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Towards a New Paradigm of Urban Water Infrastructure: Identifying Goals and Strategies to Support Multi-Benefit Municipal Wastewater Treatment

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Abstract: Over the past decade, water professionals have begun to focus on a new paradigm for urban water systems, which entails the recovery of resources from wastewater, the integration of engineered and natural systems, and coordination among agencies managing different facets of water systems. In the San Francisco Bay Area, planning for nutrient management serves as an exemplary model of this transition. We employed a variety of methodological approaches including stakeholder analysis, multi-criteria decision-making weight elicitation, and document analysis to understand and support decision-making in this context. Based on interviews with 32 stakeholders, we delineate goals that are considered to be important for achieving the new paradigm and we highlight management strategies that can help reach these goals. We identify and analyze the social, institutional, and technical impediments to planning and implementing multi-benefit wastewater infrastructure projects and identify strategies to overcome some of these challenges. Transitioning to a new paradigm for urban water infrastructure will require stakeholders to proactively forge collaborative relationships, jointly define a shared vision and objectives, and build new rules to overcome limitations of current institutional policies.

Keywords: stakeholder analysis; San Francisco Bay; nutrient management; regional planning; decision-making; integrated water resources management

1. Introduction

Throughout the world, researchers and practitioners have recognized the need to move towards a more sustainable paradigm for wastewater treatment and water management [1–10]. This new paradigm entails a shift in goals and expectations for municipal wastewater treatment by encouraging the recovery of water, energy, and nutrients from sewage, by employing natural systems for water treatment, and by coordinating among agencies managing different facets of water systems. The implication is that wastewater treatment plants should do more than meet their traditional objectives of protecting receiving water quality by removing organic matter, nutrients, and pathogens from sewage.

In the United States, much of the existing municipal wastewater infrastructure is nearing the end of its design life [11]. In the next two decades, hundreds of billions of dollars will be needed to maintain wastewater systems, which amounts to an investment of approximately $830 per person in the United States [11–13]. Population growth, the sea level rising, and concerns about the impacts of nutrients and trace organic contaminants in wastewater may require additional investments [7,14–18].

Historically, regulatory compliance has been a main driver for wastewater infrastructure planning [19]. Yet this traditional approach in which pollution problems identified by regulators are solved by retrofitting existing treatment systems may not be sufficient for transitioning urban water systems to a more sustainable state [20,21]. Instead institutional shifts that embed regulatory and political support for multi-benefit infrastructure early in planning processes may be more effective [22]. Furthermore, cooperative regional approaches to water management are often less expensive and more efficient [23] such as when preparing for uncertain future conditions [24]. Despite its potential benefits, many institutional impediments exist to implementing multi-benefit water infrastructure projects including a lack of coordination among institutions with different areas of expertise and jurisdiction, unclear roles and responsibilities of different agencies and stakeholders, poor communication, and a lack of long-term strategy [25].

Nutrient pollution exemplifies some of the key limitations of traditional wastewater infrastructure planning. Wastewater treatment facilities have historically enacted plant upgrades in response to regulatory concerns about the effects of nutrient pollution on receiving waters. These upgrades are generally energy intensive and expensive [26–28]. Upgrades frequently consist of the installation of treatment systems that employ nitrification and denitrification or biological nutrient removal [29]. Despite large capital investments, nutrient reductions do not always immediately improve conditions if water quality is severely impaired or if there are multiple pollution sources such as in Chesapeake Bay [28]. Additionally, changes to municipal water infrastructure require years or decades to plan, fundraise, and build. With unknown future conditions like those due to population growth/decline and climate change, investments in nutrient control may not always result in the desired ecological improvements [30].

In cases in which dynamic environmental conditions complicate decision-making about water infrastructure, multi-benefit technologies may hedge against the risks posed by a future uncertainty. For example, nutrient pollution may ultimately prove to be less problematic than expected if environmental conditions or population decrease. Irrespective of future conditions, a multi-benefit solution to address nutrient pollution that provides additional benefits of wildlife habitat, increased shoreline access, or resource recovery can be seen by stakeholders as a net benefit overall.

Fundamentally, transitions to more sustainable wastewater systems require clear articulation of a long-term vision. This includes the sharing of ideas among stakeholders that define the specific goals sustainable water systems should meet and general agreement about the technologies that could support these goals [31]. Despite its importance, the development of this shared vision is often overlooked even in cases that take a deliberative approach to a multi-benefit infrastructure [32,33]. A comparison of stakeholders' goals with their professional and institutional mandates can shed light on some of the barriers to implementing multi-benefit water infrastructure projects.

Case Study Background

To characterize and develop the specific, regional goals that underlie a more sustainable vision of wastewater infrastructure, we analyzed a case study of planning for nutrient management in the San Francisco Bay Area, California. The southern reach of San Francisco Bay receives approximately 34,000 kg of nitrogen each year primarily from discharges from eleven municipal wastewater treatment plants [34–36]. These discharges make the San Francisco Bay one of the most heavily nutrient-laden estuaries in the nation in terms of concentration in Bay water [37]. Domestic sewage is the main nutrient source in municipal wastewater in locations such as the San Francisco Bay Area where industrial discharges are small [38].

During the second half of the 20th century, primary productivity in the San Francisco Bay was limited by sunlight penetration. Consequently, eutrophication was not as much of a concern in the Bay as it has been in other nutrient-rich aquatic ecosystems [37]. However, water managers are concerned that current nitrogen loads could soon result in poor water quality and impairment of the Bay's beneficial uses due to shifting environmental conditions like increasing water clarity, longer water stratification periods, and declining populations of invasive bivalves [39–43].

In the Bay Area, water managers are proactively addressing nutrient pollution before the ecological situation deteriorates. They are aware that infrastructure investments can take years to materialize and that changing environmental conditions may increase nutrient over-enrichment in the future. By proactively addressing nutrient loading, Bay Area water managers have more leeway to be visionary and to consider new paradigms for multi-benefit wastewater infrastructure than by reacting to acute impairment of water quality.

As an initial step to address nutrient pollution and reduction strategies, dischargers, regulators, baylands stewards, and scientists in the region have established a stakeholder working group. It consists of a steering committee, a stakeholder advisory group, a technical working group, and a science team [44]. In 2014, the local regulator, which is the San Francisco Bay Regional Water Quality Control Board, implemented a watershed-wide nutrient-related permit for dischargers. It is valid until 2019 and it mandates that dischargers monitor nutrient loads in their effluent and annually fund scientific studies to assess nutrient effects on Bay ecology. Dischargers must also identify opportunities for removing nutrients from wastewater effluent [45]. Along with examining the potential for treatment plant upgrades to lower nutrients in wastewater effluent, the permit also specifies, "Dischargers may evaluate ways to reduce nutrient loading through alternative discharge scenarios such as water recycling or use of wetlands, in combination with, or in-lieu of, the upgrades to achieve similar levels of nutrient load reductions [45]."

The language in the 2014 permit reflects the local sentiment that next-generation wastewater treatment could achieve more than just safe effluent discharge. This sentiment applies to water management more broadly in the region: regional strategic planning documents for water like the San Francisco Bay Area Integrated Regional Water Management Plan (IRWMP) mirror the desire for multi-benefit water infrastructure. For example, the IRWMP aims to "encourage implementation of integrated, multi-benefit projects", "reduce energy use and/or use renewable resources", "plan for and adapt to sea level rise", and "increase recycled water use" [46]. A regulator at the San Francisco Regional Water Quality Control Board explained in an interview:

> "We're not just going down this linear path to deal with nutrients. We've said from Day One that we want it to be more complicated than that because we want to make a wise decision in terms of the future of managing water and wastewater ... we want to feel good about the decision we made 50 years from now."

Nationally, there has been a push in recent years to address excessive nutrient loading into surface waters [47]. After the complicated and costly experience of trying to control nutrients in the Chesapeake Bay [27,28], many water managers across the country are looking to the Bay Area for guidance on how to proceed with nutrient management in a manner that encourages a long-term transition to multi-benefit water infrastructure. According to a regulator at the Environmental Protection Agency Region IX (EPA):

> "Most of the folks in DC who I've talked to about the San Francisco example view it as potentially ... a national model on how to do this right."

Therefore, the case of the Bay Area offers insight into nutrient management strategies nationwide as well as highlights opportunities and obstacles to transitioning to a new paradigm of multi-benefit urban water infrastructure more broadly. Since nutrient management is a global issue of great concern, the case is also of high interest internationally. Our case is especially interesting because the involved individuals have high motivation for developing multi-benefit infrastructure and have power within bureaucratic, historically slow-to-innovate regulatory agencies and wastewater utilities.

By focusing on this important case study, our research aims to identify general strategies for planning for next-generation water systems that fulfill multiple goals. It does so by characterizing stakeholders' long-term objectives and by analyzing the social, institutional, and technical impediments to planning and implementing a multi-benefit wastewater infrastructure. It examines the ways in which current institutional structures and modes of decision-making help or hinder the transition to a new paradigm for urban water systems. It also investigates the possibility of new institutions, relationships, or processes that can support these objectives. By demonstrating the ways in which well-established techniques for eliciting context-specific goals and strategies with local stakeholders including stakeholder analysis, multi-criteria weight elicitation, and secondary document analysis can be employed as part of an integrative, mixed-method approach for making decisions about real-world environmental policy issues, we provide a replicable example to support planning for other multi-benefit water resources initiatives.

2. Materials and Methods

2.1. Methods Overview

To assess stakeholder perspectives on long-term goals for nutrient management, barriers to implementation of multi-benefit wastewater infrastructure, and suggestions for overcoming these barriers, we used a mixed-method approach. We proceeded in the following step-wise manner.

1. We conducted initial interviews with a broad set of stakeholders. These were designed to elicit perspectives on long-term goals for nutrient management in the region as well as potential management options. The results of interviews were integrated to provide objectives for "good nutrient management."
2. We conducted in-depth, follow-up interviews with a subset of the original stakeholder group. The interviews were designed to elicit the relative importance of different objectives to decision-making about nutrient management. These interviews built upon results from initial interviews. We used both a qualitative approach (in-depth explanations) as well as a method borrowed from Multi-Criteria Decision Analysis (MCDA) to elicit relative weights of objectives.
3. We included stakeholder/institutional analysis. Information from both sets of interviews was synthesized to understand stakeholder perspectives on barriers for implementation of wastewater infrastructure that met the diverse set of goals mentioned as well as strategies to overcome these barriers.
4. We conducted an analysis of regional planning documents (e.g., [46,48]), strategic water management plans at the utility and city scale [49–54], and official mission statements and job descriptions that were conducted to contextualize and triangulate interview responses. A comparison of official institutional documents with interview responses provided insight into institutional drivers and barriers to multi-benefit water infrastructure. Findings from the document analysis are presented in the discussion in relation to the results of stakeholder interviews.

2.2. Initial Interviews

Stratified sampling and snowball sampling were combined [55] to select stakeholders for first-round interviews. Stakeholders were initially identified based on their professional interest in nutrient loading in the San Francisco Bay including whether they were involved with the decision-making or would be affected by decisions made [56,57]. The selected group included water managers, baylands stewards, researchers, engineers, regulators, urban planners, flood control managers, and advocates for the coastal industry or the environment at local, regional, and federal scales [58]. Individuals within organizations were selected based on their professional involvement with the San Francisco Bay nutrient management, which is shown by their authorship of documents or presentations pertaining to the issue. If no one in an organization was closely affiliated with nutrient management, the person with the most responsibility for strategic planning was contacted using publicly available professional email addresses. A set of stakeholders with diverse professional roles who were operating on different scales (i.e., local, regional, and federal) were sampled.

Once interviews commenced, snowball sampling [59,60] was used to identify other stakeholders. Participants were asked to rate their own influence over decision-making as well as how much decisions made about nutrients would affect them on a scale of 1–7. They also rated the influence and extent to which others would be affected. This information was used to determine the set of stakeholders involved and to better characterize the local social networks [55]. Multiple stakeholders from a single organization were contacted when they had distinct roles in the decision-making process about nutrient management and when they were identified by other stakeholders in snowball sampling. Several stakeholders represented more than one organization (e.g., one person was the director of an industrial advocacy group and on the board of a public wastewater utility). Of the 88 individuals contacted initially, 32 stakeholders (representing 29 different organizations) agreed to participate in an interview. They were categorized according to their professional role and their relevance to decision-making (see Supplemental Information, Table S1).

We conducted these initial in-depth, semi-structured interviews with 32 stakeholders. We used open-ended questions to elicit information about their goals for "good nutrient management" in the San Francisco Bay. "Good nutrient management" was chosen as the primary management objective based on a previous study of sustainable water infrastructure planning in which stakeholders described goals for "good water supply and wastewater disposal infrastructure" [55,61]. We chose the phrase "nutrient management" (rather than "nutrient control") to reflect the language in the regional Nutrient Management Strategy [44].

These interviews yielded more than 60 goals for "good nutrient management" as a response to: "In your opinion, what are the most important goals for any nutrient management scheme or technology?", and "What are the most important goals for good nutrient management in San Francisco Bay?" (Table S2). Objectives concerned the process of managing nutrients (e.g., collaboration among people in different fields to develop a management plan and base regulatory limits on site-specific scientific evidence of effects) as well as goals characterizing the result of nutrient management (e.g., building systems that are resilient to a sea level rise or the result in good water quality). Goals that characterized the end result of good nutrient management based on the philosophy of "value focused thinking" [62–65] were emphasized. To reduce the number of fundamental objectives for ease of mental processing [66,67], similar goals were combined (e.g., "low costs" and "low initial capital investment"). Goals that had a more fundamental objective (e.g., "consider the low-hanging fruit for infrastructure upgrades" was deemed to be a means to "low initial capital investment") were eliminated [68]. One objective was added by the researchers ("ease of use of the nutrient control technology or system") since decision-makers tend not to articulate all objectives that are important to them for any decision [69]. This process yielded 13 separate goals.

We created an objectives hierarchy from the final list of objectives by categorizing them into overarching categories. The sub-objectives describe the scope of different goals in each category [68]. Even though they were not included in the objectives hierarchy, the process-oriented goals are characterized in the discussion section of this paper.

Initial interviews lasted 30–90 min and were conducted primarily one-on-one over the phone with the exception of four individuals from one organization who asked to be interviewed in person together. These four individuals filled out surveys with open-ended questions first to elicit individual preferences and points of view and then engaged in group discussion for the remainder of the two hour interview.

2.3. Follow-Up Interviews

Follow-up interviews were conducted with nine stakeholders and decision-makers (a subset of the original 32) who were closely involved in planning for nutrient management in the San Francisco Bay Area. We chose this subset by performing a cluster analysis based on each stakeholders' stated goals for nutrient management in the first interview (see [70]). From each of the seven resulting clusters, we contacted those stakeholders who we classified as being the most relevant to decision-making to participate in a second interview (on a scale of 1 to 4 with 1 being most engaged with or affected by decision-making about nutrient loading, Table S1).

In follow-up interviews, stakeholders verbally confirmed the objectives' hierarchy by examining the list. Stakeholders were asked to explain whether they would endorse or oppose hypothetical options for nutrient management (i.e., wetlands for wastewater treatment or traditional upgrades). Their responses also were analyzed to confirm that all stated goals were represented in the objectives' hierarchy.

Furthermore, in-depth explanations of the importance of each objective were elicited as well as the objectives' relative importance to decision-making from each stakeholders' perspective. Elicitation of the objectives' relative importance is standard practice in MCDA. We applied the popular Swing method [71,72] where interviewees assigned points (from 0–100) for the importance of improving each of the objectives from its worst to its best state. These point values were then confirmed by comparison to an initial ranking of the importance of each objective. Quantitative weights (on a scale of 0–1) were then calculated for each objective and each stakeholder by normalizing the points they had assigned.

Weight elicitation requires the respondent to make trade-offs between achieving different objectives [73]. In order for weight elicitation to be most accurate, it is especially important to consider the range, i.e., the best-possible and worst-possible outcome of each objective [68]. These best-possible and worst-possible values were carefully prepared beforehand. They were derived from specific decision options about nutrient control that emerged from initial interviews and from relevant local documents on nutrient management (i.e., permits and planning documents [45,74]).

These nutrient management options included: (i) doing nothing, (ii) building traditional wastewater treatment plant upgrades for nutrient control at each nutrient discharge location (i.e., biological nutrient removal), (iii) constructing shoreline wetlands downstream of nutrient discharge locations to remove nutrients from secondary wastewater effluent, (iv) increasing wastewater recycling (i.e., diversion of nutrient-laden effluent from the Bay), and (v) developing urine source-separation and treatment with reuse of nutrients as fertilizer. The development of the options is described in more detail in a companion paper, which uses a formal MCDA-process to find regional strategies for nutrient management in the San Francisco Bay Area [70].

Follow-up interviews were conducted in person and took 60 min to 120 min. All interview notes and recordings were transcribed and then coded using MaxQDA software (VERBI Software GmbH, Berlin, Germany).

The research protocols and interview guidelines, were approved by the Institutional Review Board of the Committee for the Protection of Human Subjects at the University of California, Berkeley (protocol #2015-01-7091). All interview participants gave informed consent for inclusion before they participated in an interview.

2.4. Stakeholder/Institutional Analysis

Interview questions eliciting information about stakeholders' relative decision-making power and influence in initial interviews were triangulated with documents about decision-making procedures for nutrients and for water quality regionally and federally. For example, some respondents indicated that the regulators at the US Environmental Protection Agency (EPA) had ultimate power over decision-making about nutrients, which was confirmed by documents on EPA's power to promulgate water quality standards [75].

Interview questions in which stakeholders described their institutional roles and constraints in initial interviews were triangulated with official job descriptions, organizational websites and mission statements, and regional and organizational strategic planning documents. For example, a discharger's statement explains that they were obligated to evaluate different options for nutrient control, which was confirmed in the official nutrient watershed permit [45].

Responses about barriers to multi-benefit infrastructure and strategies to overcome them emerged in different parts of the interviews. Some of these were elicited by asking about the process of decision-making in the initial interviews (e.g., "Tell me about the process of decision-making about nutrient management thus far. What have been some of the milestones in the process?"). Other barriers and strategies to overcome them emerged from elicitation of potential management options in the initial interviews (e.g., "How are people in the field talking about solving the nutrient problem? What do you think should be done, if anything?"). Still other barriers and strategies to overcome them were offered in the second follow-up interviews during discussion of the objectives and potential management options.

3. Results

3.1. *Objectives for Good Nutrient Management*

Thirteen fundamental objectives for "good nutrient management" in San Francisco Bay were developed and grouped into five overarching categories (Figure 1). These objectives were developed to be as complete as possible (i.e., they take into account the most important factors influencing the decision) without redundancies (i.e., objectives do not have overlapping meaning) and are measurable (as accurately and unambiguously as possible) [68].

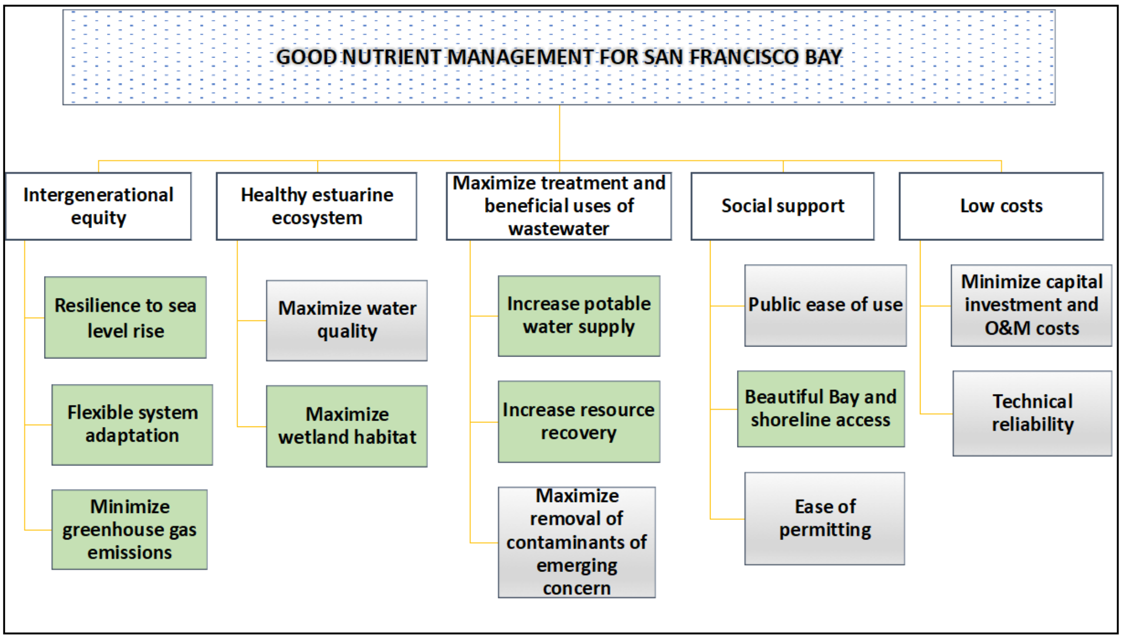

Figure 1. Objectives hierarchy for good nutrient management for San Francisco Bay were derived from interviews with 32 stakeholders. Objectives are color-coded by overarching categories (white background) Objectives that are characteristic of traditional wastewater infrastructure upgrades have a grey background and objectives that are indicative of a new paradigm for multi-benefit wastewater treatment have a green background. Reasons for the categorization are explained in the text.

Descriptions of the objectives (in the order shown in Figure 1) are given below. Supporting quotations from stakeholders who described the importance of each objective are in the Supplemental Information (Table S3).

Resilience to the sea level rise: Much of the Bay Area's wastewater treatment infrastructure is located at the shore of the Bay and is vulnerable to the sea level rise [16]. Developing resilience to the sea level rise while investing in wastewater infrastructure is important for many stakeholders.

Flexible system adaptation: Good nutrient management should be able to adapt quickly and easily to shifting external conditions, to tightening regulations, and to other factors like population growth (or decline). If there is an indication that the Bay ecosystem is on the cusp of eutrophication, nutrient management strategies should be able to quickly adjust accordingly.

Minimize greenhouse gas emissions: Some options for nutrient management are energy intensive or require energy-intensive materials (e.g., cement) in their construction, which embody large amounts of greenhouse gasses in the system's life-cycle [76,77].

Maximize Bay water quality related to nutrients: Good nutrient management should prevent any deviation from ambient nutrient-related conditions that could impair the Bay's beneficial uses, which include biological goals like a fish habitat and spawning as well as human goals like recreation [78].

Maximize wetland habitat: The increased wetland habitat was seen by several stakeholders as a relevant goal for good nutrient management. Healthy wetland ecosystems are considered imperative for a thriving Bay ecosystem [79–81] because they provide habitats for rare, endangered, and migratory species as well as help increase shoreline resiliency to the sea level rise [82,83].

Increase useable water supply: After enduring a long drought between 2011–2017, water supply is at the forefront of many Bay Area water managers' thoughts. Stakeholders stated that, as they address nutrient-related concerns, wastewater utilities should concurrently consider ways to augment water supplies through increased recycling of wastewater for irrigation or potable uses [84].

Increase resource recovery: Currently, there is little economic incentive to recover and reuse nutrients. However, generating a potential revenue stream and contributing to a closed-loop nitrogen and/or phosphorus cycle by applying wastewater-derived nutrients as fertilizer to crops [1] were viewed as goals of nutrient management.

Maximize removal of contaminants of emerging concern: Good nutrient management may also control other unregulated chemicals present in wastewater (e.g., pharmaceuticals, personal care products, or pesticides), which are not completely removed by most secondary wastewater treatment systems [14].

Public ease of use: The urban wastewater system is currently extremely easy for the public to use. Properties are directly connected to a sewer system that requires little to no maintenance by the public. To assess potential responses to source-separating toilets designed to recover nitrogen-rich urine from wastewater [85], the researchers added the "public ease of use" objective. This objective helps to differentiate between the existing plumbing system and a urine-separating system that might require adjustments by members of the public (e.g., men might be required to sit when urinating and source-separating toilets might require additional maintenance).

Beautiful Bay and shoreline access: Controlling nutrient loading to the Bay is likely to incur significant public costs in the form of rate increases for wastewater treatment. To garner support for nutrient control spending, it is important that the public be able to appreciate their spending by improved shoreline access to aesthetically pleasing places on the Bay shoreline.

Ease of permitting: Ease of permitting for nutrient control saves wastewater utility staff time and money. It also implies agreement among multiple stakeholders (wastewater managers and regulators) about the legitimacy of a nutrient management option (e.g., it reduces uncertainty about whether the option will be controversial or subject to delays and added requirements).

Minimize initial capital investment, operations, and maintenance costs: By convention and due to the nature of public utilities, good nutrient management systems (like all urban water systems) should minimize costs.

Technical reliability: Knowing with confidence that a wastewater treatment technology will perform in a reliable manner has historically been a leading decision criterion for wastewater engineers [29].

Not every stakeholder mentioned each of these goals in initial interviews (Table 1). However, when the goals mentioned by other stakeholders were presented as possibilities in follow-up interviews, most were considered as important to decision-making even by people who had not originally mentioned them. This finding underscores the importance of gathering a broad set of stakeholder goals and then weighing the relative importance of these goals in two separate steps since any individual stakeholder is unlikely to mention all the objectives that he or she actually takes into consideration in a decision context [86].

Table 1. Number of stakeholders who mentioned each goal for "good nutrient management" in initial interviews (of 32 total).

Goal	Number of Stakeholders
Resilience to sea level rise	4
Flexible system adaptation	4
Minimize greenhouse gas emissions	4
Maximize Bay water quality related to nutrients	24
Maximize wetland habitat	9
Increase useable water supply	13
Increase resource recovery	8
Maximize removal of contaminants of emerging concern	7
Public ease of use	1
Beautiful Bay and shoreline access	3
Ease of permitting	1
Minimize initial capital investment, operations, and maintenance costs	12
Technical reliability	3

The nine stakeholders who participated in the follow-up interview had differing opinions about the relative importance of each goal to decision-making about nutrient management (Figure 2). It is notable that many less-traditional goals for nutrient management (like the provision of a wetland habitat increased resource recovery and increased shoreline access) were important to most stakeholders. There was wide variation in the importance of incorporating resilience to a sea level rise in decision-making with some stakeholders listing it as the most important criteria and others assessing it of no importance (for specific point values assigned to criteria, see Supplemental Information, Figure S1, and for individual stakeholder opinions for criteria, see Figure S2).

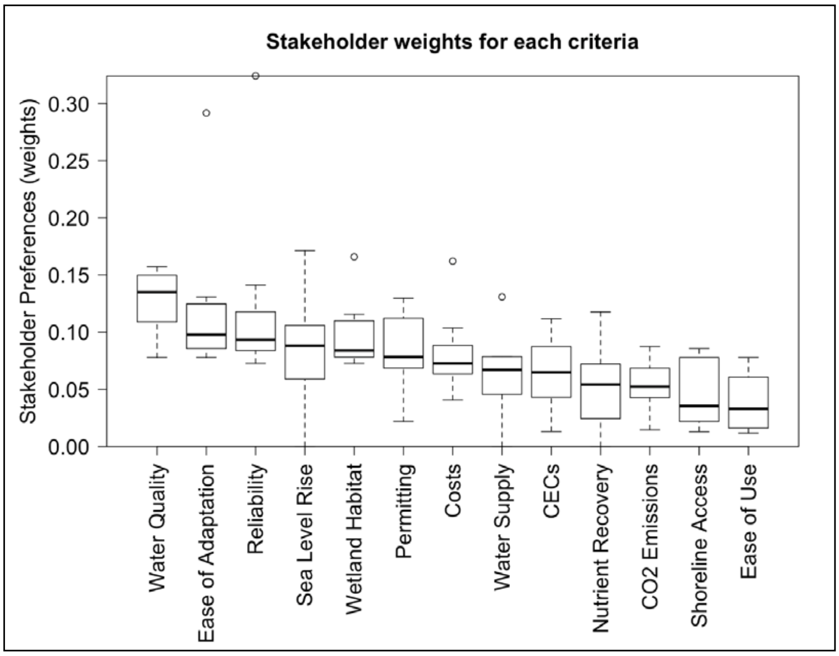

Figure 2. Relative weights of goals for Bay Area nutrient management derived from interviews with nine stakeholders. Boxplot midlines denote median values of responses, boxes represent the interquartile range, and whiskers extend to 1.5 times the interquartile range. Outliers are marked with a circle. Each stakeholders' total weights are added to one.

When grouped into main objectives for nutrient management, results varied depending on whether the average values per category or summed values within each category are presented (see Supplemental Information, Figure S3). This is because some categories like "Intergenerational Equity" have three sub-objectives (resilience to sea level rise, flexible system adaptation, and minimize greenhouse gas emissions) while others like "Ecosystem" have only two sub-objectives (maximize water quality and maximize wetland habitat). In both cases, preservation of the Bay ecosystem ranks among the most important main objectives and social support ranks the lowest.

The 13 goals can be categorized into those that are in line with traditional wastewater infrastructure upgrades and those that are indicative of a new paradigm of increased expectations for multi-benefit wastewater treatment (Figure 1). These categorizations were made by document analysis as well as from stakeholder interviews.

While some goals fall within the institutional purview of the stakeholders, others fall outside of their professional mandates. Traditional wastewater infrastructure goals tend to fall within the dischargers' institutional mandates: they must gain regulatory permission to use new technologies (ease of permitting) and comply with regulations like the Clean Water Act that protects water quality (maximize water quality). They must also be fiscally responsible with public funds (minimize costs) and consistently meet regulations (technical reliability). Regulators' mandates also support traditional wastewater infrastructure goals. they must develop permits that dischargers can meet (ease of permitting) and they must protect beneficial uses in the Bay (maximize water quality).

Of the goals that are indicative of a new paradigm of wastewater infrastructure, several fall within the mandates of professionals who are usually not responsible for planning municipal wastewater treatment plant operations such as urban planners (beautiful bay and shoreline access), water supply agencies (increase potable water supply), and baylands stewards (maximize wetland habitat). In the San Francisco Bay case, some entities that operate municipal wastewater treatment plants are also responsible for the water supply (e.g., San Francisco Public Utilities Commission) and the region's nutrient stakeholder working group includes baylands stewards and scientists on its Steering Committee [44]. Thus, entities responsible for the goals of increasing potable water supply and maximizing wetland habitat are involved in the Bay Area nutrient issue. However, staff members usually responsible for the issue work in different divisions of the organization and may not have the ability to allocate resources from one part of the agency to another to solve the problem.

Many of the goals stakeholders have for nutrient management do not fall within the institutional mandates of the stakeholders including flexible system adaption, resource recovery from wastewater, minimizing greenhouse gas emissions, shoreline access, and resilience to the sea level rise (Table 2). These goals are indicative of a new paradigm of wastewater infrastructure. The fact that they are being considered by representatives involved with nutrient management is indicative of the resolve of stakeholders to enact their vision of next-generation wastewater infrastructure.

Table 2. Stakeholders institutionally mandated to fulfill stated goals for "good nutrient management."

Goal	Institution Mandated to Achieve Goal
Resilience to a sea level rise	None
Flexible system adaptation	None
Minimize greenhouse gas emissions	None (currently, but may fall on dischargers with passage of Assembly Bill 32—California Global Warming Solutions Act)
Maximize water quality	Regulators, dischargers, baylands stewards, scientists
Maximize wetland habitat	Baylands stewards
Increase water supply	Water supply agencies
Increase resource recovery	None
Remove contaminants of emerging concern	None (yet, regulators must respond once they have evidence contaminants are detrimental to public or environmental health)
Public ease of use	None
Beautiful Bay and shoreline access	Urban planners
Ease of permitting	Regulators, dischargers
Minimize initial capital investment, operations, and maintenance costs	Dischargers
Technical reliability	Dischargers

3.2. Impediments to Multi-Benefit Wastewater Infrastructure Planning and Implementation

Despite strong sentiments among many stakeholders that nutrient control strategies should ideally provide additional benefits to the Bay, many stakeholders identified barriers to multi-benefit wastewater infrastructure planning and implementation. These perceived barriers fall into institutional, social, and technical categories (Table 3). Supporting quotations from stakeholders are included in the Supplemental Information (Table S4).

Table 3. Perceived barriers to planning and implementation of multi-benefit wastewater systems.

Category	Barrier	Primary Concern	Description
Institutional	**Leadership**	Who is in charge?	There is concern that multi-benefit infrastructure projects would lack leadership because they bridge mandates of existing institutions. Another type of concern is that lack of institutional leadership would lead to conflicts because each institution is accountable to different board members and/or constituents.
	Collaboration	Can managers of separate organizations effectively collaborate?	There is concern about the complexity of collaboration across institutions for wastewater treatment, water supply, habitat restoration, and others to implement multi-benefit projects. Project implementation depends on social networks that individuals have established because the institutional connections are lacking. Planning for a sea level rise is particularly challenging because no one agency is currently tasked with it.
	Permitting	Can multi-benefit projects fit into existing regulatory permit structures?	There is a difficulty for obtaining regulatory permits for multi-benefit projects primarily due to a lack of regulatory precedent for many of these systems (e.g., wetlands for wastewater treatment would likely vary seasonally in their nutrient removal efficacy) or for innovative technologies that have less of a track record.
	Risk tolerance	Can decision makers tolerate the higher level of risk needed to adopt innovative technologies?	There is a difficulty in adopting innovative multi-benefit technologies because of a strong value among wastewater utility managers for technologies that can reliably comply with regulations. Multi-benefit wastewater infrastructure projects that rely on natural systems for water treatment (e.g., constructed wetlands) or those that depend on the public to employ new technology (e.g., source-separating toilets) are inherently less reliable than traditional infrastructure where most ambient conditions are controlled.
Social	**Public opinion**	For decentralized options, can the public agree to interact more with wastewater treatment?	There is a concern that some multi-benefit technologies (e.g., urine source-separation with nutrients recovery) could require a behavior change from users. Citizens may have to shift from having little role in wastewater treatment (currently limited to flushing the toilet and paying a sewage bill) to taking a more active role. While some stakeholders found the idea repugnant, others thought there might be a learning curve with an education campaign.
	Public compliance	How do we ensure compliance for technologies that require user responsibility?	There is skepticism that the public can be relied upon to consistently participate in decentralized technologies like urine source separation.
Technical	**Effects on existing treatment**	How will new treatment options change the function of existing systems?	There is concern that innovative technologies may change the composition of influent or effluent existing wastewater treatment plants. For example, decentralized or satellite water recycling technologies might result in less influence to municipal wastewater treatment plants.

3.3. Strategies to Overcome Barriers to Multi-Benefit Wastewater Infrastructure

Many stakeholders provided practical suggestions for overcoming some of the barriers to multi-benefit wastewater infrastructure planning and implementation. Each suggestion requires a set of stakeholders from particular roles to take action to overcome these barriers (Table 4). Supporting quotations can be found in the Supplemental Information (Table S5).

Table 4. Suggested strategies to overcome barriers to multi-benefit wastewater infrastructure in the San Francisco Bay Area. N/A: No interview responses addressed how to overcome this barrier.

Category	Barrier	Strategies to Overcome Barriers	Stakeholders Implicated for Action
Institutional	**Leadership**	N/A	
	Collaboration	Establish networking relationships among agencies, organizations, and water managers before decisions need to be made to support cross-sectoral problem-solving (e.g., through meetings to discuss regional water quality monitoring)	All
		Conduct integrated assessments of the Bay's ecology (in addition to site-specific monitoring to ensure regulatory compliance) to lay the groundwork for holistic regional visioning and planning	Scientists, researchers
		Structure permits regionally to encourage interaction and collaboration among dischargers	Regulators
	Permitting	Increased permit length	Regulators
		Regulators, dischargers, and technology developers/researchers collaborate to develop regulations that support adoption of innovative technologies	Regulators, dischargers, technology developers/researchers
		Conduct site-specific and temporally specific studies of nutrient effects to inform context-specific regulation	Scientists, regulators
	Risk tolerance	Increased institutional funding for research on innovative technologies especially for pilot projects	Wastewater utility managers
		Find ways to share costs of multi-benefit projects	Wastewater utility managers, regulators, baylands stewards
		Develop easily implemented and adaptable technologies that can be quickly "ramped up" should conditions change	Engineers, scientists
Social	**Public opinion**	Make wastewater treatment more visible to encourage public support for funding multi-benefit projects	Wastewater utility managers, engineers
	Public compliance	N/A	
Technical	**Effects on existing treatment**	N/A	

4. Discussion

Our results suggest that, in addition to objectives for nutrient management pertaining to the traditional role of wastewater treatment (e.g., good water quality, technical reliability, and low costs), other objectives related to the development of a multi-benefit infrastructure are also prominent for many stakeholders in the Bay Area. However, it is noteworthy that not all stakeholders are interested in a new paradigm of wastewater infrastructure. For example, one stakeholder we interviewed primarily expressed goals related to traditional water infrastructure paradigms and was strongly averse to goals that were outside that scope (e.g., they gave no value to resilience to sea level rise and recovery of nutrients from wastewater and water supply). Defining the role of wastewater treatment in response to issues beyond nutrient pollution may be necessary before stakeholders choose regional solutions for nutrient management.

Some of the broader goals stakeholders mentioned could arguably be cast as prudent engineering. For example, flexible system adaptation is not a mandate for dischargers, but it is considered good practice to build a wastewater treatment system that will be useful throughout a design life of three or four decades. Likewise, removing contaminants of emerging concern from wastewater could preempt a need to build additional treatment systems if compounds are regulated in the future [29].

Other less-traditional goals for nutrient management like resilience to the sea level rise, increasing the area of a wetland habitat, and reducing greenhouse gas emissions may improve wastewater utilities' public images by explicitly aligning their actions with local pro-environmental values. Improving utilities' "brand" in this way may help make it easier for them to gain the support of the community and to raise funds for projects [87].

Despite the benefits of achieving these broader objectives, it is notable that many of the goals reflective of a new paradigm of water infrastructure fall outside of stakeholders' institutional mandates. Dischargers are tasked with regulatory compliance and reliable service. Regulators must uphold state and federal rules for preventing the impairment of water bodies like the federal Clean Water Act and California's Porter-Cologne Act [88]. To conceptualize and implement next-generation water infrastructure, stakeholders may need to go beyond their professional and institutional mandates and think creatively about how to develop rules, collaborations, and decision-making processes that support their vision. Additionally, regional, state, or federal policy to indicate that multi-benefit water projects should take priority over single-purpose water systems when possible since it could help support the implementation of a new paradigm for water infrastructure.

Regional enthusiasm for multi-benefit approaches in the Bay Area case may stem from the overall pro-environmental culture of the Bay Area, which is shown by the recent passage of a bill to raise a Bay Area parcel tax to fund wetland restoration [89]. The same enthusiasm may not exist elsewhere. At a national level, green infrastructure approaches are championed by the national Environmental Protection Agency [90] but may not be reflected in the perspectives of stakeholders in any particular locale.

4.1. Lessons for Planning and Implementing Multi-Benefit Infrastructure

Stakeholders pointed to the importance of having existing connections, trust, and communication channels in place between water managers, regulators, and ecological stewards that can be drawn upon in a decision-making context. These provide the foundation for the collaboration necessary for multi-benefit projects to be successful. The Regional Monitoring Program for Water Quality in the San Francisco Bay, which is a partnership between regulatory agencies and regulated utilities, has been important in this regard [91,92]. Regional monitoring also supports multi-benefit projects because it provides an integrated assessment of the Bay's ecology as opposed to the common site-specific monitoring to ensure regulatory compliance. The holistic view provided by regional monitoring, which tracks natural variability as well as cumulative impacts of human activity also allows managers to prioritize regional management actions and goals [93,94].

Bay Area dischargers also collaborate on other aspects of regional environmental stewardship. Their relationship is formalized through an advocacy organization called the Bay Area Clean Water Agencies (BACWA), which provides a unified voice for local wastewater utilities in regulatory and scientific settings [94]. Additionally, regional regulatory permits for total maximum daily loads for polychlorinated biphenyls and mercury currently exist and another for selenium is underway [91]. All of these require communication and collaboration between dischargers to meet these limits.

When nutrients came to the forefront as a potential issue in the Bay, dischargers were able to use existing networks to coordinate their response. A wastewater treatment plant manager reported the importance of BACWA for organizing the formal nutrient stakeholder working group: "The (Nutrient Management Strategy group) was conceived, I think, of probably a few of us sitting around at BACWA just trying to figure out what's going in with nutrients ... As we started to look and talk about it, we realized, for a number of reasons, this is way too big to take the typical approach."

This collaborative approach exemplifies an important step in moving towards more sustainable water infrastructure including the development of a coalition of diverse actors who share a common vision and trigger institutional change [95]. The Bay Area's Nutrient Management Strategy is made up of a broad set of actors including nutrient dischargers (e.g., wastewater treatment plant managers, stormwater managers, and industrial dischargers), environmental advocates, regulatory organizations, and resource trustee agencies (e.g., Department of Fish and Wildlife) [44].

Another benefit of establishing these social networks is the possibility of collaboration between regulators and dischargers to support multi-benefit technologies. Traditional technologies are currently the simplest for regulators to permit because there is precedent for them and they fit neatly within institutional mandates. In contrast, multi-benefit technologies may challenge existing regulatory structures. For instance, constructed treatment wetlands may have seasonal variations in nutrient removal and may be subject to different rules concerning endangered species [74]. Open communication channels between technology developers, users, and regulators may help establish new policies and navigate the complexities of existing policies to facilitate the adoption of new multi-benefit technologies.

Technological fixes are not the only potential solutions to nutrient control. Strong networks and partnerships between dischargers and agencies can also lay the groundwork for innovative strategies to manage nutrients like trading credits for nutrient discharge within the estuary [96].

Critics of integrated water management and multi-benefit water infrastructure argue that the complexities of considering multiple goals in a single water infrastructure project are too difficult for one agency to master and the hurdles of institutional collaboration are too great [97]. Yet, the Bay Area nutrient management case shows that, even without formalized institutional collaboration, individuals with strong motivation for a multi-benefit infrastructure have the capacity to gather the necessary communication and teamwork. These social networks underpin the "collaborative advocacy coalitions" that can change public policy [98] and sway planning for urban water systems into a mode that would support the development of multi-benefit infrastructure.

However, broad-based collaborative governance is not easy and stakeholders expressed concern that the Bay's Nutrient Management Strategy would fall apart if action on nutrients becomes imperative. One stakeholder said, "Things are going really amazingly well (with the Nutrient Management Strategy), yet it's very fragile. Inherently fragile. Just because there's billions of dollars, and there's interest, and all kinds of stuff at play."

Our research shows that water managers and decision-makers in the San Francisco Bay Area case have addressed many of the barriers to sustainable urban water management addressed in the literature, which is summarized in the review by Brown et al. [25] (Table 5).

Table 5. Barriers to sustainable water infrastructure management adapted from a review by Brown and Farrelly (2009) [25] and the San Francisco Bay approach, which is identified in stakeholder interviews and document analysis.

Barrier Identified in the Literature	San Francisco Bay Case Approach	Sources
Uncoordinated institutional framework	Coordination through the Nutrient Management Strategy and BACWA; single regulatory body (San Francisco Regional Water Quality Control Board) for water quality for the entire region	Interviews, documents [44,99]
Limited community engagement	Nutrient Management Strategy advisory board and steering committee to engage disparate stakeholders	Interviews, documents [44,100]
Limits of regulatory framework	Regulators collaborate with dischargers to develop rules that would support a multi-benefit infrastructure	Interviews
Insufficient resources	Dischargers contribute $880,000/year to scientific studies about nutrient effects on the Bay	Documents [34,45]
Unclear roles and responsibilities	Some delineation of roles through the Nutrient Management Strategy, but some lack of clarity remains	Interviews, documents [44,99]
Poor organizational commitment	Committed individuals within bureaucratic organizations	Interviews
Lack of information about integrated, adaptive management	Partnership with San Francisco Estuary Institute and academic researchers, but some uncertainty remains	Interviews, documents [44]
Poor communication	Foundations for communication laid with regional water quality monitoring	Interviews, documents [91,92]
No long-term vision or strategy	Long-term visions exist (e.g., San Francisco Bay Plan) but not specific to nutrient management	Documents [82,101,102]
Technocratic path dependencies	Not addressed	Interviews
Insufficient monitoring or evaluation	May still be a problem, but partnership with the Regional Monitoring Program will help alleviate the burden	Interviews
Lack of political and public will	Committed individuals within bureaucratic organizations	Interviews

4.2. Overcoming Impediments to Multi-Benefit Infrastructure Implementation

Despite strong interest in multi-benefit wastewater infrastructure for nutrient control, substantial impediments to their implementation exist in the San Francisco Bay Area. While previous literature has focused on socio-institutional barriers [22,103–106], we also found several technical barriers.

In particular, technologies that require changes in consumer habits (e.g., urine source-separation) face substantial challenges because increased user responsibility could decrease technological reliability. Innovative multi-benefit wastewater systems could also be less reliable than traditional systems because there is less experience. To counteract the risk of lower reliability, stakeholders mentioned that it would be essential to develop wastewater technologies that were simple to implement and adapt to changing external conditions. These technologies could be deployed if riskier multi-benefit wastewater systems do not achieve the desired water quality effects. Additionally, regulatory structures to "pre-approve" adaptive technologies for quicker implementation was identified as useful to hasten implementation. Further research is needed to develop nutrient control technologies that can be easily and quickly adapted to changing conditions such as population size, rising sea levels, or tightened regulations.

Today's wastewater treatment systems are designed to essentially be 'out-of-sight, out-of-mind' for the public. Yet some stakeholders relayed the difficulties with this design. The public does not consider how wastewater is treated and is unwilling to invest in new infrastructure because it lacks awareness of insufficiencies of existing infrastructure. Making wastewater treatment systems more visible to the public may inspire respect for the systems that turn sewage into clean water and may enable further investment in innovative, multi-beneficial technology. European studies indicate that people are more open to new water technologies if they see the environmental benefit [87], but more research is required on this topic especially in the United States.

Many stakeholders also pointed out the lack of clear leadership as a barrier to planning and implementing multi-benefit infrastructure projects and no strategies to address this emerged from interviews. In the absence of consolidation of decision-making (combining agencies that manage different aspects of water management and different wastewater treatment agencies), which is unlikely to happen. One solution may involve collective goal-setting or "value-focused thinking" [62,65]. This is a useful tool for understanding and defining stakeholders' values and objectives. A leader would take this "visioning" step early on in a planning process. In the absence of a single entity in charge, coming to agreement about collective goals (and clarity about disagreements) can help fill that gap. The formation of a new agency or workgroup to facilitate this process may be necessary. Finding measures to assess the fulfillment of these goals that are acceptable to stakeholders would also help clarify how to collectively judge the success of an infrastructure project.

Identifying stakeholder goals for water infrastructure projects also sets standards for their assessment—multi-benefit water systems need to actually meet the goals in order to truly provide multiple benefits. For example, if a constructed wetland is used to control nutrients based on the premise that it will also provide a bird habitat and improved shoreline access, then these goals can provide additional guidelines and metrics for determining the success of the technology.

5. Conclusions

Development of multi-benefit wastewater infrastructure requires proactive approaches rather than reacting to acute regulatory demands for water quality improvement. Many stakeholders in the San Francisco Bay Area involved with managing nutrients have taken this proactive approach. They view it as their professional responsibility to not only effect good water quality in the Bay but also to develop infrastructure for nutrient control that provides additional benefits. These may concern resilience to a sea level rise, creation of a wetland habitat, or recovery of resources from wastewater. These views mirror a larger paradigm shift in wastewater infrastructure that envisions holistic systems that go beyond the traditional goals of removing organic pollutants from wastewater.

The methods presented in this paper are applicable for others planning nutrient management strategies and water infrastructure. More generally, the approaches are suitable for many environmental policy decisions such as identifying a broad set of stakeholder goals (for long-term water infrastructure) and soliciting stakeholder perspectives on barriers to implementing these goals as well as strategies for overcoming them. This is important in many cases. Our proposed mixed-methods approach allows including diverse insights in decision-making processes. It allows including stakeholders' knowledge of the system and honors their roles within it. It allows us to apply this knowledge to strategic management and to identify topics of disagreement and synergies to facilitate collaborative planning processes. These stakeholder perspectives are often implicitly assumed or overlooked in traditional water infrastructure planning processes. However, their inclusion is essential for developing a multi-benefit water infrastructure.

Specifically, Bay Area stakeholders' enthusiasm for a new paradigm of wastewater infrastructure in the Bay Area has resulted in actions that support planning and implementation of multi-benefit water infrastructure. They have begun to build coalitions among disparate water management agencies. They are forging new relationships and modes of decision-making to support their vision for multi-benefit wastewater infrastructure even though they still face significant barriers. Many stakeholders are working beyond the scope of their institutional mandates, which do not represent many of their goals.

The situation encountered in the San Francisco Bay is likely relevant for many other cases of planning for nutrient management and multi-benefit water infrastructure more broadly. The insights from this case may serve as a guideline and this suggests that the path for transitioning to a new paradigm of wastewater infrastructure includes the following.

- Creating a network of the disparate agencies, organizations, and researchers involved with regional water management with strong communication channels and connections prior to decision-making.
- Articulating shared regional goals for water challenges and developing metrics for assessing their fulfillment.
- Creating policies to align institutional mandates with regional goals if they are not already aligned.

In addition, implementing an innovative, multi-benefit technology inherently carries more risk for the stakeholders involved. This risk can be mitigated by easy-to-implement, highly adaptable technologies that could be deployed should the need arise. Scientists and engineers can support the transition to multi-benefit wastewater infrastructure by pursuing the development of these types of technologies.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4441/10/9/1127/s1, Figure S1: Stakeholder points for the improvement of fulfillment of criteria for nutrient management from the worst to the best state, Figure S2: Stakeholder weights for criteria for nutrient management, Figure S3: Stakeholder weights of main objective categories for nutrient management, Table S1: Stakeholders, their professional role, and relevance to nutrient management, Table S2: Respondents' stated goals for good nutrient management, Table S3: Supporting quotations for objectives, Table S4: Supporting quotations on barriers to multi-benefit water infrastructure projects, and Table S5: Supporting quotations on strategies to overcome barriers to multi-benefit water infrastructure projects.

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