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System-level Nutrient Pollution Control Strategies

Hydroeconomic modeling of resource recovery from wastewater: Implications for water quality and quantity management

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Abstract

Emerging technologies and practices allow wastewater treatment facilities to recover valuable resources such as nutrients, energy, and recycled water during the wastewater treatment process. The ability to recover resources from wastewater introduces new tradeoffs in both water quality and quantity management. In particular, the fact that communities can obtain revenue from the sale of resources that are recovered from wastewater may help internalize the externalities of insufficient wastewater treatment. In this paper, we develop a theoretical model to characterize these tradeoffs within a hydroeconomic framework of optimal wastewater treatment with resource recovery, which is particularly well suited for applications in nutrient management. We use this model to derive analytical results that describe the economically optimal level of deployment, accounting for the fact that the technology or practice is costly and it generates benefits in the form of revenue from the recovered resource, as well as other societal benefits, such as improvements in human and ecosystem health. In addition, we present two examples using specific functional forms for treatment costs to demonstrate how the model can be applied to obtain general principles regarding societally optimal deployment. Our hydroeconomic framework can be used to explore the socioeconomic implications of strategies that target deployment of wastewater treatment with resource recovery, especially nutrients, at multiple scales.

1 | INTRODUCTION

A growing literature argues that improvements in wastewater management technologies and practices will be instrumental in providing clean water, sanitation, and environmental protection to growing economies and populations. Promising developments include advances in water purification (Elimelech & Phillip, 2011; Shannon et al., 2008) and wastewater management solutions that can recover valuable resources from wastewater such as electricity, biodiesel, recycled water, biosolids, and nutrients that serve as components of fertilizer (Guest et al., 2009; Iranpour et al., 1999; López-Morales & Rodríguez-Tapia, 2019; Mo & Zhang, 2013). Wide-scale adoption of these solutions and realization of the associated societal benefits depend on the socioeconomic context in which the solutions are made available, including their cost-effectiveness relative to existing technologies and practices, constraints imposed by regulatory frameworks, and acceptance by firms and the public. Communities may also prioritize different wastewater management solutions on the basis of broader societal benefits, such as improved ambient water quality and reduced greenhouse gas emissions.

Economic optimization frameworks are useful for examining how societies can account for issues of cost-effectiveness, regulation, and public benefits tied to the deployment of innovative wastewater management solutions. This usefulness stems from the frameworks' ability to provide a formal representation of all of the societal costs and benefits associated with a wastewater management decision, as well as any constraints on those decisions imposed by budgets, regulations, or public acceptance. Despite the potential for these frameworks to inform and resolve tradeoffs associated with new wastewater management strategies such as moving toward the water resource recovery facility of the future (Mihelcic et al., 2017), the water economics literature has yet to develop a set of models that can flexibly account for the economically meaningful ways in which these innovative solutions differ from existing wastewater management problems. In particular, for technologies and practices that can recover valuable resources from wastewater, revenue from the sale of the recovered resources can help communities internalize some of the externalities of insufficient wastewater treatment. That is, resource recovery may generate revenue that can narrow the gap between the private and social net benefits of wastewater treatment, making it more likely that local governments and private entities invest in these technologies.

In this paper, we develop a general hydroeconomic model that characterizes the societal costs and benefits of adopting a technology or practice that can treat wastewater while recovering resources. We use this model to derive analytical results that describe the economically optimal level of deployment given that the technology or practice is costly and it generates benefits in the form of revenue from the recovered resource, as well as other societal benefits. In addition, we present two examples using specific functional forms for treatment costs to demonstrate how the model can be applied to obtain general principles regarding societally optimal deployment. These examples are also instructive in that they demonstrate how the availability of resource recovery fundamentally changes the economic tradeoffs associated with wastewater management.

Although our hydroeconomic framework is able to consider many types of resources that can be recovered from wastewater, for a number of reasons, it is best suited to analyzing nutrient recovery. First, there is an existing and mature set of technologies and practices that can recover nitrogen, phosphorus, and potassium from wastewater—including recovery from source-separated urine, anaerobic digestion, controlled struvite precipitation, and biosolids production—and innovation in this sector is accelerating. Second, there is a robust ongoing discussion regarding public policies and business models that can incentivize the adoption of nutrient recovery (e.g., Mayer et al., 2016; Otoo & Drechsel, 2018), the designs of which can be informed by analysis using our framework. Third, our framework explicitly considers the role of societal benefits such as improved ambient water quality in the optimal deployment of resource recovery, which is consistent with the key objectives of nutrient recovery. Fourth, our framework applies to resource recovery processes in which the recovered material is also the pollutant in the wastewater which, if discharged, will generate environmental damage. Nutrients fall under this category, unlike other recoverable resources such as recycled water and energy. Finally, our hydroeconomic framework is sufficiently general and flexible such that it can accommodate the diversity of nutrient recovery technologies and practices that exist, which vary greatly in scale (e.g., onsite vs. offsite, building scale vs. city scale) and the societal context in which they are used (e.g., urban areas in developed countries vs. rural areas in developing countries).

Core Ideas

- Wastewater treatment facilities can recover valuable resources, including nutrients.
- Resource recovery introduces new tradeoffs in water and nutrient management.
- We developed a hydroeconomic framework to characterize these tradeoffs.
- The framework is particularly well suited for applications in nutrient management.

Our paper makes two key contributions to the hydroeconomic modeling and nutrient management literatures. We conduct a literature review and describe how resource recovery technologies and practices change our current understanding of the economic costs and benefits of wastewater treatment. To our knowledge, we are the first to present a modeling framework that captures the unique economic tradeoffs that arise when resource recovery is a viable strategy for wastewater management from public utility, private operator, and broader societal perspectives.

2 | COSTS AND BENEFITS OF WASTEWATER TREATMENT WITH RESOURCE RECOVERY

In an economic analysis, it is useful to categorize the costs and benefits of wastewater treatment into those that affect the operator of the wastewater treatment facility (i.e., the internal, or private, costs and benefits) and those that relate to elements of society beyond the facility (i.e., the external costs and benefits). In the context of resource recovery from wastewater, internal costs are driven by the costs associated with building, operating, and maintaining the wastewater treatment facility, whereas internal benefits are driven by revenues obtained from the sale of the recovered resource. The external benefits of wastewater treatment stem from improved water quality, which can include improved human and ecosystem health, improved recreational opportunities, and aesthetic benefits, and offsetting of embedded energy in treated wastewater

(Mihelcic et al., 2017). Operators of wastewater treatment facilities may account for some or all of these cost and benefit categories when managing the deployment of wastewater management solutions.

The costs associated with building, operating, and maintaining the wastewater treatment facility are borne by facility operators and, in the case of utilities, often passed onto consumers of the wastewater treatment service or subsidized in whole or in part by local municipalities. The key determinants of the cost of wastewater treatment are the volume of wastewater that needs to be treated and the concentration of harmful contaminants in that wastewater that need to be removed prior to discharging the treated wastewater into the environment. The volume of wastewater to be treated most crucially depends on the size of the population that is being serviced by the wastewater treatment facility but also depends on the volume of wastewater generated per individual or residential, commercial, or industrial establishment (Hernandez-Sancho, Molinos-Senante, & Sala-Garrido, 2011; Huang Foen Chung & van Mastrigt, 2009). In addition, treatment costs depend on the composition of the wastewater and the degree to which pollutants in the wastewater are removed; that is, both influent concentrations (or mass loading) and effluent targets are factors (Bode & Grünebaum, 2000; Fraas & Munley, 1984; Friedler & Pisanty, 2006; Ishii & Boyer, 2015).

One of the most important benefits of wastewater treatment is the protection of human health. Municipal wastewater often contains human waste, which carries pathogenic viruses, bacteria, parasites, and protozoa that may cause human illnesses or death. Studies have shown that provision of sanitation infrastructure can reduce the incidence of human illnesses ranging from gastrointestinal illness (Dwight, Fernandez, Baker, Semenza, & Olson, 2005; Kumar & Vollmer, 2013) to infectious respiratory disease (Watson, 2006) to digestive cancer (Ebenstein, 2012). In all these studies, the monetized value of these human health improvements exceeded the costs of the intervention that was necessary to bring about those improvements. Studies have also shown that improved sanitation and sewerage infrastructure have led to reduced mortality and increased life expectancy (Alsan & Goldin, 2019; Fink, Günther, & Hill, 2011; Kesztenbaum & Rosenthal, 2017).

Wastewater treatment can also generate additional societal benefits by reducing the amount of contaminants discharged into waterbodies, improving ambient water quality. Improvements in ambient water quality have been linked to societal benefits through improved fishing (Massey, Newbold, & Gentner, 2006; Montgomery & Needelman, 1997), swimming (Hanley, Bell, & Alvarez-Farizo, 2003), and boating (Lipton, 2004), as well as other recreational opportunities. In addition, improved ambient water quality has been associated with increased value of waterfront and nearby properties (Poor, Pessagno, & Paul, 2007; Walsh, Milon, & Scrogin, 2011), reflecting both recreational and aesthetic benefits. Although most of these studies focus on the United States and Europe, there are also some studies that identify benefits of ambient water quality improvements in developing countries (Choe, Whittington, & Lauria, 1996; Day & Mourato, 2002).

The societal costs and benefits described so far can be linked to most wastewater treatment systems. However, wastewater management approaches that allow for resource recovery have additional cost and benefit dimensions. The exact nature of these costs and benefits depends on the type of resource recovered and the recovery process used. In the case of recycled water, societal benefits may include revenue from sales of the recycled water for various uses, or monetary savings associated with not having to procure additional freshwater. Water reuse can also decrease diversion of freshwater from and discharge of treated wastewater to sensitive aquatic ecosystems, may augment supplies for wetland and riparian habitats, and can prevent saltwater intrusion through injection of treated wastewater into coastal aquifers (USEPA, 2012). On the cost side, studies show that wastewater treatment that allows for water reuse is more costly than traditional wastewater treatment, and that the internal value of water saved is not sufficient to cover these additional costs (Godfrey, Labhasetwar, & Wate, 2009) or requires a long payback period (Sousa, Silva, & Meireles, 2019). However, when the external benefits of water reuse are also considered, the additional benefits of water reuse sometimes exceed the additional costs (Chen & Wang, 2009; Molinos-Senante, Hernández-Sancho, & Sala-Garrido, 2011; Valdes Ramos et al., 2019).

Another class of recoverable resources consists of essential fertilizer elements such as nitrogen, phosphorus, and potassium, which are available from human urine and feces (de-Bashan & Bashan, 2004; Mihelcic, Fry, & Shaw, 2011; Winker, Vinnerås, Muskolus, Arnold, & Clemens, 2009). Studies have shown that nitrogen and phosphorus recovery from source-separated urine can approximate the cost of traditional, centralized wastewater treatment, driven in part by savings from not having to treat wastewater that would otherwise be conveyed to the wastewater treatment plant (Igos et al., 2017; Ishii & Boyer, 2015; Theregowda, González-Mejía, Ma, & Garland, 2019). Other applications are also able to break even, especially if they receive subsidies based on external benefits, such as improved environmental quality and food security (Daneshgar, Buttafava, Callegari, & Capodaglio, 2019; Mayer et al., 2016; You, Valderrama, & Cortina, 2019). Composting and vermicomposting have also been shown to be economically viable approaches in some cases for treating human excrement while recovering nutrients (Lee et al., 2018; Lim, Lee, & Wu, 2016).

Anaerobic digestion can treat wastewater while producing biogas, which can be converted into heat or electricity. Studies have demonstrated that, in some cases, revenue from methane sales is sufficient to operate the digesters and that anaerobic digestion can even be a net generator of energy

(Bair, Ozcan, Calabria, Dick, & Yeh, 2015; Cowley & Brorsen, 2018; McCarty, Bae, & Kim, 2011). Anaerobic digesters can also produce a permeate with soluble nutrients that can be used for combined fertilization and irrigation (Calabria, Lens, & Yeh, 2019; Prieto, Futselaar, Lens, Bair, & Yeh, 2013). Several thermal processes such as combustion, pyrolysis, and gasification can also recover energy from wastewater in the form of bio-oil, biochar, syngas, ethanol, hydrogen, heat, and electricity (Karaca, Sözen, Orhon, & Okutan, 2018; Khiari, Marias, Zagrouba, & Vaxelaire, 2004; Samolada & Zabaniotou, 2014), but to our knowledge, no studies demonstrate that these wastewater treatment solutions are cost effective.

Some resource recovery solutions benefit from addition of other substances, such as organic (nonfecal) waste, to the wastewater that is being treated (Bair et al., 2015; Fach & Fuchs, 2010). Procuring, transporting, and handling these other substances could incur costs, though their processing through a wastewater management solution would eliminate the need for other disposal methods. A sizable literature also documents how resource recovery and other new wastewater treatment strategies impose additional costs on households and other entities generating the wastewater; these costs include a lack of acceptance by users of building-scale solutions and odor control problems (Bristow, McClure, & Fisher, 2006; Lienert & Larsen, 2009; Poortvliet, Sanders, Weijma, & De Vries, 2018). Ideally, these costs should be reflected in the economic framework used to assess the tradeoffs between different wastewater management strategies.

3 | THE HYDROECONOMIC FRAMEWORK

In this section, we develop a hydroeconomic framework that formalizes the societal costs and benefits of managing a wastewater treatment technology or practice that can recover a commercially valuable resource. Hydroeconomic frameworks allow for modeling of water resource systems, infrastructure, management options, and economic values in an integrated manner, with the goal of capturing the complexity of interactions between water and economic outcomes (Brouwer & Hofkes, 2008; Harou et al., 2009). These types of frameworks are used widely to examine water quality and quantity problems, in which management is driven by the economic value of water or the benefits of water quality improvements. However, to our knowledge, no existing study provides a flexible, theoretical framework that yields an intuitive understanding of how the economically optimal deployment of resource recovery technologies and practices is influenced by basic parameters of a wastewater treatment problem such as the quantity and composition of the wastewater that is treated. Relative to existing hydroeconomic models (e.g., Jardim, Imbroisi, Nogueira, & Conceição, 2019), the framework we present here is novel in that it incorporates model elements that are motivated by the ability to recover resources from wastewater, including new choice variables such as the proportion of the resource contained in the wastewater that is recovered and new model parameters such as the market price of the recovered resource. These novel elements introduce a new set of economic tradeoffs that are absent from existing hydroeconomic models and, in turn, allow for exploration of the economic and policy implications of moving toward a paradigm of resource recovery in wastewater management.

In our model, if the resource is not recovered from the wastewater, it is discharged into the environment and acts as a pollutant, as is typically the case with nitrogen and phosphorus, though not universally true for all recoverable resources. Figure 1 below illustrates the context in which wastewater treatment is used in our hydroeconomic framework. A collection system gathers Q liters of wastewater, which carries with it a quantity of the commercially valuable resource at a concentration of N milligrams per liter. A proportion $t \in [0, 1]$ of this wastewater is treated using the resource recovery technology, which can recover a proportion $r \in [0, 1]$ of the resource contained in the treated wastewater. The portion of the wastewater that is not treated by the system is discharged into the environment with the original resource concentration N. Given this setup, of the QN milligrams of the resource contained in the wastewater, $tQ \times rN$ milligrams are recovered and $(1 - rt) \times QN$ milligrams are discharged into the environment.

Based on an incoming volume of wastewater Q with resource concentration N, the cost of using the resource recovery technology to treat a proportion t of the wastewater and recover a proportion r of the resource is given by the cost function $C(r, t, Q, N)$. We assume that cost increases in all four of its components (i.e., $\partial C/\partial r > 0$, $\partial C/\partial t > 0$, $\partial C/\partial Q > 0$, and $\partial C/\partial N > 0$). In addition, following the standard practice for cost functions in the economics literature (see, e.g., Daly and Farley, 2011; Krugman, Wells, & Olney, 2007), we assume that C is convex in all four of its components (i.e., $\partial^2 C/\partial r^2 \geq 0$, $\partial^2 C/\partial t^2 \geq 0$, $\partial^2 C/\partial Q^2 \geq 0$, and $\partial^2 C/\partial N^2 \geq 0$).

A useful baseline model of a decision maker who operates the wastewater treatment and resource recovery system is that of a facility operator who seeks to maximize profits (i.e., maximizes the revenue from sale of the resource recovered from the wastewater minus the cost of recovering the resource through wastewater treatment). This operator's problem is to choose proportions r and t so as to

$$\max_{r,t} \; p \times tQ \times rN - C(r, t, Q, N) \tag{1}$$

where p is the price per milligram of the recovered resource, so that the first term in the expression represents the revenue from sale of the recovered resource. We assume that p

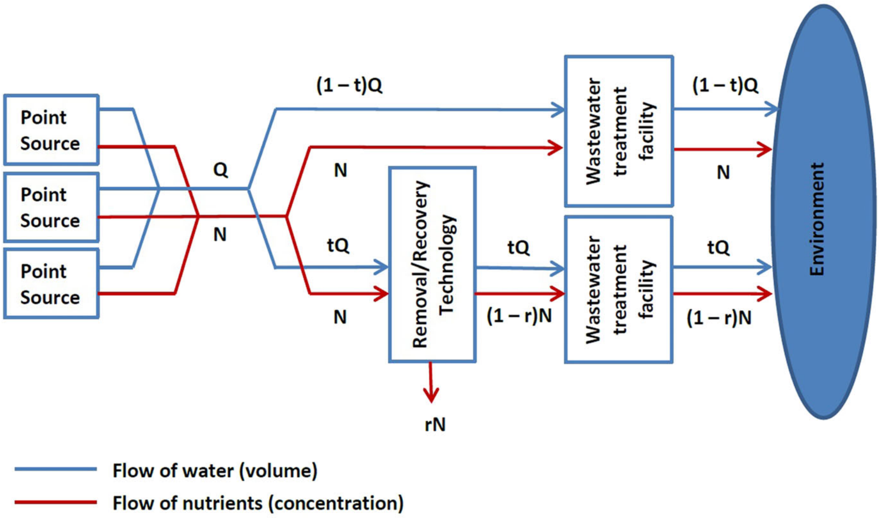

FIGURE 1 Graphical representation of the wastewater treatment context. N = resource (pollutant) concentration, Q = wastewater volume, t = proportion of wastewater treated, r = proportion of resources recovered

is fixed, but in reality, it depends on the scarcity of the recovered resource. Thus, for a nonrenewable material like phosphorus, which may become increasingly scarce over time, the added benefits of increased recovery of the material will be reflected in a higher market price, though (importantly) that market price is not driven by the individual decisions of the operator.

The first-order conditions for an interior solution (i.e., a solution in which neither r nor t is equal to zero) to the private operator's problem are

$$p \times t^{\pi} Q \times N - \frac{\partial C\left(r^{\pi}, t^{\pi}, Q, N\right)}{\partial r} = 0 \quad (2)$$

$$p \times Q \times r^{\pi} N - \frac{\partial C\left(r^{\pi}, t^{\pi}, Q, N\right)}{\partial t} = 0 \quad (3)$$

where r^{π} and t^{π} are the profit-maximizing proportions of resource recovery and wastewater treatment, respectively. Condition 2 indicates that a profit-maximizing operator will choose the proportion of resources recovered such that marginal revenue (i.e., the additional revenue from recovering and selling more of the resource) equals marginal cost (i.e., the additional cost associated with that incremental recovery). If this condition does not hold, the operator can increase profits by either increasing or decreasing the proportion of resources recovered. Similarly, Condition 3 indicates that the operator will choose the proportion of wastewater treated such that the additional revenue from treating more of the wastewater equals the additional cost of doing so.

Although the private operator considers the commercial value of the recovered resource as a benefit of wastewater treatment, it ignores other societal benefits associated with increased levels of wastewater treatment and resource recovery, namely those stemming from improved water quality. In other words, the operator does not account for the fact that lower levels of wastewater treatment and resource recovery will reduce water quality and lead to human health and ecosystem damages. The operator also does not account for increased treatment costs incurred by a water provider who uses the same water body downstream of where the treated wastewater is discharged. In contrast, a "social planner" who wishes to include the societal cost of these damages in the choice of r and t would instead solve the following optimization problem:

$$\max_{t,r}\ p \times tQ \times rN - C(r, t, Q, N) - D[(1 - rt) \times QN] \quad (4)$$

where $D(\cdot)$ is an environmental damage function that depends on the quantity of the resource or pollutant discharged to the environment, $(1 - rt) \times QN$. Following standard practices in the economic literature, we assume that $D(\cdot)$ is an increasing and convex function (Fisher & Peterson, 1976), meaning that $D'(\cdot) > 0$ and $D''(\cdot) \geq 0$. The first-order conditions for an interior solution to the social planner's problem described in Equation 4 are

$$p \times t^{*} Q \times N - \frac{\partial C\left(r^{*}, t^{*}, Q, N\right)}{\partial r} + t^{*} Q \times N \times D'\left[\left(1 - r^{*} t^{*}\right) \times QN\right] = 0 \quad (5)$$

$$p \times Q \times r^{*} N - \frac{\partial C\left(r^{*}, t^{*}, Q, N\right)}{\partial t} + Q \times r^{*} N \times D'\left[\left(1 - r^{*} t^{*}\right) \times QN\right] = 0 \quad (6)$$

where r^* and t^* represent the socially optimal levels of resource recovery and wastewater treatment. That is, r^* and t^* maximize societal benefits from wastewater treatment with resource recovery accounting for revenues from resource recovery, costs of wastewater treatment, and damages from remaining resources being discharged to the environment. Conditions 5 and 6 are similar to Conditions 2 and 3 except in that r and t are chosen such that the marginal cost of additional treatment or recovery is equal to the sum of marginal revenue and the marginal reduction in monetized environmental damages.

We have intentionally abstracted from the temporal dimension in our framework and instead characterized a static, one-time decision that focuses on the features introduced by the availability of resource recovery options. The addition of a temporal dimension to our model would introduce additional complexity which, although potentially important from a practical perspective, may make it difficult to isolate the economic implications of resource recovery. Recognizing that time plays an important role in wastewater treatment due to trends and seasonality that influence the system and due to the different timeframes over which decisions are made (e.g., short-term operational decisions vs. long-term capacity decisions), future research can examine how resource recovery and time interact within hydroeconomic modeling frameworks.

4 | TWO EXAMPLES WITH SPECIFIC COST FUNCTIONS

In this section, we present two examples in which we add more structure to the cost function C in the social planner's problem (Equation 4). These examples will demonstrate how our hydroeconomic framework can be used to examine the properties of the optimal levels of wastewater treatment and resource recovery.

Consider the following two functional forms for C:

$$\text{Type A} : C(r, t, Q, N) = tQ \times C(rN)$$

$$\text{Type B} : C(r, t, Q, N) = tQ \times N \times C(r)$$

The Type A cost function represents a technology for which costs rise linearly as more wastewater is treated, but costs rise at an increasing rate as a larger quantity of the resource is recovered. This type of technology can be thought of as being easy to scale up to treat larger volumes of wastewater, but it becomes incrementally more expensive to recover more resources from any given volume of wastewater. The Type B cost function is similar to the Type A function in that costs rise linearly as more wastewater is treated, but in contrast, costs also rise linearly in the concentration of the resource (pollutant) in the wastewater to be treated. Under a Type B cost function, convexity in the cost function is driven only by the *proportion* of resources recovered. Note that this is slightly different from the Type A cost function in which convexity in costs is driven by the recovery of greater *quantities* of the resource. Intuitively, this difference means that it is cheaper to use a technology with Type B costs when the concentration of the resource (pollutant) in the wastewater increases than to use a technology with Type A costs. For example, a technology is likely to exhibit a Type A cost function if the costs of transporting and storing the recovered resource rise rapidly as larger quantities of the resource are recovered. In contrast, a technology is likely to exhibit a Type B cost function if it involves a filtration process that can easily recover a given proportion of the resource in the wastewater from any volume of wastewater, but costs rise rapidly if the filter needs to be designed to recover a greater proportion of the resource in the wastewater. Both of these functional forms are consistent with parsimonious mathematical representations of wastewater treatment costs in the literature (Hernandez-Sancho et al., 2011).

Although the difference between the Type A and B cost functions may seem minor, analysis using our hydroeconomic framework will demonstrate that these differences have important implications for how a social planner would choose optimal levels of wastewater treatment and resource recovery. Specifically, consider the optimal strategy for a social planner who is faced with increases in the amount of incoming wastewater (i.e., an increase in Q) and/or increases in the concentration of the resource (pollutant) in the wastewater (i.e., an increase in N). Should the social planner increase, decrease, or leave unchanged the levels of r and t? The two propositions below establish the optimal strategy for the social planner when wastewater treatment and resource recovery are associated with the Type A cost function:

Proposition 1: Suppose that the cost of wastewater treatment and resource recovery is represented by a Type A cost function. It is then optimal for the social planner to respond to an increase in the concentration of the resource (pollutant) in the wastewater, N, by reducing the proportion of resources recovered, r, and increasing the proportion of wastewater treated, t.

Proof: see the Supplemental Material.

Proposition 2: Suppose that the cost of wastewater treatment and resource recovery is represented by a Type A cost function. It is then optimal for the social planner to respond to an increase in the volume of incoming wastewater, Q, by increasing the proportion of resources recovered, r, and leaving the proportion of wastewater treated, t, unchanged.

Proof: see the Supplemental Material.

According to Proposition 1, the optimal strategy for a social planner who cares about both the internal and external costs and benefits of wastewater treatment with resource recovery when faced with an increase in the concentration of the resource (pollutant) in the incoming wastewater is

TABLE 1 Influence of key parameters on optimal deployment of resource recovery

	Optimal proportion of resources recovered (r*)		Optimal proportion of wastewater treated (t*)	
Parameter	**Type A**	**Type B**	**Type A**	**Type B**
Resource (pollutant) concentration (N)	−	0	+	+
Wastewater volume (Q)	+	0	0	+
Market price (p)	0	0	+	+

Note. Plus sign (+) indicates a direct relationship between optimal proportion of resource recovered (r*) or optimal proportion of wastewater treated (t*) and the key modeling parameter (N, Q, or p); minus sign (−) indicates an inverse relationship; zero (0) indicates a lack of relationship.

to modify the proportion of wastewater treated and the proportion of resource recovered in opposite directions. Proposition 2 states that the social planner should react to an increase in the volume of incoming wastewater by only changing the proportion of resource recovered. We argue that these optimal strategies are not immediately obvious without developing and analyzing something akin to the hydroeconomic model we presented in the section above. The complexity in these optimal strategies arises from the fact that the social planner can obtain more revenue from sales of the recovered resource and reduce discharges of the pollutant in two ways: by treating more wastewater, or by recovering more of the resource. We also note that, thanks to our theoretical approach to modeling, Propositions 1 and 2 are generalizable to any wastewater treatment and resource recovery problem that is consistent with the assumed functional forms.

The next proposition establishes the optimal strategy for the social planner when resource recovery is associated with the Type B cost function:

Proposition 3: Suppose that the cost of wastewater treatment and resource recovery is represented by a Type B cost function. It is then optimal for the social planner to respond to an increase in the concentration of the resource (pollutant) in the wastewater, N, or an increase in the volume of incoming wastewater, Q, by leaving the proportion of resources recovered, r, unchanged and increasing the proportion of wastewater treated, t.
Proof: see the Supplemental Material.

Proposition 3 implies that a social planner should react to an increase in the volume of incoming wastewater and an increase in the concentration of the resource (pollutant) in the same way: by only increasing the proportion of wastewater treated. Again, this result is not necessarily obvious without the use of a hydroeconomic framework. Intuitively, a Type B cost function encourages the social planner to adjust the proportion of wastewater treated instead of the proportion of resources recovered because the former incurs constant marginal cost, whereas the latter incurs increasing marginal costs.

Our hydroeconomic framework can also help explore the policy implications of the availability of resource recovery in wastewater treatment. A variety of regulatory instruments could be applied in this context by a regulator who wishes to decrease the amount of pollutants that are discharged into the environment. For example, the regulator could rely on "command and control" approaches that require the facility operator to limit the amount of pollutant that is discharged or meet a minimum proportion of resources recovered from the wastewater. Alternatively, a regulator could provide subsidies that lower the marginal cost of wastewater treatment or resource recovery or pay an above-market price for the recovered resource to incentive the facility to undertake more resource recovery. We focus on this last policy tool, which is often used to promote renewable energy technologies; in these contexts, these mechanisms are referred to as "feed-in tariffs" (Couture & Gagnon, 2010). In our hydroeconomic framework, this subsidy can be modeled as an increase in the per-unit price of the recovered resource, p. The following proposition describes how such a subsidy affects the socially optimal proportions of wastewater treatment and resource recovery:

Proposition 4: Suppose that the cost of wastewater treatment and resource recovery is represented by a Type A or Type B cost function. It is then optimal for the social planner to respond to an increase in the per-unit price of the resource, p, by leaving the proportion of resources recovered, r, unchanged and increasing the proportion of wastewater treated, t.
Proof: see the Supplemental Material.

Thus, an important policy implication under Type A and B cost functions is that subsidizing the price of the recovered resource will not incentivize the use of technologies with greater resource recovery rates. Any induced increases in the quantity of recovered resources will be driven entirely by increases in the proportion of wastewater treated.

Table 1 provides a visual summary of the results contained in the four propositions. The table illustrates how seemingly minor variations in the form of the cost function can lead to clear differences in how a social planner should implement an optimal resource recovery strategy. The fact that these differences arise from an otherwise generic model of wastewater treatment suggests that facility operators and policymakers ought to carefully examine how economic considerations can influence optimal implementation of resource recovery in their specific wastewater management contexts.

5 | CONCLUSION

Emerging technologies and practices allow wastewater treatment facilities to recover valuable resources such as recycled water, energy, and nutrients found in fertilizer during the wastewater treatment process, and this ability to recover resources introduces new tradeoffs in both water quality and quantity management. In this paper, we introduced a general hydroeconomic framework that can help identify these tradeoffs and characterize the socially optimal deployment of these innovative wastewater management solutions. Despite a minimal amount of structure imposed on the model, we derive analytical results regarding the socially optimal wastewater treatment that are not obvious from examining individual cost and benefit components.

A strength of our framework is its applicability to different scales, owing to its general and flexible setup. It is able to describe solutions that range from household onsite systems to smaller community systems (e.g., serving a population of 10,000 or less) to larger centralized systems. This broad applicability is useful for assessing the potential deployment of solutions for which costs and benefits vary across scales. For example, in the nutrient management context, Cornejo, Zhang, and Mihelcic (2016) found that centralization of wastewater treatment plants with resource recovery yields benefits in terms of embodied energy and carbon footprint, but community-scale systems are superior for nutrient recovery. Similarly, Diaz-Elsayed, Rezaei, Guo, Mohebbi, and Zhang (2019) found that small-scale systems with onsite resource recovery and reuse are associated with lower distribution and transportation costs and energy consumption, whereas larger scales yield lower per-unit costs and energy consumption for treatment. Our framework also directly addresses management solutions that have a larger impact on human and ecological health than at the implementation scale, which is the case in some nutrient control practices (Macintosh et al., 2018). Thus, future research can use our hydroeconomic framework to explore the socioeconomic implications of strategies that target deployment of wastewater treatment with resource recovery at multiple scales.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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