2020

Examining the Complex Relationship Between Innovation and Regulation Through a Survey of Wastewater Utility Managers

Luke Sherman
University of California - Berkeley

Alida Cantor
Portland State University, acantor@pdx.edu

Anita Milman
University of Massachusetts

Michael Kiparsky
University of California - Berkeley

Citation Details

Sherman, L., Cantor, A., Milman, A., & Kiparsky, M. (2020). Examining the complex relationship between innovation and regulation through a survey of wastewater utility managers. Journal of Environmental Management, 260, 110025.

Journal of Environmental Management 260 (2020) 110025

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: http://www.elsevier.com/locate/jenvman

Research article

Examining the complex relationship between innovation and regulation through a survey of wastewater utility managers

Luke Sherman [a,b], Alida Cantor [c,a,b], Anita Milman [d], Michael Kiparsky [a,b,*]

[a] Center for Law, Energy & the Environment, UC Berkeley School of Law, United States
[b] NSF Engineering Research Center for Re-Inventing the Nation's Urban Water Infrastructure (ReNUWIt), United States
[c] Department of Geography, Portland State University, United States
[d] Department of Environmental Conservation, University of Massachusetts, Amherst, United States

ARTICLE INFO

Keywords:
Innovation
Regulation
Wastewater
POTW
NPDES
Technology diffusion

ABSTRACT

Despite pressures to increase performance and decrease costs, innovation has been slow to emerge in the municipal wastewater sector. The relationship between regulation and innovation in this sector is a particularly interesting aspect of this conundrum, given the degree to which public utility decision-making is influenced by regulation. Using a national survey, this paper examines US wastewater utility managers' perceptions of how regulation influences the adoption of new technologies. Recognizing that the relationship between innovation and regulation is complex, we develop the concept of regulation as multifaceted and examine three interrelated aspects of regulation: (1) regulatory requirements, (2) regulators and relationships, and (3) the broader regulatory environment. Specifically, we seek to understand whether and in what ways wastewater utility managers perceive these aspects of regulation as hindering or encouraging the adoption of new technologies. We find that, although stringent effluent limitations are perceived to be a moderate barrier to innovation, most survey respondents did not identify weakening them as a way to encourage innovation. Instead, respondents generally identified factors related to regulatory relationships and factors related to the broader regulatory environment as barriers to innovation, and indicated that addressing these aspects of regulation would encourage innovation. We conclude that loosening or tightening regulatory requirements is not the most effective way to promote innovation in the municipal wastewater sector. Rather, those parties with an interest in innovation can focus on helping utilities and regulators build relationships and better navigate the processes that influence decisions about new technologies.

1. Introduction

Growing urban populations, aging infrastructure, and increasing pressure on government budgets at all levels are straining the capacity of urban wastewater treatment systems in the United States (ASCE, 2017; GAO, 2019; Hering et al., 2013; Kiewiet and McCubbins, 2014), and this strain is exacerbated by expectations of improvements in water quality and environmental stewardship (Daigger, 2009; Reeves and Littlehat, 2011; Vidal-Dorsch et al., 2012). To address these challenges, the municipal wastewater sector will need to innovate in the coming years (Carter et al., 2017; Kiparsky et al., 2013; Sedlak, 2014). While innovation in other sectors, including computing, energy, and biotechnology, has dramatically accelerated during the last two decades (Schwab, 2017), technological change in the wastewater sector has been slow (Ajami et al., 2014). This "crisis of innovation" (Thomas and Ford, 2005) is particularly concerning given that key pieces of US environmental law, including the 1972 Clean Water Act (CWA) and its associated regulations, were intended to encourage the adoption of new technologies as a means toward the goal of improved environmental quality (Eisner, 2007; Gerard and Lave, 2005).

In light of this need for the development and adoption of new technologies in the wastewater sector, it is important to develop a better understanding of the barriers that impede innovation. Previous research on innovation in urban wastewater utilities suggests that utility managers identify regulatory compliance as one of several significant barriers to innovation, alongside cost/financing and risk aversion among utility decision-makers (Kiparsky et al., 2016). However, details of the relationship between regulation and innovation in the wastewater sector

* Corresponding author.
E-mail address: kiparsky@berkeley.edu (M. Kiparsky).

https://doi.org/10.1016/j.jenvman.2019.110025
Received 2 March 2019; Received in revised form 10 December 2019; Accepted 21 December 2019
Available online 24 January 2020

remain underexplored.

In the United States, 98% of sewage treatment facilities are publicly owned (EPA, 2002), with the operation of these facilities regulated by state and federal agencies. While an extensive literature evaluates environmental regulation's impacts on private sector innovation (e.g., Ambec et al., 2013; Dechezleprêtre and Sato, 2017; Driesen, 2003; Jaffe and Palmer, 1997), the municipal wastewater sector is distinct in that it is not characterized by strong market incentives (Brubaker, 2002; Wolf, 1979). Instead, a lack of innovation in the sector may be explained by price signals muted through the public utility governance structure, as well as missing incentives for environmental performance that exceed the minimum needed to achieve compliance. Regulation may address these shortcoming in the non-market context through carefully structured policies (Wolf, 1979), or it may exacerbate such failures by favoring incumbent technologies (Stewart, 1981).

In this paper, we focus on understanding the interactions between regulation and innovation in the municipal wastewater sector through a survey of wastewater utility managers. We define innovation in terms of technology diffusion, while acknowledging that other forms of innovation, such as new management practices, are also important in the sector. Recognizing that technology diffusion can be considered an aggregation of individual choices about technology adoption (Sunding and Zilberman, 2001), we examine utility managers' perceptions of how regulation affects decisions about the adoption of new technologies.

To capture the variety of ways in which regulation can influence innovation in the wastewater sector, we consider regulation not as a singular construct, but rather as a complex and multifaceted one that encompasses three major aspects: regulatory requirements, regulators and relationships, and the broader regulatory environment. Our analysis compares utility managers' perspectives on regulation and innovation within and across these different aspects of regulation. This multifaceted framing contributes a deeper and more specific understanding of how utility managers perceive regulation as a barrier to innovation, and ways that regulation might better encourage it. We find that the regulatory barriers and potential solutions identified by wastewater utility managers tend to emphasize the relational aspects of regulation and the regulatory environment, and that utility managers place less emphasis on specific regulatory requirements.

2. Regulation and innovation in the municipal wastewater sector

2.1. Wastewater utility regulation under the Clean Water Act

Since 1972, discharges from U.S. wastewater utilities have been regulated under the federal Clean Water Act (CWA) (33 U.S.C. §§ 1251–1388). The CWA requires that all point sources discharging pollutants to waters of the United States do so only in compliance with a permit under the National Pollutant Discharge Elimination System (NPDES). Municipal wastewater treatment facilities, which the CWA refers to as publicly owned treatment works (POTWs), often discharge treated effluent to rivers, lakes, or other waters of the United States. NPDES permits for these discharges contain a number of elements, including effluent limitations, monitoring and reporting requirements, and other standard or site-specific terms and conditions intended to protect water quality and ensure compliance. NPDES permits usually include two types of effluent limitations for POTWs: generally applicable "technology-based" limits and additional site-specific "water quality-based" limits (EPA, 2010). Technology-based effluent limitations for POTWs around the nation are grounded in the pollutant reductions achievable through secondary treatment processes or equivalent. These technology-based effluent limitations have remained unchanged since 1984, but water quality-based effluent limitations may be more varying and more stringent. NPDES permits are issued for up to 5 years and utilities must reapply at least 180 days before their existing permit expires. Permit requirements are likely to change with each renewal based on facility changes, regulatory efforts to meet water quality standards when receiving waters are impaired, changes to state-designated beneficial uses of receiving waters, changes to effluent limitations related to beneficial uses, and other factors. Most interactions between wastewater utilities and CWA regulators are likely to occur during the NPDES permitting process and, if violations occur, in the context of enforcement actions (see Supplemental Information A for more detailed information on POTW regulation under the NPDES program).

To complement the requirements it imposed, the CWA initially provided significant federal funding for POTW construction and improvement, which contributed to the widespread adoption of secondary treatment processes in the United States (EPA, 2000). However, amendments to the CWA in 1987 greatly reduced the amount of federal funding allocated to POTW construction and capital improvement projects (CBO, 2002). Although limited federal funds are still available, the financial burden has largely shifted to states and local governments, which have since struggled to meet their capital investment needs (Adler et al., 1993; EPA, 2016). In addition, the 1987 CWA amendments effectively ended EPA's Innovative and Alternative Wastewater Treatment Technology program (Environmental Law Institute, 1998).[1] This program provided a higher percentage of federal funding for projects employing innovative technologies, guaranteed federal funds for modification or replacement in the event of a failed innovative technology, and included an aggressive technology transfer program to disseminate information about funded projects (EPA, 1989). The termination of this program may contribute to the slow pace of innovation in the sector.

2.2. Innovation, regulation, and wastewater treatment technologies

Broadly, the CWA is considered to be a technology-forcing statute (Eisner, 2007) intended to "generate the technology needed to achieve acceptable levels of water quality" (Glicksman et al., 2010). Despite the technology-forcing intent and the effectiveness of the CWA in spurring the adoption of secondary treatment in the United States, the relationship between regulation and the diffusion of new technologies in the municipal wastewater sector remains unclear.

Secondary treatment using activated sludge is a technology that has remained largely unchanged in the last 100 years and is still widely used in POTWs (Sheik et al., 2014). Literature on the sustainability of wastewater technologies has emphasized the relative limitations of activated sludge with respect to emissions reductions, resource recovery, and other sustainability criteria (Heidrich et al., 2011; Muga and Mihelcic, 2008). In addition, there are increasing concerns about disinfection byproducts, endocrine disrupting chemicals, and nutrient pollution that are not adequately addressed by the most commonly used clean water technologies (Sedlak, 2014). With regard to nutrient pollution in particular, there are over 150 thousand miles of rivers and nearly 5 million acres of lakes and reservoirs that are considered to be impaired in the United States (EPA, 2011). Addressing these and other emerging issues will require innovation in the wastewater sector (Kiparsky et al., 2013).

In this paper, we recognize wastewater innovation as the use of new and alternative technologies and processes, or the use of existing approaches in contexts where they are not well established (e.g., Environmental Law Institute, 1998). Innovation is thus the combination of an invention that results in a new technology, plus the diffusion of that technology into markets and practice. In this sector, innovations include

[1] The Innovative and Alternative Wastewater Treatment program distinguishes between "innovative" and "alternative" technologies, however we do not make a distinction in this paper. According to EPA (1989), innovative technologies are those that have not been fully-proven for the intended application and alternative technologies as those that contribute to cost savings through resource recovery.

the use of alternative disinfectants, such as ultraviolet light and ozone, as well as various biological nutrient removal processes (Hu et al., 2012; Mezzanotte et al., 2007). Innovation may also include monitoring, software, and information technologies that have the potential to improve operations and efficiency of POTWs (Eggimann et al., 2017) or refer to the increased use of decentralized systems as an emerging paradigm shift for traditionally centralized treatment (Massoud et al., 2009; Sedlak, 2014; van Loosdrecht and Brdjanovic, 2014). Finally, innovative technologies include the use of advanced tertiary treatment techniques, such as reverse osmosis and membrane bioreactors that often accompany water recycling and reuse (Fane et al., 2011).

While the CWA may encourage the diffusion of these technologies, studies examining innovation in the wastewater sector have pointed to regulation as a barrier to the adoption of new technologies (Ajami et al., 2014; Kiparsky et al., 2016). Data from Kiparsky et al. (2016) suggest that wastewater utility managers perceive regulation as a barrier to innovation, but that these managers have diverse perceptions of exactly how regulation affects their ability to innovate. In their discussion of barriers to innovation in the water and wastewater sectors, Ajami et al. (2014) describe several barriers related to regulation, including costs associated with prolonged regulatory approval, the fragmentation between different regulatory agencies, and the need for more flexible regulatory instruments. However, both of these studies address regulation as one of a broader suite of barriers to innovation, and neither focuses specifically on the complex ways in which regulation may interact with technology diffusion.

3. The mixed relationship between regulation and innovation

3.1. Innovation and regulation in the public sector

While most scholarship on the relationship between innovation and regulation has focused on private firms, public utilities have distinct characteristics that impact the innovation-regulation dynamic (e.g., Brubaker, 2002; Markard and Truffer, 2006). In concept, a new environmental control technology may be desirable to a public utility if it abates pollution at lower cost, improves environmental outcomes, or both. Private firms under competition would be expected to seek out these innovations when regulation requires them to internalize environmental costs (Driesen, 2003). Public sector utilities, in the absence of competition and market incentives, may under- or over-invest in new technologies (Wolf, 1979). Public utility managers may, for example, identify with a mission-driven or ethical purpose (Dixit, 2002), leading them to explore the use of socially or environmentally beneficial technologies even in the absence of regulation. Utility managers may also have incentives to avoid innovation, especially to the extent that new technologies carry risk of failure, Managers may be uniquely subject to public exposure, and may prefer to avoid bringing additional visibility to their operations (Rayner et al., 2005). In general, public sector utilities have been characterized as more risk-averse and more inclined to adopt conventional technologies than private sector actors (Rayner et al., 2005; Wagner and Fain, 2018).

Regulation has the potential to push risk-averse decision-makers to consider or adopt new technologies, thereby overcoming their risk-averse behavior (Ambec et al., 2013). However, numerous variables can influence the degree to which regulation encourages or discourages innovation. These include the stringency of regulations, the characteristics of regulatory tools, the degree of uncertainty about future regulatory standards, and even the "style of regulation" (Bernauer et al., 2007; del Río González, 2009; Hemmelskamp et al., 2000; Stewart, 1981). Scholars have also noted that regulation should be sufficiently flexible, minimize uncertainty, and be designed to foster continuous improvement (Ambec et al., 2013; Porter and van der Linde, 1995). In particular, this research has emphasized the importance of stringency and the incentives for innovation that relate to the chosen policy instrument (Hemmelskamp et al., 2000; Kemp et al., 2000; Kemp and Pontoglio, 2011).

Policy instruments can generally be divided into three categories: (1) means standards[2] or technology specifications (often critiqued as deterring innovation through a lack of flexibility); (2) performance standards (generally thought to better encourage innovation via flexibility); and (3) market- or incentive-based programs (conventionally considered to be the most effective instrument for encouraging innovation) (Coglianese and Nash, 2017; Hemmelskamp et al., 2000; Kemp, 1997; Stewart, 1981). However, performance standards based on a particular technology, such as effluent limitations for POTWs based on secondary treatment, may discourage innovation by incentivizing adoption of the incumbent technology underlying the performance standard (Andreen, 2004; Stewart, 1981). Other characteristics of regulation may deter innovation as well, including cumbersome administrative processes, lengthy permitting times, and lack of regulatory agency resources for updating standards (Eisner, 2007; Fiorino, 2006; Ulibarri et al., 2017).

A number of empirical studies have attempted to examine the relationship between regulation and innovation, though most have focused on a private-sector context (Dechezleprêtre and Sato, 2017; Jaffe and Palmer, 1997; Rubashkina et al., 2015). While these studies have found that indeed, regulation has a positive impact on technology diffusion (del Río González, 2009; Horbach, 2015), they often focus primarily on regulatory stringency (for example, by relying on a proxy variable such as pollution abatement costs to represent the stringency of regulation) (Dechezleprêtre and Sato, 2017). However, the focus on regulatory stringency provides a limited understanding of the multifaceted nature of regulation (Brunel and Levinson, 2016). Recognizing this limitation, scholars have called for more research examining how various other aspects of environmental regulation affect innovation (del Río González, 2009; Kemp and Pontoglio, 2011; Rennings, 2000).

3.2. The many facets of utility regulation

To facilitate a more detailed understanding of the relationships between regulation and innovation, we conceptualize regulation as a process with three main aspects: regulatory requirements, regulators and relationships, and the broader regulatory environment (Table 1).

First, regulation involves a number of substantive and procedural *regulatory requirements*. These requirements include any environmental performance standards, technology requirements, incentive-based regulatory programs, or other process-based mandates, as well as related measures to ensure compliance. In the wastewater sector, this primarily consists of the regulation of discharge through a combination of technology-based specifications and environmentally-based performance standards, as well as related monitoring and reporting requirements.

A second and underemphasized aspect of regulation centers on *regulators and relationships* (Willman et al., 2003), the quality and tenor of which can play a significant role in encouraging or discouraging innovation. Public sector actors, in particular, may have narrow priorities that limit the attention given to innovation, but the process of collaborating with other actors may help broaden their view (Sørensen and Torfing, 2011). In this way, regulation can be considered more than just a set of rules; it also involves communication and discourse between regulators and the regulated community (Black, 2002). In the wastewater sector, these relationships primarily involve utility managers and wastewater regulators, but may also include other relevant parties.

Finally, it is important to recognize that regulation does not originate or operate in a vacuum. Instead it is embedded within a broader *regulatory environment*, sometimes referred to as "inter-institutional" and/or

[2] We prefer to use the term "means standard" in lieu of "command and control" although the latter is frequently used. As noted by Coglianese and Nash (2017) the term "command and control" often expresses an implicit policy instrument preference.

Table 1
Aspects of regulation, with descriptions and examples from the wastewater sector.

Aspect	Description	Examples
Regulatory requirements	Requirements established by the CWA and associated regulations or specified in NPDES permits	• Effluent limitations and other performance standards • Monitoring and reporting requirements • Other specific requirements in NPDES permits that regulate treatment facility operations
Regulators and relationships	Individual and institutional characteristics of wastewater regulators and their relationships with the regulated community	• Approach or "style" of individual regulators or institutions • Regulator capacity (funding, knowledge, etc.) • Relationships and communication between regulators and wastewater utility managers
Regulatory environment	The overarching regulatory context within which wastewater utilities operate, encompassing regulation under the CWA and other federal, state, and local laws	• Regulation by multiple regulators and/or regulatory agencies • Requirements associated with multiple areas of regulation (e.g., water quality, air quality, activities that affect endangered species, solid waste disposal, land use) • Uncertainty about future regulatory requirements

"intra-institutional" relations (Baldwin et al., 2012), or simply an "institutional matrix" (Kemp et al., 2000). The regulatory environment may also encompass institutional stability and the costs created by uncertainty. In the wastewater utility context, we examine the interactions between and among various sources of regulation, regulatory mechanisms, and agencies across multiple sectors and scales. We also examine the impact of uncertainty about future regulatory requirements.

Table 1 summarizes these three aspects of regulation through the lens of the municipal wastewater sector. Crucially, these aspects are interrelated and influence one another, such as when relationships between utility managers and regulators affect the content of regulatory requirements. This framework—which may apply to other regulatory contexts as well—contributes a way to consider, and to draw useful distinctions between, several important aspects of regulation. It informed the structure and content of our survey of wastewater utility managers and informs our analysis below (Supplemental Information B).

4. Methods

4.1. Survey development and distribution

To examine perceptions of the relationship between innovation and regulation in the municipal wastewater sector, we developed an online survey and distributed it nationally to wastewater utility managers.[3] The survey targeted utility staff responsible for making decisions about technology adoption at POTWs, usually with titles General Manager, Chief Technical Officer, or similar. The survey began with a gating question to ensure that those responding to the survey were appropriate decision-makers within their organizations.

The survey asked respondents about their perceptions of the relationship between regulation and the adoption of new technologies, mostly using Likert-type questions with the option for open-ended comments. Respondents were first asked about their experience with a variety of innovative treatment technologies and processes so as to evaluate their understanding of the various technologies that may be available. Respondents were then asked about their perceptions of a variety of potential regulatory barriers to the adoption of new technology, as well as the extent to which different potential solutions might encourage the adoption of new technology. Respondents were additionally asked to provide basic information about their utility.

Survey respondents were recruited in several ways. First, we partnered with national industry associations including the National Association of Clean Water Agencies (NACWA), the Water Research Foundation (WRF), and the Water Environment Federation (WEF); and state-level industry associations including the California Association of Sanitation Agencies (CASA) and state and regional chapters of the Water Environment Association (WEA). Leaders of these professional organizations assisted in piloting the survey and provided feedback on survey design, then distributed the surveys to their members via their email lists. Second, we distributed the survey via email to POTWs with listed email addresses in the public Integrated Compliance Information System for NPDES permits (ICIS-NPDES). Third, we mailed postcards with a shortened survey link to POTWs holding major NPDES permits, using the addresses listed in the ICIS-NPDES database. Email is an optional field in the database, but a physical address is a required field. In addition, we followed up with a phone call campaign to target utilities that did not respond to our email outreach efforts. Table 2 summarizes the estimated population and response rate from each of these survey distribution methods. Response rates varied widely by distribution method, with surveys targeting professional organization members receiving a much higher response rate; this variation is congruous with reviews of survey response rates (Baruch and Holtom, 2008). We encouraged recipients of our emails to forward the survey link to others, so it is impossible to know exactly how many people were contacted via email, and the response rates presented Table 2 should be considered estimates.

We received responses from 42 states across all 10 EPA regions (Fig. 1). While our survey has national coverage, limited data in some regions prevents us from resolving regional differences (e.g., Region 2; see Supplemental Information C).

While we acknowledge that our overall response rate is low, we received an adequate response rate from utilities that belong to professional organizations. These utilities tend to be larger and have greater organizational capacity. Respondent data confirm that our sample is heavily biased toward large facilities, with surveyed utilities indicating that they are responsible for sewage treatment services to roughly 35% of the sewer-connected US population (see Supplemental Information C for a more detailed description of respondent characteristics). Because of the low-overall response rate, however, other important biases may exist in the sample population.

Table 2
Response rate from different survey distribution methods. Because duplicates have been removed, the total number of utilities contacted is less than the sum of the column.

	Number of utilities contacted	Number of responses	Estimated response rate
Professional organization members	468	153	33%
NPDES database email list	2,684	97	4%
NPDES database mailing list	3,496	25	0.7%
Total	5,137	275	5%

[3] A second survey with parallel question structure was distributed to regulators of wastewater utilities; the results of this survey and comparison between the two surveyed populations will be discussed in a forthcoming paper.

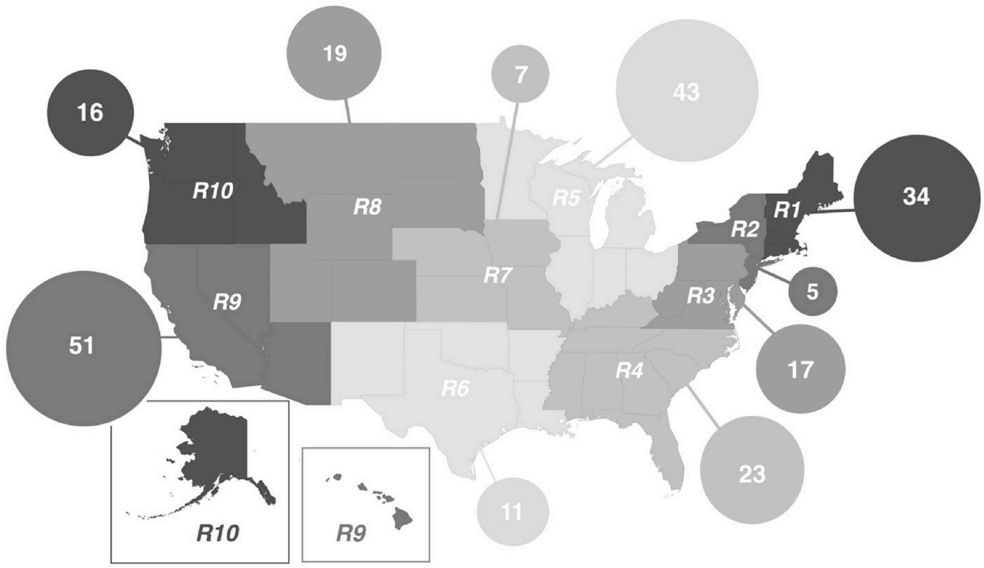

Fig. 1. Respondent distribution by EPA region. The circled number shows the response count from the corresponding EPA region. The area of the circle is proportional to the quantity of responses.

4.2. Survey analysis

Survey respondents were asked to score a list of 25 potential regulatory barriers to innovation and 28 potential opportunities to encourage innovation using a Likert-type scale from 1 to 5, with 1 representing "not a barrier" or "no encouragement" and 5 representing a "very strong barrier" or "very strong encouragement" (Supplemental Information B). We sorted individual Likert-type questions into Likert-scale thematic question groups (Boone and Boone, 2012) that reflect latent constructs revealed by the full set of survey questions. To arrive at these thematic question groups, we used exploratory factor analyses, a common survey analysis method that distills many related survey questions into underlying explanatory factors (Fricker et al., 2012). The factors analyses evaluated how responses to individual questions co-vary with one another in order to identify latent constructs. By definition, latent constructs are only observable indirectly, so we used our professional judgement to assign descriptions to the constructs that reflect the common content of the component questions (Table B-1; Table B-2).

Barriers questions were sorted into seven thematic groups and opportunity questions into eleven thematic groups. Each thematic question group includes between one and four Likert-type questions (Supplemental Information B). We further nested each of the question groups within the three aspects of regulation described in Table 1 or an "Other: Encouraging Pilot Projects" category that we include with potential opportunities. For each thematic question group, we averaged the Likert responses among the component questions to calculate a "barrier score" or "opportunity score" that reflects the relative perceived influence of the construct on innovation.

5. Results and discussion

5.1. Regulation and decisions about technology adoption

Results indicate that regulation is an important factor for utility managers considering new technologies, but are ambiguous as to whether regulation is a net incentive or a net barrier. 76% of wastewater utility managers indicated that concerns about regulatory noncompliance are a strong or very strong influence on their willingness to consider new technologies (4 or 5 Likert response). Despite the strong consensus about regulation's importance, a large plurality of respondents, 45%, indicated that regulation "sometimes discourages and sometimes encourages" innovation. Smaller percentages of respondents fell on one side or the other of this question: 19% of responding utility managers perceived regulation as "slightly" or "strongly" encouraging innovation, while 25% indicated that regulation "slightly" or "strongly" discourages innovation. This observation suggests that the situational context matters and validates the more granular analysis that follows.

5.2. Regulatory barriers to innovation and opportunities to encourage innovation

Utility mangers indicated that the strongest barriers to innovation are found within regulatory relationships and the regulatory environment. Interestingly, the impact of specific regulatory requirements on innovation were seen as more moderate. Out of the seven thematic question groups pertaining to potential barriers (Fig. 2), "uncertainty about future regulations," "regulatory approach," and "regulatory capacity" received the strongest responses. A pairwise statistical comparison of barrier scores suggests that these top three barriers are perceived as similar in priority while "stringency of water quality regulations (too strict)" and "complexities and inconsistencies" form a second tier of similar priority barriers (Supplemental Information D).

When asked about potential opportunities to encourage innovation, utility managers again emphasized the relational and contextual aspects of regulation (Fig. 3). Their responses also suggested strong support for opportunities to expand capacity and mitigate risk. Thematic question groups related to specific regulatory requirements were again perceived as less important than the other two aspects of regulation. Reducing stringency of water quality regulations *and* increasing stringency of water quality regulations were perceived as the lowest priority ways to encourage innovation. A pairwise statistical comparison between opportunity scores suggests that "increasing utility capacity and expanding funding opportunities" and "reducing regulatory risk of pilot projects" are perceived as having similarly high potential for encouraging the adoption of new technologies. A second tier of similar priority opportunities is composed of "improving collaboration between regulators and utilities," "addressing uncertainty about future regulations," and "addressing complexities and inconsistencies" (Supplemental Information D).

Above, we argued that regulation can be framed in a more nuanced

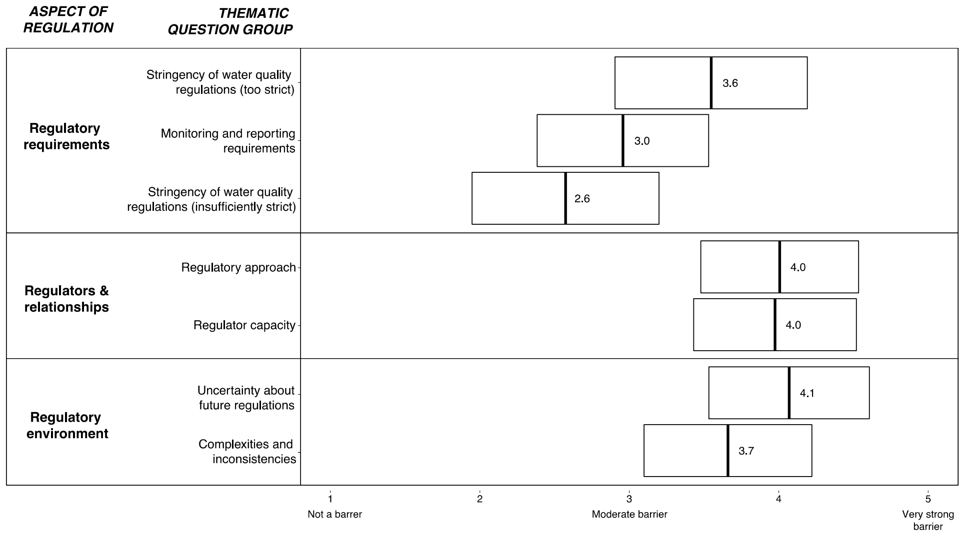

Fig. 2. Perceived regulatory barriers to innovation. The bold vertical line indicates the mean barrier score for the thematic question group, with higher scores indicating stronger perceived barriers; the width of the box illustrates one standard deviation.

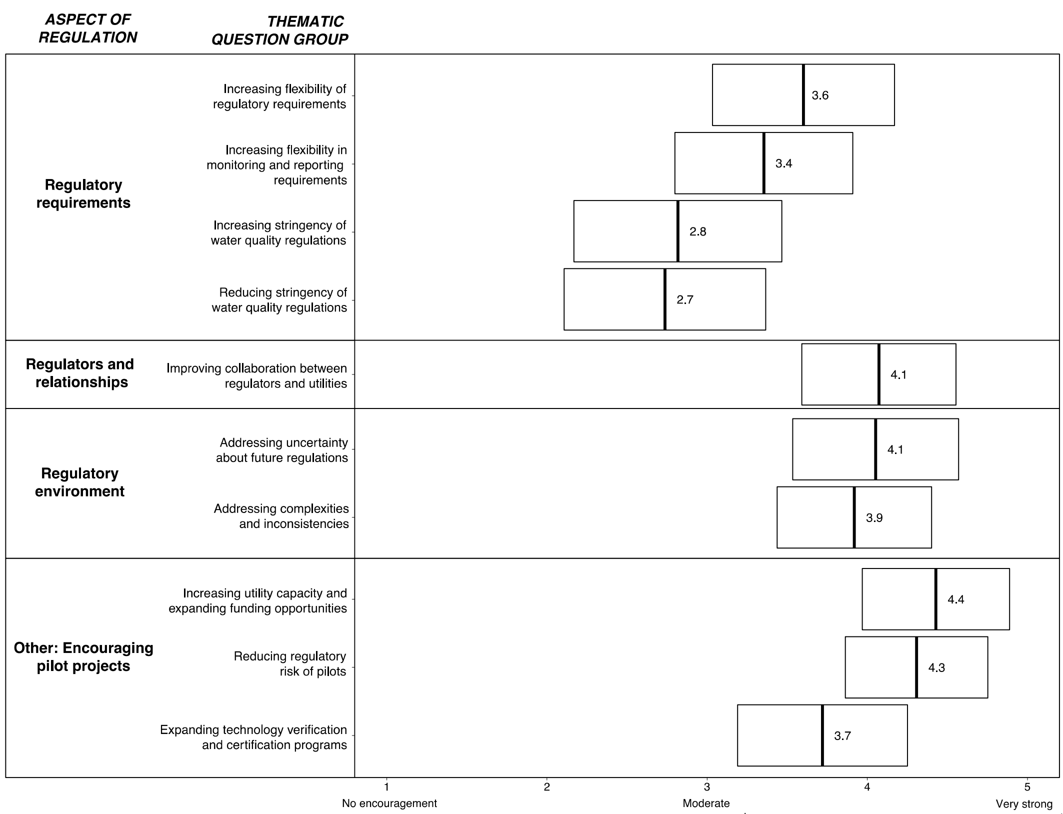

Fig. 3. Perceived regulatory opportunities to encourage innovation. The bold vertical line indicates the mean opportunity score, with higher scores indicating stronger perceived opportunities; the width of the box illustrates one standard deviation.

way. Our findings show that wastewater utility managers view regulation as a strong influence on technology decisions, but do not emphasize regulatory stringency. Instead, utility managers highlight other aspects of the regulatory process. This provides evidence in support of our proposed conceptual model of regulation and demonstrates the need to expand assumptions in both the academic literature and practical discussions about how to understand various aspects of regulation (e.g., Brunel and Levinson, 2016).

5.3. Regulatory requirements

While regulatory requirements where not emphasized by utility managers, understanding how utilities view these requirements can provide insights on utility behavior in the non-market context. Survey questions about regulatory requirements discussed particular terms and parameters associated with the CWA and the NPDES permit system.

5.3.1. Stringency of regulatory requirements

Utility managers in our survey did not indicate that they see reducing stringency of water quality regulation as an important factor for encouraging the use of new technology. While a considerable number of utility managers described overly stringent regulations as a barrier (Fig. 4, left side), it was perceived as only a moderate barrier compared to others (Fig. 2). Moreover, respondents did not indicate that reducing stringency of regulations would encourage innovation. In fact, of all proposed opportunities to encourage innovation, "less stringent regulation of water quality" was the single lowest scoring question (Fig. 4, right side), scoring lower than "more stringent regulation of water quality" as a potential way to encourage innovation (see Fig. 3).

These moderate views on stringency affirm that utilities should not be understood to behave like private firms under regulation. Under a neoclassical economic model, private firms are generally understood to be intent on limiting costs and, to that end, are expected to push for the relaxation of regulatory standards (Gerard and Lave, 2005; Harford, 1978). Utilities may be motivated by efforts to keep rates low and thus be similarly focused on costs. Instead, our finding is consistent with the notion that public utilities have a broader set of considerations. In particular, this may support the idea that utility managers are intrinsically motivated agents (Dixit, 2002; Georgellis et al., 2010) that, as one respondent put it, view themselves as "allies in protecting the environment." In the non-market context, however, this raises questions about whether utilities might behave in a risk-averse, or other non-optimal manner, that constrains the innovation process (Brown and Osborne, 2013; Lyon, 1990).

Open-ended survey data provided additional context for these views. Respondents indicated that increased stringency can encourage the adoption of new technology by mandating improved performance, but this push is tempered by the realities of limited flexibility and resources. In these cases, capacity forms a crucial barrier to innovation, pushing utilities to select "older, proven technologies" that are more likely to receive straightforward regulatory approval. Since effluent limitations are based in part on the performance of conventional technologies, limited utility capacity may further result in the under-exploration of innovative alternatives.

5.3.2. Regulatory flexibility

Utility managers emphasized the opportunity to increase the flexibility of regulatory requirements rather than the relax their stringency. 58% of utility managers indicated that increased flexibility in how effluent limitations are expressed in permits would strongly or very strongly encourage the employment of new technology (4 or 5 Likert response), compared to only 24% who gave the same response with regard to reducing regulatory stringency.

In open-ended questions, survey respondents clarified that strict "NPDES compliance schedules" and "rigidity in compliance standards" may stand in the way of innovation. For example, utility managers referenced how loading limits are expressed (instantaneous, daily, weekly, monthly, etc.), with utility managers emphasizing that shorter measurement intervals may create a greater risk of being non-compliant. Several respondents also emphasized that innovative technical approaches take time to become effective and that more relaxed ramp up periods may be necessary to allow management strategies to adapt to new processes. More rigid compliance schedules or shorter measurement intervals may or may not be demonstrably beneficial for aquatic ecosystems, however, and allowing additional flexibility when public health and ecosystems are not at risk may be an effective method for encouraging the use of new technologies.

These perceptions raise potentially interesting arguments for changing approaches to permitting. However, the extent to which increasing flexibility in permit terms, parameters, and compliance schedules is legal and consistent with CWA is well beyond the scope of this paper, as is the evaluation of any tradeoffs inherent in the alterations of permit terms.

In addition to the above discussion of flexibility in permit terms, respondents also see the lack of flexibility of regulators and agencies themselves as a barrier. To describe the perceived flexibility or rigidity in the regulators approach or "style" (del Río González, 2009; Hemmelskamp et al., 2000), respondents used phrases such as "wonderful to work with" or by contrast an "enforcer of rules instead of partners" to describe the perceived flexibility or rigidity in the regulatory approach. While related to flexibility of specific permit terms, the "lack of flexibility of regulators" elicited a much stronger response from utility

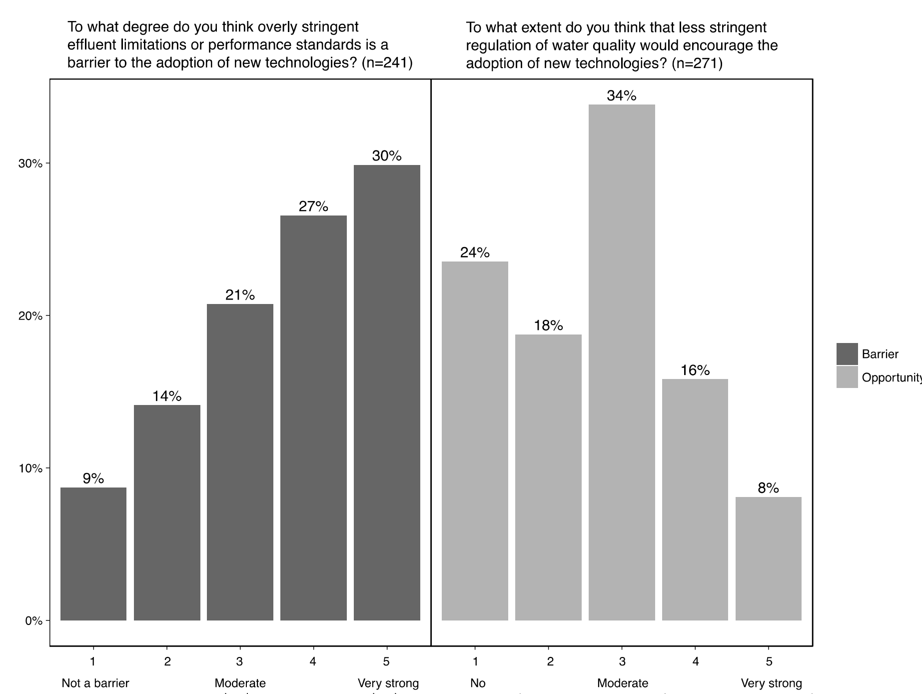

Fig. 4. Response distributions for questions about the extent to which overly stringent regulation is a barrier and how less stringent regulations would encourage innovation.

managers: 77% of utility managers indicated that the lack of flexibility of regulators is a strong or very strong barrier to the adoption of new technology (4 or 5 Likert response).

While flexibility of *regulators* was perceived as a strong barrier, opportunities associated with the flexibility of *specific regulatory tools* elicited a more moderate response, especially as compared to other proposed opportunities (see Fig. 3). Much of the literature on regulation and innovation has emphasized the necessity of sufficiently flexible regulatory instruments as a means toward promoting innovation (Ajami et al., 2014; Ambec et al., 2013; Environmental Law Institute, 1998; Jaffe and Palmer, 1997). Our survey of utility manager perceptions supports this literature but adds a key nuance: the lack of flexibility of regulators and regulatory agencies is perceived as distinct from, and potentially more important, than flexibility as it relates to specific NPDES permit requirements. This supports the notion that if regulatory change intends to spur innovation, the concept of flexible regulation should be extended so as to include both the capacity and behavior of individual regulators and the approach of regulatory agencies (Freeman and Farber, 2005). This also points to the broader importance and significance of relationships between regulators and the regulated community.

5.4. Regulators and relationships

Utility managers viewed the relationship between the regulator and the regulated entity as one of the greatest potential opportunities to encourage innovation. Yet, for regulators to engage effectively with proponents of innovative technology they require considerable capacity to evaluate the underlying science and engineering, and consider any tradeoffs.

Wastewater managers recognize that regulators as individuals are an important part of the regulatory process. But, crucially, they also recognize the practical limitations regulators face as they evaluate the potential applicability and unique needs of new technologies. Respondents identified regulator capacity (including funds, time, and staff) and knowledge of unconventional technologies as among the strongest barriers. In addition, communication and collaboration were recognized as essential: 79% of respondents indicated that "improved communication between regulators and utilities" would strongly or very strongly encourage the adoption of new technology (4 or 5 Likert response).

Innovation has been described as a process led by an individual decision-maker modulated by a complex market and information system that includes regulation as a component (Kemp et al., 2000). Broadly, we find support for this characterization of innovation, but also the perspective that the regulator him or herself may be considered a second essential decision-maker and collaborator within the innovation process and network (e.g., Black, 2002; Sørensen and Torfing, 2011). This notion was supported by the open-ended responses:

> It isn't about regulation, it's about developing relationships with the person responsible for your permit and working through them to achieve end goals.

In addition, utility managers identified other information networks as important and effective ways to promote technology diffusion. Along with utility-regulator collaboration, utilities recognized collaboration amongst utilities (utility-utility collaboration) and collaboration amongst regulators (regulator-regulator collaboration) as similarly high priority opportunities to encourage innovation (see Supplemental Information B). Technology transfer efforts that expand information networks among and between these groups, such as those emphasized by EPA's former Innovative and Alternative Wastewater Treatment program (EPA, 1989), may thus deserve revisiting.

While recent literature has highlighted that the potential benefits of increased collaboration should be tempered by realities including limited capacity (Porter and Birdi, 2018), improving communication and collaboration within and between communities of regulators and utilities was unequivocally identified by utility managers as an important strategy to promote the use of new technologies.

5.5. Regulatory environment

The regulatory environment was also viewed as more important to innovation than regulatory stringency and other specific regulatory requirements. In this section, we focus on complexities and inconsistencies across various areas of regulation and examine uncertainty about future regulations. We note that non-water quality regulations may be especially relevant within the context of innovation, as many new technologies emphasize resource recovery and multi-sector benefits.

5.5.1. Complexities and inconsistencies

Although utility managers perceive the context of navigating multiple agencies' requirements and regulations to be a barrier to the adoption of new technologies (Fig. 2), no one area of regulation was perceived as a particularly strong barrier. Fig. 5 shows utility manager responses to questions about the extent to which various statutes and corresponding regulations encourage or discourage the adoption of new technologies—although not all utilities may be subject to each of these areas of regulation.

Water quality regulations and water recycling regulation were considered more of an incentive to adopt new technologies than a barrier, while Endangered Species Act regulations, land use regulations, and general environmental review slightly discouraged utility consideration of new technologies on average (Supplemental Information B). However, almost every one of these questions was met with a neutral response by a plurality of utility mangers.

Because utility managers do not perceive any *specific* set of regulations to be a strong barrier, we conclude no single area of regulation stands out as the primary barrier associated with the multiagency context. Rather, utility managers may view the cumulative effect of layers of regulation as the principle obstacle. This finding confirms that of other studies that have identified the complexity of the multiagency context as a challenge to the efficiency of environmental permitting processes (e.g., Ulibarri et al., 2017). In order to address these barriers, utility managers expressed considerable agreement that better coordination—both between agencies at local, state, and federal scales, and between various sectors of regulation—would encourage innovation (Supplemental Information B).

5.5.2. Uncertainty about future regulations

Uncertainty about future regulations was perceived as a top priority barrier to innovation, and increasing regulatory certainty an opportunity to address this barrier. 73% of respondents indicated that uncertainty about future regulations was a strong or very strong barrier (4 or 5 Likert response), while just 9% of utility managers indicated that this was a slight or non-barrier (1 or 2 Likert response). In open-ended comments, survey respondents clarified that when utility managers discuss uncertainty about future regulations, they are predominately thinking about the lifespan of their capital investments and the potential return on those investments. Indeed, a large percentage (73%) of respondents indicated that increasing certainty across 5-year permit cycles to allow payoff of financial investment would strongly or very strongly encourage the adoption of new technologies (4 or 5 Likert response). Utility managers emphasized that changing discharge requirements in 5-year intervals does not align with the need to make long term capital investments, which often require multiple years of planning and construction with multi-decade infrastructure lifespans. As one respondent explained:

> We are being encouraged by regulators to voluntarily construct nitrogen reducing treatment processes, but we have no guidance on

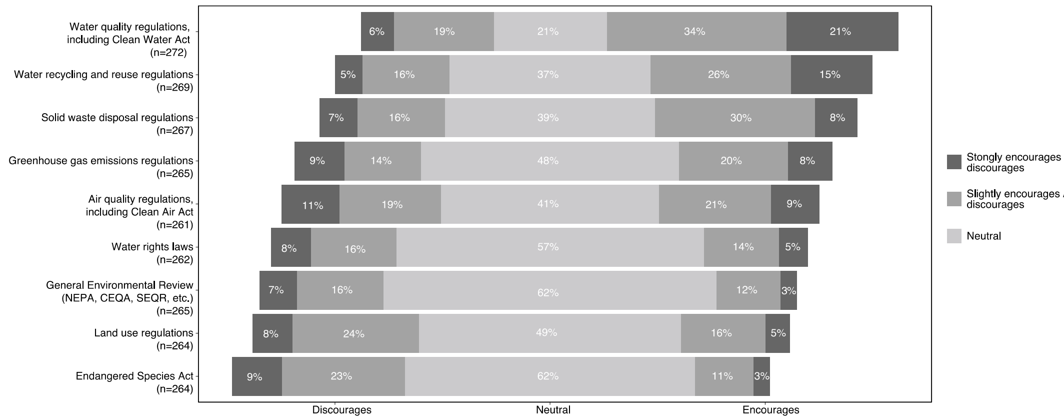

Fig. 5. Response distributions for the bipolar scale survey question: "To what extent do you think that each of the following areas of regulation encourages or discourages the adoption of new technologies?"

what future limits will be, thereby risking either over-spending or having to go back in the future and build additional treatment units.

The respondent suggests that, while the regulators have provided informal encouragement for the adoption of nutrient reduction processes, those are not a replacement for the certainty of formal standards. Since the adoption of new technologies comes with its own set of risks, further uncertainty about whether those technologies will meet future regulatory requirements may discourage their adoption.

In open-ended comments, respondents repeatedly referred to regulatory "assurances" as a potential way to address uncertainty about future regulations. To the extent that these assurances imply advance decisions about permits, they are likely to be legally untenable, although an examination of their legality is outside the scope of this paper. Additionally, as a practical matter, there are reasons the regulatory context is not static. For example, future changes in receiving water quality standards needed to protect water uses may necessitate changes in effluent limitations or other NPDES permit terms in ways that regulators are not able to predict, or at liberty to speculate on. Nevertheless, it is clear that utility managers view uncertainty as a strong barrier to innovation and that one potential solution may lie in stronger working relationships between utilities and regulators. More frequent and substantive communications between regulators and utility managers could help clarify regulators' goals and thinking. While this will never result in future regulatory certainty, it may be an opportunity to substantially mitigate uncertainty. In effect, greater communication could function as a qualitative risk sharing measure between the regulated and regulator communities (see Section 5.4).

5.6. *Encouraging pilot projects*

Some of our survey questions related to opportunities to encourage the use of pilot projects and did not fit well into our three aspects of regulation (Table 1). Unsurprisingly, utility managers indicated that the single best way to encourage the use of new technology is via additional grants, loans, and other sources of funding for pilot projects. Given the risk that utility managers face when attempting new technology deployment, funding can help create protected spaces for innovation (Kemp et al., 1998) and enable greater risk-taking among potential innovators in the face of well-established incumbent technologies.

Along with increased funding, the reduction of regulatory risk was also perceived as an important opportunity to encourage pilot projects. Risk reduction may encompass a variety of mechanisms, and utility managers emphasized in open-ended comments that leniency with regards to enforcement would encourage pilot projects. Respondents also mentioned the potential for the use of NPDES permit "variances as a tool to promote innovation." In this context, respondents additionally highlighted concerns about the potential for citizen suits when trying new technologies, which may result in utility liability even in a situation where a regulator has elected not to pursue an enforcement action (e.g., Lund, 2000; Supplemental Information A). While utility managers tended to agree that greater risk sharing by regulators would increase the utilities' willingness to run pilots, when and how such risk redistribution would be appropriate and compliant with the CWA is outside the scope of our analysis. That said, the perception of its benefits with regard to running pilots was clearly conveyed.

Lastly, utility managers responded that technology verification and certification programs would offer an opportunity to encourage the adoption of new technology. One respondent simply requested that EPA offer a list of emerging technologies that it recommends for various applications on a periodic basis along with an explanation of why EPA believes the technology could be beneficial. The expansion of these types of programs may also be helpful to capacity-limited NPDES permit writers (as discussed in Section 5.4), with the caveat that one size fits all solutions or even plug and play technical approaches will be unusual for wastewater treatment.

6. Conclusions

Regulation often describes a specific set of rules with which organizations must comply. Past empirical attempts to test how regulation affects innovation have relied on problematic attempts to measure the stringency of those rules (Dechezleprêtre and Sato, 2017; Kemp and Pontoglio, 2011). Our study contributes to a broader understanding of regulation and suggests that future attempts to assess the relationship between regulation and innovation, especially in the public sector, should consider regulation as a multidimensional concept which encompasses far more than regulatory stringency (Brunel and Levinson, 2016).

As we have discussed, regulation can alternatively be defined in a relational way, focusing on the processes of communication and the relationships between regulators and the regulated community (Black, 2002). Regulation can also describe the broader regulatory context that includes multiple agencies and other institutional factors, termed the regulatory environment or "institutional matrix" (Kemp et al., 2000). This research details the distinctions between these three aspects of regulation, with relevant findings for those seeking to encourage innovation in the wastewater treatment sector in particular, as well as for scholarship on innovation and regulation more broadly.

While a plurality of wastewater utility managers emphasize that regulation sometimes functions as a barrier to innovation, the survey showed that utility managers do not identify specific regulatory requirements, and the stringency of those requirements, as the primary obstacle in considering new technologies. Instead, utility managers viewed barriers and opportunities related to relationships with regulators, as well as those related to the broader regulatory context, as more important. Utility managers noted that taking steps to address uncertainties about future regulations and providing guidance through the process of navigating complexities and inconsistencies may help to encourage the adoption of new technologies. In addition, utility managers suggested that the regulator's approach, communication, and capacity were barriers to the adoption of new technologies, and that improved communication, collaboration, and increased flexibility are important opportunities to encourage innovation.

We stress that regulatory flexibility can take a variety of forms: in particular, utility managers emphasized flexibility of the regulatory approach taken by individual regulators and regulatory agencies. This may imply that a utility manager's perception of a regulator as an "enforcer of rules" serves as a greater deterrent to innovation than an effluent parameter's specific compliance schedule. At the same time, these negative perceptions about the regulatory approach or "style of regulation" may be connected to specific legal requirements that cannot be circumvented (Gerard and Lave, 2005).

In practical terms, our research suggests that encouraging innovation can best be supported through the expansion of funding and capacity support for both utilities *and* regulators. Increased capacity in both communities could support more frequent and substantive interactions between utility managers and regulators. Except to the extent that funding is codified, our data do not suggest that legislative efforts to amend the CWA and its affiliated regulations are an effective way to encourage innovation.

Future research should more closely examine regional differences in the perception of barriers and opportunities as well as consider the unique challenges that may face small wastewater utilities. In addition, future scholarship should more closely examine how regulatory relationships vary between local, state, and federal decision-makers as well as within and among regulatory agencies responsible for different areas of regulation. We also note that states and municipalities vary in their fiscal environment and, while we did not collect detailed information about POTW funding sources, this may have a considerable impact on investment decisions. Finally, we emphasize that open-ended responses alluded to the rich potential for future case study research in this sector, which has the potential to illuminate the ways in which specific laws and regulations function to promote or stifle the adoption of certain new technologies.

To conclude, we argue that incentivizing innovation is about more than just the loosening or tightening of regulatory standards. Based on these findings, we emphasize that regulation should be understood as more than just the black-letter text contained in statutes and permit requirements. To encourage innovation, regulation should be effectively supported with resources, knowledge, capacity, and programs geared towards supporting innovation and navigating the relational and contextual barriers to taking risks. Such efforts will not follow automatically as the result of written regulatory rules, but rather will require deliberate, thoughtful action and coordination by a range of decision-makers and stakeholders from the regulated and regulator communities alike.

Credit statement

Luke Sherman: Investigation, Data Curation, Writing – Original Draft, Writing – Review & Editing, Visualization **Alida Cantor:** Methodology, Investigation, Writing – Original Draft, Writing – Review & Editing **Anita Milman:** Conceptualization, Methodology, Writing – Review & Editing, Supervision **Michael Kiparsky:** Conceptualization, Investigation, Writing – Review & Editing, Supervision, Project Administration, Funding Acquisition.

Declaration of competing interest

None.

Acknowledgements

We thank Dave Smith, David Sedlak, and Jamie Marincola for useful conceptual discussions and guidance throughout the research process. Nell Green Nylen provided insights that strengthened the paper. Christine Keough provided capable assistance with R coding and data analysis. Haley Hayashi, Madison Burson, and Ishvaku Vashishtha also provided useful research assistance. We additionally thank Bill Eisenstein, Louise Mozingo, and Holly Doremus for helpful contributions to this project and the National Association of Clean Water Agencies (NACWA), the Water Research Foundation (WRF), the Water Environment Federation (WEF), the California Association of Sanitation Agencies (CASA), and state and regional chapters of the Water Environment Association (WEA) for assistance in piloting and distributing the survey. We also acknowledge Kevin Hardy, Jeff Moeller, Roger Peters, Adam Link, and anonymous peers for reviewing this manuscript and providing helpful feedback. This research was funded by US Environmental Protection Agency grant EPR91601-0001 through Paradigm Environmental, Inc and National Science Foundation Grant 28139880-50542-C to the ReNUWIt Engineering Research Center.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2019.110025.

References

U.S.C. §§ 1251–1388.
Adler, R.W., Landman, J.C., Cameron, D.M., 1993. The Clean Water Act 20 Years Later. Island Press, Washington, DC.
Ajami, N.K., Thompson Jr., B.H., Victor, D.G., 2014. The Path to Water Innovation. The Brookings Institution.
Ambec, S., Cohen, M.A., Elgie, S., Lanoie, P., 2013. The Porter hypothesis at 20: can environmental regulation enhance innovation and competitiveness? Rev. Environ. Econ. Policy 7, 2–22. https://doi.org/10.1093/reep/res016.
Andreen, W.L., 2004. Water quality today - has the clean water Act been a success? Alabama Law Review 55, 537–593.
ASCE, 2017. 2017 Wastewater Infrastructure Report Card.
Baldwin, R., Cave, M., Lodge, M., 2012. Understanding Regulation : Theory, Strategy, and Practice. Oxford University Press, New York.
Baruch, Y., Holtom, B.C., 2008. Survey response rate levels and trends in organizational research. Hum. Relat. 61, 1139–1160. https://doi.org/10.1177/0018726708094863.
Bernauer, T., Engel, S., Kammerer, D., Sejas Nogareda, J., 2007. Explaining green innovation – ten years after porter's win-win proposition: How to study the effects of environmental regulation? Polit. Vierteljahresschr. 39, 323–341.
Black, J., 2002. Regulatory conversations. J. Law Soc. 29, 163–196. https://doi.org/10.1111/1467-6478.00215.
Boone, H.N.J., Boone, D.A., 2012. Analyzing likert data. J. Ext. 50.
Brown, L., Osborne, S.P., 2013. Risk and innovation. Public Manag. Rev. 15, 186–208. https://doi.org/10.1080/14719037.2012.707681.
Brubaker, E., 2002. Liquid Assets: Privatizing and Regulating Canada's Water Utilities. University of Toronto Press, Toronto.
Brunel, C., Levinson, A., 2016. Measuring the stringency of environmental regulations. Rev. Environ. Econ. Policy 10, 47–67. https://doi.org/10.1093/reep/rev019.
Carter, J., Foresman, J., Brown, T., Darr, M., 2017. Fostering Innovation within Water Utilities.
CBO, 2002. Future Investment in Drinking Water and Wastewater Infrastructure.
Coglianese, C., Nash, J., 2017. The law of the test : Performance-based regulation and diesel emissions control. Yale J. Regul. 34.
Daigger, G.T., 2009. Evolving urban water and residuals management paradigms: water reclamation and reuse, decentralization, and resource recovery. Water Environ. Res. 81, 809–823.
Dechezleprêtre, A., Sato, M., 2017. The impacts of environmental regulations on competitiveness. Rev. Environ. Econ. Policy 11, 183–206. https://doi.org/10.1093/reep/rex013.
del Río González, P., 2009. The empirical analysis of the determinants for environmental technological change: a research agenda. Ecol. Econ. 68, 861–878. https://doi.org/10.1016/J.ECOLECON.2008.07.004.
Dixit, A., 2002. Incentives and organizations in the public sector: an interpretative review. J. Hum. Resour. 37, 696. https://doi.org/10.2307/3069614.

Driesen, D.M., 2003. Economic Dynamics of Environmental Law. MIT Press, Cambridge, Massachusetts.

Eggimann, S., Mutzner, L., Wani, O., Schneider, M.Y., Spuhler, D., Moy de Vitry, M., Beutler, P., Maurer, M., 2017. The potential of knowing more: a review of data-driven urban water management. Environ. Sci. Technol. 51, 2538–2553. https://doi.org/10.1021/acs.est.6b04267.

Eisner, M.A., 2007. Governing the Environment: the Transformation of Environmental Regulation. Lynne Rienner Publishers, Boulder.

EPA, 1989. Effectiveness of the Innovative and Alternative Wastewater Treatment Technology Program.

EPA, 2000. Progress in Water Quality: an Evaluation of the National Investment in Municipal Wastewater Treatment.

EPA, 2002. The Clean Water and Drinking Water Infrastructure Gap Analysis.

EPA, 2010. NPDES Permit Writers' Manual.

EPA, 2011. Waters assessed as impaired due to nutrient-related causes. https://www.epa.gov/nutrient-policy-data/waters-assessed-impaired-due-nutrient-related-causes. (Accessed 30 May 2019).

EPA, 2016. Clean Watersheds Needs Survey 2012.

Fane, A.G., Tang, C.Y., Wang, R., 2011. Membrane technology for water: microfiltration, ultrafiltration, nanofiltration, and reverse osmosis. Treatise Water Sci. 301–335. https://doi.org/10.1016/B978-0-444-53199-5.00091-9.

Fiorino, D.J., 2006. The New Environmental Regulation. Mit Press, Cambridge, Massachusetts.

Freeman, J., Farber, D., 2005. Modular environmental regulation. Duke Law J. 54, 795–912.

Fricker, R.D.J., Kulzy, W.W., Appleget, J.A., 2012. From data to information: using factor Analysis with survey data. Phalanx 45, 30–34.

GAO, 2019. The Nation's Fiscal Health: Action Is Needed to Address the Federal Government's Fiscal Future.

Georgellis, Y., Iossa, E., Tabvuma, V., 2010. Crowding out intrinsic motivation in the public sector. J. Public Adm. Res. Theory 21, 473–493. https://doi.org/10.1093/jopart/muq073.

Gerard, D., Lave, L.B., 2005. Implementing technology-forcing policies: the 1970 Clean Air Act Amendments and the introduction of advanced automotive emissions controls in the United States. Technol. Forecast. Soc. Chang. 72, 761–778. https://doi.org/10.1016/j.techfore.2004.08.003.

Glicksman, R.L., Batzel, M.R., Glicksman, R.L., Batzel, M.R., 2010. Science, politics, law, and the arc of the clean water Act: the role of assumptions in the adoption of a pollution control landmark. Wash. Univ. J. Law Policy 32, 100–138.

Harford, J.D., 1978. Firm behavior under imperfectly enforceable pollution standards and taxes. J. Environ. Econ. Manag. 5, 26–43. https://doi.org/10.1016/0095-0696(78)90003-7.

Heidrich, E.S., Curtis, T.P., Dolfing, J., 2011. Determination of the internal chemical energy of wastewater. Environ. Sci. Technol. 45, 827–832. https://doi.org/10.1021/es103058w.

Hemmelskamp, J., Rennings, K., Leone, F., 2000. Innovation-oriented Environmental Regulation: Theoretical Approaches and Empirical Analysis. Springer-Verlag, Berlin.

Hering, J.G., Waite, T.D., Luthy, R.G., Drewes, J.E., Sedlak, D.L., 2013. A changing framework for urban water systems. Environ. Sci. Technol. 47, 10721–10726. https://doi.org/10.1021/es4007096.

Horbach, J., 2015. The role of environmental policy for eco-innovation: theoretical background and empirical results for different countries. In: Crespi, F., Quatraro, F. (Eds.), The Economics of Knowledge, Innovation and Systemic Technology Policy. Routledge, New York, pp. 348–360.

Hu, Z., Houweling, D., Dold, P., 2012. Biological nutrient removal in municipal wastewater treatment: new directions in sustainability. J. Environ. Eng. 138, 307–317. https://doi.org/10.1061/(ASCE)EE.1943-7870.0000462.

Jaffe, A.B., Palmer, K., 1997. Environmental regulation and innovation: a panel data study. Rev. Econ. Stat. 79, 610–619.

Kemp, R., 1997. Environmental Policy and Technical Change : A Comparison of the Technological Impact of Policy Instruments. Edward Elgar, The Hague.

Kemp, R., Pontoglio, S., 2011. The innovation effects of environmental policy instruments — a typical case of the blind men and the elephant? Ecol. Econ. 72, 28–36. https://doi.org/10.1016/J.ECOLECON.2011.09.014.

Kemp, R., Schot, J., Hoogma, R., 1998. Regime shifts to sustainability through processes of niche formation: the approach of strategic niche management. Technol. Anal. Strateg. Manag. 10, 175–198. https://doi.org/10.1080/09537329808524310.

Kemp, R., Smith, K., Becher, G., 2000. How should we study the relationship between environmental regulation and innovation? In: Hemmelskamp, J., Rennings, K., Leone, F. (Eds.), Innovation-Oriented Environmental Regulation. Springer, pp. 43–66.

Kiewiet, D.R., McCubbins, M.D., 2014. State and local government finance: the new fiscal ice age. Annu. Rev. Pol. Sci. 17, 105–122. https://doi.org/10.1146/annurev-polisci-100711-135250.

Kiparsky, M., Sedlak, D.L., Thompson, B.H., Truffer, B., 2013. The innovation deficit in urban water: the need for an integrated perspective on institutions, organizations, and technology. Environ. Eng. Sci. 30, 395–408. https://doi.org/10.1089/ees.2012.0427.

Kiparsky, M., Thompson, B.H., Binz, C., Sedlak, D.L., Tummers, L., Truffer, B., 2016. Barriers to innovation in urban wastewater utilities: attitudes of managers in California. Environ. Manag. 57, 1204–1216. https://doi.org/10.1007/s00267-016-0685-3.

Environmental Law Institute, 1998. Barriers to Environmental Technology Innovation and Use.

Lund, L.C., 2000. Project XL: good for the environment, good for business, good for communities. Environ. Law Rep. 30, 10140–10153.

Lyon, R.M., 1990. Regulating bureaucratic polluters. Public Financ. Q. 18, 198–220. https://doi.org/10.1177/109114219001800204.

Markard, J., Truffer, B., 2006. Innovation processes in large technical systems: market liberalization as a driver for radical change? Res. Policy 35, 609–625. https://doi.org/10.1016/J.RESPOL.2006.02.008.

Massoud, M.A., Tarhini, A., Nasr, J.A., 2009. Decentralized approaches to wastewater treatment and management: applicability in developing countries. J. Environ. Manag. 90, 652–659. https://doi.org/10.1016/j.jenvman.2008.07.001.

Mezzanotte, V., Antonelli, M., Citterio, S., Nurizzo, C., 2007. Wastewater disinfection alternatives: chlorine, ozone, peracetic acid, and UV light. Water Environ. Res. 79, 2373–2379. https://doi.org/10.2175/106143007X183763.

Muga, H.E., Mihelcic, J.R., 2008. Sustainability of wastewater treatment technologies. J. Environ. Manag. 88, 437–447. https://doi.org/10.1016/J.JENVMAN.2007.03.008.

Porter, J.J., Birdi, K., 2018. 22 reasons why collaborations fail: lessons from water innovation research. Environ. Sci. Policy 89, 100–108. https://doi.org/10.1016/j.envsci.2018.07.004.

Porter, M.E., van der Linde, C., 1995. Toward a new conception of the environment-competitiveness relationship. J. Econ. Perspect. 9, 97–118. https://doi.org/10.1257/jep.9.4.97.

Rayner, S., Lach, D., Ingram, H., 2005. Weather forecasts are for wimps: why water resource managers do not use climate forecasts. Clim. Change 69, 197–227. https://doi.org/10.1007/s10584-005-3148-z.

Reeves, S., Littlehat, P., 2011. Microconstituents: what to expect in your permit. Proc. Water Environ. Fed 2251–2266. https://doi.org/10.2175/193864710798159282, 2010.

Rennings, K., 2000. Redefining innovation — eco-innovation research and the contribution from ecological economics. Ecol. Econ. 32, 319–332. https://doi.org/10.1016/S0921-8009(99)00112-3.

Rubashkina, Y., Galeotti, M., Verdolini, E., 2015. Environmental regulation and competitiveness: empirical evidence on the porter hypothesis from European manufacturing sectors. Energy Policy 83, 288–300. https://doi.org/10.1016/j.enpol.2015.02.014.

Schwab, K., 2017. The Fourth Industrial Revolution. Crown Publishing Group, New York.

Sedlak, D., 2014. Water 4.0: the Past, Present, and Future of the World's Most Vital Resource. Yale University Press.

Sheik, A.R., Muller, E.E.L., Wilmes, P., 2014. A hundred years of activated sludge: time for a rethink. Front. Microbiol. 5, 47. https://doi.org/10.3389/fmicb.2014.00047.

Sørensen, E., Torfing, J., 2011. Enhancing collaborative innovation in the public sector. Adm. Soc. 43, 842–868. https://doi.org/10.1177/0095399711418768.

Stewart, R.B., 1981. Regulation, innovation, and administrative law: a conceptual framework. Calif. Law Rev. 69, 1256–1377.

Sunding, D., Zilberman, D., 2001. Chapter 4 the agricultural innovation process: research and technology adoption in a changing agricultural sector. Handb. Agric. Econ. https://doi.org/10.1016/S1574-0072(01)10007-1.

Thomas, D.A., Ford, R.R., 2005. The Crisis of Innovation in Water and Wastewater. Edward Elgar Publishing, London.

Ulibarri, N., Cain, B.E., Ajami, N.K., 2017. A framework for building efficient environmental permitting processes. Sustain. 9, 180. https://doi.org/10.3390/su9020180.

van Loosdrecht, M.C.M., Brdjanovic, D., 2014. Water treatment. Anticipating the next century of wastewater treatment. Science 344, 1452–1453. https://doi.org/10.1126/science.1255183.

Vidal-Dorsch, D.E., Bay, S.M., Maruya, K., Snyder, S.A., Trenholm, R.A., Vanderford, B.J., 2012. Contaminants of emerging concern in municipal wastewater effluents and marine receiving water. Environ. Toxicol. Chem. 31, 2674–2682. https://doi.org/10.1002/etc.2004.

Wagner, B., Fain, N., 2018. Regulatory influences on innovation in the public sector: the role of regulatory regimes. Public Manag. Rev. 20, 1205–1227. https://doi.org/10.1080/14719037.2017.1350282.

Willman, P., Coen, D., Currie, D., Siner, M., 2003. The evolution of regulatory relationships; regulatory institutions and firm behaviour in privatized industries. Ind. Corp. Chang. 12, 69–89. https://doi.org/10.1093/icc/12.1.69.

Wolf, C.J., 1979. A theory of nonmarket failure: framework for implementation analysis. J. Law Econ. https://doi.org/10.2307/725215.