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RESEARCH ARTICLE

Cultivating effective utility-regulator relationships around innovation: Lessons from four case studies in the U.S. municipal wastewater sector

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Abstract

Regulation is critical for protecting public and environmental health but is often perceived as a barrier to innovation in the U.S. municipal wastewater sector. Before a wastewater utility can implement a new technology, it must navigate applicable regulatory processes and obtain necessary approvals, often including obtaining an updated wastewater discharge permit. While all regulatory processes involve interactions between regulators and regulated entities, innovative projects may require them to engage in new ways, heightening the importance of the relationships between them. We investigated four case studies to examine how regulatory relationships affect municipal wastewater utilities' efforts to adopt new technologies. Through cross-case analysis, we identified five interconnected characteristics of regulatory relationships that appear to facilitate innovation, and whose absence could impede it: *clarity*, *capacity building*, *continuity*, *trust*, and *bounded flexibility*. Appropriately applied *bounded flexibility*—such as using regulatory discretion to tailor permits to reflect the particular risks, benefits, and information needs of the technology at issue—may be key for enabling socially and environmentally beneficial innovation. Yet all five characteristics play important and mutually reinforcing roles in supporting innovation. By cultivating these characteristics in their relationships, both utilities and regulators can take responsibility for enabling appropriate implementation of innovative technologies. However, some parties, particularly small and under-resourced utilities, may find cultivating these characteristics difficult. Therefore, sector-wide support for effective utility-regulator relationships, including coordinated regulatory and funding programs targeted to meet small utilities' needs, may be needed to bring beneficial innovation within reach for many wastewater utilities and the communities they serve.

1. Introduction

Innovative wastewater treatment, reuse, and resource recovery solutions can help wastewater utilities meet multiple needs, but the availability of new technologies, alone, is not sufficient to names or identifying information in research results. Unattributed excerpts from interviews are provided within the manuscript. These and other interview data informed the case studies and the summary of case studies in Table 1. To maintain privacy and confidentiality, we refer to interviewees generically throughout. Publicly available documents are cited in the text when used and are, therefore, included in the reference list.

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enable their adoption [1]. Wastewater utilities provide services critical to public and environmental health [2, 3] and are, consequently, subject to extensive regulation and oversight [4, 5]. Therefore, before a utility can implement a new technology, it must obtain necessary regulatory approvals, which may include updates to the utility's wastewater discharge permit. These regulatory processes can create potential stumbling blocks for innovation [6]: while new technologies can promise greater benefits than conventional approaches, they may involve different risks, and may not fit easily within existing regulatory processes [1]. Innovation may therefore require utilities and regulators to navigate unfamiliar technical, legal, and institutional territory.

Relationships between regulators and regulated entities (often known as "permittees" in the wastewater sector) play an important role in the process and outcome of environmental regulation [6–11] by helping to determine how regulators translate broad policies and legal requirements to particular situations. Despite the importance of these interactions, the factors that contribute to effective regulatory relationships around innovation are not well understood. To date, most studies of regulatory relationships have analyzed regulators' approaches to enforcement and their implications for compliance [8, 12–21]. Few studies have focused on public-sector regulatees [20, 22, 23] or examined the interactions between the frontline actors within regulatory agencies and regulated entities who operationalize environmental policies [24, 25]. However, innovation in the municipal wastewater sector involves regulatory interactions that are separate from the enforcement process, including interactions related to permitting [26], and usually involves public sector regulatees. A better understanding of how utility-regulator relationships affect efforts to adopt new technologies could help utilities and regulators engage more effectively around innovative projects, leading to better environmental outcomes.

To provide insights about how utility-regulator relationships influence innovation, we examined four case studies of U.S. municipal wastewater utilities pursuing innovative technologies. These cases shed light on how utilities and regulators interact around innovation and how these interactions differ from interactions concerning more commonplace technologies. Through a cross-case analysis, we identified five characteristics of regulatory relationships that appear to facilitate innovation, and whose absence could impede it: *clarity*, *capacity building*, *continuity*, *trust*, and *bounded flexibility*. All five characteristics were present to some degree in the three cases of successful or ongoing innovation, but were weak or absent in the case of a failed attempt to pursue an innovative project. Four characteristics (*clarity*, *capacity building*, *continuity*, and *trust*) are likely beneficial for all regulatory relationships. The fifth, *bounded flexibility*, is important in the context of innovation, yet may not be appropriate for more commonplace technologies and activities. Since *bounded flexibility* involves adjusting and adapting the project over time and using regulatory discretion to tailor requirements to the particular risks and benefits of the technology at issue, it is essential for managing the uncertainty inherent in innovative approaches, but less applicable to well-established and well-understood technologies.

After a brief review of relevant regulatory context, we describe the four cases. We then define the five characteristics and illustrate their importance in each case. Next, we discuss the importance of utility-regulator relationships around innovation and offer lessons gleaned from the case studies and interviews for how utilities and regulators can cultivate more effective regulatory relationships around innovation. Finally, we discuss the broader implications and limitations of our research, including its relevance for regulatory relationships outside the context of innovation, meeting the needs of small and under-resourced utilities, and providing sector-wide support for effective relationships around innovation.

2. Innovation, regulation, and regulatory relationships in the municipal wastewater sector

2.1. Drivers for and barriers to innovation

Wastewater utilities increasingly need to do more with less. Aging infrastructure, population growth, emerging contaminants, changing climatic conditions, and limited funding challenge their ability to maintain existing levels of service [27–30]. Simultaneously, many wastewater utilities need to expand the range of functions they perform [1, 31, 32]. Many utilities are facing the prospect of progressively more stringent effluent limitations related to broader water quality challenges [1, 4, 33–35] or being asked to help achieve other goals, such as boosting water supplies [28, 33, 36], enhancing wildlife habitat [37, 38], meeting energy needs [39], or recovering other valuable resources from wastewater [40, 41].

Addressing these overlapping needs and challenges cost-effectively will often require innovation, defined here as "the development, application, diffusion, and utilization of new knowledge and technology" [42]. In particular, many utilities will need to adopt new technologies in order to meet all of their responsibilities effectively and at a feasible cost [2, 43–45]. Integrated innovative solutions can meet multiple needs at a lower cost than siloed conventional approaches, enable access to a broader range of funding sources, and facilitate cost sharing among multiple beneficiaries [46].

However, utilities face a range of barriers to innovation [1, 6, 44, 47, 48], even where technological barriers are low. Wastewater infrastructure is generally capital intensive and long-lived, making changing technologies difficult and failure especially risky since it can create stranded assets and cause regulatory violations that result in penalties, heighten public and environmental health risk, enhance litigation exposure, and diminish public trust [47]. Given this context, both utility managers and regulators may be risk averse [47], approaching new technologies that involve unconventional risks, benefits, and information needs tentatively.

2.2. Regulatory context

The federal Clean Water Act (CWA) is a key locus of regulatory relationships in the U.S. wastewater sector. The CWA prohibits wastewater treatment plants from discharging pollutants to "waters of the United States" except in compliance with a permit under the National Pollutant Discharge Elimination System (NPDES) (33 U.S.C. §§ 1342(a), 1362(6), (7), (12), (14)). An NPDES permit sets limits on the pollutants a point source may discharge to a receiving water. Under the CWA, all municipal wastewater utilities, also known as publicly owned treatment works (POTWs), must meet broadly applicable "technology-based effluent limitations" (considered achievable using secondary treatment processes) (33 U.S.C. § 1311(b)(1)(B); 40 C.F.R. § 122.44(a); 40 C.F.R. Part 133), as well as additional specific "water-quality-based effluent limitations," when needed to protect the state-designated beneficial uses of the receiving water (33 U.S.C. §§ 1311(b)(1)(C), 1312, 1362(11); 40 C.F.R. § 122.44(b)). NPDES permits also contain additional terms and conditions to help ensure that utilities meet effluent limitations and other requirements. For POTW operators, these include establishing and implementing a pretreatment program for significant industrial users that contribute wastes to the POTW (33 U.S.C. § 1345(g); 40 C.F.R. Part 403), abiding by restrictions on the use and disposal of sewage sludge (33 U.S.C. § 1345; 40 C.F.R. Parts 501, 503), alerting the regulator when substantial changes in the quality or quantity of wastewater are expected (40 C.F.R. § 122.42(b), meeting monitoring and reporting requirements, and properly operating and maintaining all facilities and treatment systems (33 U.S.C. §§ 1318, 1342(a); 40 C.F.R. §§ 122.41–122.50). With some exceptions, the U.S. Environmental Protection Agency (EPA) has delegated

NPDES permitting authority to states (33 U.S.C. § 1342(b)). Today, EPA is the primary permitting authority for only three states (MA, NH, and NM), the District of Columbia, and U.S. territories [49]. Eligible federally recognized Indian tribes can apply to be treated like states for the purpose of issuing and enforcing NPDES permits (33 U.S.C. § 1377(e); 40 C.F.R. § 123.31); however, none are currently approved to do so [50]. Therefore, a state agency is usually the primary wastewater regulator with which utilities interact.

In addition to the CWA, all wastewater utilities must comply with other federal, state, and local requirements. For example, additional state water quality regulation often applies to the effluent a utility discharges to water or land, air quality regulation applies to its air emissions, and solid waste regulation affects disposal of the solids it produces [51]. Utilities seeking to implement new technologies for wastewater treatment, reuse, or resource recovery may need to engage with a greater breadth and intensity of regulation than their counterparts who rely on conventional wastewater treatment technologies. The often-siloed regulatory programs they encounter may not be prepared to take into account the full range of risks and benefits associated with innovative technologies.

2.3. Regulatory relationships

Regulatory relationships develop through the accumulation of interactions over time. These interactions—between utilities, regulators, and third parties—help determine how policies and legal requirements are translated to a specific regulatee in a particular situation. Some interactions are utility-initiated, such as when a utility applies for an NPDES permit or renewal [4], submits discharge monitoring reports and reports compliance or noncompliance with its permit requirements [52], or, in certain states, seeks engineering document approval for a project that affects its influent or effluent quality or involves a change in operations (see, e.g., N.Y. Comp. Codes R. & Regs. tit. 6, § 750–2.10). Other interactions are regulator-initiated, such as when a regulator carries out inspections [53], provides compliance assistance [54], or takes an enforcement action to address permit violations [55]. The individuals involved in utility-regulator interactions may vary depending on context or evolve as a result of personnel changes over time.

Interactions often occur around well-delineated issues using standardized processes. Utilities routinely submit electronic discharge monitoring reports to regulators. Similarly, utilities periodically apply to renew their NDES permits, which can be a relatively straightforward process if there are not significant changes in facilities, operations, or regulatory requirements (although regulatory requirements often do change between permit terms and can be contentious). Strong regulatory traditions [56] for using standard processes or permit terms that are not specifically mandated by the controlling law can develop around these common interactions.

While utilities and regulators typically interact in well-defined ways, their interactions around innovation, like innovation itself [57], can be complex and non-linear. Technical and regulatory questions can arise throughout development and implementation of an innovative project, requiring utilities and regulators to engage in new ways that change the scope and intensity of their relationships. This complexity suggests that utility-regulator relationships have heightened importance in the context of regulatory approvals related to innovation, which serve a critical gatekeeping function to ensure that the technology a utility deploys will meet performance requirements. Indeed, recent research has identified regulatory relationships as a key locus of potential barriers and opportunities for wastewater innovation [6, 47].

3. Methods

3.1. Ethics statement

This study was approved by the Institutional Review Board of the UC Berkeley Committee for Protection of Human Subjects under protocol #2017-07-10135. Participation was voluntary, and we obtained verbal, informed consent from each interviewee before every interview. We obtained separate verbal consent prior to all audio recording. Each interviewee was given the opportunity to provide feedback on a draft version of the manuscript. To maintain privacy and confidentiality, we refer to interviewees generically.

3.2. Methodological approach

We examined four cases in which a municipal wastewater utility sought to implement new technology and analyzed the utilities' interactions with wastewater regulators in each case. Potential cases were identified through open-ended survey questions in a related research project [6, 47], consultation with practitioners, and publicly available information. The cases were selected to cover a range of geographic locations (Fig 1), technologies, motivating factors, utility characteristics, regulator characteristics, regulatory issues, and implementation outcomes (Table 1).

Cases were developed using a mixed-methods approach. Following intensive document review, we conducted 16 semi-structured phone interviews with wastewater utility managers and regulators from May to August 2018. Interview subjects were identified and selected

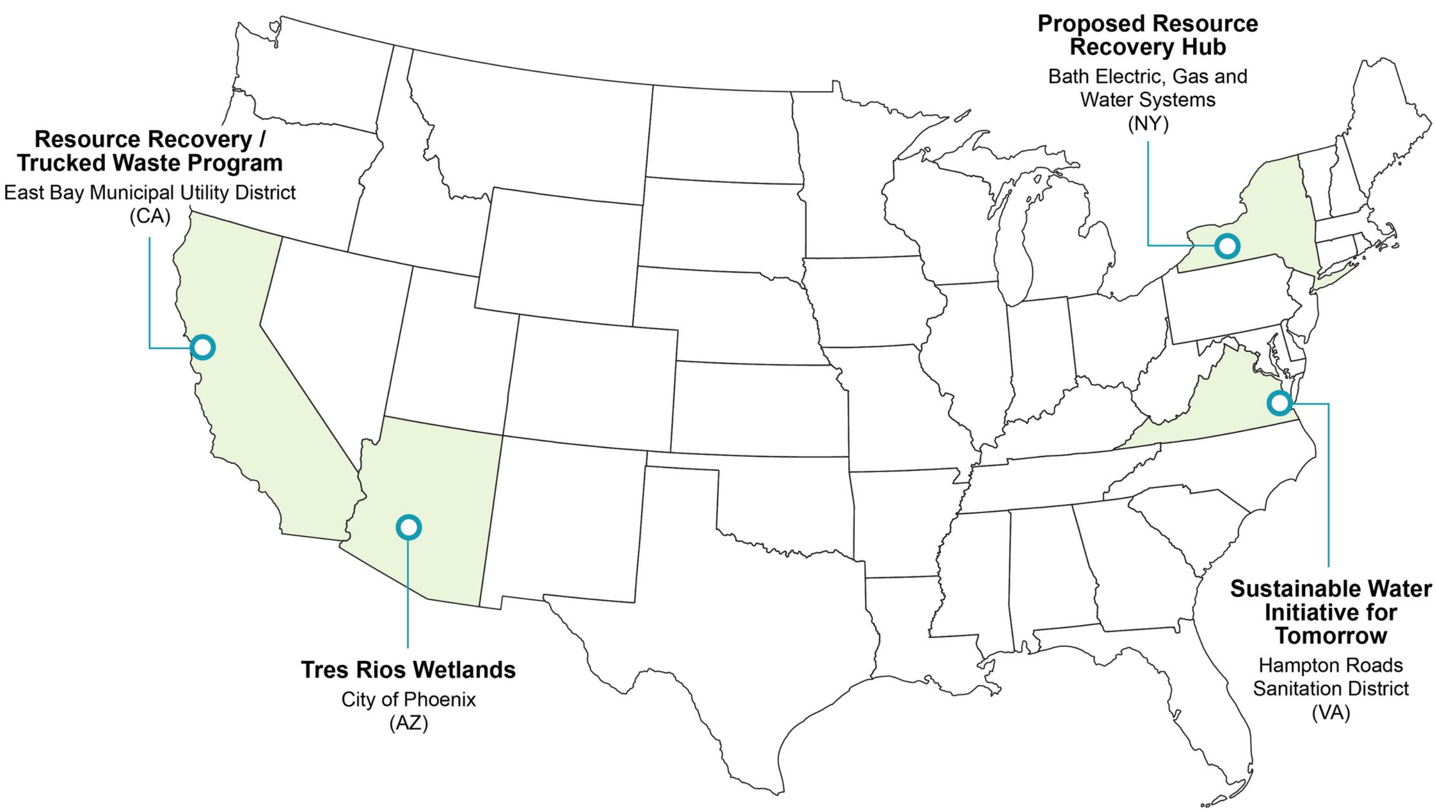

Fig 1. Geographic distribution of case studies. Map base layer from Heitordp, CC0 1.0 Universal Public Domain Dedication, via Wikimedia Commons, https://commons.wikimedia.org/wiki/File:Blank_US_Map_(states_only).svg.

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Table 1. Summary of case studies.

	Tres Rios Wetlands	Sustainable Water Initiative for Tomorrow (SWIFT)	Bath Resource Recovery Hub Proposal	EBMUD Resource Recovery / Trucked Waste Program
Location	Maricopa County (AZ)	Coastal Plain region (VA)	Village of Bath (NY)	Oakland (CA)
Technology	Large-scale constructed treatment wetlands	Indirect potable reuse via aquifer recharge	Resource recovery and integrated resource management	Resource recovery
Key factors motivating the utility to pursue the project	• Increased stringency of water quality regulations • Costs of compliance alternatives • Potential for habitat, flood-control, recreational, and educational benefits • Availability of federal funding	• Increased stringency of water quality regulations and related uncertainty • Potential to address regional groundwater overdraft and related impacts • Potential to generate nutrient credits • Potential to reprioritize planned funding	• Increased stringency of water quality regulations • Costs of compliance alternatives; potential for revenue generation and ratepayer savings • Multi-service utility • Potential to increase electricity reliability	• Excess anaerobic digester capacity • Potential for revenue generation; reduced utility rates • Buyer for surplus electricity • Potential to reduce fats, oils, and grease (FOG) related collection system blockages
Population served	~2,570,000	~1,700,000	~2,500	~740,000
Utility operator	City of Phoenix	Hampton Roads Sanitation District	Bath Electric, Gas and Water Systems	East Bay Municipal Utility District
Average wastewater flow	135 MGD[a] (5.91 m^3/s)	100 MGD[a] (4.38 m^3/s) (for the 7 plants involved in SWIFT, combined)	0.7 MGD[a] (0.03 m^3/s)	63 MGD[a] (2.8 m^3/s)
Wastewater regulator(s)	• NPDES permitting: Federal (EPA Region 9) • NPDES compliance: State (Arizona Department of Environmental Quality)	• NPDES permitting and compliance: State (Virginia Department of Environmental Quality) • UIC program[b]: Federal (EPA Region 3)	NPDES permitting and compliance: State (New York State Department of Environmental Conservation, Region 8)	NPDES permitting and compliance: State (San Francisco Bay Regional Water Quality Control Board)
Key regulatory issues	• Navigating ambiguous NPDES permitting jurisdiction • Ensuring treatment efficacy • Developing appropriate monitoring requirements • Accommodating natural processes in permitting, including by adjusting compliance locations	• Involving the state in UIC regulation when it lacked a UIC[b]: program • Getting permission to reprioritize planned spending under EPA consent decree • Deciding how to permit intermittent discharges from full-scale facilities	• Demonstrating treatment efficacy • Demonstrating technical and financial feasibility • Demonstrating that engineering document approval was warranted	• Requiring adequate pretreatment • Developing and implementing trucked waste permit program • Navigating multiple sectors of regulation (e.g., wastewater, solid waste, air emissions), including duplicative permitting requirements
Milestones	Initiated: 1992 Demo[c]: 1995–2012 Full[d]: 2010–present	Initiated: 2014 Pilot[e]: 2016 Demo[c]: 2018–present Full[f]: 2020–2032	Initiated: 2014 Pilot[e]: 2015 Abandoned: 2016	Initiated: 2002 Increment[g]: 2002–present ExpGen[h]: 2012
Status	Implemented	In progress	Abandoned	Implemented

[a] Million gallons per day.
[b] Underground Injection Control Program.
[c] Demonstration project operation.
[d] Full-scale project operation.
[e] Treatment pilot.
[f] Full-scale project design and construction, expected.
[g] Incremental addition of wastes.
[h] Expanded electricity generation capacity.

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through purposive sampling [58] guided by previous study research, document review, and our professional knowledge and supplemented by snowball sampling [59]. Interviews with utility managers addressed the project development process, the nature of the proposed technology, factors that enabled or hindered the utility's pursuit of the technology, interactions with regulatory agencies, the wastewater permitting process, and their perception of regulators' decision making related to the technology. Interviews with regulators addressed the nature of the proposed technology, their agency's prior experience with similar technologies, potential benefits and concerns associated with the technology, challenges in permitting pilot projects or full-scale implementation of the technology, interactions with the utility, and decisions regarding the proposed project. Both utility managers and regulators were asked for recommendations and lessons learned based on their the experience. Each interview lasted approximately 1 hour. We took notes during interviews and, when verbal permission was granted, made and used audio recordings to help clarify and fill gaps in our notes. Following interviews, we conducted additional document-based research as needed. We synthesized our interview notes and pre- and post-interview document-based research to develop individual case studies.

Finally, we employed an iterative, explanation-building approach [60] to identify commonalities and key aspects of utility-regulator relationships across the cases.

4. Four cases of utilities seeking to implement innovative technologies

This section provides an overview of each of the four cases we examined for this study: Tres Rios Wetlands, Sustainable Water Initiative for Tomorrow (SWIFT), Bath Resource Recovery Hub, and East Bay Municipal Utility District Resource Recovery / Trucked Waste Program. In three of the four cases the utilities successfully navigated (or are in the process of navigating) wastewater regulatory processes. However, in the case of the Bath Resource Recovery Hub, after initial efforts, the utility abandoned its plans for implementing innovative technology. Additional information related to the cases is included in Table 1 and the S1 Table that accompanies this article.

4.1. Tres Rios Wetlands—City of Phoenix (AZ)

The Tres Rios Wetlands are an innovative part of a larger multi-benefit, multi-phase project implemented by the City of Phoenix (the City) and federal partners in order to improve water quality in local waterways, reduce flooding in neighboring communities, and restore riparian habitat [61]. Design and implementation of the project occurred over a period of almost two decades and involved a staged and iterative approach.

4.1.1. Origin and development. Conceptualization of the project began in the early 1990s, when the City faced the prospect of more stringent effluent limitations for nutrients at its 91st Avenue Wastewater Treatment Plant [38]. The City operates the plant on behalf of a multi-city Subregional Operating Group [62], treating an average of 135 million gallons of wastewater per day (MGD) (5.91 m^3/s) for approximately 2.6 million people in the Metropolitan Phoenix area [63]. The estimated cost of upgrading the plant for nutrient removal was high (more than $600 million [38]), so the City analyzed other options, including rerouting all of its treated wastewater to direct or indirect reuse [64]. In considering how to address nutrients, the City weighted a broad set of interests in the region, including in the Salt River's capacity to support wildlife habitat and recreation [64]. Although the Salt River once flowed year round at this location, dams and diversions had all but eliminated natural dry season flow, making the river highly dependent on treated wastewater effluent, which generally had strong diurnal variations that are not consistent with maintaining habitat for fish and wildlife [65]. Although shifting fully to reuse would have solved the nutrient problem more cheaply, by eliminating effluent discharges to the Salt River, it would have deprived the river of its primary water source for most of the year, further compromising the waterway's capacity to support wildlife habitat and recreation [64]. Therefore, the City, in cooperation with local, state, and federal stakeholders, decided to address nutrients via a multi-benefit project entailing construction of hundreds of acres of treatment wetlands and a 4.5-mile (7,200 m) flood control levee, as well as habitat restoration along approximately 5 miles (8,000 m) of the Salt and Gila rivers [66–68]. The stakeholders involved included the Gila River Indian Community, non-profit organizations, the Arizona Department of Environmental Quality (ADEQ), Arizona Game and Fish Department, U.S. Army Corps of Engineers, U.S. Bureau of Reclamation, U.S. EPA, and U.S. Fish and Wildlife Service.

Developing the project required addressing a number of general technical questions and gathering site-specific information about wetland design and function. Beginning in 1995, the City partnered with the Bureau of Reclamation to construct and operate approximately 15 acres of demonstration wetlands that enabled direct investigation of a range of topics, from how wastewater moved through and interacted with constructed wetland systems to the importance of scale, what water quality requirements might be appropriate, effective mosquito control methods, and future budget and maintenance expectations [69]. The demonstration wetlands also helped the City understand how the public might interact with the full-scale wetlands during the course of their recreational activities in the area [70]. Portions of the demonstration wetlands continued to be operated through 2012 [62].

From 1995 to 2000, the demonstration wetlands served as a focal point for an EPA-led effort to explore policy and permitting issues associated with constructed treatment wetlands nationwide [71]. The effort culminated in development of an EPA document entitled *Guiding Principles for Constructed Treatment Wetlands* [71]. Among the document's major takeaways was the recommendation that treatment wetlands be sited in upland areas unless (1) siting them in existing waters of the United States (including existing wetland areas) would restore wetland ecosystems that had already been degraded, and (2) the constructed wetlands would meet "all applicable water quality standards and criteria" [71].

Successful construction and operation of the demonstration wetlands facilitated development of the full-scale Tres Rios project. The full-scale project was designed and constructed in phases [67] with the support of, and partial funding from, the federal government (see Water Resources Development Act of 2000, P.L. 106–541, Section 101(b)(4)). The Army Corps of Engineers released the final feasibility study and environmental impact statement for the project in April 2000 [64], and later that year Congress authorized approximately $63 million toward the expected $99.3 million cost (see Water Resources Development Act of 2000, P.L. 106–541, Section 101(b)(4)). Design and construction of Phase I, the flood control levee, was carried out from 2005 to 2008 [67]. Design for Phase II, the full-scale Tres Rios Wetlands, began in 2003 and drew on the lessons learned from both the demonstration wetlands and the effort to develop national guidance for constructed wetlands [67]. Construction of the flow-regulating portion of the wetlands was completed in 2009, followed by completion of the overbank portion of the wetlands in 2010 [67] and a special in-plant pump station for more effectively delivering effluent to the wetlands in 2012. Operation of the flow-regulating wetlands began in July 2010, and the first discharge from its outfall occurred in early August 2010 [62]. Phase III—encompassing riparian and wetland habitat restoration work—continued for several more years [67, 68].

4.1.2. Key regulatory issues: General. Under the national guidance for constructed wetlands, it would have been acceptable to site the full-scale wetlands in the bed of the degraded, effluent-dependent Salt River [71]. However, this would have significantly reduced the value added for the City. Upland treatment wetlands generally need to meet effluent limitations only where water exits the wetlands and enters a federal jurisdictional water. In contrast, wetlands constructed within the Salt River would have been considered part of that waterway under the CWA and, as a result, would have needed to meet all effluent limitations where treatment plant effluent first entered the wetlands. By building the Tres Rios wetlands in an upland location, the project was able to utilize the wetlands' ability to provide additional treatment ("polishing") of the final effluent.

Before the City could begin operating the full-scale wetlands, it needed a new NPDES permit from EPA Region 9. According to interviewees, the process of developing the 2010 permit terms began in late 1999, when the previous permit was issued. That permit expired at the end of 2003, and the plant operated under an administratively continued permit that allowed interim operation for more than 6 years [65]. An NPDES permit is considered "administratively continued" if the permittee submitted a complete application for a new permit at least 180 days before their permit expired, but the permitting authority has not issued a new permit (40 C.F.R. § 122.6). This status allows the permittee to continue to operate under the terms of the expired permit. Development of the 2010 permit was informed by knowledge gained from the demonstration wetlands, which continued to operate. EPA Region 9 permitting staff were also able to draw on the knowledge and expertise of EPA's wetlands office and the national guidance [71] created in connection with the project's demonstration phase.

EPA included unconventional terms and conditions meant to reflect the unique design and role of the wetlands in the City's 2010 NPDES permit [65] and, subsequently, its 2016 permit [62]. We describe two categories—(1) extensive monitoring requirements and (2) permit terms that accommodated natural processes—below. Some permit requirements were changed in response to the accumulation of experience and information during the permit term via built in adaptive components. Other requirements changed between the 2010 permit and the 2016 permit based on reassessment and communication between the utility and the regulator in the lead up to issuance of the 2016 permit. S1 Table summarizes many of these unconventional terms and conditions and how they changed between the 2010 and 2016 permits.

Permitting also involved navigating institutional challenges that were not specifically linked to the project's innovative nature. EPA was the sole NPDES permitting authority for Arizona until 2002. At that point, the Arizona Department of Environmental Quality (ADEQ) received authorization to administer its own program, and the City assumed it should apply to ADEQ for its new permit. However, because the discharges from the treatment plant (and, eventually, from the Tres Rios wetlands) entered the Salt River in the vicinity of a disputed boundary of Gila River Indian Community land, it was unclear whether the state actually had permitting jurisdiction in this case [65]. EPA ultimately decided to issue the new permit but delegate primary responsibility for permit management and compliance oversight to ADEQ. Since EPA's Region 9 permitting staff were based in California, this meant their interactions with the City were generally accomplished remotely.

4.1.3. Key regulatory issues: Monitoring requirements. Although constructed wetlands had been implemented elsewhere, and much was learned from the Tres Rios demonstration wetlands, EPA still had concerns about whether the full-scale wetlands would function as intended. Interviewees emphasized that the Tres Rios project explicitly sought to elevate the environmental value of the wastewater treatment plant's discharge by creating new high-value habitat and, therefore, ecosystems that would be more intensively used by wildlife (including threatened and endangered species). EPA wanted to ensure that the wetlands would actually accomplish this goal, providing adequate treatment and sufficiently attenuating the diurnal pattern of wastewater production to meet ecosystem needs. Therefore, the regulator incorporated extensive monitoring requirements in the City's 2010 NPDES permit to confirm wetland treatment efficacy, inform operational adjustments to improve treatment performance, and ensure the protection of surface water quality. In addition to monitoring at each outfall to the Salt River, the 2010 permit included requirements for monitoring at 6 additional locations: the influent point to the flow-regulating wetlands, the influent point to one of the demonstration wetlands, two locations within the flow-regulating wetlands, immediately upstream of the first outfall, and several miles downstream of the outfalls.

According to interviewees, the City initially found its monitoring responsibilities overwhelming, to the point of considering contesting the permit. The City soon realized many monitoring requirements addressed realistic concerns, but continued to feel that other requirements were unnecessary or excessive. For example, the 2010 permit required expensive accelerated monitoring if whole effluent toxicity was detected at the influent point to the wetlands. Whole effluent toxicity testing requirements are common in NPDES permits as one means of implementing the CWA's prohibition on discharging pollutants in toxic amounts [72]. The City did studies to demonstrate that whole effluent toxicity detected at that location was caused by residual chlorine, which dissipated quickly within the wetlands and did not represent a serious problem. As another example, the City thought the requirement to monitor water quality parameters miles downstream of its outfalls was not useful, since those measurements would reflect pollutant contributions from intervening sources that were beyond the City's control, such as stormwater and agricultural runoff. The City found other requirements logistically challenging, such as frequent monitoring at open-water sites within the flow-regulating portion of the wetlands.

In the lead up to its 2016 NPDES permit renewal, the City engaged with EPA about revising the permit to ensure sufficient protections while better targeting monitoring to meet information needs and removing excessive requirements. Evidentiary support for streamlining the City's monitoring burden came from multiple sources. First, the City's monitoring results and studies helped allay EPA's concerns about treatment efficacy. Second, the regulator gained personal experience with the project. Interviewees described a site visit by EPA's San Francisco-based permit writer as instrumental in helping the regulator understand the treatment system, and specific monitoring issues and challenges, in a way that remote communications could not. As a result of productive engagement, the 2016 permit limited whole effluent toxicity monitoring to outfall locations, eliminated requirements for upstream and downstream monitoring, and reduced the frequency of required within-wetland monitoring.

4.1.4. Key regulatory issues: Accommodating natural processes in permitting. The City's NPDES permits included other non-traditional terms that accommodated the natural processes responsible for many of the project's benefits.

Monitoring of the demonstration wetlands and other research had suggested that the presence of animals and the operation of natural processes within the wetland ecosystem would increase the load of bacteria, total suspended solids, and (seasonally) ammonia in the effluent that was eventually discharged to the Salt River. This might make it difficult to meet effluent limitations for these constituents at the wetlands' outfall, but would not compromise water quality in the Salt River. Therefore, the City pushed for compliance for those constituents to instead be measured at the influent point to the wetland. This compliance location demonstrated that the treatment plant was functioning properly without imposing unrealistic, and potentially harmful, requirements on wetland water quality that could reduce the habitat benefits of the project (e.g., if the City had been required to disinfect water again, after it flowed through the wetlands).

Interviewees indicated that, as experience and data accumulated, EPA became more comfortable with variations in treatment performance associated with seasonal cycles and critical maintenance activities needed to maintain wetland function, such as controlled burns. EPA allowed the non-traditional compliance location for some constituents as part of the original 2010 permit. Under both the 2010 and 2016 permits, the City's *Escherichia coli* compliance was measured at the influent point to the flow-regulating wetlands. By contrast, EPA initially required compliance for total suspended solids and ammonia to be measured at the outfall to the flow-regulating wetlands but eventually allowed compliance for these constituents to be measured at the flow-regulating wetlands' influent point instead. For total suspended solids, flexibility built into the 2010 permit enabled this change during the permit term. For ammonia, the change was made in the 2016 permit, acknowledging that ammonia levels would naturally fluctuate with seasonal changes in wetland function [73]. Well-functioning wetlands go through natural cycles that are influenced by changes in parameters such as temperature: during the growing season, plants take up available nutrients, allowing the wetland to act as a net nutrient sink, while during the cold season, plants become dormant, die back, and decay, releasing nutrients that may accumulate as detritus.

4.1.5. Perceptions of utility-regulator relationships. Overall, despite some challenges, interviewees generally described interactions between EPA and the City as "*positive*," "*very cooperative*," and "*collaborative*." Interviewees recounted having "*detailed discussions on what can and cannot be done*," consistent with applicable laws and regulations. NPDES permit requirements related to the wetlands were described as being developed through a "*combination of the permittee and permit writers working. . .together to mesh the goals and requirements of each*." Over time, the City developed a better relationship and more credibility with EPA's permitting staff and ADEQ's compliance staff. Regulators described City staff as "*always very responsive, even prior to this project and on other facilities*," proactive about reaching out for input and feedback, and straightforward about the challenges the City encountered. "*The collaborative process, the very open process that the utility encouraged. . .and the fact that they were proposing to do a pilot project, and do a phased implementation. . .gave [the regulator] a lot of comfort with their approach*." As a result of this phased approach, interviewees described the City as having progressively developed the technical expertise and information base it needed to proactively investigate problems and develop evidence-backed proposals to address them, instead of simply asking regulators what it should do. Many interviewees suggested that, today, EPA and ADEQ recognize the deep expertise the City has developed. Consequently, both agencies use the City as a resource and example for other wastewater utilities. Interviewees noted that turnover in compliance staff at ADEQ has made the City an important resource for helping new staff gain familiarity with the project and its unique permit terms.

4.2. Sustainable Water Initiative for Tomorrow (SWIFT)—Hampton Roads Sanitation District (VA)

The Sustainable Water Initiative for Tomorrow (SWIFT) is a groundwater recharge project under development in Virginia's Coastal Plain that would employ municipal wastewater treated to drinking water standards as the source water for recharge. This case study draws on additional in-depth research presented in Green Nylen (2021) [74].

4.2.1. Origin and development. In 2010, EPA established limits on the total amounts of nitrogen, phosphorus, and sediment allowed to be discharged to surface waters in the Chesapeake Bay watershed [75, 76], providing impetus for the SWIFT project. This type of limit is known as a Total Maximum Daily Load (TMDL). The Chesapeake Bay TMDL specifies pollutant allocations for large dischargers in the watershed (9 Va. Admin. Code §§ 25-820-70, 25-720-60(C), 25-720-120(C)). As part of its efforts to implement the Chesapeake Bay TMDL, the Virginia Department of Environmental Quality (VDEQ) developed a general discharge permit (Code of Virginia § 62.1–44.19:14; 9 Va. Admin. Code §§ 25-820-10 through 25-820-80). Hampton Roads Sanitation District (HRSD) operates 16 wastewater treatment plants, including seven larger plants within the Chesapeake Bay watershed. Collectively, HRSD's plants treat an average of 225 million gallons of wastewater per day (9.9 m^3/s) for approximately 1.9 million people in 20 counties and cities within Virginia's Coastal Plain [77]. Today, the seven plants that will be involved in full-scale SWIFT implementation collectively treat about 100 million gallons of wastewater per day (4.38 m^3/s) [78].

While HRSD is able to meet its current nutrient allocations under the TMDL, the potential for more stringent requirements in the future led it to explore the idea of proactively treating its effluent to drinking water standards and using the water to combat regional groundwater overdraft in the Potomac Aquifer System [79, 80]. A 2014 feasibility study suggested the concept had merit, and HRSD sought input on and support for moving forward with such a project, in the process reaching out to the governor, VDEQ, the Virginia Department of Health (VDH), and a range of other stakeholders [81].

In 2016, HRSD piloted two advanced wastewater treatment processes, settling on a carbon-based process that used less energy, generated less waste, and produced effluent expected to be more chemically compatible with the aquifer than effluent produced through reverse osmosis [82–85]. In 2018, HRSD began operating the 1-million-gallon-per-day (0.04 m^3/s) SWIFT Research Center with extensive monitoring to demonstrate proof-of-concept, study impacts on groundwater, develop the technical capability to operate and maintain full-scale SWIFT facilities, and inform planning for full-scale implementation [86–88]. To track water quality changes in the aquifer, HRSD is monitoring the interaction of recharged water with groundwater and aquifer materials as it migrates outward from the demonstration site's injection well [74]. HRSD plans to monitor recharge similarly when it moves to full-scale implementation of SWIFT facilities. If a water quality problem is detected soon after injection, HRSD can reverse the direction of its recharge pumps to remove the affected water, something it has already had occasion to practice [89–92]. Shortly after HRSD began operating the Research Center, it realized that, because the new SWIFT treatment system's biological filters had not yet gained full functionality, it had introduced almost 5 million gallons ($2x10^4$ m^3) of water that exceeded specified nitrite levels into the Potomac Aquifer System. This event led HRSD to put additional protections in place, including continuous nitrite monitoring, and gave it practice with operating the recharge pumps in reverse when it pumped out 20 million gallons ($8x10^4$ m^3) of water to ensure that the high-nitrite water was fully removed. HRSD has also identified other contingencies in case delayed-onset water quality problems develop.

HRSD initiated design on the first full-scale SWIFT facility in 2020 [93] and hopes to complete all five planned facilities, serving seven of its wastewater treatment plants in the Chesapeake Bay watershed [74], by 2032 [94, 95]. When fully implemented, SWIFT stands to slash nutrient discharges from those wastewater treatment plants, generating excess nutrient credits it can trade to other dischargers [96, 97].

4.2.2. Key regulatory issues. HRSD has engaged with multiple regulatory agencies on wastewater issues throughout SWIFT development and implementation. Sometimes this engagement has involved regulators functioning in their formal capacity, as a result of an agency's direct approval or permitting authority over some aspect of the Initiative, and sometimes it has occurred more informally, outside traditional regulatory processes. For example, HRSD has engaged in initial discussions with VDEQ about what NPDES permit changes will be needed to support full-scale SWIFT implementation, incorporating the SWIFT treatment process as a means to achieve nutrient reductions required under Virginia's strategy to meet the Chesapeake Bay TMDL. VDEQ will need to use its regulatory discretion to decide what combination of concentration-based and mass-based effluent limitations would be appropriate for the greatly reduced and intermittent discharges expected from wastewater treatment plants involved in SWIFT.

However, at the current stage of the project, the core regulatory issues associated with moving SWIFT forward revolve around its planned injection of approximately 100 million gallons of highly treated wastewater per day (4.38 m^3/s) into the Potomac Aquifer System [33], an important source of drinking water for hundreds of thousands of Virginia residents. Injection of water into the aquifer falls within the jurisdiction of EPA's Region 3 Underground Injection Control (UIC) program under the federal Safe Drinking Water Act [98]. HRSD has been working with that agency and others to identify appropriate water quality parameters, regulatory limits, and monitoring requirements to ensure aquifer protection. In particular, although the state of Virginia lacks direct regulatory authority over underground injection, HRSD has worked with VDEQ and VDH to identify and address their concerns, recognizing the state's role in establishing groundwater quality standards (9 Va. Admin. Code §§ 25-280-10 through 25-280-90) and its obvious and significant stake in safe and effective implementation of SWIFT [86, 99]. EPA's UIC Program has likewise recognized the importance of the state's interests, and has solicited input from VDEQ and VDH on regulatory requirements for SWIFT water quality [86]. One of the challenges all entities involved in the project and its regulation face is that current federal drinking water quality standards have not been amended in decades, and do not address some of the contaminants the state is worried about (including contaminants of emerging concern). However, with VDH's input and EPA's support, HRSD is developing an extensive monitoring program that includes performance indicators for a range of unregulated contaminants [86] and has employed bioassays to look for negative effects.

Most notably, HRSD actively sought additional regulatory oversight for SWIFT. With VDH's and VDEQ's support, the utility successfully pursued state legislation in 2019 to create an oversight body for SWIFT, the Potomac Aquifer Recharge Oversight Committee. The Committee includes representatives from both state agencies, creating and codifying a clear state oversight role over SWIFT recharge (Code of Virginia §§ 62.1–271 to 62.1–275) that also serves as a vehicle for implementing state groundwater quality standards.

4.2.3. Perceptions of utility-regulator relationships. As reflected above, interviewees described good, collaborative relationships among HRSD, VDEQ, VDH, and EPA Region 3's UIC program. One interviewee emphasized that bringing together multiple regulatory agencies has been time consuming but necessary, and that it has helped for these interactions to occur at multiple levels, including between individuals in leadership roles and between technical staff.

However, EPA has many subdivisions, and interactions with another part of EPA generated considerable uncertainty for several years. HRSD hoped to pay for full-scale SWIFT implementation by reprioritizing much of the funding planned for capital improvements under a 2010 EPA consent decree on wet-weather sanitary-sewer overflows over the next 10 years. This type of reprioritization is possible under an Integrated Plan developed in accordance with EPA's 2012 Integrated Municipal Stormwater and Wastewater Planning Approach Framework, which allows municipal utilities to address multiple CWA requirements simultaneously by prioritizing the projects and actions likely to be most beneficial in the near-term benefits for earlier implementation (33 U.S.C. § 1342(s)). Although SWIFT will not reduce sanitary-sewer overflows, its projected surface water quality benefits exceed those expected over the next decade under the previous schedule of overflow-specific improvements. Therefore, HRSD submitted an Integrated Plan to EPA requesting to shift these funds in September 2017 [100–102]. EPA and other parties to the consent decree finally came to an agreement in principle to allow the funding reprioritization in 2020, and, as of July 2021, final approvals appeared imminent, clearing the path forward for full-scale SWIFT implementation [103].

4.3. Bath Resource Recovery Hub proposal—Bath Electric, Gas and Water Systems (NY)

The Bath Resource Recovery Hub proposal aimed to convert the Village of Bath's wastewater treatment plant into a multi-benefit wastewater treatment and energy generation facility. The proposal was not implemented due to barriers that arose during the engineering document approval process required under New York state water quality law.

4.3.1. Origin and development. The Village of Bath is a small community in western New York state. It operates its own water, wastewater, electricity, and gas utilities, collectively known as Bath Electric, Gas and Water Systems (BEGWS). A Director, a five-member Municipal Utilities Commission, Bath's mayor, and a Village Board of Trustees are all involved in utility decision making. BEGWS's wastewater treatment plant is small, processing an average of 0.7 MGD (0.03 m^3/s) of municipal wastewater for approximately 2,500 residents of Bath and surrounding areas [104]. The plant is located within the Chesapeake Bay watershed, and, as with SWIFT, implementation of the Chesapeake Bay TMDL required significant reductions in nutrient discharges from the wastewater treatment plant.

In January 2014, the Village Board approved a $15.5 million bond resolution to support upgrades and improvements, including nutrient removal technology and other renovations to the aging plant [105]. Soon after, Bath hired a new Director for BEGWS. Under the new Director's leadership, the utility began exploring an alternative that would convert the wastewater treatment plant into a "resource recovery hub." The proposal would meet water quality requirements while supporting integration of local resource management (including of municipal wastewater, industrial high-strength organic waste, and energy), increasing local energy resilience, raising revenue, and reducing costs for utility customers [106, 107].

In July 2014, the Bath Municipal Utilities Commission voted to move forward with planning for the resource recovery hub [108], and, in August, BEGWS presented the proposed project to the Village Board and the community [109]. At the time, the proposal was generally well received, gaining strong support from the mayor's office and many village residents.

The proposed resource recovery hub project was ambitious, involving multiple interrelated components. BEGWS would upgrade its wastewater treatment plant with both a biological nutrient removal system based on the widely used Modified-Ludzack Ettinger process and a new chemically enhanced primary settling technology from ClearCove Systems [110–112]. It would construct an anaerobic digester to produce biogas from a combination of municipal sludge, septage, and high-strength organic wastes trucked in from regional food and beverage processors, fueling an internal combustion engine that would co-generate electricity and heat [112, 113]. (BEGWS is not currently an energy producer; instead it makes wholesale purchases and distributes electricity and gas to its customers.) BEGWS would integrate the electricity into a new micro grid with energy storage capabilities and advanced metering instrumentation, increasing local energy resilience and reducing transmission purchases and the possibility of winter power outages (like a significant outage BEGWS experienced in February 2014) [113]. The solids remaining after digestion would be composted and made available for local agricultural use [112]. Finally, some of the plant's treated effluent would be used to irrigate a golf course and suppress dust on local roads, and BEGWS would discharge the remainder through constructed wetlands for additional polishing [111].

A number of concrete steps were taken to move the proposal forward. BEGWS pursued and received a $100,000 grant to support an engineering feasibility study for deploying a community microgrid in April 2015 [114, 115]. For several months in mid-2015, BEGWS piloted the ClearCove treatment technology at its wastewater treatment plant, building on a previous pilot in Ithaca, New York [116]. The Water Research Foundation followed the proposal's progress as a case study during 2015 and 2016 [117].

Although the New York State Department of Environmental Conservation (NYSDEC) was the NPDES permitting authority, regional and national U.S. EPA staff focused on innovation learned of the proposed project and became involved [118, 119]. Interviewees indicated that, beginning in fall 2015, EPA staff tried to facilitate the project, attempting to move it forward in discussions with NYSDEC's Region 8 office and NYSDEC's main wastewater office, which deferred to Region 8. EPA was interested in the Bath proposal because most wastewater treatment plants in United States are small, while most utilities that have adopted innovative technologies to date have been considerably larger and better resourced [118, 119]. If Bath successfully implemented the resource recovery hub concept, it could help clarify pathways to innovation for other small utilities. To support and inform the effort, EPA's Office of Research and Development initiated an environmental life cycle assessment and cost analysis in June 2016 [112, 117, 120, 121]. The analysis results, published a year later, suggested the proposed project would reduce the plant's net nutrient impacts by 25–40%, while estimates of global warming potential, total energy demand, and cost feasibility varied widely, depending on the co-digestion capacity, specific performance of anaerobic digestion, and composting scenarios examined [121].

4.3.2. Key regulatory issues. To implement the proposed project, BEGWS would need NYSDEC's Region 8 office to approve its engineering documents and to revise its existing NPDES permit. We focus here on the former, because the proposal did not reach the NPDES permitting stage. Notably, engineering document approval is not a standard regulatory function under the federal CWA.

New York state law goes beyond the requirements of the federal CWA in requiring permittees who intend to modify their treatment systems to submit an engineering report, plans, and specifications prepared by a New York-licensed professional engineer to the appropriate NYSDEC regional water engineer for review and approval (N.Y. Comp. Codes R. & Regs. tit. 6, § 750–2.10). Approval is warranted when the proposed change is consistent with accepted design standards or, for an "innovative" treatment system outside those design standards, when the permittee's design engineer has demonstrated that the system "will provide adequate, reliable and long-term treatment that complies with permit requirements, without excessive energy consumption or operator attention" [122]. NYSDEC defines an "innovative system" as "any wastewater treatment system that is not in. . .[its] Design Standards [for Intermediate Sized Wastewater Treatment Systems]," including "an entirely new technology, or one that has been accepted for use in other states or countries but is new to New York State, or that has proven effective in a field other than wastewater treatment" [122]. The NYSDEC's main wastewater office is generally deferential to the decisions of its regional offices.

Based on our interviews, it appears that BEGWS initially assumed engineering document approval would be relatively quick and straightforward. After the utility met with the NYSDEC's Region 8 office in October 2014 to present the general concept, it reported that the regulator's initial reaction was favorable, although it was "looking for more detail" [123].

However, as BEGWS provided more detailed engineering information about the project to NYSDEC's Region 8 office, problems arose. A cycle began in which the regulator repeatedly requested revisions and additional information and BEGWS responded, leading to further questions as the regulator remained unsatisfied with BEGWS's responses. In October 2015, the Region 8 office approved the utility's plans for the wastewater treatment plant upgrades targeted at nutrient removal, but not for the plant's conversion to a resource recovery hub [119]. The utility had put forward an ambitious, complex, and multi-faceted project it intended to implement quickly, rather than proposing a phased approach [117] that would have provided both the utility and the regulator with the opportunity to sequentially develop needed technical expertise and a shared information base.

Interviewees described NYSDEC's Region 8 office as interpreting its regulatory role to include protecting small and under-resourced communities, like Bath, from taking on unnecessary risk and expense that could lead to future failure to meet water quality requirements. Some interviewees felt the regulator's interpretation was too expansive.

A key challenge the proposal faced was a chicken-and-egg problem related to funding. Having funding lined up (especially grant funding) would have made BEGWS's proposal more financially feasible, potentially easing NYSDEC Region 8's concerns and making eventual approval of BEGWS's engineering documents more likely. However, in order to apply for key state and federal funding through New York's Clean Water State Revolving Fund, BEGWS needed to submit approvable engineering documents that analyzed technically feasible alternatives based on their life-cycle costs and benefits [124, 125] and selected the alternative "that maximizes the potential for efficient water use, reuse, recapture, and conservation, and energy conservation" taking into account the costs of construction, operation, and maintenance (33 U.S.C. § 1382(b)(13) [126]. (The life cycle assessment and cost analysis EPA began in June 2016 would likely have helped BEGWS satisfy some aspects of this requirement, if BEGWS had continued to pursue to proposal.) NYSDEC's Region 8 office reviewed BEGWS's engineering documents with this context in mind and did not think the ClearCove technology, or the broader proposal, compared favorably to more standard technologies for achieving CWA compliance.

NYSDEC Region 8 staff had a range of concerns about the proposal. Most questions related to the technical and financial feasibility of the complex and potentially risky project for the small utility or to whether the project made financial sense in comparison to available conventional options. According to interviewees, the NYSDEC Region 8 office questioned all of the following:

- the effectiveness and efficiency of ClearCove's process, whether the BEGWS and Ithaca pilots were portrayed accurately, and whether the company had accurately characterized how that technology worked;
- the cost-effectiveness of retrofitting an existing small wastewater plant to incorporate either the ClearCove technology or an anaerobic digester;
- whether sufficient quantities of high-strength organic wastes would be available to support the project (for example, one of the plants BEGWS said it expected to receive waste from was shutting down [127]);
- whether accepting additional waste for energy generation would cause non-compliance with the nutrient limits that provided the impetus for the proposal in the first place;
- whether BEGWS could cost-effectively address biogas impurities to ensure it was useable;
- whether the community's energy costs were high enough to justify the project (on the basis that the community's energy costs were among the lowest in the region, reducing the potential economic benefit of the ClearCove technology);
- whether the golf course would actually accept reclaimed water;
- why engineering documents were submitted without the seal of a New York licensed Professional Engineer; and
- apparent inconsistencies in the assumptions underlying BEGWS's proposed plans.

Finally, NYSDEC Region 8 questioned EPA's interests in supporting the project and how they might differ from the community's interests in pursuing it. For example, if the project went forward but failed to meet water quality requirements or other community needs, it would still provide invaluable lessons for future attempts at innovation at small wastewater treatment plants—and would thus be useful for EPA. However, the community of Bath would be heavily burdened by such failure. First, a corrective project would add to the community's outstanding debt, likely without the benefit of additional state or federal low-interest loans or grants for the same compliance items. Second, Bath could be at risk of penalties for delayed compliance.

Interviewees indicated that staff from NYSDEC's Region 8 office eventually took their concerns about efficacy and cost directly to Bath's mayor. As a result, the mayor withdrew his support for the proposal and urged other Village decision makers to do the same. In May 2016, the Bath Municipal Utilities Commission voted to "stop the Clear Cove Process" [128]. By late June, the Mayor issued a stop-work order on any work not directly related to compliance with nutrient limits under Bath's NPDES permit while the Village Board of Trustees directed a cost comparison of options [129]. In mid-August, the Board voted to scrap the proposal [130]. Several months later, EPA presented its, now largely moot, preliminary environmental life cycle assessment and cost analysis findings to the Municipal Utility Commission [131]. Finally, the Board fired the Director of BEGWS, who had originated the proposal [132].

4.3.3. Perceptions of utility-regulator relationships. Our interviews indicated that the relationship between NYSDEC Region 8 and BEGWS around the resource recovery hub proposal started on a positive note but rapidly deteriorated as the office analyzed the utility's engineering documents, found them inadequate, and was deterred by the perceived risks. Communication problems and a lack of trust between BEGWS and NYSDEC's Region 8 office, as well as between Region 8 and EPA, contributed to the proposal's failure. Several interviewees described the utility as having a history of poor management prior to 2014, which likely fed into this dynamic but was compounded by the utility's attempt to take on "*too much too soon*."

4.4. EBMUD resource recovery/trucked waste program—east bay municipal utility district(CA)

East Bay Municipal Utility District (EBMUD) incrementally developed a resource recovery program at its Main Wastewater Treatment Plant in Oakland, California, where the utility produces more energy than required to operate the wastewater plant through anaerobic co-digestion of organic trucked wastes.

4.4.1. Origin and development. EBMUD provides wastewater services for approximately 740,000 people in the eastern San Francisco Bay Area, treating an average of 63 million gallons of wastewater each day (2.8 m^3/s) [133]. The utility has generated electricity from the biogas its suite of anaerobic digesters produce since the mid-1980s [134]. By the late 1990s, many of the canneries and other industrial food processors that historically operated in the area had closed, leading to a decrease in the quantity and "strength" of wastewater flowing into the plant, and creating significant excess treatment capacity [41, 135]. As of 2000, the plant's 11 digesters were operating at half their design capacity, and EBMUD began to explore how it could employ this unused capacity and bring in new revenue. The utility identified the possibility of accepting organic trucked wastes for co-digestion with its municipal sewage sludge. This would enable it to charge tipping fees, produce more biogas, and increase electricity production, reducing costs for ratepayers.

EBMUD initiated its trucked waste program in 2002, when it built a receiving station for and started accepting hauled septage [135]. The utility then began looking for wastes with higher chemical oxygen demand ("high-strength" wastes) to increase biogas production, and identified strong market potential for accepting fats, oils, and grease (FOG). At that time, the waste haulers that pumped out FOG interceptors for restaurants and other commercial operations had limited options for disposal. EBMUD estimated that low tipping fees for FOG, due to its economies of scale, would make it an attractive option for haulers in the broader region. Initially, haulers simply dumped the material into a manhole near the plant's headworks.

However, this approach caused grease to build up throughout the plant and endangered its primary treatment system. EBMUD was able to work through the problem with extensive engagement from the San Francisco Bay Regional Water Quality Control Board (Regional Board), the primary wastewater permitting agency. As a result, the utility developed a means of routing FOG more directly to its digesters, adding a solid-liquid waste receiving station in 2004 [135].

Whereas EBMUD actively pursued FOG, its acceptance of some types of wastes arose more opportunistically. For example, a waste hauling broker asked if the utility would consider accepting blood waste from a poultry processing facility. EBMUD found that poultry blood was regulated by the California Department of Food and Agriculture (CDFA) and that accepting it would require the utility to get a renderer's license. EBMUD carried out studies to demonstrate that its anaerobic digestion process would provide adequate treatment, addressing both its own and CDFA's concerns about the possibility of infectious disease and the potential for ammonia toxicity in the plant's digesters. Over the course of the studies, the utility ramped up slowly from one truck load every few days to six truck loads per day. Although ammonia increased, the digesters continued to function well.

The volume and composition of EBMUD's trucked waste streams continue to evolve. For example, FOG deliveries to EBMUD peaked in 2008 at approximately 75,000 gallons per day ($3.3x10^{-3}$ m^3/s), most of Northern California's FOG production. As other wastewater utilities began accepting FOG, the amount available to EBMUD decreased [136]. With still more room in its digesters, the utility has continued to explore what other wastes it might accept, evaluating each new type of waste on a case-by-case basis. When EBMUD considers accepting a new material, it generally engages in pilot testing to address any concerns regulators or utility operations staff have about effects on anaerobic digestion, other plant operations, and wastewater effluent quality. This incremental approach to adding new types of waste has helped ensure that, when problems arise, the utility can identify and address the source. As of 2018, more than 20 million gallons ($8x10^4$ m^3) of liquid waste were being brought to the treatment plant each month by approximately 250 haulers in approximately 4,000 truck loads [135, 137]. The trucked waste program currently accepts more than twenty types of liquid waste streams [138, 139]. As we explain below, EBMUD maintains a detailed permitting, tracking, and audit system for these wastes.

In addition to liquid trucked wastes, EBMUD has piloted a solid food waste acceptance program in partnership with several other entities. This program is subject to solid waste regulation by the California Department of Resources Recycling and Recovery (CalRecycle) and related oversight by the Alameda County Public Health Department. Beginning in 2004, EBMUD began to accept small amounts of solid commercial source-separated organics, which are mostly composed of solid food wastes, and conducted small-scale pilots with EPA support under a notification exclusion in state solid waste regulations [41, 135, 136, 140]. After promising initial results, the utility sought to scale up its solid food waste program incrementally. However, it ran into challenges, including the need to remove contaminant metal and glass objects, the need to partner with individual food waste suppliers, and the need to expand its biogas handling facilities to accommodate increased production [135, 136]. As of October 2019, EBMUD was receiving one truckload of commercial source-separated organics each day from the Central Contra Costa Solid Waste Authority [141]. This amount was expected to increase in 2020, following the installation of preprocessing equipment at the transfer station where food waste is prepared for delivery to EBMUD [141]. The state goal to divert 75% of organic waste from landfills by 2025 to help reduce methane emissions, established by state Senate Bill 1383 in 2016 (Cal. Health & Safety Code § 39730.6), makes this an important potential growth area.

The Trucked Waste Program has greatly increased EBMUD's biogas production, and the utility has sought ways to beneficially use as much of the biogas as possible. Most of these efforts have involved engagement with the Bay Area Air Quality Management District around air emissions permitting [142]. By 2008, the facility was producing more biogas than it could use to generate electricity with its three existing internal combustion engines that collectively provide ~6.5 MW of generating capacity [41]. Around 2007, EBMUD explored the possibility of injecting surplus gas into Pacific Gas & Electric's (PG&E's) natural gas pipeline, but at that time the power utility would not allow it due to concerns about corrosion from trace contaminants. In 2012, EBMUD brought a new 4.5 MW gas turbine online, enabling it to produce more energy than it uses (becoming one of the first POTWs in North America to achieve that goal) [135]. It sells the surplus electricity to the Port of Oakland [135] under a power purchase agreement that has helped the Port meet California's renewable energy purchase requirements and reduced costs for EBMUD's ratepayers [39]. In 2014, EBMUD added a FOG / high-strength waste receiving station and blend tanks to ensure a more consistent mix of these wastes and municipal sludge [143] that is less likely to upset the digesters and helps the utility maintain more consistent levels of biogas production [144].

However, continued excess biogas production and declining renewable energy prices have led EBMUD to continue to explore ways to optimize biogas production and use. Despite its expanded electricity generation capacity, as of 2019, EBMUD still needed to flare about 10% of the biogas it produced [145]. Furthermore, the utility projects a broad decline in the price of renewable energy, which will reduce its revenues in the future [145]. EBMUD has considered other options, such as "upgrading" its biogas to enable injection into PG&E's natural gas distribution system or its use as transportation fuel; however, offsite use of the biogas would eliminate an on-site use exemption and subject the facility to more stringent workplace health and safety regulations the utility considers prohibitively expensive [146]. Therefore, EBMUD has opted to focus on identifying ways to smooth out variation in waste deliveries (such as variable tipping fees that are lower on the weekend and higher during the week) to optimize energy generation and reduce the amount of flaring necessary [141, 146].

4.4.2. Key regulatory issues. As EBMUD incrementally accepted an increasing array of organic trucked wastes, and the nature and volume of material it received changed, it connected with the wastewater regulators on a number of issues. Interviewees suggested that some of the utility's earlier program-related regulatory interactions with the Regional Board, such as those associated with FOG-related challenges, were informal and largely occurred without major changes to EBMUD's NPDES permit. Other interactions were more formal. For example, when industry migrated away from the Bay Area, reducing the pollutant load of wastewater flowing into the plant, EBMUD had unused allowable loadings it could accept under its pretreatment program. The utility proposed using a methodology for calculate loadings that would maintain concentration-based local limits for industrial users who contributed pollutants to the plant via EBMUD's sanitary sewer system, while moving to mass-based limits for those contributing higher-strength wastes through its Trucked Waste Program. After discussions with EPA and the Regional Board, EBMUD was allowed to make this atypical change to its pretreatment program, effectively reapportioning excess allowable pollutant loadings to the Trucked Waste Program on a mass basis.

Similarly, the Regional Board has included terms related to EBMUD's Trucked Waste Program in the utility's more recent NPDES permits, namely requirements for the utility to develop and implement Standard Operating Procedures for safely receiving, handling, and processing trucked solid waste. For example, EBMUD's 2015 NPDES permit explicitly required it to "maintain records for a minimum of three years for each load received, describing the hauler, waste type, and quantity received" and to evaluate its Standard Operating

Procedures annually, updating them "as appropriate," and documenting any updates in its annual self-monitoring report [147]. To comply with these requirements and meet its own information needs, EBMUD has established a detailed trucked waste permitting, tracking, and audit system. The system helps ensure that EBMUD staff, regulators, and others understand what enters the plant by truck, and that each waste source complies with applicable pretreatment requirements. The utility tracks every truck that delivers waste, its driver, and its load [135, 138, 139]. For each new waste stream source, the first load is tested for constituents like metals, sulfur, salt, and nitrogen at an onsite laboratory [135, 137]. After this initial testing, EBMUD randomly samples truck loads on an ongoing basis. If it finds a violation, the utility can take informal or formal enforcement actions, including revoking the hauler's permit [138].

Another issue EBMUD faces is the prospect of more stringent future effluent limitations. The utility's Trucked Waste Program has raised the salinity and nutrient concentrations of the effluent it discharges to San Francisco Bay [137]. The excess salt has not been a serious problem to date, and is unlikely to become so, since the Bay is a saline water body (although it could limit alternative uses of the effluent as recycled water) [148]. On the other hand, while San Francisco Bay is not currently considered nutrient impaired, that could change in the near future, leading to the introduction of nutrient limits that EBMUD would be unable to meet with its current treatment capabilities [148]. Therefore, to help major dischargers like EBMUD prepare for this possibility, the Regional Board has issued a watershed-wide nutrient permit requiring them to identify and begin to cost out nutrient removal technologies and other potential solutions [149].

Beyond wastewater regulators and wastewater regulation, EBMUD has interacted with regulators across multiple sectors of regulation in connection with its Trucked Waste Program. We mentioned some of these interactions above. Interviewees emphasized that the resulting array of sometimes duplicative or conflicting regulatory requirements has created challenges for the Program at times, and there is no clear map for utilities to use to navigate regulatory conflicts. However, some aspects of regulatory overlap were successfully resolved. For example: The State Water Resources Control Board and Regional Board worked with EBMUD and CalRecycle over many years to reduce redundant solid waste permitting. Interviewees described EBMUD bringing together staff from these and other regulatory agencies in meetings where "*everybody could hear each other's concerns and work together toward trying to reduce the regulatory burden*." As a result, the Regional Board incorporated relevant solid waste provisions into EBMUD's 2015 NPDES permit and the Standard Operating Procedures referenced in and required by it [147]. Subsequently, CalRecycle adopted similar, broadly applicable regulations that explicitly exempt any POTW accepting solid "anaerobically digestible material" for co-digestion with wastewater from its permitting requirements if it complies with a new standard wastewater permit condition established by the State Water Resources Control Board (Cal. Code Regs. tit. 14, § 17896.6(a)(1)) [150].

EBMUD's interactions with regulators around its trucked waste program have not always gone smoothly. At one point, a disconnect between the utility and EPA on hazardous waste permitting led to an enforcement action. During a 2014 inspection, EPA alleged it found violations of the Resource Conservation and Recovery Act (RCRA) associated with the program [151]. For two years, EBMUD had accepted shipments of low-flash-point ignitable alcohol waste as a feedstock for energy production but lacked the required permit, and some containers of the material were not labeled as hazardous waste [152]. The utility settled the matter in 2015 by agreeing to pay a $99,900 penalty, and EPA reported that EBMUD had "returned to compliance" [151]. At the time, an EBMUD spokesperson contended that the utility had been "following all regulations and keeping all regulators informed, but. . .EPA felt differently" [153].

4.4.3. Perceptions of utility-regulator relationships. Interviewees described interactions between EBMUD and wastewater regulators in generally positive terms. For example, one interviewee described "*a good partnership*" in which "*both the Regional Board and the EPA have been very supportive of the program*" because they understand its specific benefits for the Bay Area, as well its value "*as a model for other utilities*." In the words of another interviewee:"-*Here the regulators are owning the approach to resource recovery. The San Francisco Bay Region is getting national recognition for this program. We're not pushing a rock uphill*." The RCRA compliance issue summarized above was a notable exception.

5. Results of cross-case analysis

5.1. Five characteristics of effective utility-regulator relationships around innovation

The four cases provide a window into how utility-regulator relationships can affect wastewater utilities' adoption of new technologies. Analysis across the cases indicates five characteristics of regulatory relationships that appear to be important for innovation: *clarity*, *capacity building*, *continuity*, *trust*, and *bounded flexibility*. We posit that utility-regulator relationships with these characteristics are more likely to facilitate socially and environmentally beneficial innovation, while relationships that lack some or all of these characteristics could impede innovation. In this section, we describe the five characteristics and how they manifested in each of the case studies. Interrelationships between the characteristics are addressed in Section 5.2. Fig 2 summarizes the characteristics and potential interconnections between them.

5.1.1. Clarity. The four case studies illustrate how regulatory relationships that foster mutual *clarity* about the utility's and regulator's goals and responsibilities can facilitate innovation. While each has obvious roles in protecting public and environmental health, they may interpret these roles (and others) in different ways.

Achieving clarity requires effective utility-regulator communication. One interviewee described the importance of utilities meeting with regulators before deciding whether and how to pursue an innovative project as follows: "*You come in with a concept, sit down with the regulators, and give a high-level overview of what you'd like to do. This allows the regulator to tell you their concerns [and identify] stumbling blocks, [and any] dead-on-arrival issues*."

In three of the cases, utilities and regulators developed mutual understandings of each party's respective goals and responsibilities through their interactions around the project, taking steps to clarify and reinforce their understandings when ambiguity or lack of clarity arose. Consistent with the notion that a written record can increase transparency and support institutional memory, these understandings were often reflected in planning documents, policy guidance, permits, or legislation. In the Tres Rios case, cooperative development of the project over time provided an important avenue for cultivating clarity about project goals and responsibilities. The City of Phoenix worked with wastewater regulators and other local, state, and federal stakeholders to address a suite of clearly identified priorities, including improving water quality, reducing flooding in neighboring communities, and restoring riparian habitat. A demonstration project informed the development of nationwide policy and permitting guidance. These processes helped to elucidate each party's water quality related responsibilities, subsequently informing the NPDES permit updates needed for the full-scale project. In the SWIFT case, the state's role in regulating recharge under the Initiative was initially indirect and poorly defined. HRSD worked with key state regulatory agencies to cultivate clarity throughout project development, seeking extensive input and feedback from VDEQ and VDH. HRSD then

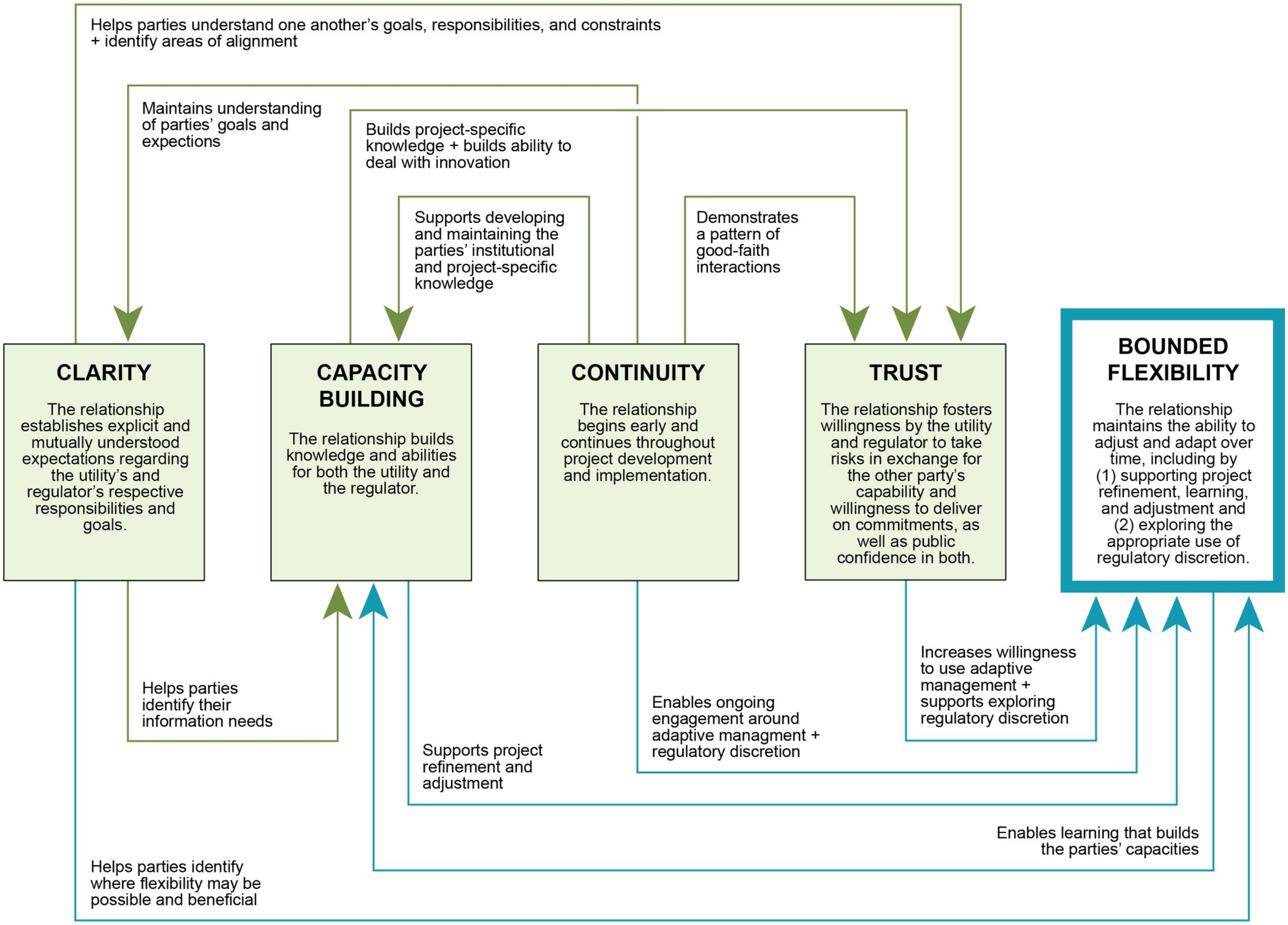

Fig 2. Potential interconnections between the five relationship characteristics. Connections involving *bounded flexibility* are shown in aqua, while other connections are shown in green.

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successfully advocated for new legislation that created and codified a clear state oversight role that was mutually acceptable. In the EBMUD case, the Regional Board consistently conveyed to EBMUD the importance of ensuring that the program does not impair treatment effectiveness or create pollution problems, including by adding a requirement for procedures to ensure the safe acceptance and use of trucked waste to its NPDES permit. EBMUD has, in turn, demonstrated its commitment to effective oversight by establishing a robust formal trucked waste permitting, tracking, and audit system. However, EBMUD was not always on the same page as regulators: differing interpretations of hazardous waste permitting requirements for one of the wastes the utility accepted led EPA to pursue an enforcement action, clarifying the situation for both parties and highlighting for EBMUD the importance of engaging with regulators earlier to make sure requirements are clear.

Clarity largely eluded the parties in the Bath case, who never developed a mutual understanding of their respective roles or the feasibility of the Proposal itself. BEGWS and Region 8 of the NYSDEC had difficulty interpreting one another's motives and expectations. For example, BEGWS initially assumed securing approval of its engineering documents would be relatively quick and straightforward if it communicated to the regulator that it expected the project would meet water quality requirements. However, the regulator—which under state law has approval authority over engineering reports, plans, and specifications—interpreted its role more broadly, adopting a hands-on approach to protect the small, under-resourced community from what it saw as an unnecessarily risky and complex project that could jeopardize water quality. The regulator repeatedly asked questions, requested revisions, and required BEGWS to submit additional information. In the end, the regulator concluded that the utility's responses inadequately addressed its concerns about the proposal's technical and financial feasibility. A Water Research Foundation study concluded that BEGWS lacked clarity about the boundaries between the responsibilities of NYSDEC, the primary wastewater regulator, and EPA, which was not functioning in a regulatory capacity [117]. Although BEGWS gained a better understanding of how NYSDEC Region 8 viewed its role over the course of 2015 and 2016, the parties never saw eye to eye about BEGWS's responsibilities or the feasibility of the proposal. A clearer articulation of state regulatory responsibilities and roles, conveyed through ongoing outreach and engagement to BEGWS and other wastewater utilities, might have helped to align the parties' expectations from the beginning.

5.1.2. Capacity building. The case studies illustrate that building *capacity* to address unconventional technologies is another important aspect of regulatory relationships around innovation. Because innovation is by definition new, both the utility and the regulator need to develop project-specific knowledge, technical competence, and institutional faculty to engage effectively around an innovative project. Building capacity involves both drawing on existing relevant external expertise and developing new internal expertise. Phasing, pilots, and demonstration projects may be particularly effective for building mutual capacity while de-risking new approaches.

Interviewees generally saw capacity building as an important part of innovative projects. For example, many interviewees stressed the critical role of pilot projects and site-specific studies. One described the utility of phasing a project, including "*a pilot effort that would allow any unknown issues to be investigated,. . .of sufficient duration and with monitoring rigorous enough to be able to ascertain whether a full-scale project would be successful*." Another emphasized the importance of adaptive management and the benefits of "*an incremental approach*," noting that, "*although periodically you're going to invest in infrastructure which requires a little bit of a leap,. . .you have to be adaptive. Things don't always work the way you expected in the beginning, so you have to be ready to change over time*."

In three of the four cases, the parties successfully developed needed technical capabilities, filled critical knowledge gaps, and met ongoing information needs. In the Tres Rios case, the required capacity building occurred in two key ways. First, the parties drew on existing external expertise. For example, EPA Region 9 permitting staff engaged with staff from EPA's national wetlands office and consulted the national guidance developed in connection with the project's demonstration phase. Second, the City and EPA explicitly built learning into the project. Experience gained during the demonstration stage helped each develop the knowledge and skills needed to implement and permit the full-scale project. The parties used knowledge gained from extensive monitoring during full-scale operations to improve wetland performance and adjust monitoring requirements over time. Similarly, in the SWIFT case, a phased approach helped build technical capacity and knowledge. Piloting treatment technologies and operating a demonstration facility with extensive monitoring helped the utility and regulators understand impacts on groundwater and helped the utility develop the technical capabilities needed to operate and maintain SWIFT facilities at scale. In the EBMUD case, an incremental approach to testing and accepting new wastes helped utility staff and regulators understand how each type of waste affected treatment processes and enabled them to identify and address problems as they arose.

By contrast, in the Bath case, beyond briefly piloting a new proprietary treatment technology at its wastewater treatment plant, BEGWS did not design its proposal to systematically address information gaps or build needed technical and managerial capacity. By presenting the complex, multi-faceted project concept to the regulator without a phased approach to development and implementation, the small utility missed the opportunity to co-develop technical expertise and a shared information base. Consequently both the utility and the regulator lacked the knowledge and the technical basis for evaluating the full range of potential outcomes of the project, and there was no opportunity to use learning to adapt the project design to mitigate risks and maximize benefits. Without this capacity, the utility could not adequately address the regulator's concerns, and the regulator could not in good faith provide the engineering document approvals needed for the project to go forward. However, this outcome was not necessarily inevitable. Effective technical assistance might have helped address BEGWS's initial capacity limitations, enabling the utility to develop an acceptable proposal—designed to build needed capacities and address critical information needs—in close consultation with regulators.

5.1.3. Continuity. The case studies also indicate that *continuity* in utility-regulator relationships can facilitate innovation. *Continuity* does not require constant interaction, rather it entails interaction of sufficient frequency and substance to support effective engagement around the project. Ideally, engagement will begin early and continue throughout project development, implementation, and operation. Stable staffing that supports ongoing personal relationships between the utility and regulator may be helpful, but is not necessarily essential. In some cases, changing personnel can bring fresh eyes or additional capacity to creative problem solving around difficult issues.

Interviewees in all four case studies expressed the importance of continuity. One utility interviewee framed it as a necessity, urging others to *"interact with regulatory agency staff early and often. If the first time you're talking about an issue with your regulators across the table is when your permit is being renewed, you've already lost."* Other interviewees noted that continuity also helps maintain momentum on multi-year projects for which there will inevitably be some turnover in personnel.

In three of the four cases, utility-regulator relationships demonstrated significant continuity that supported innovation. For the Tres Rios and SWIFT cases, wastewater regulator involvement began in the early stages of project development and continues through the present. Both projects were phased, and each included a prominent demonstration phase, which lasted more than a decade for Tres Rios and has been ongoing since 2018 for SWIFT. In the Tres Rios case, the wastewater compliance and reporting staff at ADEQ that the City of Phoenix interacts with have changed multiple times. To ensure continuity, the City has worked to bring new regulatory staff up to speed on the wetlands and their unique permit requirements. In the EBMUD case, the utility has periodically engaged with the Regional Board as the nature and volume of the trucked wastes it receives has changed incrementally over the years.

In the fourth case, our interviews suggested that BEGWS did not solicit input or feedback from the NYSDEC during early project development. Instead, interviewees implied that the utility initially viewed the regulator's involvement in engineering document approval and related permitting changes primarily as a formality, rather than as a collaborative process through which the project might change and improve with constructive regulator input. Based on our interviews, it appears the utility recognized retrospectively that approaching the Resource Recovery Hub as a phased project, and seeking regulator input at each stage, might have led to a more successful project outcome. At the same time, changing or supplementing the regulatory agency personnel that interacted with BEGWS around the proposal might have facilitated the development of a more collaborative, solution-oriented relationship between the parties.

5.1.4. Trust. A fourth characteristic of utility-regulator relationships that influenced innovation in the case studies is trust, which can be defined as "the willingness to take risks and to be vulnerable to another party in exchange for expected behavior from the other party" [154]. Trust hinges on the expectation that the other party is capable of, and willing to, deliver on its commitments—including protecting public and environmental health—and is enhanced by willingness to work to find mutually beneficial solutions to problems [19]. Trust is not a static feature of a relationship, but one that can ebb and flow, and be earned, fostered, or lost as a result of the parties' behavior [154]. Trust is generally developed and maintained over time [154].

One utility interviewee described the trust dynamic as follows: *"You've got to build trust between the regulator and the regulated community. . ..If you've done something wrong, you need to let them know. We would have been much more challenged to jump into this [innovative project] if we had been at odds with our regulator before this. We probably did operate that way 15 to 20 years ago–took them to court for every permit change. Innovation is great, but you need to build a record of being able to compromise to do something unusual."* Similarly, a regulator interviewee credited "*[t]he collaborative process, the very open process the utility encouraged*," as important factor in creating "*comfort with. . .[that utility's] approach*."

Trust, or its lack, played an important role in all of the case studies. In the Tres Rios case, interviewees described how the City of Phoenix progressively built trust with EPA and ADEQ over many years by soliciting their input and feedback, being straightforward about the challenges it encountered, and developing the information and technical capabilities it needed to support development, implementation, and operation of the Tres Rios project. Multiple interviewees explained that, as a result, both regulators have come to respect and rely on the City's expertise, frequently using it as a resource for other utilities. In the SWIFT case, interviewees recounted how HRSD made a point of gaining the trust of state wastewater and public health regulators, in part by creating a direct regulatory role for them where none previously existed. Initially, that role was informal, with HRSD and EPA's UIC Program soliciting input and feedback from VDEQ and VDH to understand their concerns about the planned injection of large quantities of highly treated wastewater into the Potomac Aquifer System. HRSD's successful pursuit of legislation to formalize the state's role is a remarkable concretization of both trust and clarity—seeking an additional layer of regulatory oversight demonstrates recognition of and dedication to the state's interests in achieving positive outcomes for the range of potentially affected stakeholders. The utility's willingness to initiate extensive monitoring of recharge impacts and plan contingencies for potential problems have also enhanced trust with regulators and the public, as has its openness about temporary setbacks at the SWIFT Research Center. In the EBMUD case, interviewees explained that the utility's robust trucked waste permitting and tracking program, and its honest communication with the Regional Board about the problems it encountered, have increased the regulator's trust in EBMUD. Meanwhile, the efforts of the State Water Resources Control Board and Regional Board to work with CalRecycle to reduce redundant regulation increased the utility's trust in the water quality regulators.

In the Bath case, the parties did not overcome an initial lack of trust. Interviewees expressed regret over the absence of trust and described how it contributed to the proposal's abandonment. NYSDEC Region 8 did not think BEGWS's plans for the Hub were technically or financially sound, that it had the capacity to carry them out, or that, if implemented, the water quality and cost benefits upon which the project was predicated would materialize. Essentially, the regulator did not think BEGWS was capable of delivering on its promises to the regulator or the community. Interviewees suggested that support for the project by EPA's Office of Research and Development did not mitigate this lack of trust or alleviate the state regulator's concerns but, instead, may have increased them, because NYSDEC Region 8 did not think EPA's interests in supporting the project necessarily aligned with the community's interests. Effective technical assistance as part of a more collaborative approach by the state regulator might have helped address BEGWS's capacity limitations and build trust between the parties in their ability to problem solve and adaptively address the proposal's deficiencies together.

5.1.5. Bounded flexibility. Lastly, the case studies illustrate the importance of *bounded flexibility* in supporting innovation. Here *bounded flexibility* refers to two, often interconnected, aspects. The first aspect encompasses initial project refinement based on input and feedback from regulators and others with a stake in the project's success or failure, project design that facilitates learning and adjustment, and effective oversight to ensure that needed adjustments actually occur. This is essentially a form of adaptive management, and is tightly linked to *capacity building*, described in Section 5.1.2.

The second aspect of *bounded flexibility* is exploration of the appropriate use of regulatory discretion to tailor regulatory requirements to reflect the particular risks, benefits, and information needs of the technology at issue—often in support of the adaptive approach described above. We recognize that a key concern with encouraging more collaborative relationships between regulators and regulated entities more generally—and the use of regulatory discretion to further that collaboration in particular—is the potential for regulators to lose sight of the broader public interests they are tasked with protecting while acting to support innovation [155]. Our conception of *bounded flexibility* responds to this concern by keeping the crucial goal and shared responsibility of protecting public and environmental health front and center at all times.

Both regulator and utility manager interviewees described the need to employ available flexibility related to regulatory discretion to support (rather than subvert) water quality protections. As one regulator put it: *"We seek flexibility, if it is available, to make beneficial projects happen. . ..There's the actual law, the Clean Water Act and CFR regulations, then there's. . .policy and practice. . ..As an agency, our goal is to make sure the environment is protected. If it can be protected. . .and other benefits can also be achieved for the discharger,. . . it makes sense to apply flexibility to get all those benefits into the community*." As a utility interviewee explained, while"*[t]he NPDES permit rules are very complex, as are water quality standards,"* by "*working together we felt we could come up with a solution. . .a combination of the permittee and permit writers working on this together to mesh the goals and requirements of each. We needed to work as a group to come up with solutions."* Another spoke favorably about the wastewater regulators they dealt with as more "*practiced*" in "*sitting down, brainstorming, negotiating, and bringing flexibility and innovation to the regulatory process*" than the air quality regulators they had encountered.

In three of the case studies, the first aspect of bounded flexibility had an important role in advancing innovation. In the Tres Rios case, the project was developed and refined in conjunction with regulators and other stakeholders and planned and carried out in stages with extensive monitoring to enable learning and adjustment at each step. Similarly, in the SWIFT case, regulators and other stakeholders informed project development and priority setting, and HRSD is implementing the project in phases—including small-scale treatment pilots and large-scale demonstration of the treatment and injection technology before full-scale implementation. Additionally, the creation of the Potomac Aquifer Recharge Oversight Committee will likely help ensure that future implementation and operations are adjusted as necessary to meet project goals. In the EBMUD case, the utility's incremental acceptance of new wastes and its trucked waste permitting, tracking, and audit program (which responds to an NPDES permit requirement) has created accountability and informed program adjustments.

By contrast, in the Bath case, the proposed project did not build in opportunities for learning and adjustment or facilitate effective oversight and feedback.

In three of the case studies, the second aspect of *bounded flexibility*, associated with the exercise of regulatory discretion, has facilitated innovation. In the Tres Rios case, EPA permitting staff included, a number of unconventional terms and conditions in the City's NPDES permits, reflecting the unique design and role of the Tres Rios Wetlands. These conditions initially included extensive monitoring requirements, which were modified over time to support more targeted learning and adjustment. Additionally, the City advocated for, and EPA eventually allowed, measurement of regulatory compliance at non-traditional locations for some constituents, reflecting the likelihood that their concentrations would increase within the wetland as a result of natural ecosystem process. In the SWIFT case, EPA's UIC program staff and HRSD, in collaboration with VDH and VDEQ, are developing project-specific regulatory limits and monitoring requirements, including for a suite of non-regulatory water quality performance indicators. In the EBMUD case, with the utility's engagement and encouragement, the Regional Board exercised regulatory discretion to fold solid food waste requirements (with CalRecycle's support) into the utility's NPDES permit. It also established a watershed-wide nutrient permit designed to help EBMUD and other San Francisco Bay dischargers prepare for potential future nutrient limits by tasking them with gathering information and exploring possible means of reducing their nutrient discharges before nutrient limits are established. Finally, interviewees explained that the Regional Board and EPA supported EBMUD's atypical proposal to reapportion excess allowable pollutant loading as part of the utility's pretreatment program.

In the SWIFT case, regulatory discretion will likely continue to play an important role as the initiative moves to full scale implementation. When issuing NPDES permits for wastewater treatment plants associated with SWIFT facilities, VDEQ will need to decide whether standard concentration-based effluent limitations or alternative limits (such as mass-based limits) are appropriate for the small and intermittent effluent discharges expected after full-scale implementation. But perhaps more important to the Initiative's near-term viability was EPA's recent decision to exercise its discretion in a non-permitting context. It agreed to support amending HRSD's wet weather consent decree to allow the utility to reprioritize planned spending toward SWIFT implementation, allowing the Initiative to move forward on secure financial footing.

In the Bath case, NYSDEC Region 8 had regulatory discretion, but did not exercise it to facilitate innovation. Instead, the regulator used its discretion around engineering document approval primarily to request revisions and additional information when it did not find the utility's submissions sufficient. Assuming both that the regulator's concerns were valid and the proposal had merit, facilitating technical assistance and sitting down with the utility and technology developer to provide constructive feedback and discuss the potential for project phasing or redesign would have been more supportive of innovation here.

5.2. Synergies and interdependencies between the five characteristics

The five characteristics described above can interact with and reinforce one another (Fig 2). For example, mutual *clarity* about each party's needs and constraints—including what outcomes they are working toward, what responsibilities they have, and what risks they face [47, 156–158]—can develop over time through repeated interactions [21, 56, 159] (*continuity*) and help to foster *trust* in the other party's motives [160], demonstrate where they are in alignment, identify where *bounded flexibility* may be both possible and beneficial, and highlight where *capacity building* is needed. Sustained interactions can help to build *trust* and legitimacy [161]. At the same time, changing or supplementing the personnel involved in regulatory relationships around innovation may be critical to enabling innovation, such as where bringing more experienced personnel supports effective *capacity building* or fresh eyes support creative problem solving around difficult issues.

Relationships characterized by *trust*, *continuity*, and *clarity* about the parties' respective goals and responsibilities can more readily deploy *bounded flexibility* and collectively build *capacity* to adapt to changing conditions, needs, and opportunities.

The Tres Rios and SWIFT cases provide thorough illustrations of these positive synergies in action. In both cases, utilities engaged with regulators beginning early in project development (*continuity*), which enabled the parties to establish a clear understanding of one another's goals, concerns, and responsibilities (*clarity*). To ensure that the projects would meet the parties' respective goals and responsibilities, utilities in both cases included an extended demonstration phase to generate critical information, build technical competence, and foster mutual confidence (cultivating *continuity*, *capacity building*, and *trust*). Results from those demonstration projects have guided project adjustment, planning for full-scale implementation, and the development of permit terms that acknowledge the risks and benefits associated with the project (cultivating appropriate *bounded flexibility*).

Conversely, a deficiency in one characteristic may impair the others, establishing negative feedback loops that undermine the regulatory relationship and prospects for innovation. Such feedbacks can be direct (such as where a utility's lack of relevant technical expertise diminishes the regulator's trust in the utility's ability to successfully implement a new technology). They can also be indirect, such as where the resulting lack of trust makes the regulator less willing to exercise available regulatory discretion needed to enable the technology. The relationship between BEGWS and NYSDEC Region 8 suffered from both direct and indirect negative feedback.

On the other hand, the presence of all five characteristics is not necessarily a precondition for innovation. Inconsistencies or interruptions in one characteristic may be overcome by strong showings in others. For example, although the state's role in regulating recharge through the SWIFT program was initially indirect and unclear, HRSD worked to build *trust* through ongoing engagement with VDEQ and VDH and successfully pushed for legislation to increase *clarity* about that role. In the Tres Rios case, interviewees explained that personnel turnover, especially in regulatory compliance staff, disrupted the *continuity* of their relationships with regulators. However, the impact of these disruptions has been mitigated by the high degree of *trust* the City has developed with both EPA Region 9 and ADEQ as a result of *clarity* about the parties' responsibilities and goals and the development of project-specific and more general capacities over time. Similarly, while there has been intermittent interaction, not constant intense engagement, between EBMUD and the Regional Board over the course of incrementally building out its Trucked Waste Program, the permitting and oversight system EBMUD has developed to track the additional wastes it receives and their effects on POTW operation have given the Regional Board confidence in the Program.

The importance of each characteristic can vary considerably depending on the circumstances. For example, if implementing a new technology would not substantially change the utility's operations or introduce additional risks, flexibility might not be appropriate (as discussed in Section 6.2), and it might not be necessary for the regulator or the utility to build significant new capacity. However, *clarity* and *trust* could play an important role in helping the parties recognize this.

6. Discussion

6.1. Importance of utility-regulator relationships around innovation

The four case studies we examined illustrate the importance of regulatory interactions to innovation. Innovative projects involving new technologies and concepts often, but not always, require utilities and regulators to engage in ways that differ from status quo regulatory interactions. Novel technologies frequently involve different benefits, risks, and information needs than those in common use, especially when a utility intends to transform its system to more holistically address multiple community goals and needs [46]. These differences can impede permitting and other regulatory approvals for innovative projects that would improve social and environmental outcomes. Standard terms and conditions are necessary safeguards in traditional contexts. However, they are rarely geared toward supporting innovative approaches or the iterative, adaptive processes that may be needed to manage risks, maximize benefits, and move efficiently toward full implementation of new technologies. Enabling beneficial innovation may require a fundamental shift in regulatory thinking and flexibility.

The case studies indicate a more collaborative and iterative approach could help to overcome regulatory barriers. *Bounded flexibility* is a key ingredient. Because permits are devices regulators use to translate broadly applicable regulations to specific regulatee's circumstances, they frequently have some discretion in deciding what terms and conditions to include [162]. Regulators can use their discretion to tailor permit requirements to appropriately reflect the specific benefits, risks, and information needs associated with a new technology. Examples of *bounded flexibility* from the case studies include allowing non-traditional locations for measuring compliance with an effluent limitation (Tres Rios), targeting monitoring to address important information needs (Tres Rios, SWIFT, EBMUD), and building in mechanisms for adaptive management (Tres Rios, SWIFT).

Developing tailored requirements often requires more effort on the part of the regulator and more active engagement between the utility and the regulator. As a result, how utilities and regulators approach their interactions will have greater influence on the process of regulation—and how it manifests in substantive regulatory requirements—for an innovative project than for a conventional project, with important implications for the project's outcome. In effect, the heightened importance of regulatory relationships for implementing new technologies makes actively cultivating *clarity*, *capacity building*, *continuity*, *trust*, and *bounded flexibility* more critical for the success of an innovative project.

6.2. Lessons for cultivating more effective regulatory relationships around innovation

Along with providing insights into how utility-regulator relationships can affect the adoption of innovative technologies, the case studies reveal lessons for cultivating the five characteristics. These lessons, synthesized in Table 2, include steps that utilities and regulators can take to contribute to developing regulatory relationships characterized by *clarity*, *capacity building*, *continuity*, *trust*, and *bounded flexibility*. The listed activities and approaches were drawn from interviewee's responses and extrapolated from patterns across the four case studies. They may be useful starting points for utilities and regulators interested in cultivating more effective relationships around innovation.

Additional useful lessons for utility-regulator relationships around innovation might be drawn from other analytical frameworks. Notably, the five characteristics we identify here overlap with themes in the literature on collaborative approaches to environmental governance, including studies that point to the potential value of co-production [163–170] or

Table 2. Lessons from case studies for cultivating effective utility-regulator relationships around innovation, organized by relationship characteristic and party.

Characteristic	#	Lessons for utilities	Lessons for regulators
Clarity (The relationship establishes explicit and mutually understood expectations regarding the utility's and regulator's respective responsibilities and goals.)	Cl-1	Work internally to understand and articulate both general and project-specific responsibilities and goals.	
	Cl-2	Communicate with the regulator (and the public) to clarify the utility's general responsibilities and goals (e.g., protecting public and environmental health through effective utility design, construction, operation, and maintenance; regulatory compliance; providing affordable and effective service; and helping to more effectively and cost-effectively achieve goals).	Communicate with the utility (and the public) to clarify the regulator's general responsibilities and goals (e.g., protecting public and environmental health by effectively regulating utilities; developing and enforcing regulatory requirements that are consistent with those responsibilities; and facilitating socially and environmentally beneficial innovation).
	Cl-3	Communicate with one another (and the public) to clarify responsibilities and goals in the context of the project.	
Capacity building (The relationship builds knowledge and abilities for both the utility and the regulator.)	Cb-1	Assess relevant existing internal and external capacities (including technical expertise and experience).	
	Cb-2	Effectively utilize and leverage existing internal and external capacities.	
	Cb-3	Design the project to develop needed technical competencies and produce salient project-specific knowledge that reduces uncertainties, and meets ongoing information needs.	Design regulatory requirements to require development of needed technical competencies and production of salient project-specific knowledge that reduces uncertainties, and meets ongoing information needs.
	Cb-4	Identify lessons for future interactions, including with other regulators and projects.	Identify lessons for future interactions, including with other utilities and projects.
Continuity (The relationship begins early and continues throughout project development and implementation.)	Cn-1	Begin engagement with the regulator early in project development.	Support engagement with the utility early in project development.
	Cn-2	Engage with the regulator throughout all phases of project development, implementation, and operation.	Engage with the utility throughout all phases of project development, implementation, and operation.
	Cn-3	Maintain continuity of institutional knowledge and relationships across regulatory contexts (e.g., permitting, engineering document approval, compliance assistance, enforcement) and through time.	
Trust (The relationship fosters willingness by the utility and regulator to take risks in exchange for the other party's capability and willingness to deliver on commitments, as well as public confidence in both.)	Tr-1	Demonstrate ongoing commitment to protecting public and environmental health, including by pursuing only projects that are consistent with these responsibilities and maintaining regulatory compliance.	Demonstrate ongoing commitment to working with utilities and the public to support new technology adoption, consistent with meeting public and environmental health protection responsibilities.
	Tr-2	Be open and honest about risks, uncertainties, assumptions, difficulties, and capacity limitations.	Be open and honest about concerns, assumptions, and capacity limitations.
	Tr-3	Proactively work to understand and address regulator and stakeholder concerns about the project.	Proactively work to understand and address stakeholder concerns about the project.
	Tr-4	Demonstrate why the use of regulatory discretion is appropriate and warranted.	Appropriately exercise available regulatory discretion to enable the use of beneficial non-standard technology.
Bounded flexibility (The relationship maintains the ability to adjust and adapt over time, including by (1) supporting project refinement, learning, and adjustment and (2) exploring the appropriate use of regulatory discretion.)	Bf-1	Engage with the regulator early in project development to ask questions and seek input / feedback.	Engage with the utility early in project development to answer questions and provide other input/ feedback.
	Bf-2	Design the project to facilitate learning, refinement, and operational adjustments over time.	Require phased implementation, enhanced monitoring, and other approaches as needed to facilitate project-specific learning, refinement, and operational adjustments.
	Bf-3	Identify how regulatory discretion might be appropriately used to tailor regulatory requirements to reflect the specific risks and benefits associated with the project.	
	Bf-4	Adjust the project over time to ensure it meets regulatory requirements.	Tailor and adjust regulatory requirements to reflect the project's risks and benefits, protect public and environmental health, and support learning to test assumptions, demonstrate efficacy, and reduce uncertainty about technology performance.
	Bf-5	Adaptively manage project implementation and operation.	Adjust regulatory requirements over time, as appropriate, based on new information and lessons learned.

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adaptive co-management [156, 171–173] in environmental decision making. The process of regulation around wastewater innovation, in effect, co-produces that innovation, the knowledge necessary to implement it successfully, and the community services it provides. Future research could elucidate how other actors [174–178]—such as consultants, technology vendors, political decision makers, community members, and environmental and community advocacy organizations—are, or could more usefully be, involved in regulatory relationships and collaboration around innovation.

Analyzing our findings from a regulatory governance perspective might offer further insights. As noted in Section 2, utility-regulator relationships occur within a broader legal, institutional, and normative context. This context includes the regulatory governance system [179] that influences the decisions and actions of both regulators and utilities, and therefore the relationships between them, as they seek to address innovation. Cultivating any or all of the five relationship characteristics we identify here as important for innovation requires a regulatory governance system that creates space for utilities and regulators to take actions like those in Table 2. The specific constraints of the current regulatory governance system, the political economy of regulators within the broader context of society, and societal attitudes towards risk may facilitate or impede effective regulatory relationships. These factors vary from jurisdiction to jurisdiction and can change over time, for example, with shifts in political leadership that drive different approaches to regulation. Future research could examine which state and federal regulatory governance systems best enable utilities and regulators to cultivate the five characteristics in their relationships around innovation, as well as how the internal practices of regulatory agencies and the external constraints upon regulators and utilities (such as legislation) could better support effective regulatory relationships around innovation. Such research should also seek to understand how changes in the political economy of regulation may affect regulatory relationships.

6.3. Broader implications and limitations

6.3.1. Relevance for regulatory relationships outside the context of innovation. Even when a utility is not currently considering innovation, *clarity*, *capacity building*, *continuity*, and *trust* may add value to their regulatory relationships. Cultivating these characteristics can improve commonplace regulatory interactions and help set the stage for success if a utility decides to pursue an innovative project in the future.

Bounded flexibility needs to be exercised carefully and may not be appropriate in most regulatory relationships related to more commonplace technologies and activities. Cultivating flexibility without a clear purpose and need—for example, in the context of commonplace regulatory interactions around established technologies—could have harmful consequences. Other studies have warned that unnecessary flexibility can send mixed signals that "undermine[] regulatees' understanding of rules and the development of shared expectations concerning compliance" [21]. Flexibility without sufficient *clarity*, *capacity building*, *continuity*, and *trust* can create unaccountability.

However, *bounded flexibility* may be appropriate in some contexts involving more traditional technologies. Departing from standard regulatory processes and requirements demands a compelling reason, such as the potential to enable socially and environmentally beneficial innovation while minimizing its risks. *Bounded flexibility* may also be appropriate when considering implementation of wastewater discharge permit requirements in a community with limited financial capabilities or the potential for an integrated plan to more effectively structure implementation of stormwater and wastewater improvements in a community where both are needed [180].

6.3.2. Meeting the needs of small and under-resourced utilities. Individual utilities and regulators can work to cultivate the five characteristics in their regulatory relationships around innovation. However, some will find it much more challenging than others to cultivate adequate levels of *clarity*, *capacity building*, *continuity*, *trust*, and *bounded flexibility*. Small utilities, in particular, may face serious challenges.

Anecdotally, utility size correlates with innovation progress and outcomes in the municipal wastewater sector, and this relationship is reflected in our small sample of four case studies. The three cases of successful or in-progress innovation involved large utilities that each treat more than 50 million gallons of wastewater per day (2 m^3/s) and serve more than 500,000 people (Table 1). In contrast, the utility that abandoned its efforts at innovation treats less than 1 MGD (0.04 m^3/s) and serves only about 2,500 people.

Assuming the apparent relationship between utility size and innovation is real, it is concerning. Most wastewater utilities in the United States are small. Approximately 78% of U.S. POTWs discharge, on average, 1 million or fewer gallons per day (0.04 m^3/s or less) [181]. Many small utilities could more effectively and affordably meet the challenges they face with an integrated response that includes innovative technology. Unfortunately, some of the features that characterized the successful projects we analyzed—such as long project timelines with gradual phasing and extensive onsite pilots and demonstration projects—may not be feasible for small utilities, or for the often small technology companies developing new technologies that may be especially relevant to and accessible for small utilities that lack the economies of scale and broad ratepayer bases many large utilities enjoy.

By taking the lead in cultivating effective regulatory relationships, large, sophisticated wastewater utilities may be able to succeed at innovation even where regulators are initially skeptical of the technology, are uncertain about their own roles and responsibilities, or have rapidly shifting priorities as a result of changes in state or federal political leadership. Small utilities are unlikely to have this option. Instead, resource constraints and capacity limitations may make working with regulators (even enthusiastic regulators) challenging for them.

External support will be necessary to bridge the innovation gap for many small and under-resourced utilities. Bringing beneficial innovation within their reach will require federal and state investment in proactive technical and financial assistance targeted to build critical capacities quickly and efficiently. Additionally, our case studies suggest that developing models for (a) demonstrating whether new technology will meet regulatory requirements without extensive onsite piloting or lengthy phased implementation, (b) targeting monitoring and reporting requirements to meet critical information needs, and (c) effectively providing needed technical and financial assistance would be helpful. Future research in this vein could examine options for shifting the costs and risks of trying new technologies and strategies with significant potential for collective benefit from individual small utilities to the federal government, state governments, and industry collaboratives. If designed as intensive learning opportunities, this kind of risk redistribution could be crucial for building the knowledge and experience needed to streamline future permitting and implementation of similar technologies by other utilities, both small and large.

6.3.3. Providing sector-wide support for effective relationships around innovation. The case studies described here all share a common feature: regulatory processes around innovation are often more complex and challenging and require greater effort and interaction from both utilities and regulators than status quo approaches. However, institutional and individual capacities to engage around innovation vary significantly. For example, larger, better-resourced regulatory agencies may be more prepared to engage around innovation in general, and higher-level individuals within a regulatory agency may feel more confident in their own ability and authority to identify and appropriately exercise available regulatory discretion than individuals at the same agency who perceive themselves as having less authority to make important judgment calls.

Interviewees suggested a number of specific policy actions that would support the development of effective relationships around innovation across the U.S. wastewater sector to help accelerate the implementation of socially and environmentally beneficial new technologies. These actions include:

1. Creating a clear path—and sufficient capacity—for utilities and new technology developers and purveyors to consult with wastewater regulators early in project development;
2. Establishing clear guidance on possibilities and best practices to (a) help regulators develop NPDES permits that appropriately reflect the risks and benefits associated with particular innovative projects and (b) help utilities understand what permitting flexibility exists and when its use might be justified;
3. Developing and offering ongoing trainings [182] to help utilities and regulators understand that guidance;
4. Developing and maintaining explicit avenues for information sharing among and between the utility, regulator, new technology developer and purveyor, and consultant communities; and
5. Targeting coordinated regulatory and funding programs, including proactive outreach and technical assistance, toward meeting the specific needs of small and under-resourced utilities.

As the agency with ultimate responsibility for effectively implementing the federal Clean Water Act and its permitting provisions, the U.S. EPA is the natural choice to lead on most or all of these actions, working in collaboration with state regulators, utilities, and other stakeholders.

Implementing these actions will require funding. Some funding for capacity building at the utility level can come from rate increases or cost-sharing with other entities that stand to gain from multi-benefit innovative projects. However, additional funding will need to come from state- and federal-government investments in building utility and regulator capacity, predicated on the potential benefits to be realized from successful innovation at the project scale and at the national scale as successful innovations diffuse throughout the sector.

7. Conclusion

Our examination of four case studies indicates that effective regulatory relationships are important for successful adoption of new technologies in the U.S. municipal wastewater sector. Innovative projects that involve new technologies often have different benefits, risks, and information needs than those based on common technologies, requiring utilities and regulators to navigate unfamiliar technical, legal, and institutional territory. These differences can impede permitting and other regulatory approvals for innovative projects that would improve social and environmental outcomes. However, a more collaborative and iterative approach could help to overcome regulatory barriers.

We identified five interconnected characteristics of regulatory relationships that appear to facilitate innovation: *clarity*, *capacity building*, *continuity*, *trust*, and *bounded flexibility*. A regulatory relationship demonstrates *clarity* when it establishes explicit and mutually understood expectations regarding the utility's and regulator's respective responsibilities and goals. A relationship that builds knowledge and abilities for both the utility and the regulator demonstrates *capacity building*. A relationship that begins early and continues throughout project development and implementation has *continuity*. *Trust* develops when a relationship fosters willingness by the utility and regulator to take risks in exchange for the other party's capability and willingness to deliver on commitments, as well as public confidence in both. Finally, a regulatory relationship demonstrates *bounded flexibility* if it maintains the ability to adjust and adapt over time, including by (1) supporting project refinement, learning, and adjustment and (2) exploring the appropriate use of regulatory discretion, such as tailoring permit requirements to appropriately reflect the specific benefits, risks, and information needs associated with a new technology. Key examples of the second from the case studies include allowing non-traditional locations for measuring compliance with effluent limitations, targeting monitoring to address important information needs, and building in mechanisms for adaptive management.

All five characteristics appear to play important and mutually reinforcing roles in supporting innovation, however, appropriately applied *bounded flexibility* may be critical for enabling socially and environmentally beneficial innovation. While a deficiency in one characteristic may impair the others, inconsistencies or interruptions in one characteristic may be overcome by strong showings in others. Notably, relationships characterized by *trust*, *continuity*, and *clarity* about the parties' respective goals and responsibilities are more likely to support effective *capacity building* and the appropriate exercise of *bounded flexibility*.

Both utilities and regulators can take responsibility for enabling appropriate implementation of innovative technologies by working to cultivate the five characteristics in their relationships with one another. Table 2 summarizes actionable lessons from the case studies for cultivating effective regulatory relationships around innovation, organized by characteristic and party. Because some parties may find cultivating these characteristics difficult, sector-wide support for effective regulatory relationships will likely be needed to bring beneficial innovation within reach for many wastewater utilities and the communities they serve. Sector-wide needs include clear paths for early consultation on project development, clear guidance coupled with ongoing training opportunities, and explicit avenues for information sharing. Additionally, small and under-resourced utilities may require coordinated regulatory and funding programs that are targeted to meet their specific needs.

Supporting information

S1 Table. Comparison of some Tres Rios Wetlands-related monitoring and compliance requirements in the City's 2010 and 2016 NPDES permits for the 91st Avenue Wastewater Treatment Plant.
(DOCX)

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