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Research article

A formal model concerning policy strategies to build public acceptance of potable water reuse

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ABSTRACT

Water stress is an increasing burden in regions with arid climates, aquifer vulnerability, and erratic rainfall. Population growth and competing domestic, industrial, and agricultural uses are also stretching the capacity of water supply systems. Beyond groundwater extraction, surface water overuse, and inter-basin transfers, governments are exploring alternative sources amidst looming supply threats. These alternatives include desalination, greywater recycling, and reclaimed or recycled wastewater. The latter, also known as water reuse with varying levels of treatment, has been applied for irrigation, street cleaning, industrial processes, and groundwater recharge. However, reused water for potable purposes has seen limited uptake, due in part to lack of public acceptance. This article examines the dynamics of public acceptance for potable water reuse. The article's theoretical contribution is a formal mathematical model for understanding public acceptance of water reuse. The model conceptualizes how governments, water utilities and the public interact to facilitate or hinder acceptance of water supply sources, including potable reuse. The article concludes by applying the model to cases of water reuse in Windhoek, Namibia, and Singapore.

1. Introduction

Limited access to safe and affordable potable water threatens human health and economic development, particularly in developing countries. An estimated 780 million people around the world lack such access, 2.5 billion lack access to adequate sanitation, and millions are afflicted with preventable waterborne diseases (CDC, 2016). With growing challenges such as erratic weather patterns and competition over scarce water supply, many governments are struggling to maintain supply service and quality levels while facing limited institutional and fiscal capacity. Moreover, water challenges are not isolated to developing countries. While most developed countries have built systems to support high standards of water quality and supply reliability, maintaining this standard is increasingly costly and risky given the uncertainty of climate-change impacts and the resistance of water consumers to change their usage behavior.

Water reuse for both potable and non-potable uses has been used to address water scarcity, with numerous projects undertaken in the past three decades (for a summary of such projects in the United States, see EPA (2017)). By providing an additional source to enhance supply redundancy and stability, water reuse has the potential to support public health efforts while reducing the negative environmental impacts of over-extraction from natural sources (e.g. surface and groundwater). Various reuse technologies have existed for decades, and advancements in the science of purification have reduced both the complexity and costs of treatment. Water reuse is thus recognized in scientific circles and increasingly by water utilities as a source of clean, safe, and reliable water for residential, industrial, and agricultural purposes.

Despite these benefits, there remain social and political barriers to the adoption of potable reuse, including concerns about chemicals and pathogens (Hosler et al., 2015) and social stigma (i.e. the "yuck" factor). While the academic literature has thoroughly examined these issues, there remains a dearth of formal mathematical models to support systematic and rigorous research about the interplay among information, public perception, and political support concerning alternative water sources. This article introduces a formal mathematical model to theoretically illustrate policy strategies for building public acceptance to water reuse, with particular reference to the role of information and communication. The article also addresses challenges faced by governments in encouraging popular support for water reuse (hereafter, "reuse" refers to potable water).

The study's contribution to theory is an analytical model around

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which empirical studies can be framed, and its contribution to practice is a suite of theoretically-supported initiatives around which governments can build water reuse information campaigns. From a broader perspective, the article focuses on an increasingly urgent environmental issue borne of growing water demand and reducing certainty about supply reliability. The article is therefore part of a growing body of literature about resource conservation and the role of governments in meeting collectively agreed sustainability targets outlined in the Paris Agreement, UN Sustainable Development Goals, and others.

The article first provides a brief review of literature addressing the cognitive dynamics of public acceptance and their relationship to knowledge dissemination, including the identification of an appropriate theoretical lens. It then presents a model that conceptualizes the relationship between government and the public, and how this relationship influences acceptance and adoption of water reuse. A policy implications section describes how the model provides guidance about information and communication strategies for increasing public acceptance. The model is then applied to cases of water reuse in Windhoek, Namibia, and Singapore. The conclusion outlines limitations and issues a call for further research about the mechanisms through which public perceptions of water reuse are shaped.

2. Literature review

This review focuses on findings about government-circulated information and the relationship between the public, governments, and water utilities. It also includes a brief overview of theories. The cognitive and contextual determinants of public acceptance for and opposition to water reuse have been robustly explored by the literature and are outside the scope of this review. The current state of the literature is summarized usefully by Fielding et al. (2018) in a review that finds, among other things, a consistently positive relationship between acceptance and dissemination of information (e.g. about recycling processes, safety, and benefits). The authors observe this pattern across differing research methodologies, including studies based on case analyses and experiments. Structural equation modeling (SEM) has also been employed to examine such relationships, producing findings that are relevant to the methods and analysis in this article. For example, Hurlimann et al. (2008) find communication by and public trust in water utilities to be a significant determinant of consumer satisfaction with water reuse programs, while Ross et al. (2014) find that a community's shared identity with water utilities regarding recycled water schemes was dependent on consultative exchange and information-sharing, ultimately improving trust in a way that lowered perceptions of risk and raised levels of acceptance. Trust in government was found to exert influence on attitudes, and thereby intended consumption behavior, in an SEM-based study of water reuse in Australia (Leviston et al., 2006). Trust (in both science and government) was likewise identified as a determinant of public acceptance of various water sources, including reuse, stormwater, and desalination, in an Australian case (Fielding et al., 2015).

There is less consensus about the role of information as a determinant of water reuse acceptance. De Franca Doria et al. (2005) find that external information is a relatively weak predictor of public acceptance. However, a South Africa-based study conducted by Adewumi et al. (2014) find that knowledge about the advantages of water reuse and trust in suppliers (utilities) predicted respondents' intention to accept water reuse for both domestic and non-domestic purposes, with knowledge having the highest path coefficient of all determinants among domestic-use respondents. By using SEM, studies such as those above have been able to identify the types of latent variables that are often difficult to measure in socio-political contexts. Their findings largely confirm those of non-SEM-based and qualitative studies.

Experimental research has also been valuable in identifying determinants of public acceptance, particularly with reference to information and communication. According to Fielding et al. (2018, p. 18), "experimental or field studies comparing informed and non-informed participants conclude that providing factual information about recycled water increases knowledge about, and acceptance of, recycled water." The authors argue that further experimental research is needed to identify causal relationships between knowledge and acceptance, and to understand varying dynamics across user group types. Examples of experiment-based research are numerous, but a comprehensive review is beyond the scope of this study (see Fielding et al., 2018 for additional summaries). Nevertheless, two studies are directly relevant to this article and deserve mention. In an experiment involving 1,000 Australian citizens, Dolnicar et al. (2010) find a positive association between information provision and likelihood of use for both desalinated and recycled water; the authors argue that factual information should be prioritized by governments over campaigns based on persuasion. This is of particular importance when considering the role of information and the competition over narratives between government and utilities on one hand and interest groups or water reuse skeptics on the other. In a survey-based study, Dolnicar and Schäfer (2006) find varying public perceptions about determinants of quality, health, and risk between desalinated and recycled water, with higher cognitive reservations about the safety of recycled water. The study is useful in identifying trends among dimensions of knowledge as measured by science-related statements; statements about which respondents exhibited lower levels of understanding (e.g. those addressing environmental impacts, energy consumption, and contribution to systemic resilience) provide guidance about which topics public officials may consider when crafting communications and knowledge-sharing strategies.

The importance of information and communication is confirmed in numerous theoretical and empirical studies about public perception and the legitimacy of water reuse programs (see: Hui and Cain, 2018; Harris-Lovett et al., 2015; Fielding and Roiko, 2014; Hartley, 2006; Christen, 2005). The focus on communication as a catalyst for public acceptance emerges from what Fielding et al. (2018) describe as the "information-deficit approach" (p. 17); the authors find that the literature on water reuse exhibits a broad consensus that knowledge and acceptance have a positive relationship. Nevertheless, Kemp et al. (2012) find that effective communication does not necessarily inoculate the public against the support-dampening effects of anti-reuse "scare" campaigns, with a strong recency effect observed for the process of influencing perceptions. Lack of knowledge about sources of water, implying a weak communication effort, has been shown to negatively affect levels of acceptance of *de facto* water reuse (Rice et al., 2016). Examples of knowledge-sharing from the government-to-public perspective are numerous, but those in the reverse (public-to-government) are scarcer. Beecher et al. (2005) employ risk communication theory in emphasizing the importance of two-way communication between the public and water authorities, recognizing that the public possesses useful knowledge regarding waste management in general; the authors argue that "sharing control of the research process with diverse stakeholders can make research more focused, relevant, and widely understood" (p. 122). The importance of public-to-government communication for water reuse programs is likewise underscored in a study by Gibson and Burton (2014) of governments' information gathering approaches, stated-preference questions, and the influence of latent attitudes on interpreting both. Indeed, such two-way exchange of information is acknowledged in the literature as a means to build public trust of government institutions more generally (Gil-Garcia et al., 2014; Hong, 2013; Torres, 2007; Hartley, 2006).

Finally, it is necessary to acknowledge the need to situate this study within a broader theoretical frame. Various theories have been deployed to examine consumer behavior related to water reuse (e.g. moral foundations theory (Wester et al., 2015)) and pro-environmental behavior more broadly (e.g. appraisal theory (Bissing-Olson et al., 2016), altruism, empathy, and social cognition (Schultz, 2002), and cognitive stress theory (Homburg and Stolberg, 2006)). Turaga et al. (2010) and

Stern, (2000) provide useful overviews of theories examining pro-environmental behavior. Much scholarship about environmental behavior in general (Cordano and Frieze, 2000) and water reuse specifically (Nancarrow et al., 2009) references or extends Ajzen's (1985) theory of planned behavior – a theory holding that human behavior is a direct function of intention as informed by attitudes, subjective norms, and perceived behavioral control. The behavioral variables used for this study's model are derived largely with Ajzen's theory under consideration.

A search for literature employing formal theoretical or mathematical modeling returned no studies that focused specifically on establishing a conceptual or mathematically conceptualized basis for understanding the relationship between public policy and public acceptance of water reuse. The practical problem is that the absence of such a model gives practitioners little theoretical support for investing in water reuse. The model in this article aims to generate a novel platform for more rigorous empirical studies by focusing on government actions to improve communication and knowledge dissemination, both of which have been shown by the literature to be crucial in building public trust and acceptance. Policy implications emerging from the model build on research by Tortajada and Nambiar (2019) about public communications strategies addressing both technological innovations and governance dimensions of water reuse. According to the authors, public communications through the media play a central role in the development of public policies and their acceptance by the public.

A model is introduced in the next section that describes how equilibrium levels of acceptance can be manipulated through changes in variables such as investment, communication, and credibility. In particular, the model provides guidance on the degree to which policymakers' efforts to influence public mindset can raise acceptance of water reuse. The sections following the next discuss practical implications and apply the model to water reuse cases.

3. A model for water supply source acceptance

3.1. Background and conceptual framing

The model introduced in this section is based on the following assumptions. In a given water management setting, societal or public benefit results from investment by water utility companies or agencies (hereafter "WUs") in the supply portfolio and the sustainability of that portfolio. This model focuses on the behavior of WUs rather than that of "government," as the latter is multidimensional and often internally contradictory regarding policies. WUs are assumed to be increasingly interested in water reuse due to reliability and lower cost relative to other source options, including water transfers and desalination. This assumption is based on observed trends; regulatory standards regarding the quality of discharged treated wastewater are increasingly stringent, including in the United States (Sanchez-Flores et al., 2016) (see Table 1) and in other industrialized countries (Morris et al., 2017). To remain compliant, utilities must invest more resources to treat wastewater for discharge, but this burden is compelling some to treat to reusable standard in order to by-pass the discharge process altogether. In the long-run, this strategy is potentially more financially sustainable than adjusting to mutable regulatory targets.

More WUs are advocating for water reuse not only because it provides a reliable source of clean water but also because it reduces long-run costs and because the supporting science is gaining credibility within WUs. Elected governments (as democratically beholden to public sentiment) may be less supportive of water reuse due to lack of sufficient understanding by the public about risks and the tendency to defer to concerns about stigmatization. Thus, there is a tension internal to WUs regarding the mediation of public and agency or government interests. On one hand, the monopoly status of WUs gives them more freedom to pursue water reuse options; the public, as customers, can turn to no alternative supplier. Additionally, in most cases WUs are not directly democratically accountable to the public because, like many administrative agencies, their officials and employees are not elected. On the other hand, WUs are concerned about the direct and indirect impacts of public acceptance because political sentiment impacts the behavior of elected governments and by extension influences resource allocation. In democratic systems, water reuse projects can be stalled due to opposition from the public and government authorities. This underscores the importance of communication and awareness campaigns (for cases from Singapore, Australia, and the United States, see Tortajada and Nambiar, 2019).

The public is assumed to be better off if water is supplied safely, reliably, and efficiently, and without compromising future capability to do so. This benefit can be modeled as a function of the behavior of two actors – the public (with interests expressed by government positions and public policy) and WUs – for a given water supply method (hereafter "WS"; examples being water reuse, groundwater extraction, rainfall capture, desalination, and others). The public exhibits a given level of support for a WS among multiple supply options, and WUs exhibit a given level of support through their role as water suppliers and implementers of policy. Support by the public and WUs, in some combination, is assumed to lead to an optimal balance in the supply portfolio and thereby to enhanced public benefit. A given WS can enhance this benefit by providing redundant or contingent capacity, reducing pressure on other water supply sources, and in the case of water reuse, strengthening supply security by closing the supply loop. According to the same logic, lack of support from either actor could compromise development of a given WS and thereby decrease benefit.

This article's formal theoretical model, including equations and graphs, is an adaptation of a model introduced by Vu (2009) and Lin et al. (2019) to conceptualize foreign aid and development management. This model examines support for a given WS as negotiated between the public and WUs. It is parameterized through variables shown by the literature to impact water reuse development, including public acceptance, investment, and the cost of WS project failure. To existing studies, the model adds a theoretical basis for further empirical research

Table 1
Selected examples of recent water reuse efforts in the United States (information from EPA, 2017).

Name and location	Date commenced	Details about treatment
Cambria Emergency Water Supply (California)	2014	Ultra-filtration, reverse osmosis, ultraviolet radiation, advanced oxidation
Big Spring – Colorado River Municipal Water District	2013	Microfiltration, reverse osmosis, ultraviolet radiation, advanced oxidation, conventional treatment
San Diego Advanced Water Purification Demonstration Project	2012	Ozone disinfection, biological activated carbon, microfiltration, reverse osmosis, ultraviolet radiation/advanced oxidation
Prairie Waters Project, Aurora (Colorado)	2010	Riverbank filtration, aquifer storage and recovery, softening, ultraviolet radiation/advanced oxidation, biological activated carbon, granular activated carbon, chlorination
Arapahoe County/Cotton Wood	2009	Media filtration, reverse osmosis, ultraviolet radiation/advanced oxidation, chlorination

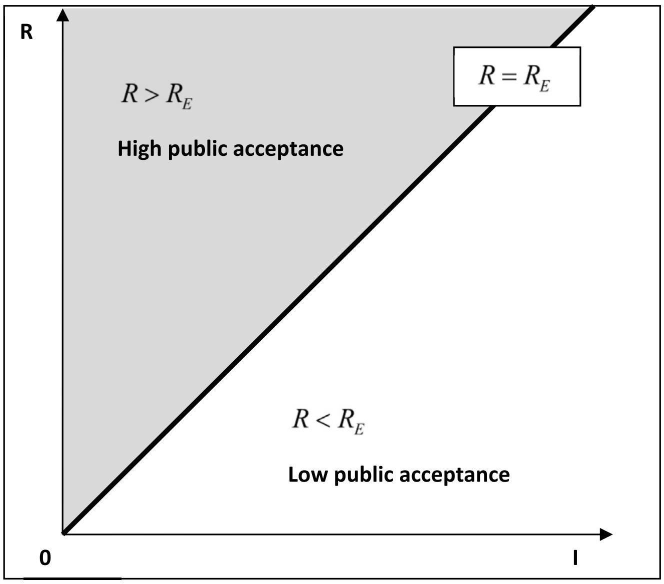

Fig. 1. Importance level and government investment for a given WS.

and for strategies governments can employ to encourage public acceptance of a given WS (provided such governments gain suitable understanding of the technologies they promote).

3.2. Model details

Assume that the function takes the following form (Eq. (1)):

$$U = M * \frac{R^{\alpha}}{(C_L/C_H)^{\pi}} + (1 - M) * \lambda * \frac{I^{\beta}}{(1 + F)} \tag{1}$$

Where:

- M is a dummy variable for the success of a given WS project: $M = 1$ if the project is successful; $M = 0$ if the project is a failure. For modeling simplicity, it is assumed that a given WS cannot be a partial failure or partial success.
- C_L and C_H ($0 < C_L, C_H \leq 1$) are, respectively, the low and high levels of public support for a given WS. Both variables are operationalized as resources that can be used to mobilize advocacy and to measure public sentiment for informing government policy (and by extension the efforts of WUs). If support is low ($C = C_L$), there is assumed to be relatively weak political pressure for implementation of a given WS. If support is high ($C = C_H$), there is assumed to be relatively strong political pressure for implementation.
- π ($\pi \geq 1$) is the mechanism by which public sentiment impacts the importance assigned to a given WS by a WU. The variable can be seen as a proxy for the responsiveness of WUs to public sentiment (see literature about democratizing public administration, including Denhardt and Denhardt's (2015) *new public service* and Frederickson's (1980) *new public administration*). The variable's placement as an exponent to a fractional term implies that its numerical value and the strength of its influence are positively related.
- R ($0 \leq R \leq 1$) is the importance level given by a WU to a given WS.
- λ($\lambda \geq 1$) is the benefit of WS project failure. This variable is present only if the public shows low support for a WS.
- I ($I \geq 0$) is the level of investment in a given WS by a WU.
- F ($F > 0$) is the credibility loss of a WS failure that accrues to a WU, particularly with reference to the sentiments of supportive citizens, interest groups, and the global knowledge community.
- α ($\alpha \geq 1$) and β ($\beta \geq 1$) are terms that respectively capture the nonlinear relationship between R and U, and I and U. U is increasing ($\partial U/\partial X > 0$) and has a concave function ($\partial^2 U/\partial^2 X < 0$) on X, where $X \in \{R, \ I\}$.

As the outcome variable (U) of the model represents overall public benefit, the public can be disaggregated to subgroups whose perceptions and intentions (Ajzen, 1985) of a WS sort them into three types: progressive (type I), indifferent (type II), and regressive (type III). A group is said to be progressive if it accepts a given WS, indifferent if it exhibits no preference either way, and regressive if it opposes a given WS. The benefit function of the group, depending on its type, can take the following form:

- If the subgroup is progressive, $U = M$; the group is happy if a WS is successful and unhappy otherwise.
- If the subgroup is indifferent, $U = 1$; the group's benefit is unchanged regardless of whether a WS is successful.
- If the subgroup is regressive, $U = 1 - M$; the group is happy if a WS is not successful and unhappy otherwise.

Given the function in Eq. (1), the public, as a rational decision maker, accepts a WS only if:

$$U|_{C=C_H} > U|_{C=C_L} \tag{2}$$

Note that:
$U|_{C=C_H} = \frac{R^{\alpha}}{(C_L/C_H)^{\pi}}$ and $U|_{C=C_L} = \frac{\lambda I^{\beta}}{(1+F)}$.
The condition (Eq. (2)) is equivalent to:

$$\Leftrightarrow \frac{R^{\alpha}}{(C_L/C_H)^{\pi}} > \frac{\lambda I^{\beta}}{(1 + F)}$$

$$\Leftrightarrow R > R_C, \ where \ R_C \equiv \left[\frac{\lambda}{(1 + F)}(C_L/C_H)^{\pi}\right]^{1/\alpha} * I^{\beta/\alpha} \tag{3}$$

Assume that $\alpha = \beta$; Eq. (3) can thus be revised to:

$$R_C \ \equiv \left[\frac{\lambda}{(1 + F)}(C_L/C_H)^{\pi}\right]^{1/\alpha} * I \tag{4}$$

or

$$R_C \ \equiv k * I \ where \ k = \left[\frac{\lambda}{(1 + F)}(C_L/C_H)^{\pi}\right]^{1/\alpha} \tag{5}$$

As a summary of Eqs. (2), (3) and (5), benefit is increased when $R > R_C$ and weakened when $R < R_C$. The relationship between a WS investment (I) and that WS's importance level (R) is graphically depicted by I on the horizontal axis and R on the vertical axis (Fig. 1). Line $R = R_E$ is the dividing line between areas representing a high WS importance level ($R > R_E$) and by extension a high level of public acceptance. In the lower area ($R < R_E$), WS importance level is relatively low, a result of a low level of public acceptance.

3.3. Public acceptance at equilibrium

Assume R^* denotes the importance level of a WS, and assume that the public's demand function is defined as:

$$R = R^*$$

At a WS importance level R^*, the public's demand for the WS is a value between 0 and $+\infty$, with the WU determining the level of investment in the WS. In Fig. 2, the public demand curve is a horizontal line crossing the vertical axis at R^*. Regarding the supply curve (with importance functioning as demand and represented on the y-axis, and investment as supply and represented on the x-axis), assume that a WS investment amount takes the following functional form:

$$I = \rho R, \qquad (\rho > 0) \tag{6}$$

The coefficient ρ and its magnitude are determined by the WU's interest in a given WS (resulting from government and public pressure,

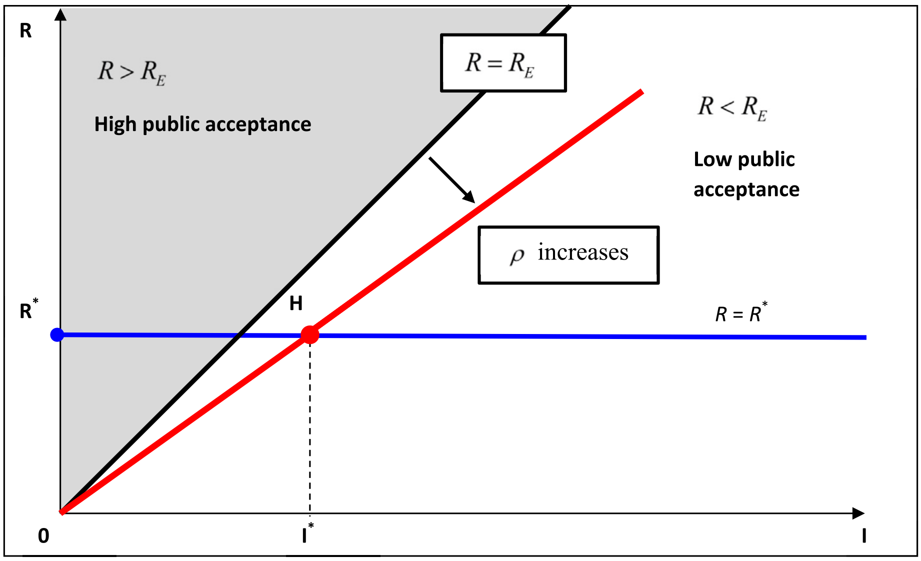

Fig. 2. Public demand at equilibrium.

scientific evidence, etc.) and by the peripherals of the case context (observable or otherwise). The magnitude of the coefficient ρ, varies in proportion to that of importance level R at given values of I.

Eq. (5) can be transformed to $R = \frac{1}{\rho}I$, indicating that the public demand curve rotates clockwise (becomes flatter) as ρ increases, and rotates counterclockwise (becomes steeper) as ρ is reduced. The public demand curve $R = R^*$ and the WS supply curve $I = \rho R$ cross at equilibrium point H, where $I = I^* = \rho R^*$ (Fig. 2). Point H can be in the lower area (low-acceptance) as shown in Fig. 2, or in the upper area (high-acceptance), depending on the relative values of ρ, I^*, and R^*.

4. Implications for water governance

4.1. Changing the equation

In Fig. 2, the equilibrium point H falls in the low-acceptance range (below line $R = R_E$) when the WS investment remains at I^*. Due to low public acceptance, investment in a WS is low and benefit is limited. This is illustrated through the following expressions:

$$R^* < R_E|_{I=I^*}$$

$$\Leftrightarrow \frac{1}{\rho}I^* < \left[\frac{\lambda}{(1+F)}(C_L/C_H)^\pi\right]^{1/\alpha} I^*$$

$$\Leftrightarrow (C_L/C_H)^\pi > \frac{1}{\lambda}\cdot\frac{(1+F)}{\rho^\alpha} \tag{7}$$

Inequality (7) illustrates that factors determining a WS's importance level include level of public support C_L/C_H, the costs F of WS failure, and the coefficient ρ. The assumed implication is that low support for a given alternative WS is an equilibrium choice made by the public based on its comfort with the *status-quo* of a given water supply mix. Further, this choice is reinforced if there are changes that increase the left-hand side or decrease the right-hand side of the inequality. Changes that reinforce the equilibrium level of low support can be illustrated through two scenarios. First, the left-hand side of the inequality is increased, with $(C_L/C_H)^\pi$ becoming higher; that is, reasons for the public to oppose a WS are higher than those to support another one, or the justification for public opposition is more convincing than that for public support. One example is a case in which public antipathy is stoked by concerns about risk and by commercial or ideological interest groups that pursue information campaigns and press engagement around WS opposition. Such strategies can be implemented by leveraging a focusing event such as the failure of a WS project or a cautionary example of a WS project that experienced budgetary over-runs. The value of the left-hand side of the inequality can also be altered through π, the exponential lever by which public sentiment impacts the level of importance assigned to a given WS by a WU. When administrative-democratic mechanisms allow public sentiment to influence WU investment behavior, an anti-WS frame ($C_L > C_H$) increases the value of the left-hand side of the inequality while a pro-WS frame ($C_L < C_H$) decreases it.

In the second scenario, the right-hand side of the inequality is decreased, which can occur for three reasons. The first is an increase in λ, the benefit of a WS project failure. This could result from the public's aforementioned comfort with the *status-quo*. Second, the credibility loss of WS failure F decreases. This could occur in situations where the given WU undertakes a WS project with weak technical, management, or local political accountability (e.g. in response to standards imposed by a national-level environmental agency) or the given WU sub-contracts a WS project to a private entity under an agreement having weak mechanisms for accountability. In effect, this decouples WU image from project outcomes. Finally, the right-hand side of the inequality is decreased when the coefficient ρ in WS supply Eq. (6) increases, as from the WU's heightened interest in a given WS through regulatory inducements, political pressure, or scientific evidence.

4.2. Pitfalls of increased investment

Assuming the importance level R^* remains the same, an increase in WU resources committed to a given WS rotates the WS supply curve clockwise, from $I = \rho R$ to $I = \rho' R$ ($\rho' < \rho$) (Fig. 3). Line $I = \rho R$ shifts across line $R = R_E$ and the equilibrium point H moves from the area of high acceptance ($R > R_E$) to the area of low acceptance ($R < R_E$) (both areas remaining stationary relative to one another). In practical terms, committing additional resources to a project whose relative importance has not proportionally increased may erode public support, as illustrated by the movement of equilibrium towards point H'. The policy implication is that additional funds appropriated to a WS must be justified by accompanying communications and information dissemination strategies about the given WS improving public outcomes (e.g. increase in benefit), in order to enlarge the area of high acceptance such that it encompasses H'.

4.3. Feasibility and legitimacy of WS

Given that adopting WS methods such as water reuse and

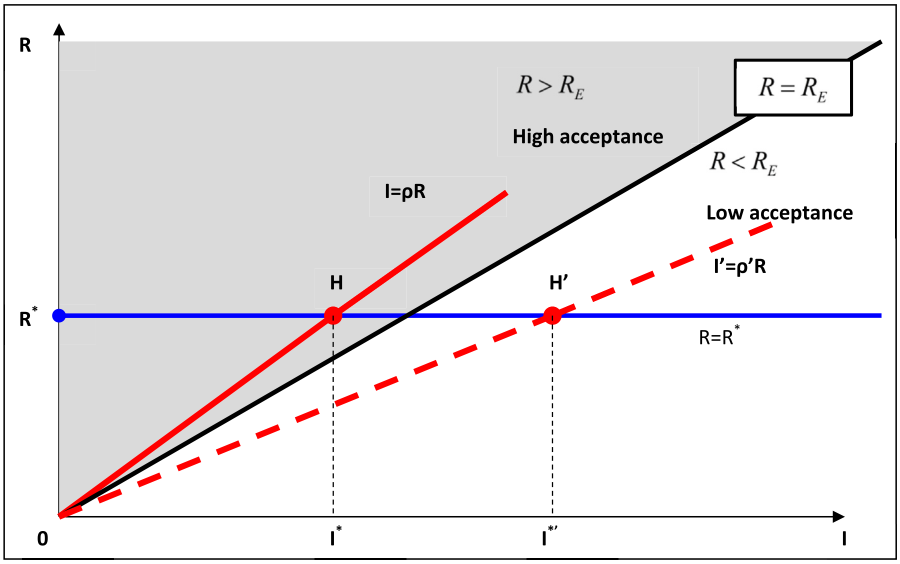

Fig. 3. Additional investment in WS.

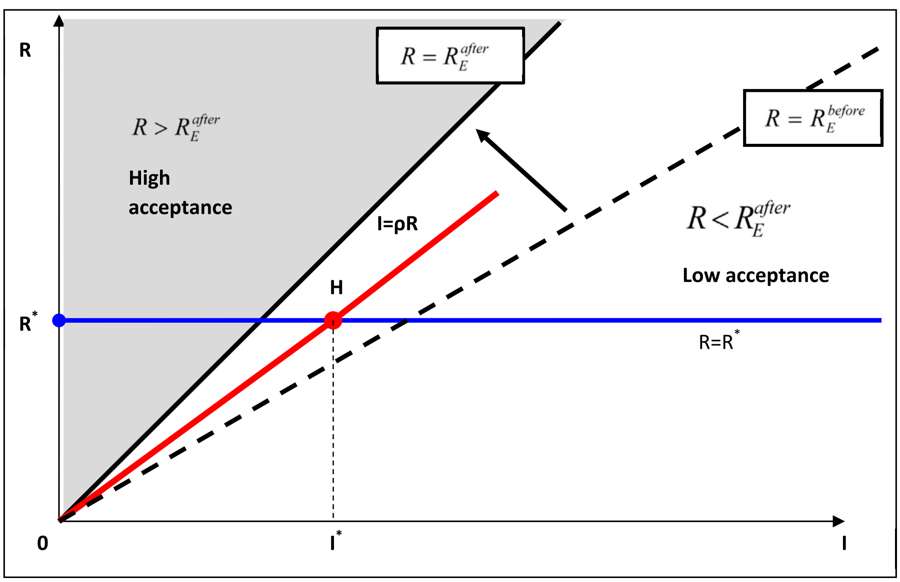

Fig. 4. Continued investment amidst lower public support.

desalination often involve significant capital outlays, strengthening fiscal feasibility and legitimacy by building public support can be a useful strategy. However, a government may choose to maintain a WS investment despite deterioration of public support. This scenario would cause a rise in coefficient $k = \left[\frac{\lambda}{(1+F)}(C_L/C_H)^{\pi}\right]^{1/\alpha}$ in Eq. (5). For example, increasing public support only for the existing water supply portfolio increases λ, while a decline in accountability for a given WS reduces the credibility loss for the WU of failure F, and deteriorating feasibility or legitimacy of that WS raises the relative public opposition level C_L/C_H. As these dynamics increase coefficient k, curve $R = R_E$ rotates counterclockwise, resulting in a reduction in the area of high public acceptance and enlarging the area of low public acceptance (Fig. 4). As a result, the equilibrium point H defaults into the area of low acceptance without a corresponding shift in the supply curve. This resulting shift of public support from high to low decreases the benefit associated with the success of a given WS.

4.4. Influencing public acceptance

The model implies that the public's acceptance level can be shifted from low to high. Targeted policies must be adopted to alter the relative areas of public acceptance such that equilibrium H falls into the high area. To achieve this, the government maintains the existing investment level ($I^{*'} = \rho' R^{*'} = I^* = \rho R^*$)) and concurrently raises the WS project's importance from R^* to $R^{*'}$. The supply curve resultingly shifts counterclockwise, moving the public's equilibrium choice from H (area of low-acceptance) to H' (area of high-acceptance) (Fig. 5).

Promoting a change in public mindset alters factors underlying Inequality (7), with equilibrium acceptance moving from the low-to the high-level. In this approach, the government does not change the level of investment in the WS but instead focuses on factors that shift the balance of Inequality (7), including reducing the left-hand side and increasing the right-hand side of the inequality. The purpose is to rotate curve $R = R_E$ clockwise to enlarge the area of high acceptance such that it encompasses equilibrium point H (Fig. 6). This approach requires a general public mindset that is more receptive to the given WS,

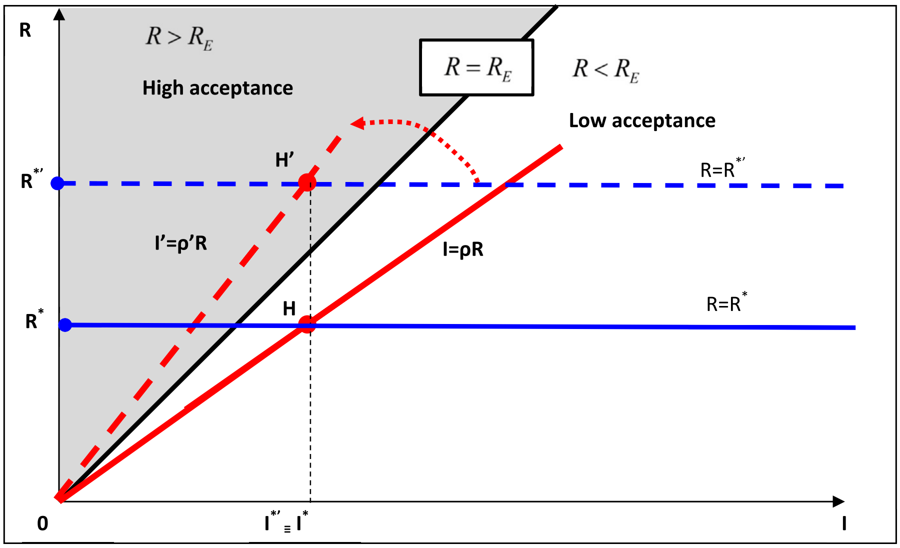

Fig. 5. Raising importance level while maintaining investment level.

something that could be fostered mutually by the government and public.

The following are strategies the government can employ towards this end. First, the government can increase the relative public acceptance level C_L/C_H. This requires the government to take a direct role in communications and the circulation of scientific evidence about the effectiveness and benefit of the WS. Regarding variable π, which is treated in the model as an exponential variable and the mechanism by which public sentiment impacts the importance level of a given WS, the government can also strengthen public sentiment monitoring mechanisms and reform institutions to magnify the influence of public sentiment on WU policy; this potentially includes the adoption of more direct feedback mechanisms between the public and WUs. Second, the WU can lower the benefit of the failure of WS λ through similar means, by circulating evidence about the lack of reliability, effectiveness, and sustainability of an overall water supply portfolio that excludes the given WS specifically and capacity redundancies and source diversity more generally. Finally, the WU can raise the disbenefit F associated with WS project failure by forecasting the costs and broader strategic setbacks of failure and by committing to robust monitoring and evaluation of WS project performance based on benchmark cases.

5. Cases

This article proceeds by applying the model to two cases of water reuse. There are few cases of reuse from which to choose; Windhoek, Namibia and Singapore are two of the world's most developed and examined. This section proceeds with brief backgrounds about both and illustrations of how the model explains dynamics among communication, acceptance, and government commitment for each. The section then highlights similarities and differences between the two in order to elucidate insights from what have been somewhat divergent strategies in public communication.

5.1. Windhoek, Namibia

The city of Windhoek, Namibia provides the world's flagship case of potable water reuse, having utilized the method since 1968. The initial water reuse facility was upgraded several times while maintaining consistently acceptable quality standards (Menge, 2010; Haarhoff and

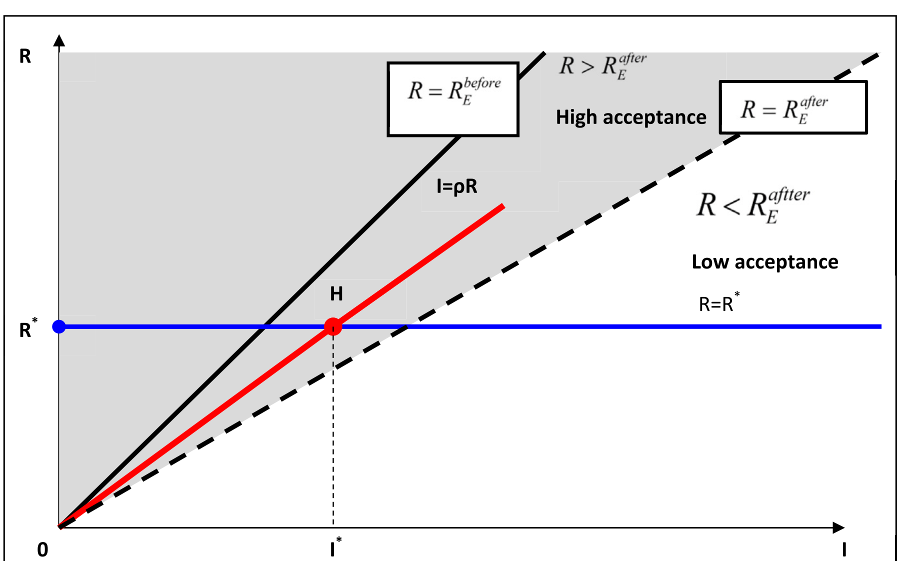

Fig. 6. Promoting changes in public mindset.

Van der Merwe, 1996). Recognizing the challenges of growing demand for water in a setting of scarcity, the city government committed in the 1990s to building a new facility. In 2002, the New Goreangab Water Reclamation Plant (NGWRP) was opened, representing an increase of 4.5 times the original capacity of the replaced facility (van Rensburg, 2016).

Although the city has utilized reused water for decades, it was in 2010 that a groundbreaking public perception research project was commissioned by Windhoek's Department of Infrastructure, Water and Technical Services (Crovello et al., 2010). Through 346 surveys of local residents, the team of students at Worcester Polytechnic Institute in the United States determined that a majority of residents had no understanding of water reuse and were unaware of NGWRP and the city's reuse history. The survey also found that respondents were largely satisfied with the quality of their tap water. The authors advised the city government to continue seeking to understand public perceptions, implement education and awareness campaigns, and circulate information about water quality. A second study (Boucher et al., n.d.) by other students at the same institute likewise found, based on a larger sample size (N = 541), that residents were unaware of NGWRP and that they were largely satisfied with water quality; the study recommended integrating awareness into school curricula and implementing media campaigns and promotion activities. Other surveys concerning public perception of water reuse in Windhoek are, to our knowledge, rather scarce. In one such study focusing on emotions, Leong (2016) found through 25 interviews in Windhoek that psychological issues centered around the themes of governance (safety and technology), trust (a lagging indicator emerging after the introduction of reuse), and sustainability; notably, the intensity of negative sentiment about water reuse (e.g. the "yuck" factor) was found to be low.

The Windhoek case can be understood through the perspective offered by this article's proposed model, in particular dynamics related to public acceptance. Based on the assumptions of the model, Windhoek's government as a politically accountable body is interested in implementing programs that have public support. A given combination of the level of investment I and (institutionally assigned) project importance R falls within either a high or low level of public acceptance, as determined by the magnitude of the coefficient (representing in this case the level of institutional interest in maintaining the operation of the project by the city government and WINGOC (the Windhoek Goreangab Operating Company) (Eq. (6)). The city government makes progress towards the action illustrated in Fig. 5 by raising the importance level through expressions of institutional commitment without also signaling it by raising the investment level in the NGWRP project. This does not move the line distinguishing high from low public acceptance ($R = R_E$) because it does not specifically promote a shift in public mindset about water reuse through persuasive arguments about safety and quality. However, it allows the investment-importance equilibrium level H to move from the area of low acceptance to high acceptance through the leftward rotation of line $I = \rho R$. The practical implication is that the public would be theoretically more inclined to support a project of rising importance that does not consume additional public resources (investment), independent of their general mindset about the safety or security of reused water itself.

The city government can also promote public support by taking actions that enlarge the theoretical area representing high public acceptance as illustrated in Fig. 6 (specifically through the rightward rotation of line $R = R_E$). This allows a stationary equilibrium level H to default from an area of low acceptance to high acceptance, as executed practically by the city government undertaking information and education campaigns (recommended by the Worcester surveys). Through the incorporation of variable π – the magnitude of influence on institutional importance by public sentiment (i.e. administrative democratization) – the model provides theoretical support for the recommendation by Crovello et al. (2010) about adopting monitoring mechanisms for public sentiment. Options available to the city government for increasing public acceptance, as illustrated by the model, also include (i) lowering the benefit of NGWRP failure or decommission perceived by those supportive of or having interests in promoting non-reuse sources (λ) by circulating information that reused water is of equal quality and healthiness as water from other (scarcer) sources such as groundwater and transported river water; and (ii) raising the disbenefit of NGWRP failure or decommission (F) by emphasizing that this source of water is incapable of being cheaply or quickly substituted by other sources, and that the removal of any single source, including reuse, compromises resilience by weakening the diversity of the supply portfolio.

5.2. Singapore

As an island-bound city-state facing scarcity in land and other resources, Singapore is a uniquely situated case for water management. Given its highly advanced economy, Singapore consistently ranks among the global top-ten in GDP per capita and the country's per-capita water demand profile is similar to that of the world's most developed and consumption-oriented countries. After initially relying on rainwater catchment and water imports from neighboring Malaysia for a significant portion of supply, Singapore made a commitment to diversify its portfolio and now supplements legacy sources with desalination, and, most notably, potable and non-potable water reuse. Branded NEWater and commencing in 2003, Singapore's water reuse program is capable of meeting up to 40% of demand as needed. NEWater is the result of nearly five decades of research and experimentation and has moved forward due in large part to improvements in the quality and financial feasibility of purification technologies. Recycled to a purity grade exceeding that of the World Health Organization's standards for potability, NEWater is produced at several facilities around the island and delivered through a separate supply system to industrial users that require highly purified water. NEWater also serves as an indirect potable source added to reservoirs from which raw water is drawn and treated through standard methods.

The model can be used to explain interactions among three crucial elements of Singapore's NEWater story: (i) the importance assigned to water reuse by the government and WU (PUB; the Public Utilities Board, Singapore's national water agency), (ii) investment in the development of the program including research, demonstration projects, and infrastructure, and (iii) efforts by the government to communicate with and educate the public. The PUB was proactive in raising public awareness even in advance of the 2003 inception of the program, effectively aiming to push line $R = R_E$ in the model clockwise to the extent that the area of high public acceptance would encompass equilibrium H under multiple combinations of importance and investment levels. This strategy would ensure equilibrium within the area of high acceptance from an early stage of project development, during which importance level was high. In this scenario, the public's pent-up concern would compel the government to resolve the issue of urgency (water scarcity) while communication about the reliability and safety of water reuse would strengthen the political feasibility of NEWater as a means for that resolution. NEWater has been linked to the country's survival, amidst what seemed to be a deadlock at that time between the governments of Malaysia and Singapore concerning water transfer to Singapore (Tortajada and Pobre, 2011). The public would thus be largely aware of the importance of this source for the self-sufficiency and security of the city-state.

Each type of water supply system requires its own form of up-front capital investment, and the model implies in Fig. 3 that increasing the level of investment I in a WS while importance level R remains constant induces equilibrium H to shift into the area of low public acceptance; as this situation continues in the long run, the effect on public acceptance would be negative, shifting line $R = R_E$ counterclockwise. For this reason, the PUB pursued a long-term communications campaign for public awareness and education as it began to make investments in reuse facilities. This proactive effort accomplished two things, as represented by shifting dynamics within the model: (i) raising importance level R^* to $R^{*\prime}$ such that line $I = \rho R$ shifts counterclockwise, crossing line $R = R_E$ and returning equilibrium H to the area of high public acceptance (Fig. 5), and (ii) shifting line $R = R_E$ clockwise, crossing line $I = \rho R$ such that equilibrium H defaults into an enlarged area of high public acceptance.

5.3. Similarities and differences between the Windhoek and Singapore cases

The Singapore case is similar to the Windhoek case in two ways. First, water scarcity was a fundamental driver for reuse. In Windhoek, the extreme aridity of the climate, scarcity and depletion of groundwater, and vast distance (hundreds of kilometers) from the city to the country's reliably flowing rivers effectively made the adoption of an alternative source a mandate. In Singapore, rapid growth in population and economic development required additional and reliable sources of water, and political tensions with Malaysia – the primary source for Singapore's water supply – compelled the government to turn inwards in the search for alternative supply sources.

Second, both cases exhibit the dynamics of public awareness. In Singapore, the government is open and promotional about the country's overall water supply, structuring awareness campaigns around PUB's “Four Taps” supply framework (rainwater, imports, reuse, and desalination). Singapore also cultivated a favorable impression among the local media by sponsoring field visits to observe and learn from one of the world's most successful water reuse projects (Orange County, California) and by integrating a narrative of environmental sustainability and self-sufficiency into outreach programs, tours, and events held at the NEWater facility visitor center. Windhoek's efforts to raise awareness, although important and well founded, do not include the mix and depth of activities seen in the Singapore case. After decades of NGWRP operating without substantial public awareness (as found by the Worcester surveys), the 2015–2017 (Scott et al., 2018) and 2019 droughts have raised public awareness about the importance of alternative water sources including reuse. Additionally, for some time there have been organized site visits to the NGWRP facility as a means to educate the public about the process.

The cases also differ in two ways. First, Windhoek's water reuse history predates Singapore's by over three decades, and in the early 2000s Windhoek recommitted to reuse by investing in an expanded and technologically updated facility. By contrast, Singapore proceeded to develop water reuse on a more measured and deliberative basis, experimenting with and tailoring it before rolling it out nearly 30 years after the idea was first considered. Despite this, the period of learning for both governments has been considerably lengthy – in Windhoek throughout the history operation (an “on-the-job training” approach) and in Singapore prior to operation (a more cautious approach).

Second, the water reuse initiatives of both cases were undertaken largely by government fiat without an upswell of demand from the general public; in Windhoek by the South Africa-based administration that governed the territory until Namibia's independence in 1990, and in Singapore by the government in collaboration with technical experts and policymakers. Singapore's PUB had conducted perception surveys prior to the roll-out of NEWater, while a similar approach was not evident in Windhoek. Furthermore, Singapore's communications efforts were undertaken after the internal decision to commit to NEWater but prior to the project's full-scale rollout in 2003. Windhoek undertook substantial communications efforts after the water reuse project was commissioned. Arguably in both cases, public input played little role in the initial decision whether to adopt water reuse. However, Singapore employed strategic use of communications to prime the public for acceptance before its reuse project was fully commissioned.

6. Policy implications

Water reuse is a cornerstone of supply self-sufficiency and advancements in technology have made the purification process more financially and operationally feasible. There is high potential for broader societal and ecological benefit through water reuse. Nevertheless, negative public perceptions about water reuse remain a barrier to adoption. Water utilities should demonstrate institutional competence, adherence to robust safety and public health protocols, use of independent experts for evaluation purposes, and stakeholder engagement in project development, while considering social and environmental impacts (EPA, 2018). Governments can then embark on information and promotion campaigns to raise awareness and understanding about the necessity and safety of water reuse. This section briefly outlines policy implications related to acceptance, as derived from the model.

The model indicates that public support for a given WS settles at an equilibrium level that can be considered low relative to that needed for government support. This can be explained in a variety of ways, including the general public's skepticism about new water supply and purification methods and a preference for stability and predictability in the pricing and reliability of a crucial good. Entrenched interests, such as those of private firms or administrative units involved in operating the supply mix as it currently exists, may resist disruption of *status-quo* as their investments and expertise are oriented towards legacy sources. As such, information campaigns focusing on high risk and cost have been deployed to threaten the political feasibility of new WSs (as conceptually illustrated in Inequality (7)). Thus, the model in this article provides a theoretical illustration of the importance of communication strategies in building public acceptance of WS, as illustrated in Fig. 6. By circulating information, the government can demystify WS processes that the public may originally find difficult to understand. The model also illustrates another potential point of emphasis for communication: the importance of a diversified supply portfolio with redundancies, and the role of a given WS within it. The model indicates that this can be achieved by deploying either a benefit- or risk-focused narrative. Establishing monitoring systems also ensures the supply of reliable data by which WS projects can be evaluated, thus focusing debates on facts rather than assumptions and strengthening the quality of communication between the public and WUs.

Communications are crucial throughout the several stages of water reuse development. An increasingly popular option for water supply, water utilities that provide timely information to the media and public are likely to improve understanding of the messages provided (Tortajada and Nambiar, 2019). Thus, information “priming” provides the public with the understanding to interpret both factual and ideological messages about supply safety. There are numerous strategies for such priming, including engagement and education outreach programs, framing of public relations and media narratives around the science of water reuse and its contribution to sustainability and self-sufficiency, the fiscal and operational benefits of water reuse technologies, and the emphasis on end-product aspects of water as clean and reliable.

The nature of communication should be calibrated to a given information campaign's objectives and the characteristics of the audience. For example, according to Cook et al. (2009; p. 33), “the public has some difficultly in understanding terms such as ‘low risk’, ‘probability’ and ‘uncertainty’. It is important to communicate these terms in public forums.” Singapore's NEWater exhibits how such information campaigns can build public support for water reuse (Joo and Heng, 2017; Mainali et al., 2011; Tortajada and Nambiar, 2019; Guan and Toh, 2011). As indicated by this article's model, WUs must consider communications as an *ex-ante* strategy to build legitimacy for a WS. In the event of WS failure risk, this strategy lowers the failure benefit and increases the potential credibility loss for the WU, compelling the WU to commit sufficient resources to ensure WS success. Furthermore, communication cannot substitute for substantive involvement of the public in all stages of water reuse planning. According to a United States Bureau of Reclamation report (2004), the public's "fears and concerns should be considered real and valid and mitigated with accurate information and, if necessary, changes in project design" (p. 19).

While the adoption of new WS projects can entail technical, financial, and managerial challenges, the model illustrates the importance of public acceptance as a determinant of WS success and the crucial role of communication in shaping a debate environment informed by facts rather than emotions. WS is a process improved over time by visionary management and planning as well as refinement of technology. Ostensibly, it could be assumed that technology-based options are a trustworthy alternative, particularly with respect to health and environmental factors. Such a narrative would hold that the more sophisticated a technology is, the cleaner the water would be and the fewer health risks there would be. WUs often argue that technology has developed to such an extent that the health and environmental risks of water reuse are minimal. Nevertheless, it is clear from the literature that, in many cases, water reuse continues to be stigmatized by the public perception that recycled wastewater should not be used for potable purposes. This article advances the discussion about how governments can overcome this challenge.

7. Conclusion

In an era of increasing water stress, governments are exploring new options for water supply. The improvement of purification technologies has reduced the cost and increased the reliability of wastewater treatment, generating new opportunities to introduce water reuse into existing supply portfolios. However, public acceptance of water reuse has hindered wider adoption of these technologies and remains a hobgoblin for policymakers and WUs. The academic literature has examined this phenomenon through a variety of case studies and empirical research. To the scholarly discourse, this article contributes a formal mathematical model that conceptualizes the relationship between government and the public in regard to water reuse investment and public acceptance. The model provides a theoretical basis to systematize empirical studies and to design policy initiatives that cultivate support for water reuse, particularly around benefit- or risk-focused narratives as constitutive of broader communications and information campaigns.

The limitations of this study are similar to the types of limitations facing most formal behavioral models. Growing largely out of the economics literature, behavioral models are built largely on the assumption of rationality among individual agents; each behaves in a way that serves her or his own economic interest. The assumed predictability of actor behavior enhances the certainty of model predictions. However, challenges to rational choice theory and related modeling assumptions have emerged around the notion of bounded rationality and around the tensions between self-interest and observance of universalized codes of behavior. As such, rational actor models cannot be taken as a basis on which to predict behavior with high certitude. Furthermore, the model is conceptual in nature but its translation into empirical settings presents some challenges related to variable operationalization; for example, variables representing credibility loss, benefits of project failure, and mechanisms by which public sentiment impacts the importance of a project are dependent on socio-political context. In this instance, comparative studies must consider cases whose intangible variables (e.g. cultural factors) are comparable. These limitations notwithstanding, the model is a potentially useful tool to conceptualize the relationship between public preferences and government efforts to institute water reuse projects. Thus, it is an important early contribution to what is likely to be a scholarly conversation of growing relevance and importance in the face of increasing water stress.

Rapidly evolving developments in water supply technology, along with increasing supply urgency, mandate further research on several fronts. First, there is a need for better understanding about methods to improve the reach and effectiveness of public engagement efforts for water reuse. More specifically, further studies should examine the extent to which indirect contact with water reuse raises comfort levels and encourages individuals to embrace direct contact with reused water. Support for non-potable water reuse may build a pathway to more support for potable reuse. Second, further research should identify proven strategies for improving institutional trust among constituents and levels of government, as this is a crucial factor in implementing public engagement and minimizing conflicting policies. Such research might proceed by examining how public perceptions about recycled and desalinated water were originally formed, how transparency and accountability are built into water planning efforts, and how best practices can be incorporated to strengthen relationships between agencies and the public (e.g. how a community responds to particular types of outreach). Finally, additional research should seek to better understand emotional responses to the framing of water reuse information, in order to identify types of messaging that overcome pathogen aversion.

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