvested when compared to traditional approaches to dealing with nutrient pollution on Cape Cod, MA, USA. The timing of the pollution cleanup matters.

ABSTRACT: Policies and regulations designed to address nutrient pollution in coastal waters are often complicated by delays in environmental and social systems. Social and political inertia may delay the implementation of cleanup projects, and even after the best nutrient pollution management practices are developed and implemented, long groundwater travel times may delay the impact of inland or upstream interventions. These delays and the varying costs of nutrient removal alternatives used to meet water quality goals combine to create a complex dynamic decision problem with tradeoffs about when, where, and how to intervene. We use multi-objective optimization to quantify the tradeoffs between costs and minimizing the time to meet in-bay nutrient reduction goals represented as a Total Maximum Daily Load (TMDL). We calculate the impact of using in-bay (in situ) nutrient removal through shellfish aquaculture relative to waiting for traditional source control to be implemented. We apply these methods to the Three Bays Watershed in Cape Cod, Massachusetts. In gross benefit terms, not accounting for any social costs, this equates to an average value of 37¢ (2035 TMDL target date) and 11¢ (2060 TMDL target date) per animal harvested over the plan implementation period. Our results encourage the consideration of alternative and in situ approaches to tackle coastal pollution while traditional source control is implemented and its effects realized over time.

(KEYWORDS: groundwater; dynamic optimization; aquaculture; coastal pollution.)

INTRODUCTION

There are often time delays between an intervention in an environmental system and the resulting improvements. These delays can be caused by the transport times of pollutants from sources, long-term storages and slow material cycling in natural systems, or inertia in the effects of a policy on economic actors, as examples. As a result, many environmental management problems become complex dynamic decision problems. These decisions are dynamic in the sense that today's choices affect the trajectories of elements in a coupled social-ecological system through time, and complex because there may be long-term feedbacks and tradeoffs among interventions which are not evident when components of the system are examined independently. This makes the environmental management decisions not just concerned with where and how to intervene, but also when and to what extent.

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This paper presents the issue of addressing coastal eutrophication caused by excess nitrogen as a dynamic rather than static planning problem. By coupling a dynamic simulation model with multi-objective optimization, we are able to explore the tradeoffs between the time to achieve environmental goals and the costs of implementing traditional source-control infrastructure (centralized wastewater treatment) in watershed-wide plans to meet pollution targets. The approach allows us to estimate the economic value of including an in situ abatement technique — here, the use of shellfish aquaculture. While we present work applied to nitrogen pollution in an estuary embayment system on Cape Cod (Barnstable County, Massachusetts), the issues of water pollution and delays in its transport are widespread (Sharpley et al. 2013; Venier et al. 2014; Van Meter et al. 2016, 2018) making the dynamic problem tackled in this paper informative to a wide range of watershed-scale pollution problems. Our methods could also be adapted to estimate the value of the inclusion of other types of in situ or source control abatement approaches not covered in this paper.

BACKGROUND

More than 30 embayments on Cape Cod are impaired due to excess nitrogen primarily from septic systems (Cape Cod Commission 2015). Excess nutrient loading to an estuary, particularly nitrogen in saltwater environments, stimulates conditions that lead to undesirable growth of phytoplankton and macroalgae followed by their mass death. These conditions can lead to many negative effects on ecosystem health and human uses of the waterbody. Potential effects include anoxic conditions, degraded coastal habitats and decreased water clarity (Bricker et al. 1999; Driscoll et al. 2003). These ecological impacts can be directly and indirectly tied to changes in social value and uses of the estuary systems (Merrill et al. 2018).

Pollution targets, known as Total Maximum Daily Loads (TMDLs), were developed using mathematical modeling to provide target thresholds for loadings to resolve the impairments for each embayment (MEP 2007). The Cape's towns are developing town-level Comprehensive Wastewater Management Plans (CWMPs) to address the nitrogen targets for watersheds within their town boundaries. These CWMPs include a description of the reduction strategies that are either traditional centralized wastewater treatment or chosen from a set of alternative strategies. More than thirty alternative interventions are under consideration for nitrogen abatement on Cape Cod. In general, these interventions can be grouped into three types: *source control* (also referred to as reduction; primarily through sewering and the use of centralized wastewater treatment plants or upgrading septic systems to treat for nitrogen), *in-estuary approaches* (e.g., aquaculture or dredging), or *interception* (e.g., permeable reactive barriers [PRBs] or wetland restoration efforts) (Horsley et al. 2016; Cape Cod Commission 2019a). Many of the towns on Cape Cod are considering some of the in-estuary and interception interventions in hopes of offsetting some of the large and much better-understood costs of installing and maintaining traditional sewers and wastewater treatment plants to meet the TMDL. As an illustrative example, we use our model of the system to value the addition of commercial shellfish aquaculture leases in addressing coastal nutrient pollution. This is an option under serious consideration across Cape Cod (Carmichael et al. 2012; Reitsma et al. 2017), but also much more broadly in coastal communities around the world (Pollack et al. 2013; Rose et al. 2014).

The CWMPs estimate timelines for implementing components of the cleanup effort, although there is no set deadline in the policy process for meeting the TMDLs at the estuaries. Time is an important component of the planning process as a reduction in nitrogen loading, the incurrence costs, and resulting improvements to the estuaries will take place over decades or more. Here, we explored the time dimension for meeting the TMDLs, to expand upon previous static or equilibrium models of the system (MADEP 2007; Cape Cod Commission 2017; Cape Cod Commission 2019b).

The intuitive solution to this type of pollution problem is to address the problem at its source, or in most cases, sources, rather than after it becomes diluted in ground or surface waters. However, because of the slow travel time of groundwater, the primary transport mechanism for nitrogen on the Cape, there is a connection between the spatial location of an intervention in the watershed or estuary and the time at which the effect of the intervention is realized at the bay. Therefore, beyond the considerable costs of source control options, it will take a long time to have the desired ecological impact on the bay. The time it takes effluent from household and commercial septic systems, the primary sources of nitrogen on the Cape, to travel to the estuary systems ranges from immediate for sites close to the bay to longer than 100 years from septic systems upland and away from the coast (Walter et al. 2005). This has led to a legacy of pollutants en route to the receiving water even after source control mitigates additions of nitrogen to the system (Van Meter et al. 2016; Van Meter et al. 2018). The cleanup problem is further complicated by the natural attenuation of nitrogen taking place in freshwater bodies (streams, ponds, and wetlands) distributed throughout the landscape.

Finding the right balance among choices of actions is more complicated than simply implementing the option with the fastest impact time or the one that is the least expensive, since travel time, natural nutrient abatement, costs, and scalability combine to make the economically efficient choices more nuanced across space and time. From a policy perspective, these factors disconnect the resources spent to clean up sources and the measurable ecological and social improvements in the waterbody. Given people's time preferences, interventions that affect the waterbody sooner would be preferred, *ceteris paribus*. Therefore, the addition of in-estuary and interception types of interventions that abate nitrogen, such as allowing expanded shellfish aquaculture, are appealing given their possibilities of more immediate effect and ability to offset some source control efforts. While there are temporal and economic advantages to using in situ clean up measures, nutrients are still being released into the system if only in situ mechanisms are implemented. Therefore, considerations of the use of aquaculture are almost always coupled with source-control measures to prevent the release of nutrients into the system in the first place.

Inorganic (and some forms of organic) nitrogen are taken up by phytoplankton in estuary waters, which are consumed by shellfish. The shellfish assimilate the nitrogen into their tissues and shell, which is then removed from the system upon harvest (Rose et al. 2014). Nitrogen isotope data for quahogs and oysters on Cape Cod have indicated significant uptake of nitrogen (Carmichael et al. 2012; Reitsma et al. 2017).

Hart (2003) introduces the concept in a dynamic application to the problem of nitrogen loading and shellfish aquaculture in the Baltic Sea, near Sweden. He finds the addition of shellfish aquaculture to be an economically viable addition to the nutrient cleanup efforts. He also shows the advantage of aquaculture in its ability to induce an immediate impact, which is preferred when the cleanup effort is set up as a discounted present value problem.

Real-world planning problems rarely collapse easily around a single metric such as cost. In order to do so, the costs of infrastructure and interventions would have to be put on the same monetary scale as the pollution damages. In particular, a reasonable pollution damage function, consisting of ecological and social factors, is often unattainable. Therefore, we use Hart's (2003) framework to analyze a similar nutrient cleanup effort on Cape Cod, but expand on his ideas through the use of multi-objective optimization to quantify the tradeoffs across multiple factors of the planning problem that vie for the public's and decision makers' favor. These objectives cover the ecological objectives of improving estuary health, as well as the social objectives of minimizing cost and having impacts sooner. Specifically, we include objectives to (1) minimize the discounted present value costs of various cleanup plans, (2) meet the pollution targets (seeing results) as soon as possible. By framing the problem this way, we can estimate dynamically efficient plans to meet the TMDL targets for nitrogen. We define efficient plans as the plans that meet the TMDL by a certain year at the least cost. Including the cost objective also allows us to estimate the benefits of the addition of technologies other than traditional source control, such as shellfish aquaculture, to remediation plans. We present a description of the model followed by an application to the Three Bays embayment system on Cape Cod.

CONCEPTUAL MODEL

The nutrient conditions in an estuary are a function of the load it receives from atmospheric deposition, point and nonpoint sources, travel time, groundwater discharge, tidal flushing, and nutrient decay processes in the watershed and during transport to the estuary (Valiela et al. 2004; Figure 1). In this study, we consider two general classes of nutrient abatement options: those targeting upgradient sources (source control) and in-estuary (in situ) options. We put the interception technologies aside in this paper for clarity of interpretation (see Discussion). In-estuary interventions may have a near-immediate impact on the nutrient conditions in the embayment, whereas the impact of upgradient interventions is delayed relative to the time of implementation.

We represent nitrogen loading to the embayment over time, t, and account for reductions due to source abatement and natural attenuation in transit. Figure 2 shows a timeline explaining the dynamic nature of the model and the various time parameters. The load, $L(t)$, entering the estuary at time, t, is the sum of n individual loading sources, i.

$$L(t) = \sum_{i}^{n} N_i(t-\tau_i) S_i(y_i-\tau_i) k_i, \tag{1a}$$

where, $N_i(t - \tau_i)$ — is the N load from source i in time $t - \tau_i$. There is a time delay from source to estuary of τ_i. $S_i(y_i - \tau_i)$ — is the abatement effort or intervention to source i at time $y_i - \tau_i$, represented below with a percent removal *r_source*. k_i — is the natural attenuation of source i.

To handle the addition of sources over time to account for historic building, we allow for sources to be added over the past time periods. So, $N_i(t)$ is a matrix of loads based on the time the source is

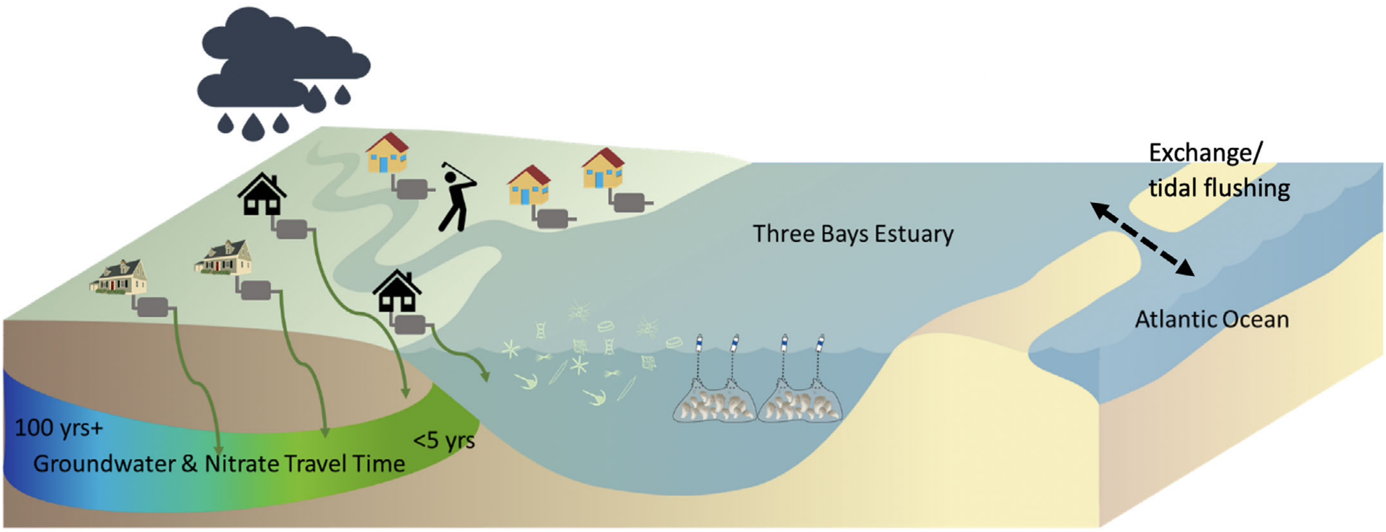

FIGURE 1. Nitrogen loading and processing in Three Bays, Massachusetts. Nitrogen loads to the Three Bays Estuary are primarily from household and commercial septic systems on Cape Cod. Nitrogen loads flow via groundwater to the bay. Abatement options include source control via centralized wastewater treatment, in situ treatment via shellfish aquaculture and interception technologies like permeable reactive barriers. Symbols and images Courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/symbols/).

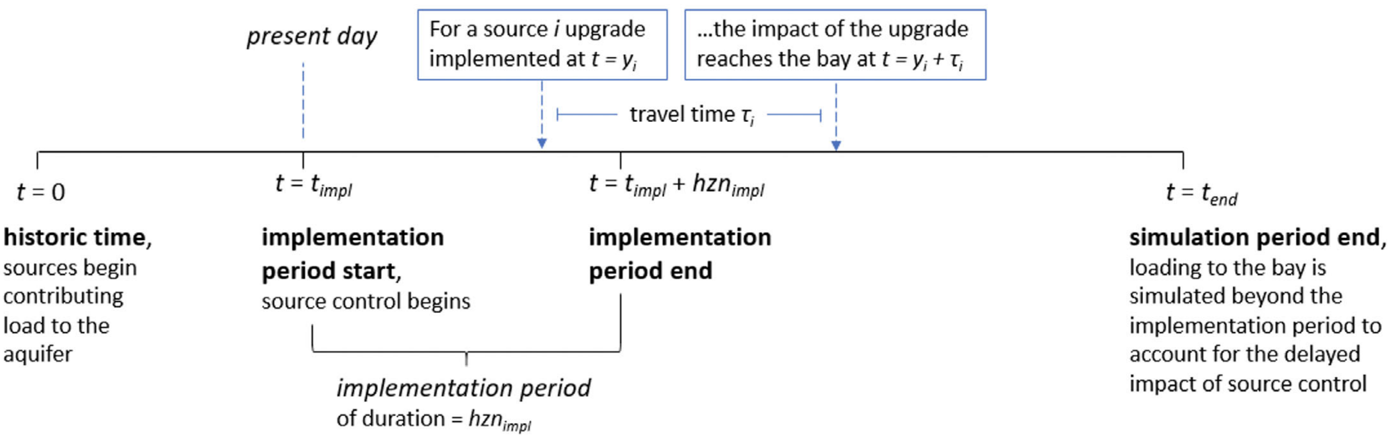

FIGURE 2. Timeline and time variables used in the N load simulation and optimization. The simulation includes historical loading, an implementation period where source control occurs and a simulation period for the model to reach steady state. Source control has a delayed effect depending on the groundwater travel time to the estuary.

initiated in the watershed, where it is zero before its initiation time and constant afterward.

If the present time t is less than the travel time τ_i of a source i, then that source load has not yet reached the embayment, meaning that (Equation 1a) is subject to:

$$N_i(t-\tau_i) = \begin{pmatrix} N_i & \text{for} t > \tau_i \\ 0 & \text{otherwise} \end{pmatrix}. \tag{1b}$$

Furthermore, the impact of a source control intervention S at time y_i is only realized at the embayment after the load from source i, reduced by a constant percent removal by source-control technology r_source, has had time to reach the embayment. This means that (Equation 1a) is also subject to:

$$S(y_i-\tau_i) = \begin{pmatrix} 1 & \text{for} t < \tau_i + y_i \\ 1 - r\_source & \text{otherwise} \end{pmatrix}. \tag{1c}$$

With in situ interventions in addition to source abatement, the load in the embayment $E(t)$ is represented as the load from sources $L(t)$ minus the sequestration and removal of nitrogen from in situ approaches, A. We represent the in situ option, shellfish aquaculture, as having an instantaneous impact (when considered in an annual time step or greater) on the nitrogen load in the embayment,

$$E(t) = L(t) - A(xa), \quad (2)$$

where, A — is the nitrogen load removed from implementing xa units of aquaculture with a removal rate of r_aquac. $E(t)$ — is the resulting nitrogen load contributing to the TMDL for the estuary after accounting for nitrogen removal from aquaculture A.

METHODS

Multiobjective optimization is a method for addressing this type of planning problem due to its ability to manage the competing interests (objectives) of minimizing the cost of the abatement plans to meet the TMDL, while also improving the water quality as quickly as possible. We apply a multiobjective evolutionary algorithm (MOEA) to approximate the Pareto optimal front of solutions, or set of abatement plans, in this study. A solution is considered to be Pareto optimal if its performance in one objective cannot be improved, for example, reducing cost, without degrading its performance in another objective, for example, increasing the amount of time (Coello Coello 1999).

Optimization problems are commonly represented in terms of decision variables, objectives, and constraints. A set of decision variables represents a solution to an optimization problem. In this work, the abatement plans (or solutions) are described by decision variables that specify when, where, and how much to implement source control. Specifically, we represented source control as connections to sewering for residential properties (i.e., sources) in the Three Bays watershed during any time period in a Y-long planning horizon (see Table 1 for parameter values). We grouped the properties by travel time into Z zones (see details in Section 'parametrization' and Table 1). This results in $Y \times Z$ decision variables for source control; in other words, the MOEA selects how many properties, $xs_{y,z}$, in each zone, z, to connect to sewers in each time period, y. We assume the amount of shellfish aquaculture to be constant, xa, and implemented at the start of the planning horizon within the embayment. The complete set of decision variables $\mathbf{d}$ can be described as:

$$\mathbf{d} = \left[xs_{y=1,z=1}, xs_{y=2,z=1}, \ldots xs_{y=Y,z=Z} | xa\right]. \quad (3)$$

Goals or objectives in optimization problems are used to evaluate the performance of the solutions. Multiobjective optimization affords the ability to evaluate solutions according to multiple objectives simultaneously without having to aggregate them into a single metric or index. Here, minimizing the cost of abatement plans and minimizing the amount of time to restore the embayment are the objectives. The cost objective is written in discounted present value, PV, terms:

TABLE 1. Model parameters.

Parameter		Value	Units	Source	Notes
	Total controllable load	46,221	kg N/Y	Total Maximum Daily Load (TMDL)	
	Wastewater load	34,376	kg N/Y	TMDL	
	Total septic system load	32,084	kg N/Y	Watershed MVP	See Table 2 for details by zone
TMDL	TMDL target	25,643	kg N/Y	TMDL	In terms of controllable load
$C(xs_{y,z})$	Sewer cost	240–518	\$/kg N/Y	Town and County of Barnstable	See Appendix for details
r_source	Sewer nitrogen abatement	100	%		
τ_i	Groundwater travel-time by source		Years	United States Geological Survey	See Table 2 for details by zone
k_i	natural attenuation by source		%	Watershed MVP	See Table 2 for details by zone
xa	Additional aquaculture leases	10	Acres		
r_aquac	Aquaculture nitrogen abatement	13–140	Kg N/acre/Y	MADMF, Reitsma et al. (2017)	yield of 50-500k animals per acre per year; see Appendix for details
t_impl	Start year of implementation	2,020	Year		
hzn_impl	length of implementation	100	Years		
t_end	End year of simulation	2,220	Year		
r	discount rate	5	%		
y_incrm	year increment for plans	5	Years		

TABLE 2. Three bays parameterization details.

Zones	1	2	3	4	5	6	7
travel time (years)	5	15	25	35	45	75	100
# of sources	3,544	1,149	514	178	119	241	451
Attenuated load	19,800	5,198	2,199	713	594	1,189	2,391
Unattenuated load	28,098	8,148	3,446	1,305	941	1,710	3,162
Attenuation	30%	36%	36%	45%	37%	30%	24%

$$\text{Minimize}\,\mathrm{PV}(t)=\sum_{t=t_{\mathrm{impl}}}^{t_{\mathrm{end}}} e^{-rt}[C(xs_{y,z})] \quad \text{for all with}\, y \le t, \tag{4}$$

where, r – is the discount rate. $C(xs_{y,z})$ — is a cost function that depends on the number of residential properties, xs, sewered in each zone z during each time period y. Note that although aquaculture is also simulated (see Equation 2), it is assumed to be costless.

The time objective is representative of the water quality goal to meet the TMDL in the bay as soon as possible.

$$\text{Minimize}\,\boldsymbol{t}_{\mathrm{TMDL}}[0], \tag{5}$$

where $\boldsymbol{t}_{\mathrm{TMDL}}$ is a sorted vector of time values corresponding to solutions that meet the TMDL, that is, $E(\boldsymbol{t}_{\mathrm{TMDL}}) \le$ TMDL for all t in $\boldsymbol{t}_{\mathrm{TMDL}}$, and $\boldsymbol{t}_{\mathrm{TMDL}}[0]$ is the first or earliest t in $\boldsymbol{t}_{\mathrm{TMDL}}$.

Constraints are used in optimization to limit the feasible solution space. We include a constraint to ensure that abatement plans, after initially meeting the TMDL in the embayment, continue to meet the TMDL into the future.

$$|\boldsymbol{t}_{\mathrm{TMDL}}| = t_{\mathrm{end}} - t_{\mathrm{impl}}. \tag{6}$$

Using this problem formulation of decision variables, objectives, and constraints, the MOEA yields a set of Pareto optimal abatement plans comprised of different combinations of source control locations and timing. The set of solutions, or Pareto optimal fronts, reflect the tradeoffs between the cost and time until the TMDL is met. These solutions not only show efficient plans over time, but also allow us to quantify the tradeoffs between cost and time, as well as value the addition of other nutrient abatement options, such as shellfish aquaculture, in these two dimensions.

We expect it will be more expensive to meet the TMDL sooner given the discount rate used. The costs incurred later in the horizon are smaller from today's perspective. In addition, the costs of source control, once initiated, continue over the remainder of the planning horizon, making delaying action cheaper in total from today's perspective. We expect those travel time zones that have shorter groundwater transport times to the estuary to be preferred for source control. For the same cost incurred to implement source control in a zone, the beneficial effect on the time objectives is larger for zones with short groundwater transport times. Lastly, we expect that those zones with lower natural attenuation rates to be preferred for source control relative to those with more attenuation, *ceteris paribus*, because the net N load reduction at the bay would be lower in zones with high natural attenuation for the same money spent on sewering.

We expect the addition of shellfish aquaculture to shift the Pareto optimal front, making the problem easier, in the sense that the total abatement needed from source control will be reduced. Additionally, shellfish aquaculture helps meet the TMDL more quickly because of its more immediate, in situ impact. We use this shift in the Pareto front to quantify the value of the inclusion of in situ N removal options in the plans. Calculating the shift in these fronts, with and without aquaculture, allows us to answer the question: *for the same time target, how much cheaper can a plan meet the TMDL?* Below, we describe the Three Bays estuary and parametrization followed by the results.

SITE PROFILE AND DATA SOURCES

Three Bays estuary system is located in Barnstable, Massachusetts (on Cape Cod). The Massachusetts Estuary Program (MEP) classified the water quality and aquatic health of Three Bays as overall moderately to severely degraded (Cape Cod Commission 2017). The 1,251-acre embayment system is composed of three main sub-embayments (North Bay, West Bay, and Cotuit Bay) ranging from 1.2 to 2.2 km^2, as well as several smaller embayments. Until the 1990s, the estuary contained a number of sensitive habitats including seagrass beds, although seagrass beds are virtually nonexistent today (MADEP 2007). Like other estuaries on Cape Cod, the TMDL targets were set based on the conditions necessary to support seagrass habitat as a sensitive yet important indicator of overall estuary health.

Three Bays hosts multiple recreation access points, marinas, beaches, shellfish grounds and commercial aquaculture operations, although each of its three subembayments are affected by nitrogen pollution.

There are currently 56 acres of shellfish aquaculture leases in Three Bays (ACCOL 2020, C. Nappi, Town of Barnstable, October 19, 2020, personal communication). The bay is degraded to the point that commercially and ecologically important shellfish populations (especially scallops) are sharply lower than historical estimates. Large macroalgal blooms from nitrogen pollution deplete the water of oxygen which can cause fish kills and threaten commercial oyster operations. The northern part of the bay, North Bay and part of Cotuit Bay, are closed to recreational and commercial shellfishing due to bacteria concerns.

Like the other estuaries on Cape Cod, the primary sources of controllable nitrogen loading within Three Bays watershed are wastewater (75%), fertilizer use (11%), and stormwater (10%). The TMDL total nitrogen reduction target for Three Bays aims to reduce controllable nitrogen loading by 45% (Cape Cod Commission 2017).

We parameterized our model of the system using the TMDL documents and watershed reports from the Cape Cod Commission (MEP 2007; Cape Cod Commission 2017). These provided estimates of the loading by source category (considered "controllable:" wastewater, fertilizer, stormwater, atmospheric deposition to vacant land, and from landfills) and the target nitrogen loading. Policy choices made in the estuary and watersheds only affect the controllable load (also referred to as "watershed load" in some reports). Therefore, we present the loading and target load numbers in terms of controllable rather than total load, following the convention of the Three Bays Watershed Report and the TMDL process (Table 1). We treat Three Bays as a single unit, while the TMDL reports break down loading targets by subembayment. This level of spatial discretization is left for future work. The TMDL process is focused on the conditions of estuary waters and the load paths of pollution, not the condition of ponds or rivers up the watershed. Some of the nutrient attenuation assumed in the TMDL modeling process may be another person's pollution-impacted freshwater pond by another name. Our simulation model does not capture the changes in conditions of these important water features.

Nitrogen Load

While the TMDL report specifies the types of the nitrogen load and overall target, the interventions to address the TMDL occur at specific sources (primarily at residential septic systems) that are dispersed spatially over the watershed. We use parcel-level loading estimates compiled in the Watershed MVP database by the Cape Cod Commission, a regional planning body (Cape Cod Commission 2019b). These data are meant to be representative of the wastewater load in the years 2009–2011 based on the parcel level analysis that went into creating the original TMDL reports to the extent possible. We assume no additional sources of nitrogen are added over the time horizon, implying no further buildout in the watershed. The population on Cape Cod has been steady since 2000 (Cape Cod Commission 2020).

There are other sources of nitrogen load to the estuary besides wastewater, including additional non-point sources, loads from fertilizer and stormwater runoff. However of the controllable load, wastewater represents 74% in this watershed and is the focus of this paper. Approaches to addressing other non-point sources may also face steep challenges related to uncertainties in location and amount of pollution being generated, unknown intervention efficiencies, and individual homeowner behavior (Segerson 1988).

Groundwater Travel Times

To estimate travel times of nitrogen to the estuary, we use results from a modeling effort by the United States Geological Survey (USGS). The USGS report spatially demarcated areas with different groundwater travel times to the estuary or other surface water (pond, stream or estuary; Walter et al. 2005, Figure 3; Table 2). During the MEP's modeling effort to set the TMDLs, it was assumed that once the nitrogen reached any surface water it was quickly transported to the estuary, at least when compared to multiple year or decadal periods underground (MEP 2007). Using GIS, we performed a spatial join to connect this travel time data with the nitrogen loading information from the Watershed MVP and assign each source a travel time for its effluent to the estuary. The Buzzards Bay National Estuary Program conducted a similar analysis and provided the spatially referenced USGS data (J. Costa, Buzzards Bay National Estuary Program, December 1, 2017, personal communication; Costa 2018).

Historic Load and Attenuation

In the process of connecting the MVP data spatially with the parcel-level data, we retain information on when the structures on the parcels were built. We use this information to estimate a historic nitrogen load in order to set the initial conditions of our problem (see Figure 2 for a timeline). In each year at the estuary, there exists nitrogen loading from past years based on the year, the parcel was built and the groundwater travel time. The TMDL target was set based on an assumption that the system is in a steady state and the TMDL policy goal was formulated as a static concept.

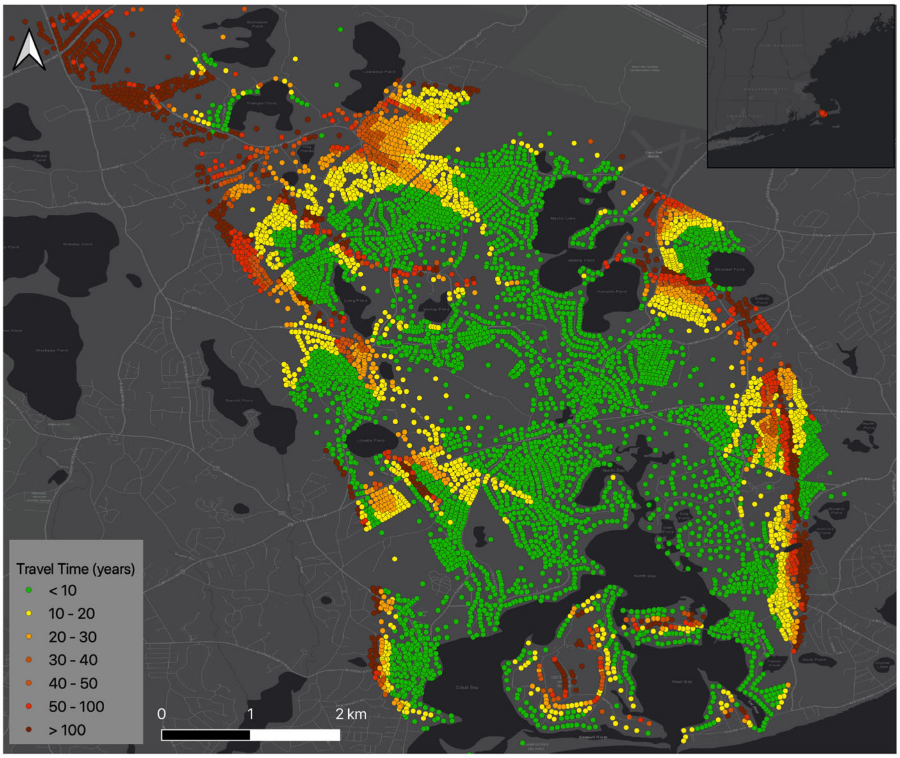

FIGURE 3. Groundwater travel times to Three Bays Estuary, Massachusetts. Estimates of groundwater travel time from Walter et al. (2005) overlaid on wastewater pollution sources in the embayment ground watershed. See Table 2 for loading by travel time group.

By estimating a historic load curve, we deviate, to some extent, from the original static MEP modeling.

In addition to the delay in transport, nitrogen from each source may be attenuated by natural processes en route to the estuary. We use estimates of attenuation by parcel from the Watershed MVP model. The MVP model assumes some denitrification happens on the way to the estuary if the groundwater intercepts streams, ponds, or wetlands (see MEP 2007).

Simulation and Implementation Time Horizons

Due to the historic load and pollution delays, we simulate the system starting in 1940. The implementation horizon, where source control can be added, begins in 2020 (t_{impl} in Figure 2) and continues for 50 years (hzn_{impl} in Figure 2) through 2070. This implementation horizon is broken into five-year increments in which decisions on how much additional source control to implement by zone can be made. To allow the effect of the implemented source control to make its way to the bay, we simulate the system for another 100 years after the end of the implementation horizon to 2170 to ensure the system reaches steady state. We calculate and total the discounted costs of cleanup plans from the start of the implementation horizon to the end of the simulation using a 5% discount rate. The choice of this discount rate is reflective of the historic long-term cost of capital for public infrastructure projects and to match inputs to previous costing estimates of wastewater infrastructure in the region (Barnstable County Wastewater Cost Task Force 2014; Cape Cod Commission 2019a).

Interventions

Based on discussions with Cape Cod and Three Bays stakeholders and the current plans for the watershed, we explore two representative options: (1) traditional source control via centralized wastewater treatment (hereafter “sewering”), and (2) traditional source control coupled with in situ remediation via expansion of shellfish aquaculture-leased acreage. The inclusion of many other intervention options, such as denitrifying septic systems, PRBs, cranberry bog restoration, urine-diverting toilets, or fertigation wells, is feasible and our general methodology could be applied in future work. For the purposes of clarity, we use the two representative and widely discussed technologies (sewering and aquaculture) to estimate the tradeoffs across the time and cost objectives.

We summarize abatement technology costs in equivalent annualized cost terms, \$/kg N abated/year, including installation, operation, maintenance, monitoring, financing, and replacement at the end of its design life (see Appendix for specifics by technology). For our application, we use a range of costs for sewering, bounded by a conservative (i.e. higher) cost, and more optimistic (lower cost) local estimates. We set the effect of sewering in Three Bays to a 100% reduction in nutrient load from those sources connected as the effluent is transported out of the watershed to the treatment plant and disposal (Table 1 and Appendix for details; Barnstable County Wastewater Cost Task Force 2014; Town of Barnstable Department of Public Works 2017).

As a part of the Commonwealth of Massachusetts, in Three Bays and other Cape Cod waters, commercial shellfish farmers lease area from the towns to grow oysters (*Crassostrea virginica*) and clams (*Mercenaria mercenaria*). There are currently 56 acres of shellfish leases in Three Bays, the effects of which were taken into account in the studies setting the TMDL targets (MEP 2007). Therefore, in this work, we are simulating the effect of *additional* leased acres as the effect of these would be counted toward improvement over current conditions.

Nutrient abatement from aquaculture results from removal of the animals from the bay (Rose et al. 2014; Reitsma et al. 2017), whereas the potential for any denitrification benefits of animals left in the bay is less certain (Kellogg et al. 2014; Ray et al. 2019). The variation in nitrogen content of the shellfish removed is relatively small (0.19 N(g)–0.32 N(g) per animal) even between species at harvest weight (Reitsma et al. 2017). The annual yield from farms is much more variable, ranging from 2,766–73,907 animals harvested per acre, per year across Cape Cod towns for 2016 (DMF 2016). For the simulation, on the low end we use rates reflecting current average shellfish yields from farms in the town of Barnstable (46,130 animals/acre) and on the high end (500,000 animals/acre) as a localized estimate of potential yield (see Table 1 and Appendix for details).

We represent aquaculture as costless in the simulation. The primary costs of shellfish aquaculture farms are borne by the owners and are presumed to be included as operating expenses for a profitable business. We expand on the implications of this assumption further in the discussion. Therefore, we choose to represent aquaculture not as a choice variable, but through scenarios. Put another way, we ask, *how does the addition of leased shellfish aquaculture acres affect the cleanup problem in terms of offsetting source control and having a more immediate effect?* This is referred to generally as an avoided cost approach to valuation (De Groot et al. 2002; Thurston 2011).

Numerical Optimization

We simulate the system using Python 3.6. With multiple zones and a 50-year planning horizon, depending on the year increments of decisions, the choice space could be prohibitively large. We reduce the number of choice variables in our dynamic model to a reasonable level by binning nitrogen sources into seven zones by travel times and reducing decisions to five-year periods rather than annually. We assign the sources in each bin the travel time of the middle of the bin (<10 bin set to 5 and the 10–20 bin set to 15 years, for instance). For any sources with estimated travel times greater than 100 years, we set them at 100 years. A five-year choice space increment (10 time periods) and seven zones results in 70 choice variables. A choice variable discretization of 100 would lead to 100^{70} possible combinations of choice variable values.

The specific MOEA used in this work is the Borg MOEA (Hadka and Reed 2013) which has been shown to have superior performance relative to other similar MOEAs (Woodruff et al. 2012; Zheng et al. 2016). The Borg MOEA supplies six search operators and adaptively selects these operators based on feedbacks received during the search process (Hadka and Reed 2013). For each optimization scenario, the Borg MOEA was run for a search duration of 100,000 function evaluations. This search duration was deemed sufficient by incrementally increasing the number of function evaluations for a sequence of optimizations until the solution sets of each optimization were nearly the same.

RESULTS

The addition of 10 acres of aquaculture saves between \$1.9M–\$18.5M in 2019USD (high and low assumptions of aquaculture yield) toward an estuary

TABLE 3. Value of aquaculture to cleanup plan. Aquaculture may reduce the need to control some sources and has a more immediate effect on the estuary. When considered in a discounted present value problem, the addition of ten acres represents sizeable economic value, in terms of reduced cost of source control. These figures do not include any social costs incurred by the additional aquaculture operations, thus are gross benefit estimates.

Aquaculture yield (10 acres)	**TMDL target 2035**	**TMDL target 2060**
High cost of source control		
High yield	\$18.5M	\$5.6M
Low yield	\$1.9M	\$0.53M
Low cost of source control		
High yield	\$8.2M	\$2.4M
Low yield	\$0.72M	\$0.28M

cleanup effort designed to meet the TMDL in 2035, or \$529K–\$5.6M for a target date of 2060, both under the assumption of high costs for sewering (a sensitivity analysis can be found in Table 3). This equates to an average value of 37¢ (2035 target date) and 11¢ per animal (2060 target date) harvested during the 100-year implementation horizon. These figures do not include any social costs incurred by the additional aquaculture operations, thus are gross benefit estimates.

The full results of the multi-objective optimization are sets of efficient plans for meeting the TMDL in a given time frame with source control (with and without the additional aquaculture leases). We can show the tradeoff between our two objectives within efficient plans; time to reaching the TMDL target and cost in a plot (Figure 4). These Pareto fronts can be thought of as (least)-cost curves to reaching the TMDL target in those time frames across the *x*-axis. The results confirm our initial expectations of a downward sloping curve with early success in achieving the TMDL coming at a higher cost, nearly \$300M for plans meeting the TMDL earliest (by 2030) to less than \$50M for plans that are delayed (meeting the TMDL by 2075).

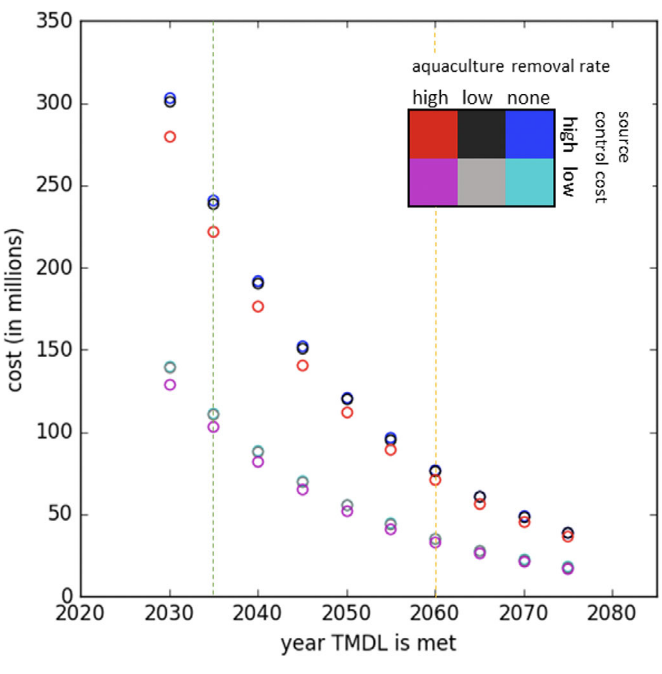

FIGURE 4. Pareto-efficient Fronts. The sets of curves show fronts across high and low source control costs (difference between the two groups of curves) and through high, low, and no aquaculture nutrient abatement. The vertical distance between the no aquaculture scenarios and the other curves captures the value of the addition of aquaculture to the estuary cleanup plans. The two vertical lines refer to the TMDL target date results displayed in Table 3 and Figures 5 and 6.

Adding aquaculture shifts the Pareto fronts by offsetting costs of sewering and having more immediate impact. The curves with aquaculture added to the solution (red, purple, gray, and black in Figure 4) show the shift in the efficient solutions away from the blue and teal curves (without aquaculture). This inward shift shows the improvement in the efficiency of solutions with aquaculture added. This can be quantified as the vertical distances between the curves in Figure 4. The addition of aquaculture is worth more for plans that seek to meet an earlier target date, reflecting the larger value of aquaculture's more immediate impact on the estuary. The low aquaculture (black and gray) and no aquaculture curves (blue and teal) are very similar and stacked closely in Figure 4.

The history of pollution loading leads to a system that is not in equilibrium at the start of the implementation time frame (2020). Even with our assumption that no additional sources of N will be added to the watershed, if no cleanup plan is implemented, loading at the estuary could continue to increase until reaching equilibrium in 80 years because of the legacy of nitrogen in the groundwater still in transit (blue line in Figure 5). Any of the plans must contend with this legacy, as the system may not flush out this historic pollution until after 2100. To demonstrate the impacts of the plans on nitrogen loading through time, the effect of two efficient plans on estuary pollution loads can be seen in Figure 5, showing variation in when the nitrogen loading at the estuary meets and maintains the TMDL target load indicated by the dotted red line.

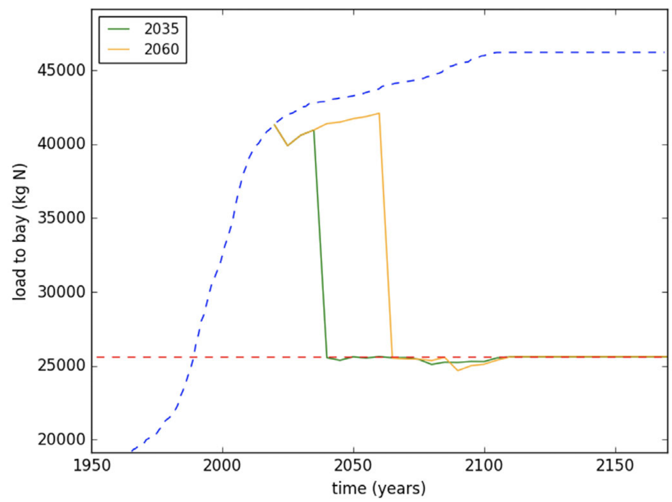

FIGURE 5. Time series of pollution loading. Historic pollution loading and groundwater travel time leads to an increasing load to the estuary (blue line) without a clean-up plan. Two efficient plans (green and yellow line) show the effect on loading and the years the TMDL target (red line) is met. The step down in loading in initial years represents the contribution of 10 acres of aquaculture to the overall pollution load reduction.

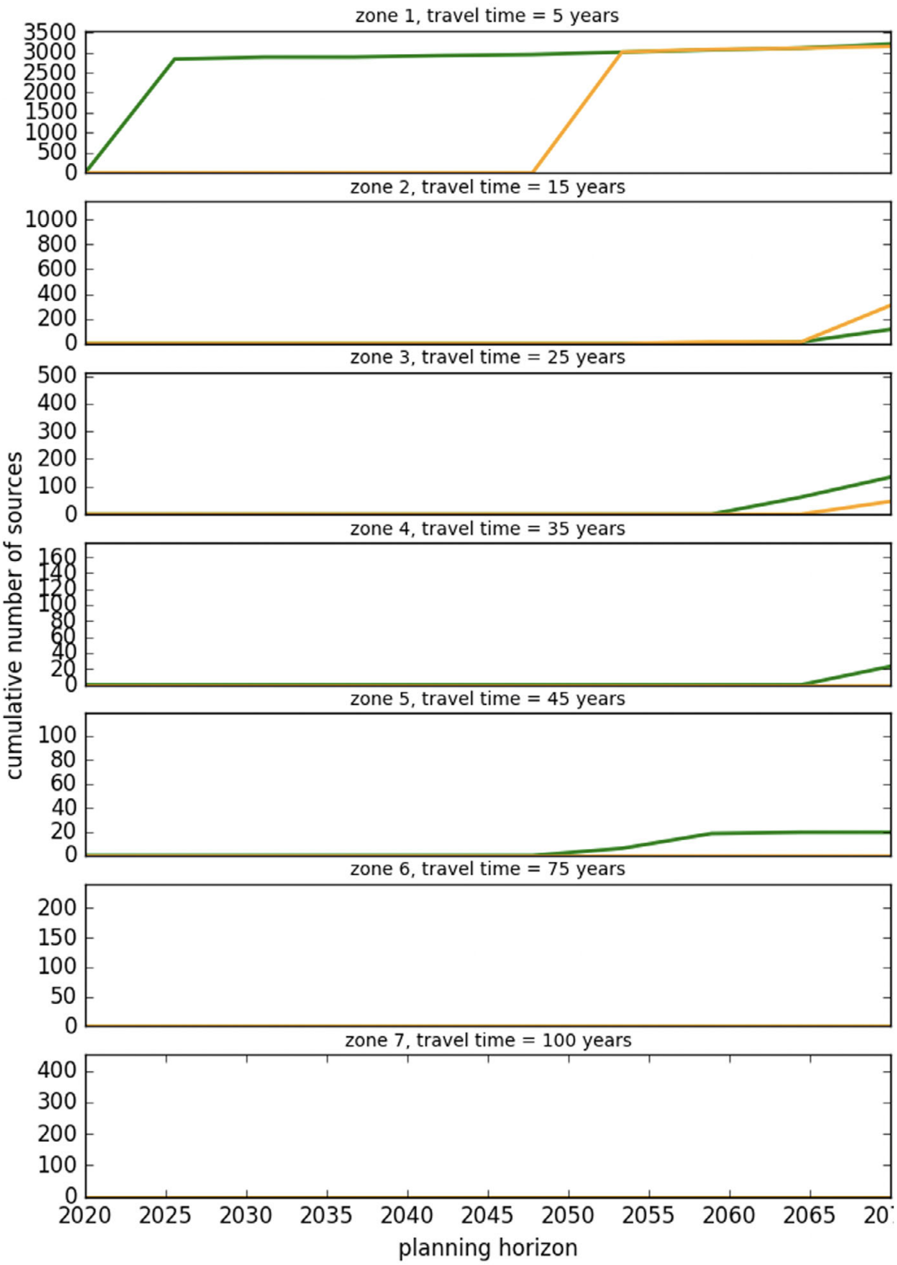

FIGURE 6. Source control through time and by zone. The clean-up plans vary in terms of when and how many sources are abated. The green line corresponds to the two plans in Figure 5. The majority of pollution sources are in zone 1 with a short groundwater travel distance, but reaching and maintaining estuary loading at the TMDL target requires work in the more delayed zones.

The variation in these plans comes from when, where, and how much source control gets implemented in each of the zones, which each have their own travel time to the estuary and natural attenuation. The plans vary in what pace the source control is implemented, but the shortest travel time zone is preferred with progressively less and delayed attention paid to sources further in groundwater travel time from the estuary (Figure 6). This preference is the result of the earlier effect for the same cost for attention to sources of nitrogen closer to the estuary. No effort is made to address load from the longest travel time zones (75+ years of travel time), as it is the least efficient for applying source control and the total load in those zones is small enough that it does not need to be reduced to meet the TMDL in equilibrium.

For plans meeting the TMDL early in the horizon, the effort is generally shifted earlier in each zone, but still follows that same relative trend of preference to short travel time zones. To meet the TMDL in a short period of time (by 2035), sources in zone 1, the majority of the load, are mostly sewered in the first decade. Naturally, the time at which this large group of homes in the short travel time zone are sewered leads to the largest variation in the time until TMDL is met. Work in this zone alone is insufficient to meet the target and keep the loading below the target given the historic load. In each solution, there is effort eventually needed in zones 2–5 to avoid the estuary loading from returning above the TMDL target later in the horizon.

DISCUSSION

We found large marginal benefits for including additional aquaculture in the cleanup plans, yet we represented aquaculture as costless from the simulation's perspective. We did this for a few reasons. While there are private costs incurred by the commercial operators, these are covered by revenues if the leases are profitable. There are also social costs which we did not include. The town incurs costs overseeing the operations, and the farms themselves introduce some costs in terms of reduced amenities to the public by taking up space that could be used for other activities and negatively affecting viewsheds for some homeowners and visitors (Dalton and Jin 2018). The additional supply of shellfish resulting from water quality goals may also depress market prices, negatively affecting other growers. A comprehensive estimate of the social costs is not available for Three Bays, or for the region in general, but would be a useful addition to our base of knowledge. Therefore, our results represent and should be interpreted just the marginal benefit of aquaculture leases, not a net social value.

To answer the larger question of whether and how many additional leases are economically optimal from a social perspective, one would compare our estimated cost-saving, or time savings toward the objectives, to the unknown social cost of the additional leases. The scale of benefits shown in our results implies the social costs of aquaculture would have to be significant to overcome the large social benefits it generates toward the TMDL cleanup effort. The social costs of aquaculture would need to be larger than \$2,500 per year per acre to make the value of additional aquaculture leases net-negative at the margin under the most conservative assumptions and later TMDL target date, or as high as \$90,000 per year per acre with early target dates and higher yielding aquaculture acreage.

Although there is a case, at the margin, for increased leased shellfish growing acreage being economically valuable to the TMDL effort, the total scale of the impact of additional acreage is limited given physical and social constraints around the bay. To put the scale of possible impact into perspective, under the high estimates of leased acre productivity, the nitrogen removed from harvest from an additional acre (140 KG/year high yield assumptions in our simulation) is only 0.7% of the amount estimated as needing to be removed every year per the TMDL limits. An additional acre assuming current shellfish yields on an average leased acre in Barnstable (13 KG/year, low yield assumptions in our simulation) would only represent 0.07% of the needed reduction.

Space is limited that may be suitable for leasing. As part of the planning for the TMDL an additional 43 acres was estimated as a maximum buildout for future leases in the bay (Cape Cod Commission 2017). Additional spatial and visual use conflicts are likely with recreationalists and waterfront homeowners (Dalton et al. 2017). These physical limitations and social costs increase (in total and likely marginal terms) with the scale of additional leases, limiting the total amount of the overall TMDL effort that can be addressed with this alternative. Given the relatively low observed average yield per leased acre in the town of Barnstable (48k animals in 2016), which we used as our low yield assumption, increasing the yield off already-existing acres could achieve the same effect as additional leased acres, subject to localized physical and biological limitation of the bay (Byron et al. 2011; DMF 2016). We present our benefit estimates in per animal terms in addition to per acre terms to be more generally applied to this potential method of increased denitrification from shellfish harvesting. The per animal benefit estimates would similarly be applicable to any additional recreation and wild harvest impacts.

We chose to base our estimates on the cost of sewering as opposed to the other largely cited source control option of installing innovative and alternative (I/A) septic systems designed to denitrify wastewater before it enters the groundwater. The reductions in nitrogen loading resulting from I/A systems, as currently permitted, cannot achieve the needed load reductions to meet the TMDL by their use alone, even if installed at all of the more than 6,000 homes in the watershed. In addition, at the current estimates of costs for installation, operation and monitoring, they are more expensive per KG of N abated than even the high-end cost estimates of sewering (see Appendix for costing information for I/A septics and centralized treatment). Our linear treatment of the cost of nitrogen abatement technologies would lead to sewering being the dominant choice throughout the watershed from an optimization perspective. In practice, there are likely areas within the watershed where sewering will be impractical or more expensive than installing I/A systems and any final buildout plan will likely include both types of source control to some extent. Research is ongoing with more advanced septic systems that seek to lower the effluent nutrient concentrations and overall costs of installation, operation, and monitoring (MASSTC 2019; Martin and Johnson 2019). This distinction between the types of source control and costs would not drastically affect the setup and results of our simulation as it would just shift the size of the avoided costs attributed to aquaculture.

Using our method to assess the value of other alternatives to source control (PRBs, wetland restoration, fertigation wells, etc.) would follow similarly to what we did with aquaculture leases. To do so, each technology would need to be costed in equivalent terms (annualized and discounted) per unit of nitrogen abated. This is straightforward for other source control options, such as the I/A discussion above and in the Appendix, however, more research is needed on the denitrification efficiency and life-cycle costs of the I/A systems. It is worth stating that for any *avoided* costs, these technologies would have to be cheaper than the centralized treatment, a feature that that has yet to be shown at scale for any alternative technology under consideration.

A system as complex as this economic and ground watershed model has many compounding uncertainties in cost and effectiveness of technologies, groundwater travel times and future development, in addition to the uncertainties in the setting of the TMDL limits. Beyond the cost and time differences to various approaches to coastal nutrient control, the interventions vary in the certainty in which they might achieve the nitrogen reduction goals (Stephenson and Shabman 2015). We presented a sensitivity analysis in the dimensions that most directly affected our valuation for aquaculture (aquaculture yield and sewering costs), but there is ample scope to narrow uncertainties in the system with future pilots of alternative technologies and additional groundwater research and modeling, for instance.

Optimal frontiers, such as the ones found in this paper can provide benchmarks to measure variations of real-world plans against as a measure of relative efficiency. While town planners may use the results and generalizations from watershed optimizations, such as the one we presented, the ultimate sewer plan (and overall CWMP) will deviate from the optimal for practical reasons that may be complicated and beyond the scope of this optimization (Town of Barnstable Department of Public Works 2019). In the case of sewer plans, these confounding factors may include concurrent road construction activities, additional spatial considerations for contiguous neighborhoods, or town bond issue schedules, for example. We did not include funding or construction capacity constraints in the five-year increments in the simulation. Doing so would have spread the sewering out over time in the optimization if they were binding in any period. Using optimization and necessarily simplifying the problem, we present a lower bound of costs for the cleanup, as actual plans may deviate, likely upwards in costs, due to these unmodeled factors. In the big picture, avoided cost approaches do not require that the costs being avoided be based on an "optimal" plan as defined by a modeling effort. In fact, the value of additions of alternative technologies to an inefficient sewer plan would be greater than indicated in this exercise. As with any effort with long time frames like this one, the ability to incorporate new information and plans is necessary for adaptive management.

There are many other embayment and watershed systems on Cape Cod that are undergoing similar pollution cleanup planning efforts, as well as efforts ongoing in Long Island, NY and Great Bay, NH. Our method could inform those efforts. Given the differences in pollution sources, distribution and degree of natural attenuation and ground and surface water delivery mechanisms, we expect that the avoided costs of nonsource-control technologies in other watershed-embayment systems would differ from our results. For example, while the long groundwater travel times in Cape Cod (decades to over 100 years) complicate the cleanup effort, the aquifer underlying Long Island, New York has more extreme groundwater travel times, from 100 to 1000 years and beyond (Misut and Monti 2016).

CONCLUSION

The issue of the legacy of pollutants and the time delay in transport of those pollutants to receiving waters is being increasingly recognized as a complication to policies being designed to address the impacts (e.g., Shortle et al. 2016; Van Meter et al. 2018). While a great deal of watershed optimization work addresses where actions might take place spatially, fewer tackle the dynamic nature of the problem. Static views of these coupled human-natural systems miss an important social aspect, time preferences and the time value of money, or put simply, the desire to see results soon for resources spent. Legacy pollution and time delays in its transport work against these priorities.

By exploring the time dimension of pollution transport and cleanup efforts, we were able to quantify the value of alternative technologies to traditional wastewater infrastructure, considering costs, time preferences and natural attenuation. Simply comparing static costs may underrepresent the possible value of including approaches that have a more immediate effect on the waters of interest. We demonstrated this concept by estimating the potential considerable value of including aquaculture leases as an in situ treatment while traditional source control and wastewater treatment are implemented over time. Natural systems that result in long time delays in the transport of pollutants to receiving waters enhance the economic case for considering, testing and including alternative and in situ approaches in pollution cleanup efforts.

APPENDIX

SOURCE CONTROL COSTS

The costs of adding sewers, wastewater collection and treatment plant upgrades came from two sources. The lower-cost estimates are from a report by the Barnstable County Wastewater Task Force which estimated the cost and effectiveness of a wide range of technologies under consideration on Cape Cod (Barnstable County Wastewater Cost Task Force 2014). This report also provided much of the basis for the Cape Cod Commission's Tech Matrix (Cape Cod Commission 2019a). They are representative of what the average cost for sewering might be across Cape Cod. The higher-cost estimates are from the town of Barnstable's proposed sewer plans which included costs of collection, plant upgrades needed and solid waste disposal (Town of Barnstable Department of Public Works 2017). While these town-level cost estimates are preliminary, they are specific to the town where most of Three Bay's watershed lies. This plan is phased over 80 years and we used the average of the costs across the phases. For the impact of centralized wastewater treatment on Three Bays, we assume a 100% reduction rate because wastewater treatment plants in Barnstable discharge into different estuaries. While this reduction is appropriate from the perspective of Three Bays, at a larger, town-scale, the effluent from the wastewater treatment plants must still be incorporated into other TMDLs.

The input and intermediate steps for creating the equivalent annual cost, EAC/Kg N, for centralized treatment and innovative and alternative's (I/A) (for comparison) are in the table below. The gallons per day (GPD) is set to create town-wide EAC/Kg N, therefore the scale is set to the GPD used in the Town of Barnstable's centralized treatment calculations.

TABLE A1. Costing parameters and assumptions.

General parameters		
r-borrowing rate		5%
Sewer replacement (#years between replacements)		20
Septic replacement		20
GPD per property		175
Number of properties		10,231
GPD total		1,790,500
Title V effluent to groundwater		26 mg/L
I/A effluent to groundwater		19 mg/L
Advanced I/A effluent to groundwater		13 mg/L
Centralized wastewater treatment	**Low cost**	**High cost**
Plant construction/GPD	$19	$22
Collection cost per property	$26,275	$47,765
O + M/GPD	$2	$2
Septic		
Cost of title V (capital install)		$12,880
Cost of operating and maintenance + monitoring cost for title V (per year)		$165
Cost of I/A (capital install)		$22,400
Cost of operating and maintenance + monitoring cost for I/A (per year)		$1,375
Cost of advanced I/A (capital install)		$28,000
Cost of operating and maintenance + monitoring cost for advanced I/A (per year)		$3,850

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AUTHORS' CONTRIBUTIONS

Nathaniel H. Merrill: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; supervision; visualization; writing-original draft; writing-review & editing. **Amy N. Piscopo:** Conceptualization; data curation; formal analysis; investigation; methodology; resources; software; visualization; writing-original draft; writing-review & editing. **Stephen Balogh:** Conceptualization; data curation; formal analysis; investigation; methodology; resources; software; supervision; visualization; writing-original draft; writing-review & editing. **Ryan P. Furey:** Data curation; formal analysis; investigation; methodology; writing-original draft; writing-review & editing. **Kate K. Mulvaney:** Conceptualization; investigation; methodology; supervision; writing-original draft; writing-review & editing.

TABLE A2. Equivalent annual cost calculations.

	Title V	Conventional treatment (low)	Conventional treatment (high)	I/A	Advanced I/A
GPD	1,790,500	1,790,500	1,790,500	1,790,500	1,790,500
LPD (liters per day)	6,777,777	6,777,777	6,777,777	6,777,777	6,777,777
Effluent concentration (N mg/L)	26	0	0	19	13
% reduction of N		100.00%	100.00%	27.62%	50.48%
kg/day	178	0	0	129	88
N load per year	64,940	0	0	47,004	32,161
N removed over Title 5		64,940	64,940	17,936	32,779
Collection cost		$268,830,786	$488,700,000		
Construction of plant		$34,019,500	$39,150,000		
Capital cost	$131,780,800	$302,850,286	$527,850,000	$229,184,000	$286,480,000
O&M (operations and maintenance) + monitoring costs	$1,688,186	$3,581,000	$3,581,000	$14,068,214	$39,391,000
Finance cost	$10,574,432	$24,301,490	$42,356,050	$18,390,317	$22,987,896
EAC (equivalent annual cost)	$12,262,618	$27,882,490	$45,937,050	$32,458,531	$62,378,896
EAC over title V		$15,619,872	$33,674,432	$20,195,913	$50,116,278
EAC/KG N removed		$429	$707	$1,810	$1,903
EAC/Lbs N removed		$195	$322	$823	$865
Less title V costs					
EAC/KG N removed		$241	$519	$1,126	$1,529
EAC/Lbs N removed		$109	$236	$512	$695

TABLE A3. Aquaculture yield and nitrogen content. The variation in nitrogen content is minimal for oysters vs. quahogs. No estimates were available for the maximum number of mixed quahogs and oysters, but 500,000 oysters were identified as a reasonable assumption for yield from a leased acre by the Cape Cod Commission's expert panel for the use of shellfish in their Technology Matrix (Cape Cod Commission 2019a).

		Yield/acre/Y	
	g N per animal	Low	High
Oyster	0.28	46,130	500,000
Quahog	0.22	1,807	0
Total animals		47,936	500,000
kg N/acre/Y		13.30	140.4

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