SOCIO-HYDROLOGICAL PLANNING AND INTEGRATED WATER MANAGEMENT CONSIDERATIONS FOR OʻAHU, HAWAIʻI

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Abstract

Urban development in the United States during the 20th century often occurred without fully considering the environmental and social implications of water management practices. These unchecked impacts create legacy problems that manifest both in the built environment and the overarching governance structure, and become amplified by 21st century challenges. Integrated, socio-hydrological water management approaches—such as One Water (e.g., Cesanek et al., 2017; US Water Alliance, 2016, 2017), Water Sensitive Cities (e.g., Brown et al., 2009), or Soft Path Solutions for the 21st century (e.g., Christian-Smith et al., 2012; Gleick, 2003)—aim to adapt water management systems to address these dual sets of challenges. This dissertation includes three articles that examine the following applied water management questions through an integrated, socio-hydrological planning lens:

1. Does expressed intention to conserve water match household water use behavior?
2. Where do stormwater management priorities converge or diverge between community leaders and water managers?
3. How do concepts of equity intersect with the implementation of a stormwater utility?

Each question relates to understanding how O‘ahu, Hawai‘i (also the City and County of Honolulu) can progress towards integrated water management and greater water productivity. This research is rooted in collaborative planning theory (e.g., Forester, 1989; Healey, 1997, 2003; Innes & Booher, 2010) and Patsy Healey’s (1997) definition of governance as the interaction between formal institutions (e.g., rules, laws, or organizational entities) and relational institutions (e.g., norms, conventions, or codes-of-conduct). O‘ahu provides a unique place to study these research questions because the island has jurisdiction over its watersheds—from mountain to coast—and has an interrupted history of integrated resource management by the Kānaka Maoli.

In the first article, I address the first question through an Ordinary Least Squares (OLS) regression analysis of water use survey data matched with billing data for water utility customers on the island of O‘ahu. I find no connection between the stated intention to conserve water and actual behavior. However, the data show that participating in water conservation programs and installing water-saving fixtures relate to lower water use. I situate my findings in the literature to discuss how policies and programs can address this intention-behavior gap. I also discuss how urban planning decisions can shape social norms and serve a critical role in influencing household water use and conservation. These concepts are essential to understanding how to feasibly achieve Hawai‘i’s water conservation goals as part of the State’s sustainability objectives. This article adds to the body of literature researching the intention-behavior gap in residential water usage, where few studies use actual water use data in their analysis.

The second article is motivated by the U.S. Army Corps of Engineers (USACE) Ala Wai Flood Risk Management Study that mobilized strong community opposition, in part, because of an opaque planning process. I use Q-methodology—a mixed-methods approach—to elucidate prominent narratives about stormwater management in the Ala Wai watershed. I interview 18 key people from various community, government, or professional leadership positions and ask each to prioritize a set of 25 ideas about stormwater management relative to one another. I use Principal Component Analysis (PCA) to identify four narrative groups from the prioritization of the 25 ideas and understand where there are consensus and dissensus between groups. By finding shared narratives between community members and stormwater managers, the use of Q-methodology in this study differs from previous applications of the method in stormwater that

focus solely on stormwater managers. From this analysis, I develop a framework for understanding the dimensionality of choices and decisions related to stormwater management infrastructure, responsibilities, and planning approaches that adds to the body of literature discussing soft-path solutions to stormwater management.

Finally, I base the third article on a plan to implement a stormwater utility (SWU) in O‘ahu that would establish a fee and credit system for stormwater runoff applied to all property owners. The third research question is motivated by ideas of “fairness” that were continually raised during community outreach meetings regarding the SWU. I tackle this question in two parts. In Part I, I conduct a systematic literature review to develop a framework for understanding “fairness” in stormwater issues and financing in terms of economic efficiency and concepts of equity. In Part II, I apply this framework with O‘ahu as an illustrative example to understand how notions of “fairness” are discussed. I look into how the proposed hardship relief correlates with socioeconomic characteristics as an example of distributive equity. Additionally, I challenge the assumptions behind setting a stormwater fee based solely on the total impervious area as an example of economic efficiency. This article’s major contribution to the body of literature on stormwater financing and management is to separately define economic efficiency and concepts of equity, which are often conflated in the literature and discourse around SWUs.

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Introduction

Water resources management developed over more than a century in the U.S. with little consideration for long-term social, ecological, or economic costs (Christian-Smith et al., 2012; Condon & Maxwell, 2019; Gleick, 2003; Pahl-Wostl et al., 2007; Vogel et al., 2015). Success has largely been defined by the ability to reliably supply freshwater to meet consumer demand while staying out of public and political scrutiny (Gober et al., 2013). In that respect, water management in the U.S. was massively successful in its goal. This conventional model of water resources management is characterized by fragmented management of various aspects of water and related sectors, top-down implementation of projects, expert-driven solutions that do not seek to incorporate stakeholder viewpoints, and where adverse consequences to the environment are far secondary to meeting water demand (Mukheibir et al., 2014). The resulting groundwater overdraft, surface water diversions, wetland drainage, and dam building has led to widespread and often irreversible destruction of terrestrial, aquatic, and coastal ecosystems along with the valuable ecosystem services that they provide (e.g., specifically related to the U.S.: Barnett 2008; Glennon 2004; Grunwald 2006; Reisner 1993), which is further compounded by water quality degradation via point and non-point source pollution (Andreen, 2004), the costs of which will burden future generations to come (Mack & Wrase, 2017).

As a result of the now-apparent issues that stem from conventional water management systems, there is a panoply of research, agendas, and strategies calling for better integration of coupled human-water systems that consider the consequences and outcomes of water use (Montanari et al., 2015). Gleick (2003) pens this concept in terms of moving away from "hard path" towards "soft path" solutions to water resources management that: Carefully plan and manage infrastructure and facilities fit for the context; improve the productivity of water use rather than seek endless sources of new supply; match water services and qualities of water to user needs; use economic tools to encourage efficient use and equitable distribution of water; and include local communities in decisions about water management, allocation, and use. Soft path solutions challenge the core idea of successful water management in the conventional sense and realign successful water management to be based on conservation, efficient resource use, water reuse, ecosystem health, stakeholder collaboration, social and generational equity, as well as water supply and safety (Christian-Smith et al., 2012; Gleick, 2003, 2016). Moreover, climate change imposes greater challenges to reframing water resources management for the current and future challenges. A no-analog future requires greater use of forecasting tools for water supply and flood control infrastructure and engineering solutions (Postel, 2010). This approach, however, comes with greater uncertainty that requires specific tools for mitigating uncertainty and the ability to course-correct management methods with new lessons learned.

Many management theories incorporate aspects of integrated water management.[1] For example, Integrated Water Resources Management (IWRM) was introduced as an approach to incorporate the inherent interconnectedness of water within the broader social-ecological system from the watershed-scale (Loucks et al., 2005). Since its introduction in the 1980s, IWRM has

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[1] Here I am specifically referring to the integrated water management concepts developed through global and academic discourse. Integrated water management is not a novel concept, and can be found in many indigenous epistemologies, for example, the *ahupuaʻa* system of the native Hawaiians (e.g., Sproat 2009), discussed in the next section.

evolved from many angles through critique by researchers and practitioners of the theory and its application. This has led to the introduction of other integrated water management approaches that either address more specific water resource applications or serve a broader theoretical approach to managing water systems. The One Water framework, for example, generally tailors integrated water management to systems applications that are not necessarily tied to a watershed or basin (US Water Alliance, 2016). Nexus frameworks that integrate water with food and energy systems address the critique that IWRM is not integrative enough, whereas water security approaches attempt to address the criticism that IWRM has no clear objective (Varady et al., 2016). In general, however, as Bogardi et al. (2012) points out, IWRM or any similar approach requires careful consideration and adaptation of water governance to allow for success.

Governance as a planning practice (Healey, 2009) encompasses both management and policymaking (T. A. Scott & Thomas, 2017). As Dietz et al. (2003) argue, successful governance requires that institutions evolve. In the face of making critical decisions under complexity, uncertainty, and growing constraints, it logically follows that successful water governance systems cannot be static in the outcomes that they intend to achieve, nor can the methods be rigid in accomplishing such outcomes. Young (2013) aptly refers to governance as "a social function centered on steering human groups toward desired outcomes and away from undesirable outcomes." Institutions that comprise a governance system can be defined as rules, laws, and organizational entities that form formal practices that interact with informal practices, such as norms, conventions, or codes of conduct, to guide people's actions (Armitage et al., 2009). Directed by public and private interactions, governance is a means by which institutions are developed, applied, and enabled. Therefore, twenty-first century water governance may be an evolution that lies in the interaction of formal and informal institutions towards soft path water management solutions.

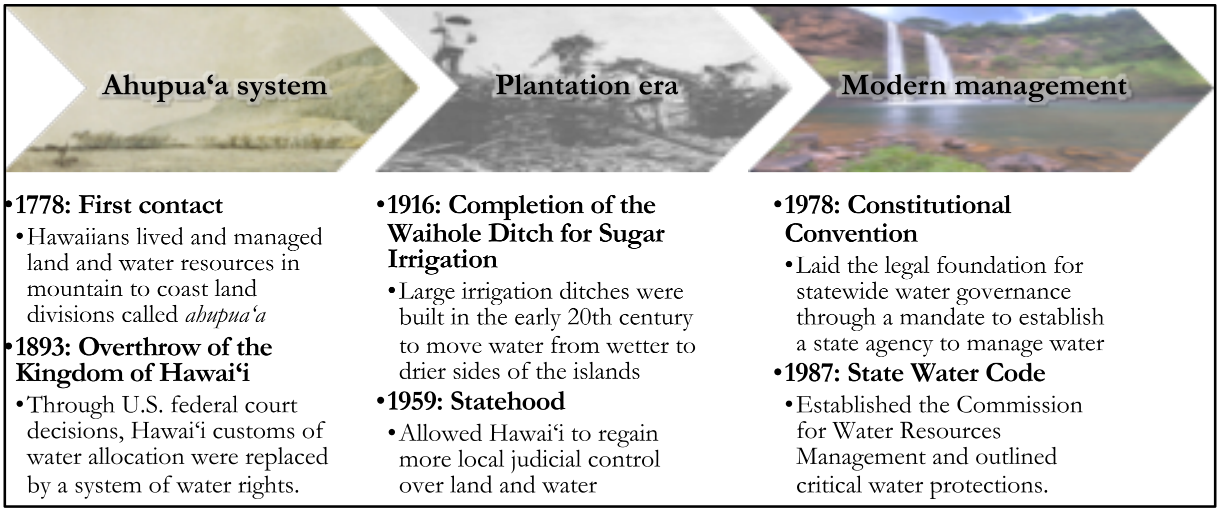
In this dissertation, I focus on the city of Honolulu, Hawaiʻi as a major population and economic hub of the Pacific region, and a location where the geographic isolation constrains water resource management to the island of Oʻahu (also the City and County of Honolulu). In the most recent National Climate Assessment, the first key message for Hawaiʻi and U.S.-Affiliated Pacific Islands is that climate change poses a major threat to water supplies in the face of changing rainfall patterns and the expectation of more intense storm events (Keener et al., 2018). Moreover, the 2019 Oʻahu Resilience Strategy calls for the design and implementation of a Climate Adaptation Strategy that promotes a "One Water" approach to managing potable-, storm-, and waste-water (City and County of Honolulu, 2019, p. 88). I aim to understand how urban water governance in Hawaiʻi, through the example of Honolulu, is poised to contend with the water management needs of the 21st century and its associated issues. The subsequent articles included in this dissertation are framed by this inquiry and address individual applied research questions. This introductory chapter provides scaffolding for understanding contemporary water governance through a socio-hydrological lens (Pande & Sivapalan, 2017; Sivapalan & Blöschl, 2015; Vogel et al., 2015). First, to consider Hawaiʻi's water future, I provide a context to understand the history of water resources management in the Hawaiian Islands and the various forces that shaped the current water management structures, institutions, and policies. Second, I frame my approach to socio-hydrological planning through literature discussions of integrated water management solutions, collaborative planning, and adaptive governance concepts.

A Brief History of Water Management in Hawaiʻi

Hawaiian culture and history play an influential role in contemporary water management. There are three defining eras of water management in Hawaiʻi (K. M. Burnett et al., 2020): Water under the ahupuaʻa system, the plantation era, and modern management (Figure 1). Before Western contact in 1778, Hawaiians lived under a land and water management system within mountain-to-coast land units, ahupuaʻa, for the production of agriculture (Hawaiian Studies Institute, 1987). Although ahupuaʻa had defined political boundaries, which evolved over roughly three centuries, the land units were generally divided based on resource availability for the resident population and managed as integrated resource units with water as a shared resource (La Croix, 2019; Sproat, 2009). The management system implemented through the ahupuaʻa system reflects the understanding of the connectivity of humans to the land and the water by the Kānaka Maoli (Sproat, 2009, 2015). Water in Hawaiian culture has a deep spiritual connection and is recognized as a source of wealth, as evidenced through the language, where wai means water and waiwai means wealth (Beamer, 2014; Sproat, 2014).

After Western contact in 1778, the Hawaiian Islands underwent rapid changes over the following decades that ultimately led to the introduction of sugarcane cultivation, which shaped much of the governance, demographics, economy, and resource use for the better part of the twentieth century (Wilcox, 1996). Despite adaptive efforts such as the Māhele in 1848, which gave Hawaiians the opportunity to claim land they tenured in their ahupuaʻa, and the constitutions of 1840, 1852, and 1864 by the reigning Hawaiian monarchy, the institutions of governance were unable to withstand the pressures of foreign corporate interests in sugar cultivation and the increasing U.S. Military power in the Pacific (La Croix, 2019). The shifting governance of land and seizure of land by foreign interests brought change in water resource governance, which was tied together within the ahupuaʻa resource management system. The combination of these geopolitical factors culminated in the U.S.-supported overthrow of the Hawaiian Kingdom in 1893, which usurped power from Hawaiians, especially in terms of their legal control over land and water resources (Hutchins, 1946). Eventually, Hawaiʻi became a U.S. Territory subject to federal laws. Through U.S. federal court decisions, a system of water rights was established to replace the Hawaiian customs and water allocation methods (Anderson, 1985). For the first time in Hawaiian history, large amounts of water were being transported across ahupuaʻa and across watershed boundaries through large irrigation ditches built to transfer stream water from wetter to drier sides of the islands (Wilcox, 1996). When Hawaiʻi became a state in 1959, one major victory was the ability for judges to be appointed locally instead of by the federal government, thereby allowing a legal means to advocate for water rights with a closer reflection of local and indigenous values (Miike, 2004; Sproat, 2009, 2015).

Two centuries after first Western contact, the Constitutional Convention of 1978 set in motion Hawaiʻi's modern constitution, which began a renaissance of recognizing Hawaiian traditional and customary practices into law (MacKenzie, 2010). Ultimately, the State Water Code was enacted in 1987 with its roots in the indigenous Hawaiian concept of shared resources, governed by a public trust doctrine (Miike, 2004; Sproat, 2015). Both surface water and groundwater are held in the public trust, with four critical pillars of water resources management defined by the water code: (1) The protection of traditional and customary Hawaiian rights; (2) the protection and procreation of fish and wildlife; (3) the maintenance of proper ecological balance and scenic beauty; and (4) the preservation and enhancement of waters of the state for consumptive and recreational uses (State Water Code, 1987). In 2000, the landmark Waihole case strongly reaffirmed the public trust doctrine and put a legal emphasis on the responsibility of the State in managing water resources for the public interest in protecting and restoring stream systems. Furthermore, the case set a precedent for adopting the precautionary principle, which advises water managers to err on the side of protecting the resource in the face of uncertainty (Miike, 2004; Sproat, 2014; Wilcox, 1996). Except for some water rights held by Hawaiian homelands, Hawai‘i has no system of water rights that constrain management in the water code, unlike most other states (National Academies, 2016). However, the allocation of water resources continues to be an issue evolving through legal cases with residual claims to water stemming from the Plantation Era (Sproat, 2014).



- **1778: First contact**
  - Hawaiians lived and managed land and water resources in mountain to coast land divisions called *ahupua‘a*
- **1893: Overthrow of the Kingdom of Hawai‘i**
  - Through U.S. federal court decisions, Hawai‘i customs of water allocation were replaced by a system of water rights.
- **1916: Completion of the Waihole Ditch for Sugar Irrigation**
  - Large irrigation ditches were built in the early 20th century to move water from wetter to drier sides of the islands
- **1959: Statehood**
  - Allowed Hawai‘i to regain more local judicial control over land and water
- **1978: Constitutional Convention**
  - Laid the legal foundation for statewide water governance through a mandate to establish a state agency to manage water
- **1987: State Water Code**
  - Established the Commission for Water Resources Management and outlined critical water protections.

Figure 1. Three defining eras of water management in Hawai‘i: The ahupua‘a system, the plantation era, and modern management.

The epicenter of modern water management and policy in Hawai‘i has predominantly been O‘ahu, the population and economic hub of the Hawaiian Islands. Seventy percent of the state's population resides on the island of O‘ahu, and the economy of the urbanized island contributes 75% to the state's Gross Domestic Product (GDP) (DBEDT, 2018). Correlating to the closure of the sugar and pineapple plantations, the total freshwater use in Hawai‘i has declined markedly over the last half-century (Dieter et al., 2018). Although irrigation remains the largest water user in the state, agriculture, forestry, fishing, and hunting contribute 0.5% to the state's GDP (UHERO, 2019). Comparatively, many of the highest water users in Honolulu reflect some of the larger contributing industries to Hawai‘i's economy. Therefore, as a measure of output per water used, the current *productivity*[2] of freshwater use in Honolulu County is much higher than the other islands, contributing about $67 to the state GDP per 100 gallons of water consumed (Figure 2). Because more than 90% of municipal water is sourced from groundwater, the Pearl Harbor and Honolulu aquifers underlying the urban core of Honolulu are two of the state's most productive and critical aquifers (Gingerich & Oki, 2000). Many of the modern policy decisions

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[2] The productivity of water can be defined as any measure of output per volume of water used (Gleick, 2003). The use of Gross Domestic Product (GDP) is simply a conveniently available measured output that can be used for comparison between water uses. Inherent in using GDP as a measure of output is the absence of natural, social, and human capital that contributes to public wellbeing (Giannetti et al., 2015).

and management tools for freshwater in Hawai‘i developed out of O‘ahu, particularly concerning groundwater (Adler et al., 2018; Chun et al., 2017; C. C. K. Liu & Dai, 2012; Mink, 1980). Although all the islands that make up the State of Hawai‘i tend to have disparate issues based on local cultural and environmental factors, I consider O‘ahu (Honolulu) to serve as a critical location to (re)develop an integrated water management system that is prepared to accommodate future challenges. Integrated water management is not a new concept to Hawai‘i, where water management under the ahupua‘a system is an example of an integrated resource management model. However, the development of water resources over the 20th century in Hawai‘i largely followed management trends in the greater U.S., adopting “hard path” solutions to water management. To address 21st century forces, such as climate change, sea-level rise, population growth, and economic pressures, water planning and the evolution of water management in Hawai‘i needs to incorporate efforts to adopt “soft path” solutions into water resource governance to enhance the capability of Hawai‘i to address such pressures.

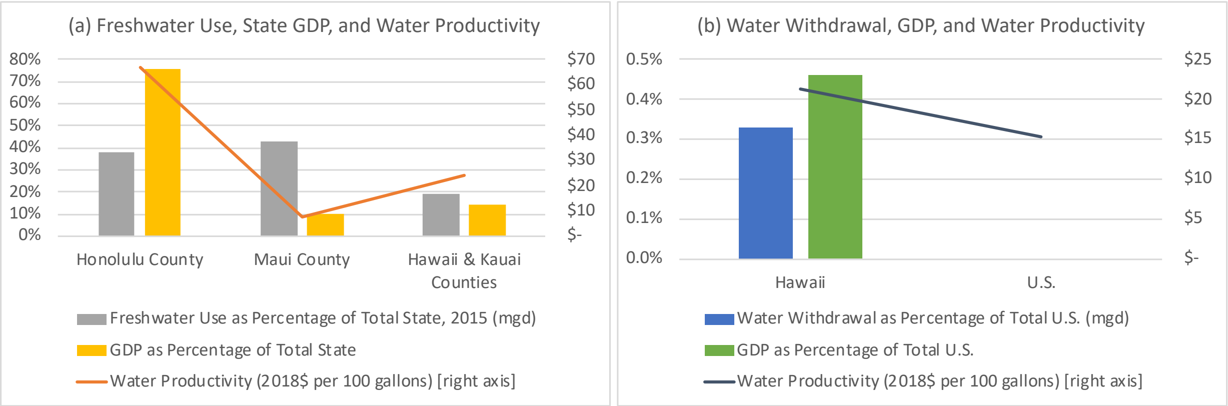

Figure 2. Water productivity as a measure of output by water used. (a) Honolulu County has high productivity of freshwater use because its contribution to the state GDP is much larger than its relative water usage. (b) The water productivity of the state of Hawai‘i is higher than the U.S. average. Data sources: DBEDT 2018; UHERO 2019

Urban Water Planning in the 21st century

Water use has fundamental and wide-ranging impacts on the environment, cultural values, public health, and the economy. The interconnected nature of the biophysical, socioeconomic, and geopolitical complexities of water systems create wicked problems that are often exacerbated by legacy problems and future concerns (Innes & Booher, 2010; Rittel & Webber, 1973). Wicked problems often involve competing and intractable trade-offs with no easy solution. Planners armed with a systems-thinking and a breadth of tools, therefore, can play a critical role in water planning, as described by the American Planning Association (Cesanek et al., 2017):

> *By virtue of their skills in fostering collaboration and community engagement, and through their understanding of regulatory tools available to manage land use, planners have important roles to play in coordinating with the various actors involved in water resource management and water services. The planning community is now rising to this challenge, as*

> *better understanding and skill in science, engineering, and consensus building across formerly siloed agencies become part of the planner toolkit.*

The purpose of this subsection is to provide a literature context for the subsequent applied research articles in this dissertation by defining a framing for socio-hydrologic water planning in the 21st century. I build my toolkit by 1) considering the future of water management through the literature on integrated water management solutions, 2) providing a context of postmodern planning through collaborative planning theory, and 3) discussing adaptive governance as a means by which to cope with the uncertainty inherent in wicked problems.

1. Integrated Water Management Solutions

1.1 Integrated Water Resources Management (IWRM)

The solidification of the concept of Integrated Water Resources Management (IWRM) can be traced back to the International Conference on Water and Environment that took place in Dublin in 1992. Put forth during this conference was a set of four founding principles, which continue to be widely accepted as the foundation of IWRM (Loucks et al., 2005, p. 45):

1. Water is a finite, vulnerable and essential resource, essential to sustain life, development and the environment.
2. Water resources development and management should be based on a participatory approach, involving users, planners, and policymakers at all levels.
3. Women play a central role in the provision, management, and safeguarding of water.
4. Water has an economic value in all its competing uses and should be recognized as an economic good.

These principles remain foundational as IWRM continues to evolve within specific contexts (Rahaman & Varis, 2005). The associated definition from the Dublin conference defines IWRM as a “process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.” IWRM is predominately applied to freshwater systems in the context of watersheds as units of management. The evolution of IWRM to other contexts (e.g., coastal systems, urban water systems, groundwater systems) has led to a common criticism that a diversity of definitions of IWRM exist in the literature and in application, which muddles the interpretation of the concept in various discussions (Biswas, 2008). IWRM is often both referred to as a specific theory of water management (Table 1) and a broad umbrella term applied to many concepts of integrated water management, which adds to the confusion of the concept.

Accordingly, decades of research around the implementation and efficacy of IWRM has led to much discussion in the literature around the ambiguity of the definition, applicability to a broad array of regions and issues, and implications of partial implementations of components under the label of IWRM. A broad assessment of IWRM as a concept, therefore, becomes difficult to evaluate between studies because of differences in implementation and research goals. Issues with the Dublin definition of IWRM as a baseline have also been raised. For example, Rahaman & Varis (2005) point out the lack of discussion around ecosystem restoration needed in some basin systems to implement IWRM. Despite the natural-waters focus of IWRM, they also indicate that fisheries and aquaculture require specific attention because of their critical role in food availability, as well as their contribution to the economy and ecosystem processes. Within the Dublin principles, privatization and water as an economic good garner further debate in the literature (Rahaman et al., 2004; Rahaman & Varis, 2005). Specifically, it raises issues of equity and accessibility and whether IWRM is more applicable in developing countries rather than developed countries (Rahaman et al., 2004).

Nonetheless, in places where full or partial implementation has occurred under the label of IWRM, failure is commonly linked to poor institutional structures or lack of funding (Loucks et al., 2005). This has led to literature discussions over what value IWRM provides. Jeffrey & Gearey (2006) point to IWRM as a theory that cannot be tested as a scientific theory, even though it has scientific backing. There is much debate over whether IWRM is a management theory, an argument for a certain approach to management, or a set of best management principles. Furthermore, the balance between complexity and breadth to any such systems approach remains a challenge. Applying IWRM to a particular location requires consideration of the specific context. Given the traditional surface water focus of this concept, this leads to the question of what is or should be "integrated" within the IWRM framework. Each added component within the integrated framework adds more complexity to the management model and might include integration across land and water, surface water and groundwater, water quantity and quality, upstream and downstream interests, human systems and economies, management levels, among others (Jonch-Clausen & Fugl, 2001).

Table 1. Select tenets of IWRM set forth by the International Water Association (from Jeffrey & Gearey 2006).

- IWRM should be applied at the catchment level
- It is critical to integrate water and environmental management
- A systems approach should be followed
- Full participation by all stakeholders, including workers and the community
- Attention to the social dimensions
- Capacity building
- Availability of information and the capacity to use it to anticipate developments
- Full-cost pricing complemented by targeted subsidies
- Central government support through the creation and maintenance of an enabling environment
- Adoption of the best existing technologies and practices
- Reliable and sustained financing
- Equitable allocation of water resources
- The recognition of water as an economic good
- Strengthening the role of women in water management

1.2 Integrated Urban Water Management (IUWM)

Although IWRM was developed to be universally applicable, it is useful to specify water issues of urban nature with growing city populations. Whereas IWRM focuses on watershed-scale management, urban areas can be situated wholly within a basin or span multiple basins, and therefore come with a distinct set of system boundaries not reflected by natural hydrological boundaries. The Global Water Partnership defined a distinct set of principles to apply to municipal water issues that build on the concepts defined by IWRM, dubbed Integrated Urban

Water Management (IUWM) (Bahri, 2012). Mitchell (2006) defines IUWM as a “comprehensive approach to urban water services, viewing water supply, drainage, and sanitation as components of an integrated physical system, and recognises [sic] that the physical system sits within an organisational [sic] framework and a broader natural landscape.” Operationalizing IUWM includes both demand- and supply-side management, utilization of alternative water supplies, and the concept of fit-for-purpose and decentralization. The key to IUWM is to find implementable ways to minimize the total impact of individual processes in the system while maximizing the collective system efficiency (Mitchell, 2006). Much like IWRM, however, Furlong et al. (2017) posit that even in locations where IUWM has been implemented, these integrated plans often overlook future uncertainty and risks related to climate change.

1.3 One Water

Similar to IUWM, One Water focuses on built water systems rather than natural hydrological systems. One Water considers the full municipal cycle of water from abstraction, diversion, capture, delivery, use to disposal (Figure 3). The framework changes the conventional paradigm of urban water management and urban design by including alternative water sources as viable and critical sources of water within the urban water budget, such as wastewater treatment and reuse, stormwater capture and management, and greywater use (Mukheibir et al., 2014; Paulson et al., 2017). Addressing both water quantity and water quality in a decentralized manner is a critical componentn to the One Water system framework, and the protection of various water bodies, including aquifers, streams, wetlands, estuaries, and coastal waters (Howe & Mukheibir, 2015). Although One Water tends to focus on the urban water cycle, the U.S. Water Alliance (2017) also adds sustainable agricultural systems as a component of the framework. Paulson et al. (2017) define One Water as an “integrated planning and implementation approach to managing finite water resources for long-term resilience and reliability, meeting both community and ecosystem needs.”

Whereas physical redesign and retrofitting of urban spaces and infrastructure to achieve One Water is capital-intensive, perhaps the greater obstacle to implementation lies within constraining institutional forces. First and foremost, One Water requires systems thinking and a cultural mindset that all water has value (US Water Alliance 2017). Furthermore, a high level of coordination between managing agencies and multi-faceted collaboration across sectors as a direct reflection of the interconnectedness of integrated water systems is an essential component of the One Water framework (Howe & Mukheibir, 2015; Paulson et al., 2017). Thus, as Mukheibir et al. (2014) explain, physical and institutional integration is by design. Overcoming institutional barriers requires agreeing on a unified, goal-oriented vision; strong leadership and political will that encourages innovative solutions; clear drivers and a sense of urgency; an integrated systems mindset across agencies and utilities; and coordinated methods and processes of data collection, information sharing, and communication (Mukheibir et al., 2014; WERF, 2015).

Although proponents of the One Water framework espouse the idea that achieving fully integrated systems lower management costs in the long run and create greater resilience (Howe & Mukheibir, 2015), this alone is unlikely to be enough to overcome the conventional management practices embedded in urban water systems. Implementing One Water requires consideration of incentives, policies, or agency structures needed to drive the implementation of working agreements between agencies and coordinated systems and overcome the considerable institutional headwinds and market forces. WERF (2015) and Paulson et al. (2017) offer case study examples where components of the One Water have been successfully implemented on various fronts. Such case studies aim to build a generic and widely applicable pathway for One Water implementation. Compared to IWRM, which is largely regarded to be achieved only if all defined tenets can be met, One Water offers flexibility in its ability to implement strategies component-wise. However, there is a paucity of evaluative research of One Water in practice, and much of the momentum around One Water lies in the adoption of components as a conceptual theory of practice rather than a proven theory of practice.

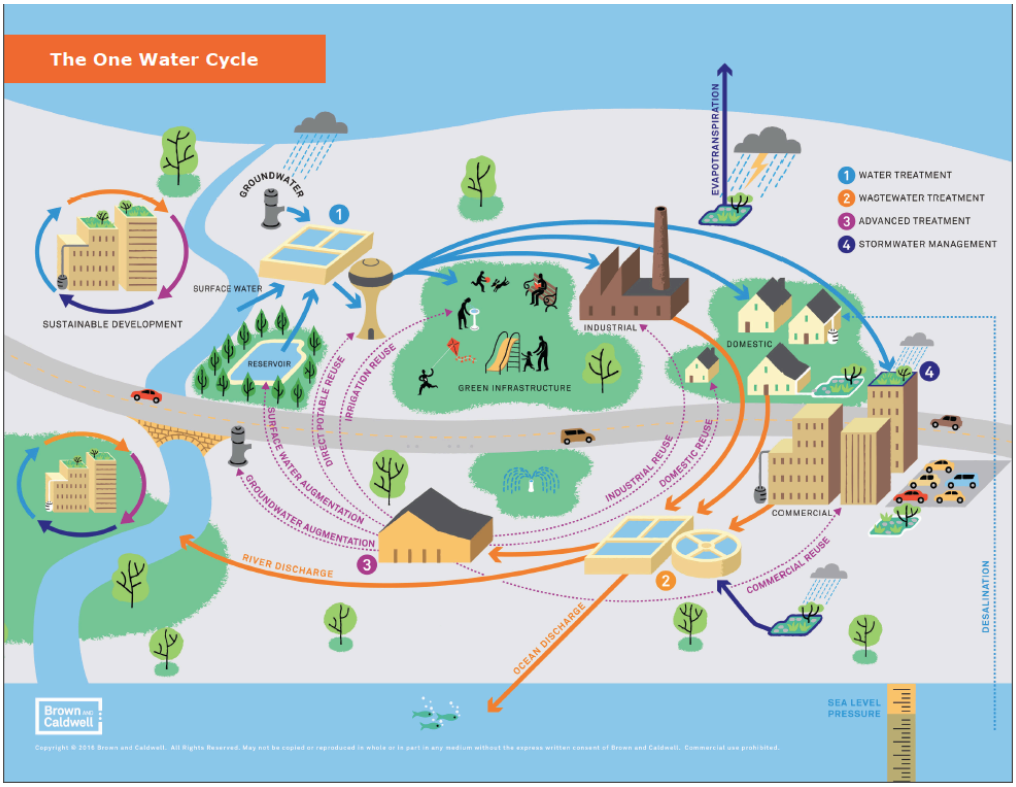

Figure 3. Conceptualization of a One Water city from Paulson et al. (2017)

1.4 Water Sensitive Cities

While the One Water framework has become increasingly recognized and embraced as an exemplary form of urban water management in the professional sector, especially in the U.S., a similar concept developed in Australia describes urban water management in terms of a six-stage evolution from a "water supply city," in its crudest form, to a "water sensitive city," in its most advanced and idealistic form (Brown et al., 2009). Whereas One Water represents an idealistic end-form framework with achievable components, the Water Sensitive Cities framework views urban water management as 'transitionary,' both in terms of service delivery functions and cumulative socio-political drivers. This dynamic framing lends itself to understanding the institutional arrangements of water management upon which to improve (Figure 4). Brown et al. (2009) build their analytical approach to understanding institutions and means of transition within the Water Sensitive Cities framework on new institutionalism and Healey's (1997) concept of "soft" and "hard infrastructure" (explained further in Section 2.1). The former represents informal networks and social or cultural structures, and the latter relates to the formal organizational structures created by policies or regulations and governance arrangements. Brown et al. (2009) suggest that a change in water management requires “a mutually reinforcing shift” within the cognitive, normative, and regulative pillars that comprise institutions.

As with any framework that aims to sustainably manage water for societal, economic, and environmental needs for now and into the future, both One Water and Water Sensitive Cities challenge the underlying obligation of municipal governments to focus solely on providing inexpensive but reliable water service and delivery. One Water offers an end goal for water management, and in fact, Mukheibir et al. (2014) consider the final stage of a Water Sensitive City interchangeable with the One Water framework. As a static framework, One Water lends itself to better understanding where there are points of operational inefficiency and waste within the flows (e.g., stormwater, greywater, wastewater, etc.) of the urban water cycle. At the same time, viewing water management as an evolution of stages, as with the Water Sensitive Cities framework, elicits a greater understanding of ‘sticking’ points between phases for any particular application.

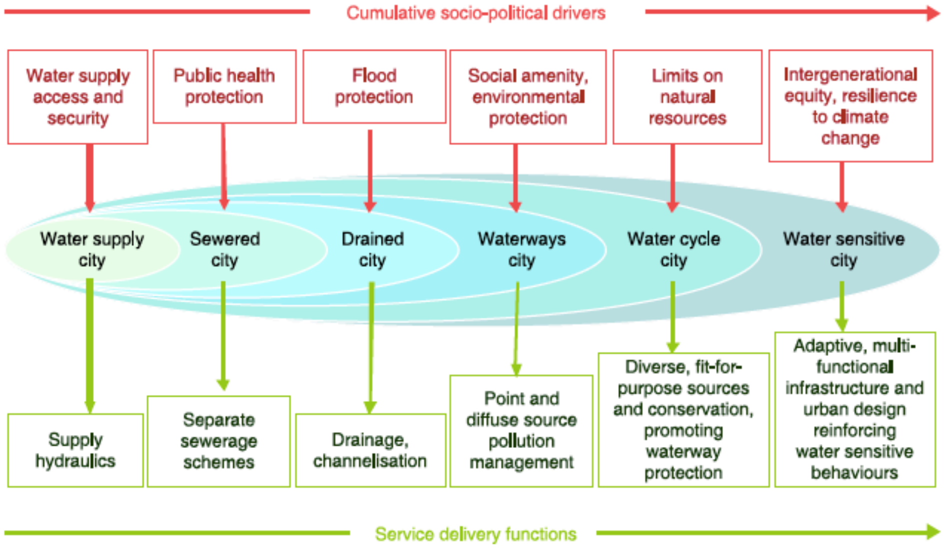

Figure 4. The progression of water management in cities, from Brown et al. (2009).

1.5 Water Security

Although the concept of water security largely formed out of issues of scarcity (Staddon & James, 2014), it now connotes both protection against the destructive side of water and the protection of water resources for the productive use of water (C. A. Scott et al., 2013). The destructive side of water security entails understanding risks and weighing the acceptability of outcomes. To compare to previous frameworks discussed, I focus on the productive face of water security and the balance required to meet the ecosystem and societal needs given the overarching hydro-climatic processes. Even more than IWRM, the broad nature of the concept of water security leads to a broad array of definitions and interpretations. Hoekstra et al. (2018) suggest that definitions vary based on the perspective from which they are defined, whether disciplinary, problem-oriented, goal-oriented, or the type of integration or perspective of the process of interest. A definition of water security as a theoretical framework comparable to IWRM and others discussed here is: “the availability of an acceptable quantity and quality of water for health, livelihoods, ecosystems and production, coupled with an acceptable level of water-related risks to people, environments and economies” (Grey & Sadoff, 2007).

Compared to IWRM and One Water, water security adds a focus on threats, shocks, and tipping points, which directly maps onto planning around vulnerability, risk, and resilience (Bakker, 2012). Furthermore, water security emphasizes the trade-offs between economic growth and sustainable development objectives, which are inherently political (Bakker, 2012; Staddon & James, 2014). Unlike IWRM, water security literature tend to focus on measurable outcomes that and has led to the development of a variety of metrics and indices for empirical evaluation of water security (Hoekstra et al., 2018). A basic formulation might consist of a weighted sum of the percentage of basic household needs met, agricultural production, the percentage of water available for the environment, measurement of risk buffering, and a measure of self-sufficiency (Lautze & Manthrithilake, 2012). Water security can also be evaluated at different scales, such as household, basin, regional, national, or even global (Grant et al., 2012). For example, Vörösmarty et al. (2010) conduct a global analysis of the incident threat to water security and river biodiversity. Just as there are a wide array of definitions, there are also various metrics for analysis to different ends and a variety of strategies for water security (including convential “water security” that does not consider the impacts of sourcing “new” water from outside of a defined system). At the very least, water security is meant to define outcomes and provide a structure by which progress towards such outcome can be measured.

1.6 Nexus Approaches

IWRM, One Water, and water security, as their names imply, remain water-centric approaches to managing resources despite promoting a systems-thinking approach. As de Loe and Patterson (2017) describe, water-centric approaches assume that other sectors and societal actors should adjust their behavior based on a shared normative view of concern over water, which may not be congruent with the missions of other various resource management sectors. Because of the intimate connection to food security (Falkenmark, 2001)—including the virtual water footprint (i.e., water imported or exported across boundaries through food and other consumer goods) (Postel, 2010) —and the energy sector (e.g., wastewater), the food-energy-water (FEW) nexus approach offers a means by which the land and energy sectors can be managed in concert with water. Recognizing the co-benefits that arise from water use in various forms in conjunction with the food and energy systems can lead to greater efficiencies across sectors. Still, it may lead to critical trade-offs that may be unpalatable when considering one sector alone. A clear example of co-benefits within the nexus framework is the increased energy efficiency that results from consuming less water, with the bulk of energy use in the urban water cycle occurring in wastewater facilities (Copeland & Carter, 2017; R. Young, 2013). Such efficiencies translate into monetary savings for water managing utilities. On the other hand, strategies such as water reclamation and recycling would increase energy consumption (Naik & Stenstrom, 2016). This lends to the central need for Nexus approaches to define clear goals and measurable outcomes.

Although not explicitly defined within a land-water nexus framing, the river basin management approach promoted through IWRM implicitly connects land and water management (Rahaman et al., 2004). The relationship between proper land management and reliable water supply is well recognized by researchers and practitioners and proves worthy of investment (Ozment et al., 2016). Water can also be considered at a much finer scale, in particular as it relates to food production. Falkenmark & Lundqvist (1998) distinguish “blue water” (i.e., flowing water such as rivers or aquifers) from “green water” (i.e., productive water loss such as transpiration from plants). They further suggest that more attention is needed to complement these two types of water and the necessity for the management of land and water in an integrated manner for greater water security. Defining an appropriate scope of a system is critical to understanding the FEW nexus. Gober et al. (2013) implicate differences in scale as an underlying reason for water and land to be managed in different sectors. In urban systems, development is rarely driven by water availability, and as such water management is usually considered “subordinate” to land use planning (Gober et al., 2013). Moreover, implementation of the One Water framework, for example, requires working at a parcel level scope to put decentralized and green infrastructure into place, especially for new development (WRF, 2018).

1.7 Water Resilience

Integrated water management concepts continues to evolve into new or repackaged framings to address current issues and upcoming challenges along the water frontier. Water resilience, for example, is an emerging concept similar to water security in addressing risks and building on the concept introduced by Falkenmark & Lundqvist (1998) of better co-management of “blue” and “green” water (Falkenmark & Lundqvist, 1998; Rockström et al., 2014). Water resilience adds the implications of planetary boundaries (Rockström et al., 2009) to the discourse and concepts of dealing with regime changes fundamental to the roots of resilience in ecology. Although water is managed locally, the connection of water within the FEW systems means that water is increasingly moved around a globalized world in virtual form (Hoekstra & Chapagain, 2008). That is, water is transported in and out of management boundaries through food and other commodities. Therefore, it becomes critical to consider water management impacts in the context of planetary boundaries. This is one benefit of water resilience, water security, and nexus approaches over IWRM and One Water, which provides the flexibility to nest integrated management of resources at multiple scales of governance. As such, water security and water resilience can provide a broader scope of coverage to interconnected issues that span inter- to intra-basin and beyond. Whereas IWRM and One Water concepts aim to shift the paradigm of local, conventional water systems to integrated systems management. Water security and water resilience are positioned to address real and upcoming challenges imposed by global climate, market, and population forces. The trade-off between greater adaptability and scope in each integrated water management theory is the complexity of implementation and the breadth of water governance change needed for integrated management success.

2. Postmodern Context: Collaborative Planning Theory

While planning is a process used to shape the future, planning theory should also be reflective to ensure that the process is adapting to meet contemporary evolving challenges (Innes, 1998). It is well-accepted that planning theory has moved into a postmodernist era (Hemmens, 1992; Irving, 1993) that is not singularly definable. However, postmodernist theory can be better understood through the hallmark characteristics of modernist planning theory and its rejection thereof. While modernist planners dealt in a realm of order and predictability, postmodernists reject that the world can be viewed as such and acknowledge the reality that politics and power play into projects, plans, and policy decisions. Postmodernists, therefore, use communication and collaboration as a key element of problem identification, solving, and capacity building to deal with the reality of politics and power. While modernist planners view problems as comprehensible and solvable with scientific and technical expertise, postmodernists embrace the idea that most social-ecological problems are complex with no definitive solution—wicked problems. Innes & Booher (2010) anoint the modernist approach as the "DAD syndrome," or "Decide, Announce, Defend." In terms of modernist planning practice, Healey (1997) describes the profession of planning in the context of three traditions: Economic planning, physical development planning, and policy analysis and planning. Each is rooted in exercising technocratic management over problems that cannot address the dimensionality of issues and their evolution in space and time.

Addressing issues of power, complexity, and communication has taken postmodern planning theories in many directions that continue to evolve and intersect and resulted in many threads of theory. Here, I focus on collaborative planning as a postmodern theory that comes from the communicative turn in planning (Innes & Booher, 2015) because it can be closely connected to governance theory and understanding roles of institutions in paradigm shifts. In contrast, other postmodern theories may focus more on the details of the planning process. I discuss how collaborative planning can be used to understand and address power, complexity, and communication. I also relate the theory to water resources management applications to discuss the benefits and challenges of viewing water governance through a collaborative planning lens. The postmodern turn in planning is congruent with the shift of water resources management toward integrated or "soft" solutions. Therefore, cross-pollination between these bodies of literature may offer ideas to move forward with integrated water management.

2.1 The Development of Collaborative Planning

In her book "Collaborative Planning," Healey (1997) distinguishes two types of infrastructure—"hard" and "soft."[3] Formal institutions of government, structures of power, and policies compose "hard infrastructure." Whereas "soft infrastructure," or informal institutions, is relational and comprised of social, intellectual, and political capital. Healey elaborates that the theory of collaborative governance is the interaction of the two, enabling consensus-building and mutual learning to address issues that arise from the co-existence of diverse people in the same spaces. Healey (2009) defines governance as "any kind of practice centered on resolving collective action problems in the public sphere or realm," and planning as "a governance practice that has evolved to address the difficulties created by the complex colocations of activities and their relations and the impacts these colocations generate across space-time." Accordingly, as a situation-based practice (Healey, 2009), collaborative governance employs nonlinear and inclusive planning towards goals that can be varied and changing (Innes & Booher, 2010). Proponents of collaborative planning suggest that it can be transformative in its ability to build institutional capacity.

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[3] Within this dissertation, I use the terms "hard infrastructure" and "soft infrastructure" to refer to gray- and green-type stormwater infrastructure, respectively. Therefore, I disambiguate what Healey (1997) refers to as "hard infrastructure" and "soft infrastructure" by using the terminology "formal institutions" and "informal institutions," respectively, instead.

Collaborative planning, as Healey (1997) describes the theory, builds on planning as a communicative practice, institutionalism thought in sociology, and spatial planning process. Drawing on the works of Anthony Giddens and Jürgen Habermas, who have also been a point of departure to other postmodern planning theorists to similar ends (Flyvbjerg, 1998; Forester, 1989; Innes, 1995; Innes & Booher, 2016), she sets the stage for collaborative planning as a marriage of new institutionalism and communicative planning. Institutionalism, as Healey describes, offers a way to overcome dilemmas through collaboration by recognizing individual and cultural differences and building shared systems of meaning and cultural conceptions. Therefore, it is incumbent on the planner to find the right balance between the individual and the collective. In this way, collaborative planning incorporates a non-physical view into the dynamics of urban systems comprised of physical elements. That is, recognizing how everyday social and work life, local economies, land and property, and the natural environment influence structures in space and time, especially in an increasingly globalized world. In this non-physical view of planning, power, complexity, and communication are particularly salient subjects discussed by postmodern planners.

2.2 The Interplay between Power and Collaboration

Politics manifest in various forms within both the formals and informal institutions of governance, where politics is more widely about power and its manifestations in various forms and at different scales and times. To create a fair and inclusive process, implementation of collaborative planning includes being able to recognize forces of power and equalize them such that governance reflects collective interests. If informal institutions are comprised of social, intellectual, and political capital (i.e., network capital), then power differentials develop when individuals or groups acquire greater amounts of these types of capital. This is why Flyvbjerg (1998) suggests that power is knowledge and not the reverse. That is, power can create its own reality, and people that hold greater network capital hold greater influence over planning and decision-making processes. Whereas it might be commonly thought that laws and regulations—that comprise formal institutions—would have greater power over informal institutions, Flyvbjerg further argues that social power can prevail over the law, rationality, and public interest. In the postmodernist planner's role to guide future action, diffusing such power towards true collaboration is imperative for professional practice, even when it may be uncomfortable (Flyvbjerg, 2013).

Forester (1989) further argues that it is the planner's professional and ethical role to recognize and understand forces of power that can be destructive and address them in the context of planning practice. Thus, it is critical to understand how to recognize these forces of power. This requires political savvy (Forester, 1989) and pragmatism (Healey, 2009; Mäntysalo, 2004). Political savvy entails recognizing the roles of individuals, groups, and institutions in the propagation of information and power. Forester (1989) uses critical theory as a reflective method to understand how historical, social, and ideological forces create structures to produce or constrain power. Mäntysalo (2004), however, argues that critical theory is insufficient by itself. Rather, having practical judgment as part of pragmatist thought allows for "discovery through experience" and offers planners tools to seek information through the planning process (Healey, 2009). In a capitalist system, equalizing power is not a trivial task and requires skillful facilitation to listen, probe, and instigate collectively beneficial outcomes (Forester, 1989).

Collaborative planning, therefore, requires a strategy of empowerment to create organizational arrangements so that important stakeholders can be represented (Ansell & Gash, 2008).

2.3 Communication in the Collaborative Process

Communication is often the key tool in the collaborative planning framework to deal with power and politics that enter into the planning process. Flyvbjerg (1998) proposes both that "power is knowledge" and that "power defines reality." Since communication is where knowledge exchange occurs, it is a means to help disperse power and redefine reality according to the collective. That is why Forester (1989) advocates the role of a planner as a facilitator to encourage inclusivity and build legitimacy in the planning process. This comes with its own set of challenges. Mainly, inclusivity means that the diversity of values, interests, knowledge, and cultures increases, and the planner must learn how to mediate conflicts and move beyond disputes. This requires recognizing context and using creativity to explore differences and engender means for joint knowledge creation to affect change to a greater collective benefit. Collaborative process skills can be learned through facilitating, moderating, mediating, or negotiating theory and tactics (Forester, 2009, 2013; Gray, 1989; Islam & Susskind, 2013; Wondolleck & Yaffee, 2000).[4] Additionally, in the pragmatic spirit (Healey, 2009; Mäntysalo, 2004), it is well-recognized that collaborative skills are honed through experience in navigating the politics of power.

Critics of collaborative planning often point to the practical difficulties in carrying out a truly inclusive and participatory process (Huxley, 2000). However, collaboration need not always be an actively facilitated process. Creating the space for informal and formal collaboration to occur organically can benefit the process. Whereas a place is a specific location, space can be thought of as the intersection of people, cultures, ideas, time, and places where knowledge exchange and shared experiences can occur. One role that a planner might fill is to provide these spaces to foster consensus-building and mutual learning (Coaffee & Healey, 2003). To that end, spaces have the power to shape informal institutions through network capital development and are therefore a critical element to collaborative planning practice. Collaborative planning that incorporates this sort of 'passive facilitation' can be strategic in targeting groups that stand to gain from network capital improvement or to create ties between social groups where lacking. Any collaborative processes that generate or build towards common ground, a common product, or consensus create power in that collaborative outcome and strengthens the informal institutions of the system.

2.4 Addressing Complexity through Collaborative Governance

The formation of the theory of collaborative governance is also a direct response to the acknowledgment that planning problems are in themselves complex. Postmodern planning recognizes that "wicked" problems that often encompass multiple dimensions do not have clear solutions (Rittel & Webber, 1973). Without solutions, collaborative governance offers an alternative way towards successful outcomes in wicked problems (Emerson et al., 2012; Innes &

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[4] There are many dimensions to consider within the tactics and theories that surround collaboration, which is discussed and debated in the literature. However, in the interest of brevity, I will not detail these components here. Margerum (2002) gives a full range of criteria by which to evaluate collaborative processes based on an extensive literature review.

Booher, 2010). For example, one first-order effect of collaboration might be building network capital within the informal institutions, while second- and third-order effects may include developing changes in perceptions or new institutions (e.g., changing the formal institutions) (Innes & Booher, 1999). Dealing with wicked problems means dealing with issues that are constantly evolving through inside and outside forces. With that comes uncertainty, however. Uncertainty in planning can be "paradoxical," as Abbott (2005) puts it, because there is both uncertainty in the issue being addressed and uncertainty that arises out of the planning process. No doubt, the process of collaboration—addressing issues of power and communication—creates greater complexity. The paradox lies in the idea that collaboration aims to address the uncertainty created by the complexity of the situation being addressed. Abbott explains further that recognizing the nature and timeframe of change of components that comprise the issue of interest can help reduce uncertainty in the planning process. Understanding how informal and formal institutions in the context of that particular issue helps elucidate the type of uncertainty encountered and whether it can be reduced through more research, policy guidance, or coordination.

2.5 Collaborative Planning and Water

In their book "Planning with Complexity," Innes & Booher (2010) begin with the statement, "water planning is a wicked problem," for which they apply the theoretical framework of collaborative planning. Water issues evolve over biophysical, socioeconomic, and geopolitical dimensions and can lead to highly contentious disputes (Islam & Susskind, 2013). It is increasingly recognized that integrative management tools that attempt to capture the co-evolving nature of these dimensions are needed to manage and plan for water resources (Bogardi et al., 2012; Sivapalan et al., 2014; Wheater & Gober, 2015), especially in the face of a no-analog future (Postel, 2010). Complexity is no stranger to water planning issues, and as proponents of collaborative planning would suggest, greater complexity and interdependence of systems leads to greater demand for collaboration (Ansell & Gash, 2008; Elshall et al., 2020; Innes & Booher, 2010). Since collaborative planning application has experienced a range of success in collaborative environmental governance cases (Bodin, 2017), it is worth understanding what constitutes the complexity of the managed system and how that contributes to uncertainty. Abbott (2005) defines uncertainty as "a perceived lack of knowledge…that is relevant to the purpose or action being undertaken." There are four types of environmental uncertainty that Abbott describes, in addition to the process uncertainty that is resultant of the planning procedure itself: uncertainty about basic relationships, uncertainty stemming from the actions and future intentions of other people or groups, uncertainty about the influence of the wider social environment, and uncertainty arising from the truly unknowable. In complex water problems, uncertainty can be crippling, especially where risk is high, that is why it is critical to know what is gained from employing a collaborative governance framework (T. A. Scott & Thomas, 2017). Table 2 outlines the benefits that can be gained through collaborative governance as proposed by Scott & Thomas (2017) and the five dimensions of uncertainties as framed by (T. A. Scott & Thomas, 2017).

Table 2. Types of uncertainty encountered in environmental planning and the potential benefits of utilizing collaborative governance to reduce uncertainty.

Type of uncertainty (Abbott, 2005)	**Collaborative governance proposed benefits** (T. A. Scott & Thomas, 2017)
value uncertainty—uncertainty stemming from the choices encountered throughout the planning process *causal uncertainty*—uncertainty about the basic causal relationships (physical, economic, and social) in the situation *human and organizational uncertainty*—the actions and future intentions of other people and organizations in the situation are difficult to predict *external uncertainty*—uncertainty about the wider social environment and how it relates to and influences the situation *chance uncertainty*—truly unknowable one-off chance events will also affect the situation.	• Gain reputational benefits • Leverage external resources • Achieve economy of scale • Enable low-level actions • Reduce network points of contact • Foster external actions that match internal goals • Leverage existing processes • Gain input from clients • Garner external expertise • Work across policy sectors • Co-opt potential litigants • Involve affected parties • Involve other jurisdictions • Leverage high-level actions • Incorporate peripheral actors • Connect mutual network partners • Enable alternative actions

Although researchers such as Bodin et al. (2016) and Sabatier et al. (2005) employ empirical methods to evaluate the efficacy of collaborative approaches in environmental and water management, as Lubell (2015) suggests, most research on collaborative partnerships ignores the fundamental reality that environmental policy is formulated in complex institutional systems. And although empirical analysis can help understand the structure of the informal institutions and how it interacts with the environmental situation of interest, it does not address the formal institutions, which is more difficult to consider within that type of analysis. Power is often nuanced and difficult to analyze systematically through these types of network systems analysis unless the power exchanges between actors can be directly measured (e.g., money flows). Nonetheless, empirical methods are inherently apolitical, and therefore are unable to contribute to a full understanding of power, either within the informal institutions or in the interaction between the informal and formal institutions. Suppose collaboration is to be understood as a communicative process. In that case, it may also be difficult to fully capture the power of the information exchanged between actors within a social map, especially as complexity increases. For example, Barnes et al. (2016) use network analysis to assess the dissemination of fishery bycatch regulations within social networks and find that information does not cross social networks mainly divided along racial divides. In their case, because they observed fishers only and one piece of information, it simplified their analysis, which may not be possible for more complex water or environmental problems. It nonetheless emphasizes the importance of dialogue within the governance network, especially across social groups. Ultimately, collaborative dialogue can increase network capital which is linked to power; power can run deep within the structures of society and can manifest when individuals make decisions on the fringe of issues. Thus, power can form through the production of ideas (Innes & Booher, 2010). These processes are much more difficult to systematically research, especially as they increase in complexity, which adds to the general uncertainty of the collaborative planning process.

Water governance—especially in the context of integrated water management—is a viable candidate to engage collaborative planning theory. Some literature has explored the arena of collaborative water governance (Sabatier et al., 2005) or collaborative governance in other environmental applications (Bodin, 2017) to evaluate the success of collaborative governance in environmental outcomes. Nonetheless, there is still a paucity of research that assesses the extent to which collaboration leads to improved environmental outcomes (Koontz & Thomas, 2006). Most research instead focuses on the direct or indirect benefits that collaboration conceptually provide in the planning process. Furthermore, evaluative methods are not able to adequately assess the interplay of power within the social governance network, nor the interplay of power between the informal and formal institutions that comprise the situation of interest. Planning theory can add a strong theoretical basis for addressing matters of power, conflict, and diversity to social-ecological systems theory. Without these components, it is difficult to capture the context of systems change (Wilkinson, 2012). Still, despite critiques and existing research gaps, it is hard to argue against the overall potential for beneficial impact that collaborative governance provides in terms of its direction-setting foundation (Margerum, 2002). This is especially the case in water governance, which is characterized by great uncertainty stemming from its co-evolving biophysical, socioeconomic, and geopolitical dimensions. Collaborative governance has the potential to quell some elements of uncertainty that arise from situational and process uncertainties.

Distrust can add uncertainty to the planning process. Lockwood et al. (2010) propose “good” institutional principles of environmental governance as legitimacy, transparency, accountability, inclusiveness, fairness, integration, capability, and adaptability. These are characteristics that may build trust between community and government. Furthermore, Tsai and Ghosal (1998, p. 465) describe trust as relational social capital:

> *Trust can act as a governance mechanism for embedded relationships. Trust is an attribute of a relationship, but trustworthiness is an attribute of an individual actor involved in the relationship. Since trust can induce joint efforts, a trustworthy actor (one who can be trusted by other actors) is likely to get other actors’ support for achieving goals to an extent that would not be possible in a situation where trust did not exist. [in-text citations omitted]*

Therefore, community trust is an important component of governance that can be fostered through collaborative planning and the dialogue between governing institutions and community institutions.

3. Adaptive Governance Concepts

Conventional resource management is aptly referred to as command-and-control resource management and does not adequately cope with uncertainty and change (Armitage et al., 2009). Adaptive governance research aims to understand the structure of institutions that comprise governance arrangements and how institutions react to changes within and external to the governed system. Governance both guides and is guided by public and private interactions towards desirable outcomes (Armitage et al., 2009; O. R. Young, 2013). Lockwood et al. (2010) propose adaptability to be among the “good” institutional principles of environmental governance. Many researchers theorize around or analyze particular cases regarding the social structure of the governance system. Lines of inquiry might focus around understanding the organizational structure of governance (Koliba et al., 2011), relevant attributes of governance systems (McGinnis & Ostrom, 2014), the role of leadership in self-organization (Giest & Howlett, 2014), how risk shapes governance networks (McAllister et al., 2015), flow of information on environmental outcomes (Barnes et al., 2016), and what effectiveness of governance is and how to assess it (Bodin et al., 2016; Provan & Kenis, 2008). These lines of inquiry are critical to conceptualizing system change, which can be abstracted in many ways. It can be analyzed at the micro-scale (i.e., actor to actor), such as processes for interventions to generate social influence or change (e.g., linking knowledge with action, enhancing collective action, promoting social learning) (Henry & Vollan, 2014; Ostrom, 2010; Valente, 2012; O. R. Young, 2002). Change can also connote macro-scale rearrangements towards more desirable outcomes of governance, such as achieving collaborative (Guerrero et al., 2015) or adaptive governance (Duit & Galaz, 2008; Folke et al., 2005; Koontz et al., 2015), or towards protecting against shocks to the system, such as enhancing system resilience (Erickson, 2015; Folke, 2006; Ostrom, 2010; Wilkinson, 2012).

Within the umbrella of adaptive management, there are the active and passive types, there is co-adaptive management, and there are governance versions of each. Active adaptive management treats an ecosystem like a laboratory where hypotheses can be actively tested, whereas passive adaptive management takes a learn-by-doing and adjust approach. Hasselman (2017) suggests that much of the confusion about the concept of adaptive management stems from differences in the underlying epistemologies of those who entered the literature discussion. Adaptive co-management, at its simplest, is a melding of the concepts of adaptive and collaborative management and differs largely from adaptive management in that it aims to empower local entities in the management process (Armitage et al., 2009). In recognition that implementing a management theory alone cannot change how resources are managed unless the structure of governance allows, these concepts can be applied to governance to allow for best direction setting in the overlying structure. Governance can also occur across scales, whereas management is usually confined to a local scale (Allan & Curtis, 2005). Collaborative governance establishes an inclusive process with collective decision-making. Adaptive governance provides more flexibility to cope with unexpected change or shocks to the system. Table 3 provides a summary of concepts, however, the delineation between each may not be so strict in practice.

While it is widely agreed across the literature that integrated social-ecological governance should include an element of adaptability (Lockwood et al., 2010), but how to achieve adaptability garners an extensive debate in the literature. Governing common pool resources is not a simple prescriptive task (Dietz et al., 2003), and there is no panacea for environmental governance (Ostrom, 2007). The need for adaptive mechanisms to management and governance gave rise to the concept of adaptive management, which stems from ecological literature on resilience (Holling, 1973). There is little consensus over how adaptive management is defined much less how it should be applied (Hasselman, 2017). Consequently, differing concepts of built-in, reflective change have sprouted out of the ambiguity of adaptive management. Each concept aims to address issues of uncertainty that stem from incomplete knowledge (i.e., multiple perspectives are needed to complete the understanding of a system), imperfect knowledge (i.e., knowledge is inadequate or inexact and can be reduced through research), or unpredictability (i.e., variability and change in the system and requires the ability to cope or respond) (Hasselman, 2017).

Table 3. Summary of concepts encouraging adaptability. (Adapted from Hasselman 2017; definition of collaborative governance from Ansell & Gash 2008, Emerson & Gerlak 2014, Koontz et al. 2004; definition of active and passive adaptive management from Allan & Curtis 2005)

Approach and definition	**Uncertainty addressed**	**Objective**	**Context of application**
Passive adaptive management is an active approach to reflection comprising effective evaluation, rewards for thinking and reflection, and appropriate communication fora for all project participants; and provision of mechanisms for incorporating learning into planning and management.	Incomplete knowledge and unpredictability	Responsiveness	Policy- or issue-specific; Government-led responsibility
Active adaptive management is passive adaptive management, plus management activities are specifically designed to test hypotheses through ecosystem-scale holistic experiments; complexity is embraced; provision of mechanisms for multidisciplinary and multi-stakeholder involvement; and there is a strong emphasis on social learning.	Imperfect knowledge	Experimentation	Policy- or issue-specific; Government responsibility
Adaptive co-management is a type of adaptive management that empowers resource users and managers in experimentation, monitoring, deliberations, and responsive management of local-scale resources, supported by, and working with, various organizations at different levels.	Imperfect, incomplete, and unpredictability	Local empowerment	Issue- and location-specific; Local responsibility supported by government
Collaborative governance is a governing arrangement where one or more public agencies directly engage non-state stakeholders in a collective decision-making process that is formal, consensus-oriented, and deliberative and that aims to make or implement public policy or manage public programs or assets.	Predominantly incomplete knowledge	Inclusiveness	Across governance scales; Local responsibility supported by government
Adaptive governance systematically integrates adaptive management across the political processes, polity and policy aspects of governance, with the implications to legitimacy and accountability addressed by the structures and agents present.	Predominantly unpredictability	Flexibility	Across governance scales; Shared responsibility between government and non-government

3.1 Adaptability in Water Governance

Water systems face great uncertainty stemming from imperfect knowledge, incomplete knowledge, and unpredictability, and are thus suitable candidates to apply concepts that incorporate adaptability. Adaptability with critical and continuous learning can minimize the adverse impacts of any given decision if evaluation and course correction are incorporated into the governance structure. Systematic multidisciplinary research has demonstrated that a wide diversity of adaptive governance systems have been effective in resource management applications (Dietz et al., 2003; Peat et al., 2017), because adaptive governance enables heuristics to occur. Adaptive governance and collaborative governance are applied to different ends; however, one does not preclude the other from being applied. Perhaps the clearest difference between the two theories is in how knowledge is generated. While collaborative governance theory emphasizes shared learning to generate capacity, adaptive governance builds capacity through cognitive flexibility and using new information to develop new responses as needed (Emerson & Gerlak, 2014). Still, these approaches can be used in concert with each other in the appropriate setting, scope, and scale for water governance (Huitema et al., 2009; Innes & Booher, 2010).

Incorporating adaptability into urban water governance comes with its challenges. Physical water infrastructure, for example, is put into place with the intent of lasting many decades. On the other hand, adaptive action related to physical infrastructure is unlikely to be achieved without an adaptive governance structure in a water system to enable change to occur. Even though physical infrastructure can create a strong constraint to adaptability, it can also be constrained by the formal institutions of governance through multiple levels of regulations, codes, and agencies. For example, in some U.S. states, stormwater capture and greywater use—critical alternative water sources—may be unlawful and require legislative solutions to enable widespread implementation (National Academies, 2016). More research is needed to understand what types of laws, regulations, and codes can accommodate adaptive governance while maintaining clean, reliable water standards. The interaction between formal and informal institutions also add to the challenge of adaptability. As Abbott (2005) points out, even though adaptability aims to reduce certain types of uncertainty encountered in decision-making, the planning processes themselves add uncertainty and complexity. Critical elements of the planning process that are not met, such as consensus (Susskind et al., 2010), could lead to a failure to produce the desired outcome.

Summary

This introduction frames and contextualizes the articles of this dissertation that follow withing literature on integrated water management solutions, collaborative planning, and adaptive governance. I regard this literature as my socio-hydrologic planning lens. That is, I consider how collaborative planning and adaptive governance can help shape systems of water and people to evolve together towards better management solutions. Certain integrated water management solutions offer a means by which to address legacy water management issues and current and upcoming challenges depending on the context of the challenges. For this dissertation, I focus on the City and County of Honolulu (also the island of Oʻahu). For the context of water management and the challenges faced by Oʻahu, I particularly find the One Water (e.g., Cesanek et al., 2017; US Water Alliance, 2016, 2017) and Water Sensitive Cities (e.g., Brown et al., 2009) frameworks to be useful tools for defining a better state of management. Soft path solutions (e.g., Christian-Smith et al., 2012; Gleick, 2003) also provide objectives for adapting water management towards addressing legacy water management impacts and future water challenges.

Article 1 —
Do you put your ‘water’ where your mouth is? A study of residential water conservation in an island setting

Abstract

Water conservation is often a cost-effective means to meet future water demand. Since residential water use is a significant sector in total urban water demand, understanding what motivates residential water conservation is critical to shaping effective programs and policies. This study analyzes factors that predict measurable reductions in household water consumption by using data from a survey conducted in Honolulu, Hawaiʻi matched with utility billing data. In particular, I distinguish expressed intention to limit water use from water-saving actions. While I do not find expressed water conservation intention to have a measurable relationship with actual water use, I find that participation in water conservation programs relates to a 4-16% reduction in water use. Moreover, outdoor-specific water conservation program participation relates to a 7-24% reduction in water use. Water-saving fixtures tend to relate to reduced household consumption, with rain catchment systems driving reductions observed among households. Although outdoor irrigation is a measurable driver of total household water use, expressed factors influencing outdoor landscaping decisions have no discernable relation to actual water use. The difference in findings between expressed water conservation intentions and water-saving actions highlight the need for informational feedback about water use and for the development of programs and policies that help shift social and cultural norms around water use.

1. Introduction

Success in conventional water resources management has primarily been defined by the ability to reliably source freshwater supply to meet consumer demand. This has lead to water utilities endlessly seeking new sources of freshwater supply as water demand grows (Gleick, 2003; Gober et al., 2013). From that narrow metric, however, water management in many U.S. cities has mostly been successful. At the same time, the development of many cities has disregarded the long-term social, ecological, and economic costs of meeting additional demand with new freshwater supply (Christian-Smith et al., 2012; Condon & Maxwell, 2019; Gleick & Palaniappan, 2010; Pahl-Wostl et al., 2007; Vogel et al., 2015). Moreover, freshwater supply is fundamentally changing in many regions around the world due to increasing water scarcity (IPCC, 2014; Mekonnen & Hoekstra, 2016) compounded by a continuing history of overexploitation (Alley et al., 2002; Gleeson et al., 2010). Many scholars and practitioners are calling for better solutions to water management that redefines the scope of successful water management to include a more holistic view of an urban system. For example, ‘One Water’ conceptualizes both a physical and institutional reorganization of water management such that a city would operate on multiple closed water loops that recycle wastewater and capture stormwater (Howe & Mukheibir, 2015; Paulson et al., 2017; US Water Alliance, 2017). The ‘Water Sensitive Cities’ framework similarly envisions a dynamic progression of water management from focusing solely on supplying water to incorporating goals of intergenerational equity and resilience to climate change, with various stages in between (Brown et al., 2009).

Although discussion and innovation in water management are increasingly focused on alternative water supplies to meet water demand, conservation is usually the first line of defense to ensure adequate and cost-effective water supply into the future (Cooley & Phurisamban, 2016; Grant et al., 2012; Vickers, 2001). Therefore, understanding the role that conservation plays in water demand is critical to planning for future water supply. Furthermore, understanding what motivates people to conserve water is key to developing strategies for effective water conservation programs.

This research utilizes data from a household survey conducted in 2015, matched with billed water usage, to understand factors that influence residential water demand. The survey explores household fixtures, appliances, water use habits, and water conservation attitudes. This research adds to the relative paucity of studies on water conservation that connect survey to water billing data by exploring how intentions to limit water use relate to actual water use as compared with behaviors in Oʻahu, Hawaiʻi (also the City and County of Honolulu). Hawaiʻi offers a unique perspective on attitudes towards long-term water supply since it is geographically isolated and has a diverse set of microclimates over a small land area. In Hawaiʻi and on other Pacific Islands that are bound by geography, maintaining a freshwater supply is especially critical, where local sources are the only recourse for water resources supply, and climate change poses an imminent threat to water resources (Keener et al., 2018). Despite its geographically-mandated self-sufficiency, Hawaiʻi has the fifth largest residential water consumption per capita of all the states (Donnelly & Cooley, 2015). Therefore, there is ample opportunity for a reduction in total residential water use. This study discusses the best ways to achieve water use reduction from the household-level and scaling up to urban policies and programs.

2. Water conservation behavior in context

2.1 Factors that influence residential water usage

Studies have analyzed a variety of factors that may impact water usage, ranging from sociodemographic, environmental, technological, and psychosocial variables. Attitudinal studies find that concerns about the environment tend to positively relate to self-reported conservation behavior (Dolnicar et al., 2012; Grafton et al., 2011; B. S. Jorgensen et al., 2015). Few studies use actual water usage as the behavioral measurement, compared to most studies that use self-reported behavior (Dolnicar et al., 2012; Russell & Fielding, 2010). The use of self-reported usage data can be problematic because perceptions of water use are often not well-matched with actual water use (Beal et al., 2013; De Oliver, 1999). However, there is some indication that a positive attitude towards water conservation has a positive relationship with reduced water usage. For example, a study in the southwestern U.S. found that survey respondents who claimed they were primarily motivated by environmental and social considerations used less water on average than consumers who were motivated by cost and convenience (Maas et al., 2017). An end-use study conducted in Gold Coast, Australia also found that users who expressed a positive attitude towards the environment tended to use less water (Willis et al., 2011). Understanding how attitudes towards water conservation translate to actual water use reduction has substantial implications for strategic outreach and program implementation around residential water conservation.

Studies also explore the role of information and feedback on water conservation. Many studies find that information on water usage and comparison to neighbors is an effective method in reducing household water usage (Bhanot, 2017; Landon et al., 2018; Otaki et al., 2017). However, results can be incongruous in cases where informational feedback leads to low water users increasing their consumption (Landon et al., 2018). Furthermore, the type of information users receive may be a critical factor in behavioral changes. For example, a survey of high and low water users in Tokyo showed that feedback in the form of emoticons[5] was effective in reducing consumption for high water users. In contrast, low water users were more likely to reduce their water consumption further when they saw improvement in their water savings results (Otaki et al., 2017). Other studies look at detailed "smart water" information as a key to future conservation efforts and research, with detailed information about the percentage of water used towards the shower, toilet, outdoor, leaks, and other uses (Boyle et al., 2013; Fielding et al., 2013; A. Liu et al., 2016; Willis et al., 2013). Although informational feedback programs may show signs of success in encouraging water use reduction, their long-term effectiveness may decline or rebound to original levels in as little as one year following the end of a program (Fielding et al., 2013).

Other external factors may motivate residential water use patterns. Price, in particular, is frequently explored and debated in the literature as a mechanism to promote water conservation (H. E. Campbell et al., 2004; Rogers et al., 2002; Saurí, 2013). It is generally well-accepted that residential water demand is relatively price-inelastic, meaning there is little response in consumption with changing prices (H. E. Campbell et al., 2004; DeMaagd & Roberts, 2020a; Kenney et al., 2008; Wichman, 2014). In the case of two Arizona cities, a block rate structure in Tucson with higher average water prices combined with lower average residential usage than Phoenix suggests that price can affect usage; however, the water history and cultural context may also explain differences in water usage and pricing structures between the two neighboring cities (Gober, 2018). However, complicated pricing structures meant to discourage higher use of water may not lead to expected results. For example, Wichman (2014) finds that residential water customers are responsive to average price rather than marginal prices. Moreover, households predisposed to pro-environmental attitudes are more responsive to both monetary and non-monetary incentives to reduce water consumption, with a higher impact from non-monetary incentives (Rajapaksa et al., 2019).

Weather is also often considered in patterns of water demand. For households with a lawn, outdoor water use may comprise a substantial portion of the total water use. A study conducted in the Phoenix metropolitan area, for example, found that although climatic conditions had a statistically significant effect on water use, the magnitude of response was relatively low and likely attributable to outdoor water use. Whereas, other studies have found households to be unresponsive to changing prices or weather (Maas et al., 2017). The location and scope of analysis certainly add to the variation in findings across studies, which include the heterogeneity of weather across studies. Through a comprehensive review of 256 studies on residential water conservation, Cook et al. (2012) underscore that the scale of study matters in consideration of what social and ecological factors drive urban water conservation, down to the level of considering the front versus back yard.

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[5] From Otaki et al. (2017): "Emoticons have the following meanings: Crying face ((T д T)) means 'very disappointed', not-so-good face ((_ _。)・・・) means 'disappointed', smiley face ((^_^)) means 'good', and perfect smiley face (ヾ(@^▽^@)ノ) means 'very good'."

Engineering and technological solutions can be an effective means to reduce total water demand. For instance, low flow or dual flush toilets had a significant effect on water conservation in a survey conducted across ten countries (Grafton et al., 2011). However, offsetting behavior can serve to negate potential water savings from the installations of water-reducing devices where water users adopt practices that increase water consumption (H. E. Campbell et al., 2004; Inman & Jeffrey, 2006; Lee et al., 2011). An example of offsetting behavior might be where water users who install low-flow showerheads take longer showers or use more water elsewhere and thus neutralize or negate the potential water savings. Campbell et al. (2004) suggest that offering incentives to install water-reducing devices should be paired with informational campaigns to alleviate offsetting effects. Another concern for implementing water-saving solutions is the rebound effect where initial water reduction wanes with time. For example, Koop et al. (2019) found that behavioral interventions tended to provide water reduction for only 1-3 months. The rebound of water use highlights the need for technological and behavioral solutions to be paired with other social, political, or economic mechanisms to encourage water conservation (Saurí, 2013). The implementation of water-saving features can be compelled through policy mandates or encouraged through incentives or education. However, the success of conservation technologies may be contingent on a broader discourse to shape the culture of water use practices around the adoption of water-efficient features (Bell, 2015).

2.2 Theoretical underpinnings: The theory of planned behavior (TPB)

It is difficult to pinpoint singular factors that influence water consumption patterns without referencing culture, knowledge, attitude, or behavior as corresponding influences in water use. The theory of planned behavior (TPB) is a framework increasingly used in water conservation literature to explore the connection between intention and behavior (Russell & Fielding, 2010; Yuriev et al., 2020). TPB is useful for understanding the relationship between intentions and behavior in a particular context, and also for developing effective behavioral interventions, because it considers intention and behavior separately, where subjective norm, attitude towards a behavior, and perceived behavioral control as motivational factors in intention (Ajzen, 2012; Yuriev et al., 2020). Figure 5 shows a conceptual model of the interactions within the TPB model. Generally, for any given behavior, the stronger one's intention to engage in that behavior, the more likely it is to happen (Ajzen, 2012). Therefore, to promote behavioral change, it is vital to understand how to motivate the intention to engage in a behavior. Within TPB, intention has three motivations: 1) the subjective norm, which reflects the environmental conditions and is the perceived social pressure on someone to participate in a behavior; 2) the attitude towards the behavior, which is the favorability one has of that behavior; and 3) one's perceived behavioral control, which is a judgment of how well a person would be able to carry out a behavior (Ajzen, 2012; Yuriev et al., 2020). There are cases where perceived behavioral control would break down, for example, in conditions where there is little information available (Ajzen, 1985, 2012). Analyses employing TPB usually contain an assessment of factors that influence behavior and evaluation of direct and indirect predictors of intention (Yuriev et al., 2020).

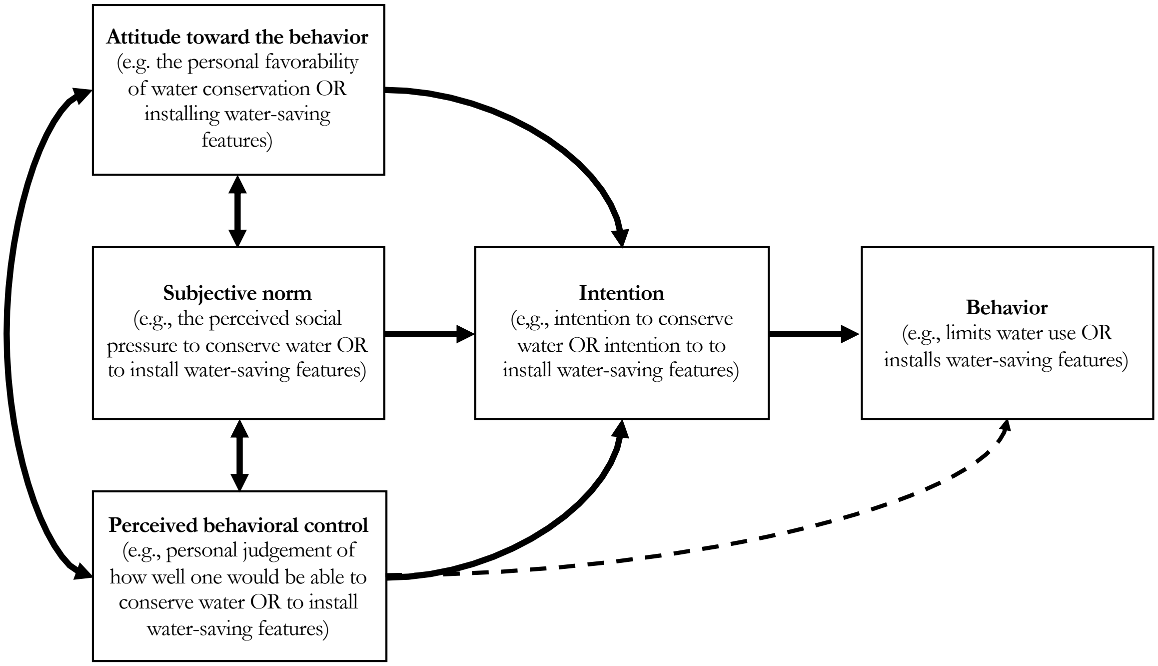

Figure 5. Conceptual model of the Theory of Planned Behavior (TPB) adapted from Ajzen (2012), which separates intention from behavior. Shown in each box are examples of motives that lead to water conservation or installing water-saving features.

Other behavioral theories and factors are used to understand water conservation (Russell & Fielding, 2010). Among factors that tend to be associated with water conservation, emotions and their connection to water conservation intention are not well-explored (de Miranda Coelho et al., 2016; Yuriev et al., 2020). Opportunity, motivation, and capability can be related to water conservation behavior (Addo et al., 2018). Greater knowledge about water or resource scarcity also tends to be associated with water-savings (Dean et al., 2016; Salvaggio et al., 2014). There is also discussion around the role of habits on behavior, exploring how impactful they may be on intention (Ajzen, 2011; B. S. Jorgensen et al., 2013). One of the benefits of using TPB as a basis is that it has a flexible structure that can be expanded, and may include background factors as control variables (Ajzen, 2011; Lam, 2006; Yuriev et al., 2020). Jorgensen et al. (2009) propose an integrated social and economic household water use behavior model that incorporates TPB and other factors that may influence water conservation intention and behavior; the household consumption model is based on a literature review of factors reported to influence conservation intention that, in turn, influences total water consumption. Although TPB may be useful in understanding motivations behind water conservation behavior, Yuriev et al. (2020) find that most water conservation studies measure intent alone and not behavior.

2.3 Water efficiency vs. conservation vs. productivity

Often concepts around installing efficient fixtures and water conservation behavior are referred to interchangeably despite each being differing behaviors with different motivations (Russell & Fielding, 2010). Similarly, concepts of water efficiency and water conservation tend to be used in undifferentiated contexts, but it is worth distinguishing the two. Water efficiency aims to match the water needed for a particular use with the water delivered and thus eliminates unused or unnecessarily used water in a system (Grant et al., 2012; Unver et al., 2017; Vickers, 2001). In the context of residential water use, this can be achieved through eliminating leaks and—as most often referred to in the literature—installing water-efficient fixtures and appliances. Water conservation captures water efficiency, but also adds the element of consciously reducing water usage and changing habits (B. S. Jorgensen et al., 2014; Russell & Fielding, 2010). As an illustration, a household that installs an irrigation system for a grass lawn such that it reduces waste and unnecessary watering would be considered a water-efficient house. Whereas, a household that chooses to xeriscape their yard or plant a garden that matches the climate to reduce or eliminate outdoor watering would be considered a water-conserving house. Individual households will have different water needs and preferences shaped by social and cultural norms, but not all water uses are the same. In that regard, water productivity is a useful concept to consider. By definition, water productivity aims to maximize the 'output' per volume of water used (Gleick et al., 2011). However, it is challenging to define what constitutes a favorable 'output' for residential water use (e.g., growing food vs. filling a swimming pool), and not all water usage should be considered through a punitive lens without knowing the circumstances of the choices made. Therefore, water substitution can be used as a measure of water productivity. Substitute water supplies may include rainwater and greywater use at the residential scale and recycled water at a community or municipal level (Grant et al., 2012). Table 4 summarizes water efficiency, conservation, and productivity in the context of household water use and how they are additive concepts. Although the most common vernacular used around reducing water demand is "water conservation," it is worth distinguishing the idea of maximizing "water productivity" because it gives a positive connotation to limiting total potable water use.

Table 4. Defining the concepts of water efficiency, water conservation, and water productivity for residential water use.

Concept	Measure of Success	Definition	Achievement
Water efficiency	Matching the water delivered to the water needed	Eliminating unused or unnecessarily used water in the system	• Fix leaks • Install water-efficient fixtures and appliances
Water conservation	Reducing the volume of water used per period	Cutting back usage of water in the system	• Water efficiency • Cutback water usage through behavioral changes
Water productivity	Maximizing the output per volume used per period	Getting the most return for the least amount of freshwater used in the system	• Water efficiency • Water conservation • Greywater reuse • Rainwater harvesting

2.4 Study context

The City and County of Honolulu provides a critical opportunity for the State of Hawaiʻi to meet a sustainability goal of increasing freshwater capacity by 100 million gallons per day (mgd) by 2030. This goal is part of a broader set of sustainability goals, called the "Aloha+ Challenge," that the State of Hawaiʻi adopted in 2017 (State of Hawaii, 2017). Freshwater capacity—also considered the amount of water available for consumption—is defined through this program as the total decrease in water demand combined with the increase in the water supply. Increasing freshwater capacity is to be achieved by increasing groundwater recharge, water reuse, and conservation. Measurement towards this goal is challenging to track and requires a few key assumptions. First, the goal focuses on groundwater resources and uses the 2013 total statewide water demand as a baseline for groundwater withdrawal. With population growth, it is estimated that the demand for freshwater will increase by 100 mgd. Therefore, if the 100 mgd of additional freshwater capacity needed can be met through water conservation, reuse, and recharge, then no additional groundwater extraction nor costly alternative water supplies (i.e., desalination) will be needed. The measurement of water conserved includes tracking aquifer health indicators, the rate of wastewater recycling, and annual groundwater use per resident. Most critical to this study is the stated goal of reduction in groundwater use, which equates to each Hawaiʻi resident using 15% less water or reducing the average per capita water usage from 164 to 130 gallons per day. This goal originates from the Hawaiʻi Community Foundation's Fresh Water Blueprint, which includes a plan to conserve at least 40 out of the 100 mgd through usage cutbacks (Hawaii Fresh Water Initiative, 2015).

Residential water use offers a significant opportunity towards Hawaiʻi's water conservation goal. The residential sector is the largest water user in municipal water demand, accounting for nearly two-thirds of the total municipal demand ahead of commercial, institutional, and hotel uses (CWRM, 2019). The City and County of Honolulu is home to the largest resident population of the State of Hawaiʻi and is the largest volumetric user of municipal water. In 2018, the total water use for municipalities was 139 mgd for Honolulu, and 81 mgd for all other areas of the State combined (State of Hawaii, 2019). Honolulu Board of Water Supply (BWS), which is the local water utility, is wholly reliant on groundwater to provide potable water to users (CWRM, 2019). Among the services offered, BWS offers various conservation programs to encourage and incentivize water-saving behavior for households. Currently, for example, BWS offers cash rebates for water-saving appliances and fixtures, including weather-based irrigation controllers, water-saving and energy-efficient clothes washers, and rain barrels. From 1994 to 2010, BWS offered rebates for replacing a high-volume toilet with an ultra-low flush toilet and estimates that 5,200 gallons of water are saved per year as a result of this program (Honolulu BWS, 2019). BWS also hosts an annual xeriscape plant sale and regularly offers workshops at their Xeriscape Garden located just outside of the urban core of Honolulu. New to the BWS conservation programs is the opt-in WaterSmart program that provides access to software, enabling customers to view water usage analysis, including water-saving tips and comparisons to similar households.

3. Methods

3.1. Household water usage survey

Household survey data from an online survey conducted in 2015 was used to characterize household water usage features, behavior, and attitude. A total of 406 respondents participated in the survey, with 295 participants granting permission to access their water usage data for research purposes. Three years of billing data from 2013-2016 was matched to the respondents who consented, pay a water bill to the Honolulu Board of Water Supply (BWS), and live in a residential land use zone with an individual Tax Map Key (TMK). Further data on the housing area and age of the house was obtained from the Honolulu City and County public record access using the TMK (City and County of Honolulu, 2014). In total, all data were available for 185 households. Table 5 shows the respondent characteristics for the analyzed dataset (n=185).

Table 5. Dataset summary statistics (n = 185).

Gender	
Female	54.1%
Male	45.9%
Household Size	
1 individual	4.9%
2 individuals	28.1%
3-4 individuals	45.9%
5-9 individuals	18.9%
10+ individuals	2.2%
Age	
18 - 24 yr/old	2.2%
25 - 34 yr/old	7.6%
35 - 44 yr/old	16.2%
45 - 54 yr/old	22.7%
55 - 59 yr/old	15.7%
60+ yr/old	35.7%
Income	
Below $25k	2.7%
Between $25k and $49.9k	9.7%
Between $50k and $99.9k	43.2%
Between $100k and $149.9k	25.4%
Above $150k	18.9%

Land Tenure	
Rent	10.8%
Own	89.2%
Household Type	
Single-family (1-4 bedrooms)	82.2%
Single-family (5+ bedrooms)	14.6%
Apartment	0
Townhouse	<1%
Two-family house	2.7%
Average water consumption (gphd)	
Mean (S.D.)	243 (160)
Min - Max	13 - 1,027
Average annual rainfall (mm/yr)	
Mean (S.D.)	1,145 (525)
Min - Max	546 - 3,176
Housing age (relative to 2015)	
Mean (S.D.)	44 (18)
Min - Max	4 - 113
Living area (square feet)	
Mean (S.D.)	1,744 (696)
Min - Max	560 - 4,691

Another feature of the survey was to capture information about household fixtures, appliances, and water use behaviors that influence total water use. Figure 6 provides data on indoor and outdoor household fixtures, appliances, and water use habits for the analyzed dataset. Notably, dishwashing behavior in this dataset tends to be different from U.S. average household behavior. As detailed by DeOreo et al. (2016), most U.S. single-family households have dishwashers and rarely wash dishes by hand. Whereas a majority of Honolulu households surveyed do not have dishwashers and even for those with a dishwasher, most opt to wash some number of dishes by hand. Additionally, the average household size in Honolulu tends to be larger than the U.S. average, with about 3.8 persons per household on average. Further details regarding the motivations behind the survey and its implementation are discussed in Spirandelli et al. (2016).

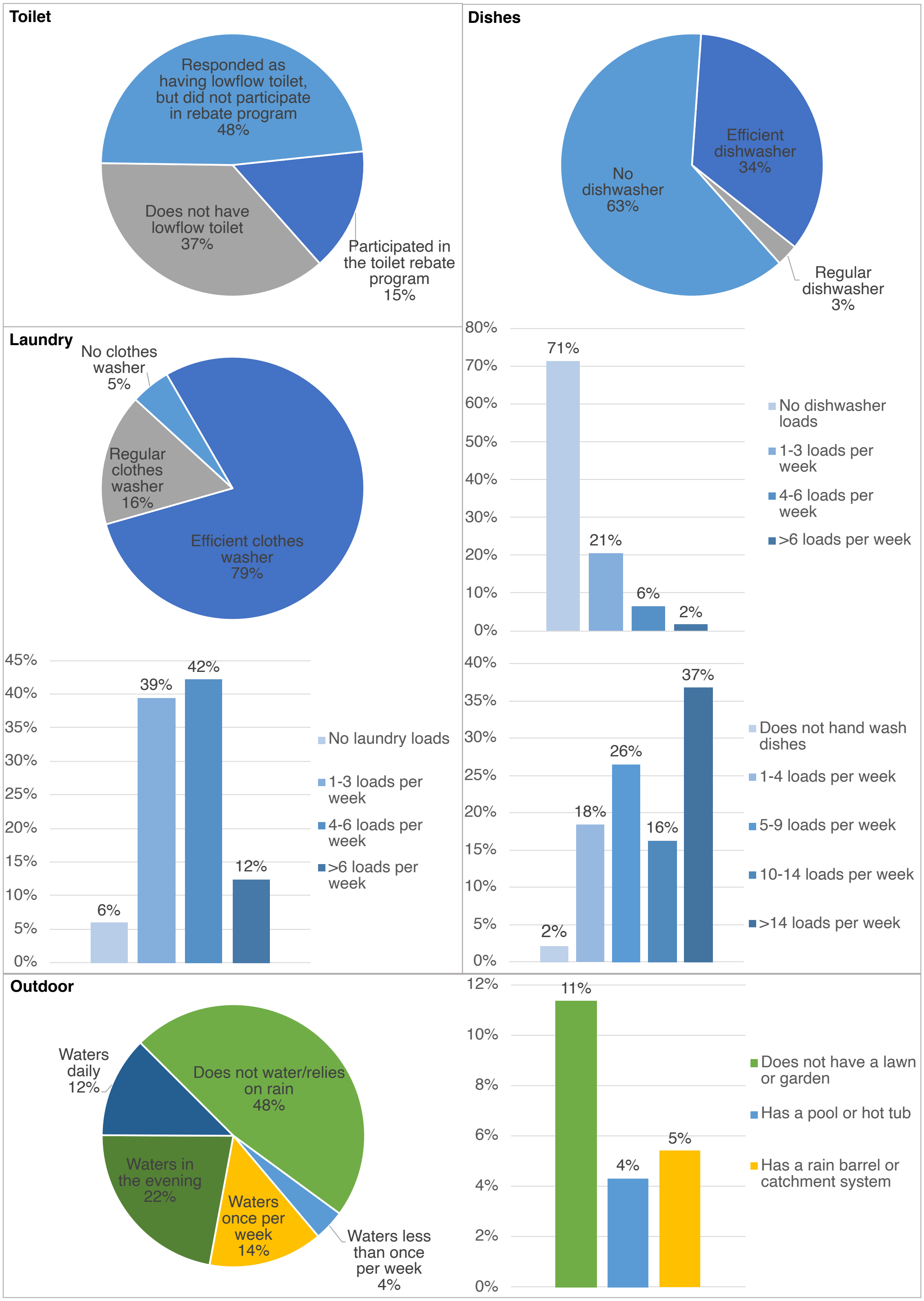

Figure 6. Summary of fixtures, appliances, and water use habits as captured by the survey for the analyzed dataset.

3.2 Analysis

3.2.1 Model Specification

The objective of this analysis is to understand what attitudes or behaviors, as determined through the survey, relate to actual household water usage. I perform this analysis using an Ordinary Least Squares (OLS) regression model to estimate the relationship between multiple variables. The variables chosen for the model specification are based on data available that fit the Jorgensen et al. (2009) integrated social and economic household water use behavior model, as shown in Figure 7. As indicated, the dependent variable is household water consumption obtained through household billing data. Jorgensen et al. (2009) include TPB motivations (i.e., attitude, subjective norm, perceived behavioral control) within their water use behavioral model. Although not directly measured for this study, the TPB motivations are used as a basis to interpret the results of this analysis, where several variables for conservation intention to test the relationship to actual water consumption. Figure 8 indicates select survey questions that are analyzed as indicators of the intention to conserve water. Additionally, demographics, dwelling characteristics, and household composition measures were used as control variables in the water use model.

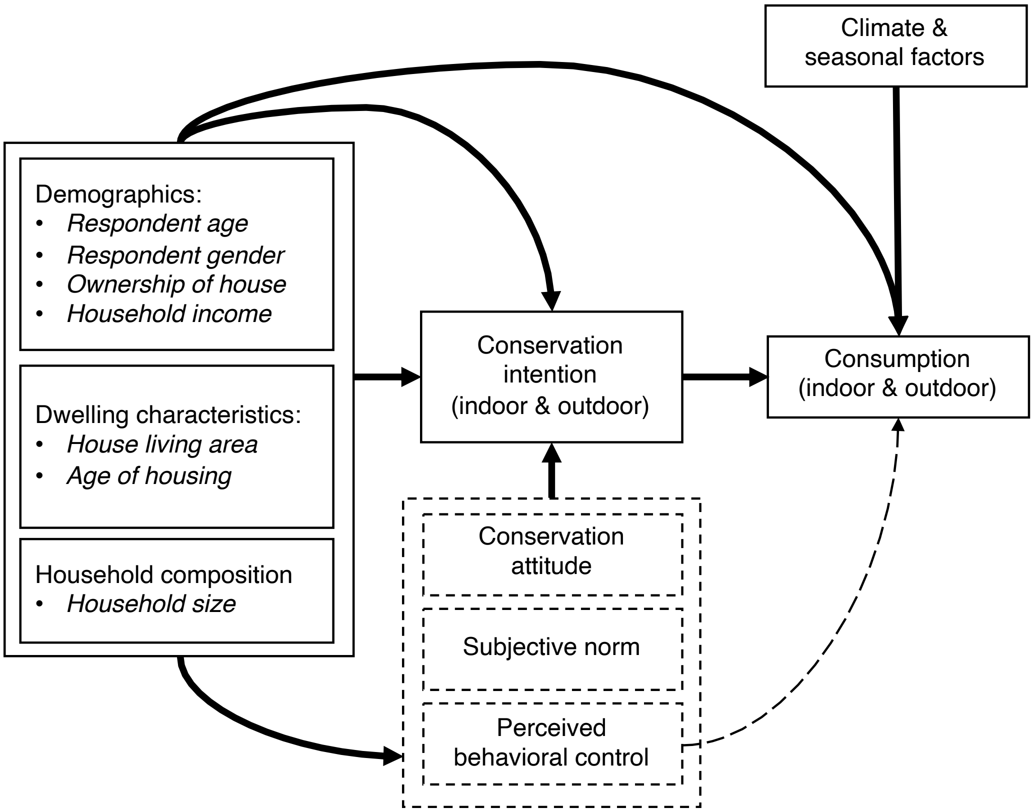

Figure 7. A conceptualization of the water consumption model used for this analysis, based on Jorgensen et al. (2009). The Theory of Planned Behavior (TPB, Figure 5) is embedded within this model as a framework for understanding what motivates water conservation intention.

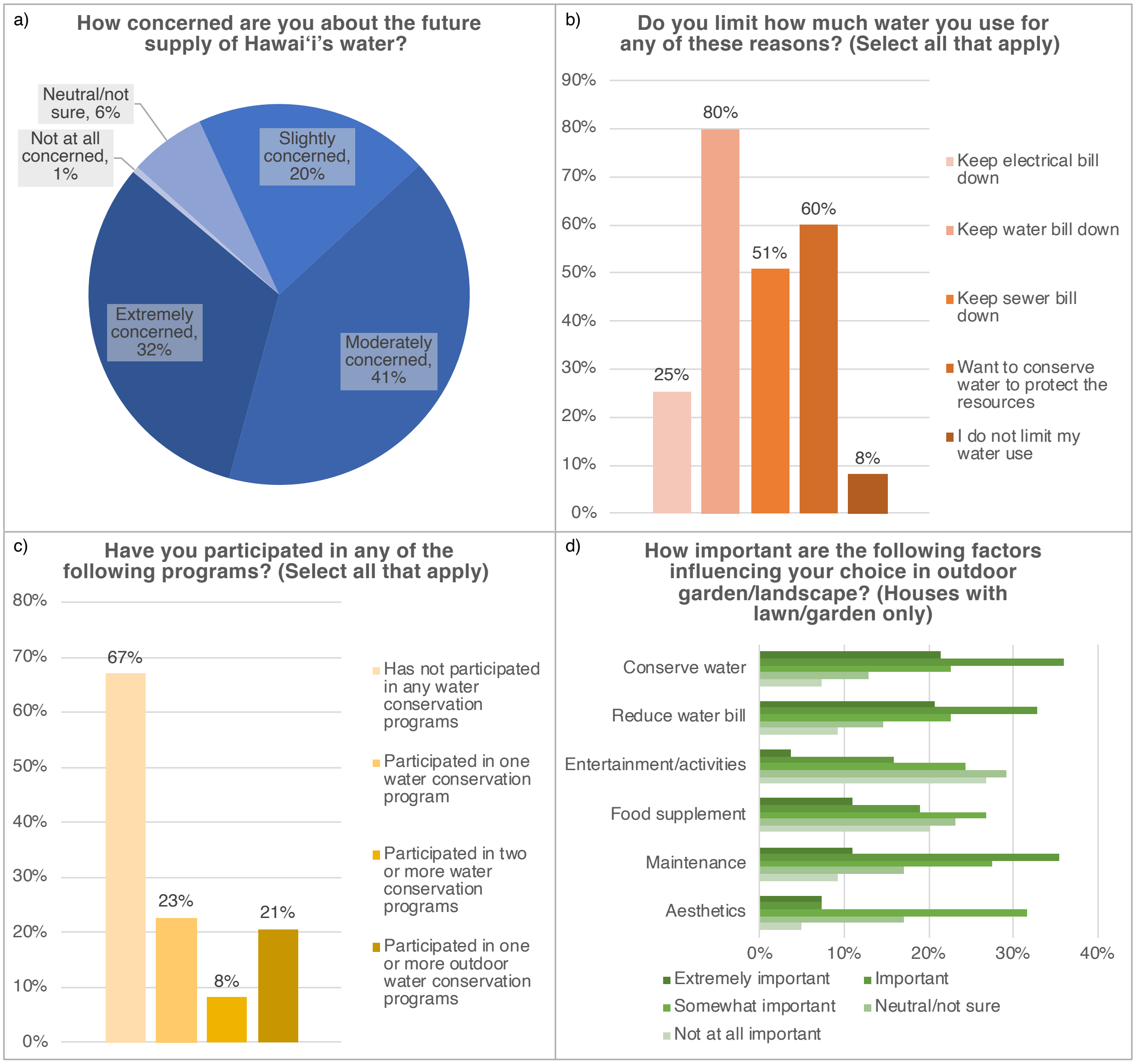

Figure 8. Select questions of interest from the survey with response statistics.

The effect of conservation intention on actual household water usage is estimated with the following specification using the *lm()* function in R:

$$\begin{aligned}\log(Water\_use_i) &= \alpha_i + \beta_o Intention_i + \beta_1 \log(Rainfall_i) + \beta_2 \log(Income_i) \\ &+ \beta_3 HH\_size_i + \beta_4 Ownership_i + \beta_5 Housing\_age_i \\ &+ \beta_6 \log(Living\_area_i) + \beta_7 Gender_i + \beta_8 Age_i + \varepsilon_i\end{aligned} \tag{1}$$

The main coefficient of interest is β_o, which measures the effect of expressed concern on the total household water usage. All other variables serve as control variables to the model. The variables of $Intention$, $Income$, HH_size, $Ownership$, $Gender$, and Age are data obtained from the survey. The household income, $Income$, is specified in the survey by ordinal choice. The median income values for the household income bracket indicated by the respondent are used for the regression. Likewise, the regression uses the median bracket value for the age of the respondent, Age, and the number of household members, HH_size, indicated in the survey by ordinal choice. Both $Ownership$ and $Gender$ are binary variables respectively indicating whether the respondent rents or owns their housing and whether the respondent is female or male. Average annual rainfall values, $Rainfall$, are based on the location of the household and obtained via the Hawai‘i Rainfall Atlas (Giambelluca et al., 2013). The dwelling age, $Housing\_age$, and the square-footage living area, $Living\_area$, are obtained through the Honolulu City & County property records database which is public record. Finally, the dependent variable, $Water\_use$, is the 3-year average total household water use as documented on the household water bill. Although the survey was conducted in 2015, prior years of water usage were included in the average to reduce year-to-year variation that may be a result of weather differences. Table 6 summarizes the variables used in the OLS regression that were obtained from sources outside of the household survey. The variables, $Water\_use$, $Rainfall$, $Income$, and $Living\_area$, were determined to be lognormally distributed based on Q-Q Plot tests and Shapiro-Wilk normality tests. The unobserved error and intercept are indicated by ε and α, respectively.

Table 6. Variables included in OLS regression not included in survey data

Variables	Mean	S.D.	Max	Min
Average water consumption (gpd)	243	160	1,027	13
Average annual rainfall (mm/yr)	1,145	525	3,176	546
Housing age (years old)	44	18	113	4
Living area (square feet)	1,744	696	4,691	560

3.2.2 Expressed Water Conservation Intention

Using the same model specification, I test several relationships with conservation intention ($Intention$). First, I assess the relationship between actual water use and expressed concern for Hawai‘i’s future water supply, which is measured on a 5-point Likert scale. Figure 8a shows the breakdown of responses to this survey question. Survey participants were also asked whether they limit their water usage for any reason, as shown in Figure 8b; reasons included, broadly, that they limit their water usage to keep utility bills down (i.e., electricity, water, or sewer), to “conserve water to protect resources,” or that they do not limit their water use. I therefore also consider the intention to conserve water by using “conserves water to protect resources” and “limits water use to keep utility bills down” as variables substituted for $Intention$ in equation 1.

3.2.3 Water-saving Actions

To compare actionable water-saving intentions to the expressed water conservation intention variables detailed in section 3.2.2, I analyze two different actions reported in the survey. First, survey respondents indicated whether they participated in any water conservation-related programs (e.g., Xeriscape Plant Sale, Rain Barrel Program, and Toilet Rebate Program), shown in Figure 8c. Program participation for each survey respondent is summed and substituted as the $Intention$ variable in equation 1, as well as the total number of outdoor-specific water conservation programs in which respondents participated. Second, to understand the role of household appliances and fixtures interacting with usage habits on total household water use, I examine the role of ultra-low flow toilets, efficient appliances, and rainwater catchment systems, and the summation thereof:

$$I_{sum} = I_{low\ flow\ toilet} + I_{efficient\ appliances} + I_{rain\ catchment\ system} \qquad (2)$$

Individually and as a sum, these variables are substituted in the model specification to estimate the relationship between water-saving fixtures and actual water use. The summation of binary variables is meant to estimate how an increasing number of water-efficient fixtures relate to total water use. To ensure consistency, households with an ultra-low flow toilet (i.e., <1.6 gallons per flush) were determined based on those who responded that they participated in the Toilet Rebate Program and that they currently have a low flow toilet or if their house was built in 2000 or later. Starting in 2000, all housing built in the City and County of Honolulu were required to install ultra-low flow toilets. Within these regression equations, a binary variable for households that have a pool or hot tub is added as a control for household fixtures and the housing age variable was removed to avoid issues of collinearity.

3.2.4 Outdoor water use

Since outdoor water use can comprise as much as 50% of a household's water use budget in the U.S. (DeOreo et al., 2016), it is useful to tease out factors in outdoor water use behavior that relate to total water use. First, I explore how outdoor watering habits relate to household water usage using the same model specification as equation 1. Those who responded that they have a lawn or garden were asked several questions in the survey about their outdoor watering habits. I separate this information into the following variables to include in the model specification: those who say they have a rain barrel or water catchment system, those who say they rely on rainfall, those who water infrequently (i.e., once per week or less), and those who water their lawn frequently (i.e., more than once per week). Finally, I isolate the subset of survey participants who say they have either a lawn or garden to explore their motivations for water use. As Jorgensen et al. (2009) suggest, the motivations for indoor vs. outdoor use differ, yet are rarely explored separately. Within the survey, those who responded that they had a lawn or garden were asked to evaluate the importance of various factors in their outdoor landscape choices based on a Likert-scale, shown in Figure 8d. These motivations include aesthetics, food supplement, water bill reduction, and conserving water. Using the subset of households with a lawn or garden, I substitute these variables into the $Intention$ variable equation 1, as well as outdoor conservation program participation, to understand the relationship between expressed motivations for outdoor choices and actual water use.

4. Results

The oft-used adage "actions speak louder than words" rings true in the case of this analysis. Those who express concern over long-term water supply or those who say they conserve water to protect resources tend to use less water but with no statistically measurable effect, as shown in Table 7. There is also no measurable relationship between those who say they limit water use to reduce utility bills, but the trend suggests that they tend to use more water. The coefficient of determination, R^2, for all three individual regressions is about 0.31, with an adjusted R^2 of 0.27.

On the other hand, water conservation program participation has a measurable relationship with actual usage, as shown in Table 8. Participation in water conservation program relates to 10.0% less water used on average per program, and 15.4% per outdoor-specific conservation programs. These relationships are statistically significant at the 10% level with a R^2 and an adjusted-R^2 of 0.32 and 0.28, respectively. In line with expectations, average rainfall has a measurable relationship to water use, with about 0.26-0.46% reduction of water usage per 1% increase in average annual rainfall amount. Likewise, for every additional person living in the household, water use increases by about 11%. The home living area and homeownership each also has a measurable relationship to household water usage. Household income, age and gender of the respondent, and the age of the house are not statistically significant predictors of water use; however, they serve as control variables in the OLS regression. For all regressions results reported in this study, the Variance Inflation Factors were calculated to test for multicollinearity and not found to be an issue.

Table 7. Estimation results for expressed concern or limits to water use relating to average daily water use (log gphd).

	Expressed concern for water supply (scalar 0-4)	Conserves water to protect resources (0 - no, 1 - yes)	Limits water use to lower utility bills (scalar 0-3)
Water conservation intention	-0.031 (0.044)	-0.084 (0.082)	0.023 (0.044)
Average annual rain (log mm/year)	-0.358*** (0.100)	-0.353*** (0.100)	-0.361*** (0.100)
Household income (log $)	0.091 (0.061)	0.099 (0.061)	0.097 (0.062)
Respondent age (years old)	0.001 (0.002)	0.001 (0.002)	0.001 (0.002)
Respondent gender (0 - female, 1 - male)	0.088 (0.082)	0.087 (0.081)	0.089 (0.082)
Number of persons living in household	0.107*** (0.020)	0.107*** (0.020)	0.108*** (0.020)
Home living area (log square-foot)	0.284** (0.113)	0.277**	0.268** (0.113)
Age of house, as of 2015 (years old)	0.003 (0.002)	0.003 (0.002)	0.003 (0.002)
Ownership of house (0 - own, 1 - rent)	0.259* (0.139)	0.256* (0.139)	0.251* (0.140)
(Intercept)	4.094*** (1.148)	3.991*** (1.152)	4.026*** (1.160)
Observations	185	185	185
R^2	0.306	0.308	0.305
R^2 adjusted	0.270	0.272	0.269

Standard errors in parentheses
*** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$

Table 8. Estimation results for conservation program participation relating to average daily water use (log gphd).

	Total conservation program participation (scalar 0-3)	Outdoor conservation program participation (scalar 0-2)
Water-saving action	-0.098* (0.059)	-0.154* (0.086)
Average annual rain (log mm/year)	-0.358*** (0.099)	-0.360*** (0.099)
Household income (log $)	0.107* (0.061)	0.103* (0.061)
Respondent age (years old)	0.001 (0.002)	0.001 (0.002)
Respondent gender (0 - female, 1 - male)	0.084 (0.081)	0.080 (0.081)
Number of persons living in household	0.108*** (0.020)	0.106*** (0.020)
Home living area (log square-foot)	0.291** (0.112)	0.287** (0.112)
Age of house, as of 2015 (years old)	0.003 (0.002)	0.003 (0.002)
Ownership of house (0 - own, 1 - rent)	0.242* (0.139)	0.238* (0.139)
(Intercept)	3.802*** (1.156)	3.913*** (1.144)
Observations	185	185
R^2	0.315	0.316
R^2 adjusted	0.279	0.281

Standard errors in parentheses
*** p < 0.01; ** p < 0.05; * p < 0.1

Extending the exploration of water-saving actions to household fixtures shows that the type of water-saving fixture and the number of actions taken to reduce water usage matter greatly. Table 9 shows the relationship between water use and water-saving fixtures, including ultra-low flow toilets, efficient clothes washers or dishwashers, and rain barrels or catchment systems. Significant to the 10% level, water consumption is reduced by 4.7-17.1% per water-saving fixture compared to houses without any of the three water-saving fixtures ($R^2 = 0.32$, R^2-adj = 0.28). Most of the statistical power comes from households that have a rain catchment system, where those households use 31.5-67.3% less water than other households, statistically significant at the 1% level ($R^2 = 0.34$, R^2-adj = 0.30). While ultra-low flow toilets and efficient appliances trend towards reduced water usage, there is no statistically measurable relationship to actual water usage. Similarly, those who have one or two of the water-saving fixtures tend to use less water but with no measurable relationship. Whereas, those who have all three of the water-saving fixtures use a median of 60.1% less water than those with no fixtures, statistically significant at the 5% level ($R^2 = 0.33$, R^2-adj = 0.28). Households with pools or hot tubs tend to use more water than households without, though not a statistically significant effect.

Table 9. Estimation results for water-saving fixtures relating to average daily water use (log gphd) as compared to households without those fixtures.

	Total water-saving fixtures (scalar 0-3)	Total water-saving fixtures as factors (N fixtures)		Water-saving fixtures by type (0 - does not have, 1 - has)	
Water-saving action	-0.109* (0.062)	N = 1	-0.051 (0.107)	Ultra-low flow toilet	-0.021 (0.106)
		N = 2	-0.141 (0.137)	Efficient appliances	-0.035 (0.101)
		N = 3	-0.601** (0.289)	Catchment system	-0.493*** (0.178)
Pool or hot tub (0 - no, 1 - yes)	0.280 (0.198)	0.328 (0.202)		0.319 (0.198)	
Average annual rain (log mm/year)	-0.320*** (0.097)	-0.311*** (0.097)		-0.284*** (0.097)	
Household income (log $)	0.120* (0.062)	0.115* (0.062)		0.110* (0.061)	
Respondent age (years old)	0.001 (0.002)	0.001 (0.002)		0.001 (0.002)	
Respondent gender (0 - female, 1 - male)	0.088 (0.081)	0.088 (0.081)		0.075 (0.080)	
Number of persons living in household	0.113*** (0.020)	0.113*** (0.020)		0.110*** (0.061)	
Home living area (log square-foot)	0.276** (0.112)	0.274** (0.112)		0.247** (0.112)	
Ownership of house (0 - own, 1 - rent)	0.215 (0.140)	0.216 (0.140)		0.214 (0.139)	
(Intercept)	3.674*** (1.168)	3.649*** (1.170)		3.719*** (1.158)	
Observations	185	185		185	
R^2	0.318	0.325		0.339	
R^2 adjusted	0.283	0.282		0.297	

Standard errors in parentheses
*** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$

Outdoor watering habits tend to have a measurable relationship to actual water usage. As shown in Table 10, those who water their lawns or gardens more than once per week use 16.7-35.7% more water than households with no lawn or garden, statistically significant at the 1% level (R^2 = 0.36, R^2-adj = 0.32). Comparatively, those who water using a rain catchment system use a median of 37.2% less water, significant at the 5% level. Although there was no statistically measurable relationship found between households that either rely on rain or those who water their lawn infrequently, the trend indicates that those households tend to use more water than households without a lawn or garden. Compared to those without, households with a lawn or garden reduce their water usage by an average of 22% per 1% increase in rainfall. Indoor water usage habits were also explored, however, no measurable effects relating water consumption to the frequency of laundry loads, dishwasher loads, or hand washed dish loads were found.

Table 10. Estimation results for outdoor watering habits relating to average daily water use (log gphd) as compared to households without a lawn or garden.

	Outdoor watering habits
Waters using a rain catchment system	-0.372** (0.178)
Relies on rain	0.081 (0.245)
Waters once per week or less	0.182 (0.112)
Waters more than once per week	0.262*** (0.095)
Average annual rain (log mm/year)	-0.222** (0.104)
Household income (log $)	0.088 (0.059)
Respondent age (years old)	0.001 (0.002)
Respondent gender (0 - female, 1 - male)	0.082 (0.079)
Number of persons living in household	0.102*** (0.020)
Home living area (log square-foot)	0.262** (0.109)
Age of house, as of 2015 (years old)	0.002 (0.002)
Ownership of house (0 - own, 1 - rent)	0.297 (0.137)
(Intercept)	3.225*** (1.134)
Observations	185
R^2	0.362
R^2 adjusted	0.318

Standard errors in parentheses
*** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$

For the subset of households with a lawn or garden shown in Table 11, the outdoor-specific programs relate to 11.8-29.2% less water consumed per program attended (R^2 = 0.34, R^2-adj = 0.30), statistically significant at the 5% level. However, there is no clear motivating factor for outdoor water usage. That is, there is no statistically measurable effect to the expressed importance of factors motivating outdoor landscaping choices (R^2 = 0.32, R^2-adj = 0.28). All factors tend to relate to higher water use, which makes sense for ‘aesthetics’ or ‘food supplement’, but not for ‘water bill reduction’ or ‘conserving water’ as motivating factors for landscaping choices. Comparing the estimation results of the subset of households with a lawn or garden (Table 11) with the full analyzed dataset (Table 8), there are a few notable differences. For the subset of houses, a 1% increase in rainfall relates to 32.1-52.5% decrease in water use, which is a slightly greater reduction observed than the full dataset. There is no notable difference between the number of persons living in the household between the two estimation results. For the households with a lawn or garden, a 1% increase in the home living area relates to 23.0% increase in water use, significant to the 10% level, compared to a 28.7% average increase for all households, significant at the 5% level. Land tenure results also differ, with no statistically significant relationship to water use for the households with a lawn or garden compared to a 23.8% increase in water use for renters over home owners for the full dataset, at a significance level of 10%.

Table 11. Estimation results for the subset of households with a lawn or garden relating to average daily water use (log gphd).

	Outdoor programs (scalar 0-2)	Aesthetics (scalar 0-4)	Food supplement (scalar 0-4)	Water bill reduction (scalar 0-4)	Conserving water (scalar 0-4)
Water conservation	-0.205**	0.063	0.037	0.029	0.021
intention	(0.087)	(0.044)	(0.034)	(0.036)	(0.038)
Average annual rain	-0.423***	-0.435***	-0.438***	-0.425***	-0.424***
(log mm/year)	(0.102)	(0.104)	(0.105)	(0.104)	(0.104)
Household income	0.096	0.084	0.095	0.099	0.093
(log $)	(0.068)	(0.069)	(0.070)	(0.071)	(0.071)
Respondent age	0.003	0.003	0.003	0.003	0.003
(years old)	(0.002)	(0.003)	(0.003)	(0.003)	(0.003)
Respondent gender	0.077	0.119	0.106	0.103	0.100
(0 - female, 1 - male)	(0.085)	(0.088)	(0.087)	(0.087)	(0.088)
Number of persons living in	0.117***	0.121***	0.121***	0.118***	0.118***
household	(0.023)	(0.023)	(0.023)	(0.023)	(0.023)
Home living area	0.230*	0.193	0.212*	0.234*	0.251*
(log square-foot)	(0.121)	(0.124)	(0.123)	(0.124)	(0.124)
Age of house, as of 2015	0.002	0.002	0.002	0.002	0.002
(years old)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Ownership of house	0.203	0.256	0.244	0.219	0.226
(0 - own, 1 - rent)	(0.156)	(0.158)	(0.158)	(0.159)	(0.159)
(Intercept)	4.751***	4.917***	4.795***	4.519***	4.631***
	(1.259)	(1.273)	(1.277)	(1.344)	(1.345)
Observations	164	164	164	164	164
R^2	0.338	0.323	0.320	0.317	0.316
R^2 adjusted	0.299	0.284	0.280	0.277	0.276

Standard errors in parentheses
*** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$

5. Discussion

5.1 Self-described limits vs. actions

The analysis conducted for this study shows that environmental concern or self-expressed reasons for limiting water use did not have a measurable relationship to actual reduced household water use. This indicates that conservation intention and behavior are not well-matched, adding to similar conclusions of previous studies that there is a lack of association between water conservation intentions and behaviors (B. S. Jorgensen et al., 2013, 2015; Newton & Meyer, 2011). The TPB framework can help explain the intention-behavior gap, which would suggest a lack of social pressure to conserve water or a low perceived judgment of water conservation ability. Information and feedback about water use is a necessary condition to judge one's ability to conserve water (Ajzen, 2012; Frick et al., 2004), and is lacking in this case. Because water use is intimately integrated into daily routines, it is imaginable that water users would lose perspective on their individual water use habits when there is no informational feedback and service is uninterrupted. For example, Beal et al. (2013) find perceptions of water use are not always well-aligned with actual water use, especially among the self-nominated low users. In the case of this analysis, most of the highest water users are those with a lawn or garden whose actual water use seems to be the least aligned with their expressed conservation intentions. On the one hand, this study suggests that outdoor watering frequency relates strongly to household water use. Yet, self-expressed motivations for outdoor landscape choices, such as water bill reduction or water conservation, have no measurable relation to household water use. Further lines of research could explore whether self-expressed motivations would change if more information or feedback were available to water users both for end-use consumption and compared to similar households.

Comparatively, water conservation program participation has a measurable relation to reduced water consumption, which suggests the importance of these programs to water conservation. Among all households, a reduction of about 10% in water use is related to participation in water conservation programs, and 15% among outdoor-specific water conservation programs. Moreover, among the households with a lawn or garden, participation in outdoor-specific water conservation programs relates to about a 21% water use reduction. Although conclusions about causation cannot be drawn from these results, there are several promising ideas that these results suggest. Conservation programs may enforce factors that motivate a person to conserve water, which help close the intention-behavior gap. Water conservation programs serve to demonstrate actions that can be taken to reduce water consumption, which can bolster one's perceived ability to conserve water; they also illustrate to participants how social norms around water consumption can change and provide tangible information about ways to reduce water usage. However, these results also raise important questions of who currently participates in water conservation programs and who should be participating. For example, Rajapaksa et al. (2019), find that incentives are more effective for people who currently hold pro-environmental attitudes or behaviors, with more impact found with non-monetary incentives. As such, conservation programs can be used as an outreach opportunity to educate participants on the connection of their water conservation habits to the sources of their water supply, and not just focusing on monetary savings from reduced water use.

5.2 Water savings potential vs. observations

Without mechanisms for individualized feedback on water usage, often the only sources of information about water-savings opportunities come from generalized estimates of household usage. For example, statements such as "high efficiency clothes washers use 30-50% less water" or "save 11,096 gallons per year by replacing a 3.5 gpf toilet with a 1.6 gpf toilet," give water users approximations of the maximum opportunity for reducing water given certain assumptions. Alternatively, water users can seek out water footprint calculators[6] to estimate various end-uses given certain household fixtures and habits. While these tools are valuable, the potential water savings often does not track with observed water use (H. E. Campbell et al., 2004; Inman & Jeffrey, 2006; Koop et al., 2019; Lee et al., 2011). Similarly, the results of this study suggest that certain indoor water-efficient fixtures amount to minor water savings in the total water budget. While the presence of ultra-low flow toilets or efficiency-rated appliances trends towards reduced water use, the results are not statistically significant. Using similar methodology to

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[6] For example, the USGS calculator (https://water.usgs.gov/edu/activity-percapita.html) or The Water Footprint Calculator (https://www.watercalculator.org).

water footprint calculators, the potential water savings in the observed dataset can be estimated. For example, I can approximate average toilet water use for households in this dataset with ultra-low flow toilets to be about 33 gphd compared to 65 gphd for households with regular toilets. This compares 1.6 and 3.5 gpf toilets (US EPA, 2013) assuming five flushes per person per day (Mayer et al., 1999). Although toilet use comprises only about 12% of a total household water budget (DeOreo et al., 2016), the lack of a clear relationship to water savings suggest that toilet water use habits change (i.e., flush more) or there is increased water use elsewhere.

The households that have ultra-low flow toilets or efficiency-rated appliances are not observed here to be maximizing their water-savings potential. Although the adoption of multiple water-saving fixtures observed here relate to greater water reductions, the indeterminate relationship to reduced water for specific indoor water-saving features may be attributable to a number of factors that are discussed in the literature. For example, water use habits can override any measurable effect of water savings by efficient fixtures or appliances through offsetting (H. E. Campbell et al., 2004; Fielding et al., 2012; Lee et al., 2011). Also, total water demand reduction from efficient fixtures or appliances installed in a household may diminish over time (Lee et al., 2011). Nevertheless, wide-scale adoption of water-saving fixtures has been observed to have measurable impact in lowering water use (DeOreo et al., 2016; Grafton et al., 2011). For example, using the same formulation, if all of the observed households were to replace regular toilets with ultra-low flow toilets, the average toilet water use would decrease from approximately 59 gphd to 30 gphd. Even if all households do not meet the maximum potential water-savings, broad adoption would likely scale up to measurable municipal-level water savings.

On the other hand, observations from this analysis show rain barrels or rain catchment systems to have a strong role in reducing water usage for the households. Having a rain barrel or catchment system in addition to ultra-low flow toilets, an efficient clothes washer or dishwasher, or both increases the water-saving effect. Although these water-saving fixtures were used in this analysis as an indication of water-conserving actions to compare to expressed intent, there is some discussion in the literature to suggest that motivations behind installing efficient fixtures or appliances are not necessarily related to the intention to conserve water (Russell & Knoeri, 2019). However, with the strong observed relationship to reduced water usage for households with a rain catchment system, it is possible that the findings reflect a small number of households with a strong conviction to limit water use, or occupants that do not spend much of their time at home. With one 55-gallon rain barrel, as offered through rebate programs (Honolulu BWS, 2019), a household might reduce their outdoor water consumption anywhere from 1.6 to 7.3 gphd, assuming they are able to cycle through the barrel volume 1-4 times per month. Given the difference between potential water-savings and observed reductions, households with a rain catchment system seemingly have a converse effect to the households with indoor water-saving features, where the presence of catchment system suggest water reduction behaviors elsewhere.

5.3 Scaling up – urban residential water

Residential water conservation can go well beyond any individual or household. Scaling lessons about conservation intentions and behaviors into broader programs and policies is not without challenges. Diversity in knowledge, concern, and attitudes is a critical consideration in designing water conservation programs that are acceptable and effective. For example, even though normative messaging and information can be a motivation for using less water, Schultz et al. (2014) find that water users with strong personal norms are less affected by messaging. It is, therefore, critical to understand what conservation program efforts are effective in aggregate and which efforts need to be targeted. Often water scarcity or known threats to water supply can be a cohesive means to motivate conservation and shift social norms around water (Dolnicar et al., 2012; Otaki et al., 2017). For example, in the case of the arid city of Las Vegas, knowledge about drought tends to drive support for water use restrictions or water price increases (Salvaggio et al., 2014). As is also the case of cultural aspects around water use and pricing in Tucson compared with Phoenix (Gober, 2018). Yet, a threatened water supply runs counter to the fundamental mission of a water utility to provide a reliable water supply to customers and therefore, would be an undesirable motivating factor to promote through most water conservation programs. A positive framing around water productivity, especially where water is not scarce, could create a more palatable shift in cultural norms around water use.

The impetus for water conservation does not wholly fall on an individual household's decisions about water-conserving behavior or installing efficiency technologies, however. Rather, urban design and land-use policies can be critical hidden drivers of water use at the urban scale. Factors such as vegetated land cover, housing density, and lot size can influence aggregate residential water use; even small design and permitting changes to single-family properties can result in substantial water savings (Stoker et al., 2019). Subjective norms around water use, therefore, may include physical and observed characteristics in an urban environment in addition to cultural aspects. For example, the perception of water waste in a city can discourage people from conserving water (Corral-Verdugo et al., 2002). This might apply especially to utilities and government entities encouraging water conservation programs, giving residents reason to question adopting water-saving behaviors if an official building, park, or public space does not adopt visible water-saving practices. Not all change needs to be unspoken, however. As Bell (2015) suggests, there is greater potential for transforming water consumption through a larger dialogue about water use practices and social norms than through water efficiency technologies alone. These shifts in social norms are especially critical where climate change could have the dual effect of reducing water supply and increasing the demand on supply (DeMaagd & Roberts, 2020b). Achieving residential water conservation is multi-dimensional across multiple scales, and needs to be tackled as such.

5.4 Limitations

There are several limitations associated with this study. First, although it is assumed that the attitudes of the survey respondents in this dataset represent the household, they may not. This is an artifact of the survey as conducted, and the level of analysis of individual vs. household is a concern noted for studies connecting water conservation intention and behavior (B. S. Jorgensen et al., 2020; Russell & Fielding, 2010). Second, the data available from the survey also limited the ability to measure motivations behind conservation intention. Motivating factors, as described through TPB, are found to have a strong association with water conservation intention (Clark & Finley, 2007; Lam, 1999; Trumbo & Keefe, 2001). Whereas this study focuses on directly relating water consumption to water conservation intention, it does have a particular advantage in that it uses actual water use compared to most studies that analyze the relationship between intent and self-described water use behavior (Dolnicar et al., 2012; Yuriev et al., 2020). Exploring the factors behind what causes the gap between intention and behavior observed is certainly an area for future research endeavors. Finally, as with most studies on water use behavior, this dataset focuses primarily on single-family households, most of which have a lawn or garden and outdoor usage habits are quite variable between households. It is difficult to understand drivers of indoor water use without being able to separate the indoor and outdoor water use budget within a household. While outdoor water use presents the largest opportunity for residential water savings within this particular dataset, it may not be representative of the residential water use for Honolulu, which includes a large set of households that reside in apartments or condos.

6. Conclusion

This study shows that without a major cultural and social shift in water use, envisioning a 15% per capita water reduction in Honolulu would be unlikely solely through individual uninformed decisions about limiting water use. Although conservation intention, as expressed through concern for long-term water supply and desire to protect resources, exhibits a trend towards lower water use, it is not a significant predictor of water use within this study. Further research is needed to understand the motivating factors, or lack thereof, that contribute to this gap between intention and behavior. A first step toward reducing the intention-behavior gap may be to provide feedback about water use so that someone with the intention to conserve water becomes aware when their behavior does not match their intention. For example, providing information about water use in comparison to similar neighbors would serve to contextualize the water use habits of a household to begin a cultural and social shift around water, as well as provide the understanding to match water conservation intentions with actions.

Certain water-conserving actions paint a more optimistic picture for residential water reduction. Water conservation programs demonstrate the most promising relationship to reduced water usage. Water-saving fixtures, including ultra-low flow toilets, efficiency-rated washers and dishwashers, and rain catchment systems together, demonstrate a measurable relationship to reduced water consumption. However, the small number of households with a rain barrel or catchment system may represent the most dedicated water-saving households. For example, in a scenario where all households have low-flow toilets, the total opportunity for water use reduction is much greater than all households irrigating using a rain barrel system. Yet, this intuition is not reflected in the actual water use of this dataset, suggesting that there is greater nuance in the individual decisions that households make about their water use that can be better discerned with information about end-water uses.

Outdoor irrigation presents a great opportunity to focus on producing measurable reductions in residential water use. A cultural shift might be more achievable by conceptualizing and demonstrating productive water use through social norms and within physical spaces, rather than solely promoting water use reduction through technological advances or limiting water use. Outdoor water conservation programs have an especially demonstrable relationship to reduced water use and might be a key target strategy for water conservation moving forward. Also, demonstrating visible water-conserving practices in public spaces and buildings. Sustaining appreciable water reductions over the long term is also critical. Thus, implementing individual household technological solutions to reduce water consumption is not enough on its own, and requires considering individual household decisions about water use in a broader urban spatial scale and the context of water productivity.

Article 2 —
Characterizing Competing Viewpoints in Stormwater Management Discourse: An Urban Honolulu Case Study

Abstract

Loss of community trust in government through poorly executed planning processes can be difficult to recover and requires extensive trust-building efforts, especially through authentic dialogue. This paper examines stormwater management priorities expressed by community leaders and residents, educators, industry professionals, and water managers. It uses Q-methodology, a mixed-method approach, to understand prevalent narratives of around stormwater management that comprise the public discourse. In the context of a contentious flood risk management project, the purpose of this research is to elucidate points of agreement and disagreement between groups. In total, 18 participants ranked an identical set of 25 idea statements relative to one another. Through principal component analysis, I identify four distinct narratives that prioritize different aspects of stormwater management objectives. The narrative analysis shows broad agreement that decentralized, soft infrastructure should be part of stormwater management solutions. However, there is widespread disagreement over funding mechanisms, the community's responsibilities in stormwater management, and the underlying planning approach to stormwater management. There was no discernable pattern in sector affiliation with any of the narratives. I summarize the dimensionality of stormwater governance and the potential spectrum of ideas about infrastructure, responsibilities, and planning approaches in a framework that characterizes competing viewpoints.

1. Introduction

Precipitation contributes to critical processes in the water cycle, including replenishing aquifers through infiltration, creating soil moisture, and generating flow to surface water bodies. Urban landscapes fundamentally alter these processes where the impervious nature of developed land leads to a reduction in infiltration, increased overland flow, flashier runoff events, and dispersion of pollutants to natural bodies of water. In developed areas, rainfall that is not absorbed into the ground and flows over the landscape as runoff is considered stormwater. Stormwater and its management have important implications for water supply, public health and safety, and ecosystem health as affected by both water quantity and quality (Porse, 2013). Watersheds hardened through development and urbanization often create a drought-flood dichotomy, where the loss of infiltration capacity in urbanized areas can increase drought conditions and increase the risk of floods through excess runoff. Changes in rainfall patterns associated with climate change exacerbate this dichotomy (Prudencio & Null, 2018). Moreover, in coastal areas, sea-level rise can compound stormwater management issues where tidal inundation can prevent stormwater infrastructure from draining and cause systems to backup (Spanger-Siegfried et al., 2014).

The legacy of water resources development and flood protection in the twentieth century is the successful rise of cities in the US, often at the expense of natural ecosystem processes that allow for infiltration of water into the ground, reduce the speed and peak of water flow, and provide natural filtration of water (National Academies, 2016). Characteristic of water resources management during the twentieth century is fragmented management of various aspects of water and related sectors, top-down implementation of projects, expert-driven solutions that do not seek to incorporate stakeholder viewpoints, and little to no consideration of the consequences to the environment when meeting water demand (Innes & Booher, 2010; Lane, 2005; Mukheibir et al., 2014). These features extend to stormwater management—or flood control. Increasingly, current water management philosophies are shifting from the conventional model with a top-down approach to promoting inclusivity of local communities in decision making and considering water as one resource to better address inter-related management issues (Christian-Smith et al., 2012; Gleick, 2003; US Water Alliance, 2017). Public engagement is key to identifying and combating environmental injustices resultant from conventional water management (Vanderwarker, 2012).

Dialogue between community and resource management agencies is fundamental to determining desired outcomes. Fostering this level of communication and coordination in stormwater management can be a particularly complicated endeavor because its governance includes a complex network of institutions and policies regulating, managing, planning, or advocating for stormwater management infrastructure and solutions. Jurisdiction over various stormwater management objectives is dispersed across many entities and is usually based on the locational occurrence of stormwater—first as rainfall then as excess runoff. The interconnected nature of the biophysical, socioeconomic, and geopolitical complexities of water systems create wicked problems that are often exacerbated by constraints created by historical systems and future concerns (Innes & Booher, 2010; Rittel & Webber, 1973). Wicked problems often involve competing and intractable tradeoffs with no easy solution. Without clear solutions, collaborative governance offers a means of seeking successful outcomes in wicked problems (Emerson et al., 2012; Innes & Booher, 2010). Healey (2009) defines such governance as "any kind of practice centered on resolving collective action problems in the public sphere or realm." Collaborative planning and the dialogue between governing institutions and policies and the community can foster trust, which is an essential component of successful governance (Tsai & Ghosal, 1998).

For this study, I focus on the perceptions of stormwater management in the Ala Wai watershed of Honolulu, Hawaiʻi. Following the designation of federal funding for a US Army Corps of Engineers (USACE) Flood Risk Management project in July 2019, contestations about the project led to an intense clash between community and government actors, upstream and downstream watershed residents, as well as new versus conventional approaches to stormwater management (Caron, 2019; Downey, 2019; Honore, 2018; Pursel, 2019; Schuler, 2019). A combination of the project proposing to exercise eminent domain and the seeming lack of transparency and public engagement in the project development galvanized watershed residents to rise in opposition (Honore, 2019b; Schaefers, 2019; Speakman, 2019). The uprising of the community in response to the USACE project is indicative of a reaction to a flawed, top-down process that tends to cultivate distrust (Forester, 1989; Huet, 2020). The purpose of this research is to use a mixed-method approach, Q-methodology, to understand narratives that are present in the current discourse around stormwater management in the Ala Wai watershed. Specifically, the question motivating this research is: *Where do stormwater management priorities for the Ala Wai watershed converge or diverge, as expressed by community members and water managers?* The Q-methodology removes stormwater objectives from the conflict's context to better understand the nuances of desired outcomes. Establishing points of agreement and disagreement between narrative groups can be useful to initiate authentic dialogue and start to rebuild trust for future stormwater management endeavors.

1.1 Study context

For this research, I chose the Ala Wai watershed as a case study because of the recent controversy between the community in the Ala Wai watershed and the U.S. Army Corps of Engineers (USACE). The Ala Wai watershed, situated in the Primary Urban Core of the city of Honolulu, serves as a major economic engine for the state of Hawaiʻi and a highly-populated area (Fujii, 2016). Contained within the watershed is the world-renowned coastal tourist destination of Waikīkī, whose development primarily exists because of the Ala Wai Canal. The 2-mile long artificial canal runs through an area that was historically wetlands and is only about a quarter-mile distance from the shoreline. Completed in 1928, the rationale for the Ala Wai canal was to "reclaim certain unsanitary lands," for which the land values skyrocketed nearly 400 in the period that the canal was being built and tourism to Waikīkī doubled (Steele, 1992). In reality, the destruction of the wetlands through the dredge-and-fill practices employed to build the Ala Wai Canal displaced and destroyed the livelihoods of many wetland taro (loʻi kalo) farmers. The story of the Ala Wai Canal and much of the land and coastal development of the surrounding areas reflects the imposition of colonial capitalism on Native Hawaiians and their land (Silva, 2004). Beginning with the destruction of the Waikīkī fishponds (indigenous coastal structures used for subsistence) in 1909 to build Fort DeRussy, the Ala Wai Canal cemented the current legacy of Waikīkī as a tourist destination and the uprooting of the long indigenous history of the area (Connelly, 2020).

The original design of the Ala Wai Canal was to have two outlets to the coast. However, due to concerns about polluted, sediment-latent water ruining the beaches of Waikīkī, the southern outlet was never completed (Cocke, 2013a). This unfortunate, incomplete design creates many further issues. For one, without a southern outlet for the flow of water, sediment build-up in the canal requires the canal to be dredged periodically. Waikīkī was initially envisioned as single-family homes but is now occupied by high-rise condos and hotels, not what the infrastructure was originally built to accommodate (Honolulu Civil Beat, 2013). During some high rainfall events, the wastewater system has been subject to overflow into the Ala Wai canal, creating dangerous water quality conditions and toxic sediment in the canal (Thompson, 2017). Along with poor ambient water quality, the canal's periodic dredging is well known to create toxic conditions detrimental to public health and aquatic wildlife (Cocke, 2013b; Glenn & McMurtry, 1995). Second, although the Ala Wai canal exists to drain the wetland area that once existed, the Ala Wai canal cannot provide flood protection against a major storm event that would devastate Waikīkī (Cocke, 2018; US ACE, 2017). Because much of the Ala Wai watershed above Waikīkī is also hardened and the drainage infrastructure was not built to accommodate the amount of development existent today, flooding is a significant concern. Third, sea-level rise will likely exacerbate these issues in the Ala Wai Canal and the drainage infrastructure in the watershed if the status quo is held (Hawaiʻi Climate Change Mitigation and Adaptation Commission, 2017).

Even with a checkered history and the public health dangers, the Ala Wai Canal is a recreational focal point for the resident community (Cocke, 2013c), just as it has become the focus of the Flood Risk Management Study. The State Department of Land and Natural Resources (DLNR) is responsible for the dredging and improvements of the Ala Wai Canal. At the request of DLNR, the USACE completed a Flood Risk Assessment of the Ala Wai Canal in 2018, after more than a decade of effort (US ACE, 2017). The recommended project aims to address stormwater issues throughout the Ala Wai watershed, focusing on the Ala Wai Canal's flooding risk. Although the USACE claims the design process included public engagement, the public only became generally aware of the proposed projects in 2018 when the project's federal funding was secured through Congress. The funding mechanism requires a state partner to match funds, which further raised community awareness of the project when the State budgeted the $125 million matching funds to $345 million in federal funds in December 2018 (Yerton, 2018; Yoshioka, 2019). As knowledge of the project spread, it received strong resistance from many Ala Wai watershed community members culminating in a lawsuit over the misfiling of an Environmental Impact Statement (Honore, 2019b; Schaefers, 2019; Speakman, 2019). As of the beginning of 2021, the USACE has held several public meetings and adjusted the project recommendations to remove three of the originally-proposed upper watershed basins that were not well-received (Honore, 2019a). The project's price tag has also nearly doubled to $651 million, leaving its fate largely in question (Schaefers, 2021).

Undoubtedly, there is a need to address stormwater issues in the Ala Wai Canal and throughout the Ala Wai watershed. However, sentiment over how stormwater should be managed ranges from wanting to see natural wetlands restored to moving forward with the USACE project (Caron, 2019; Civil Beat Editorial Board, 2019). Regardless of what the solution set looks like, many community members felt that USACE should have consulted the public throughout their assessment process (Pursel, 2019; Speakman, 2019). There is a clear range of opinions over what stormwater management does and should look like both institutionally and infrastructurally (Huet, 2020). These ideas create a discourse in the news, social media, and public meetings that portrays community against government. However, just as the issues are complex, viewpoints around stormwater management are multi-faceted and more nuanced than apparent or portrayed.

2. Q-methodology

This study employs Q-methodology, which is a mixed-method research technique used to study participant viewpoints and offers a means to bring objectivity into subjective research (Stephenson, 1935, 1953). I selected Q-method for several reasons. First, the outcome of the Q-method is to identify multiple narratives rather than finding the prevailing narrative through a survey-instrument, for example. Compared to survey instruments, Q-methodology does not require a representative sample size nor a random sampling of subjects (McKeown & Thomas, 2013; Robbins & Krueger, 2012; Zabala et al., 2018). This is because the data input for the analysis is the "Q-sort," a sorted set of identical statements unique to each respondent, rather than an analysis of the respondents as a sample population. Second, a principal component analysis is a method to statistically distinguish narrative groups that may not be readily apparent with a purely qualitative methodology. However, the interpretation of the narrative groups found through statistical analysis is aided by information gathered through semi-structured interviews. Finally, the Q-method is a useful means to understand divisive environmental management problems (Addams, 2000; Sy et al., 2018; Webler et al., 2009). The same methodology is used for stormwater management studies conducted in Chicago and Los Angeles (Cousins, 2017b, 2017a, 2017c). The Cousins studies employ the same concourse of statements in each study, and interviews are conducted solely with water managers. The focus of the research questions in those studies are in regards to understanding opinions of how stormwater should be governed. One major difference from the Cousins studies is that I include community members as participants in this study. A critical component to the conflict motivating this research study is to understand the role of community stormwater governance and whether views differ between the community and those who drive management decisions.

I summarize the steps to systematically conducting a Q-method study in three major actions in the sections below, including the process of statement collection, interviews, and data analysis (Addams, 2000; McKeown & Thomas, 2013; Watts & Stenner, 2012; Webler et al., 2009). Figure 9 shows a summary of how to conduct a Q-methodological study and the sub-steps employed for each main action.

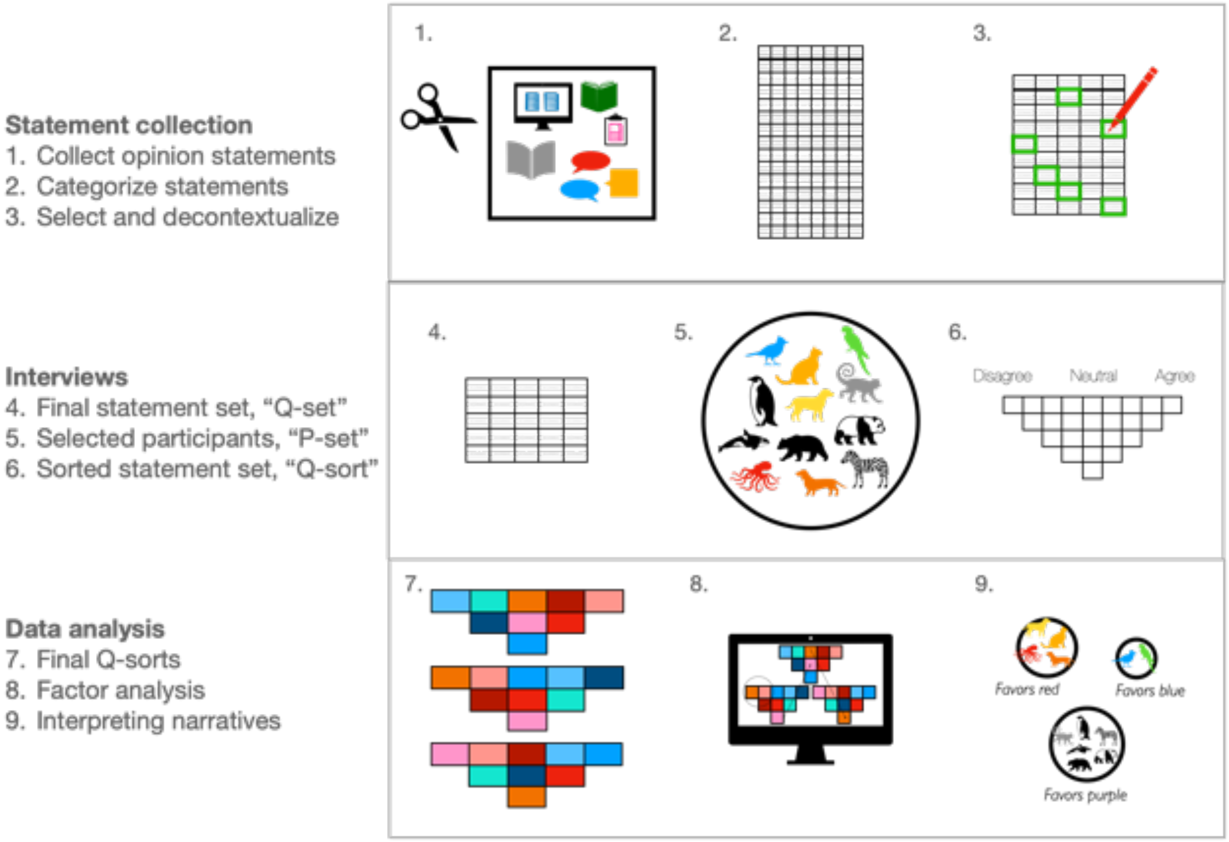

Figure 9. Nine steps in Q-methodology include the creation of a statement set, interviews, and data analysis to interpret the narratives.

2.1 Statement collection

The concourse of statements, or the "Q-set," is a selection of opinion statements that are not readily provable (Webler et al., 2009). The statements are meant to be interpreted differently by different sorters and reacted to in relation to one another. At the same time, each statement is intended to be a stand-alone sentence or two that can be interpreted independently. To gather statements for this step, I conducted a thorough search of local news media sources and article comments, YouTube videos and comments, Twitter, Instagram, and Facebook to gather sentiments related to stormwater in the Ala Wai watershed. Although some online spaces tend to garner deconstructive and critical commentary, I only selected statements that added potentially constructive ideas to the dialogue. The statements were primarily collected in June and July 2019, reflecting a period during which local news outlets extensively covered the USACE project. To add more range of ideas into the set of statements, I searched through websites of local organizations working on various aspects of stormwater either in the Ala Wai specifically, in the city or state, or more broadly. Additionally, I searched statements collected during previous semi-structured interviews (Chun et al., 2017) and took note of ideas expressed during public forums or other communications with key individuals. Finally, I pulled relevant statements used for two Q-method studies specific to stormwater management (Cousins, 2017b, 2017a). The objective of this task is to reach a point of saturation such that no new ideas are emerging in statements (Corbin & Strauss, 2008). In total, I collected 160 statements from 34 sources, representing a variety of sectors.

Each statement was categorized according to the primary outcome expressed. To capture the multiplex aspects of stormwater management, I used a categorization system shown in Table 12. The first five objectives come from Gleick (2003) to situate best practices for stormwater management in the concept of moving away from "hard" to "soft path" solutions. Objectives 6 through 14 are from the US Environmental Protection Agency (EPA) guidelines for voluntary long-term stormwater planning (2016). Finally, the last objective is inspired by Pascua et al. (2017) to incorporate indigenous relationships with the ecosystem that are often suppressed under colonial management systems. From an indigenous Hawaiian perspective, these include cultural ecosystem services such as *'Ike* (Knowledge), *Mana* (Spiritual Landscapes), *Pilina Kanaka* (Social Interactions), and *Ola Mau* (Physical and Mental Wellbeing). Some aspects of stormwater management can be multi-objective. I used best judgment to assess the main objective of any given statement and also tagged secondary benefits. I had between 5 and 25 associated idea statements for each category.

Table 12. Fifteen objectives for stormwater planning and management.[7]

Objectives of Twenty-First Century Stormwater Planning	**Reference**
1. Carefully plan and manage infrastructure and facilities fit for the context	Gleick (2003)
2. Improve the productivity of water use rather than seek endless sources of new supply	
3. Match water services and qualities of water to user needs	
4. Use economic tools to encourage efficient use and equitable distribution of water	
5. Include local communities in decisions about water management, allocation, and use	
6. Stormwater runoff reduction, increasing infiltration, groundwater recharge, and rainwater harvesting	EPA (2016)
7. Water quality	
8. Capital improvements	
9. Flooding reduction	
10. Resiliency	
11. Economic development to attract resources to the community	
12. Social amenities for the health or wellbeing of the community	
13. Open space preservation	
14. Natural channel, watershed, shoreline, and natural floodplain functions protection	
15. Indigenous infrastructure, knowledge, and practices	Pascua et al. (2017)

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[7] In hindsight and based on a conversation with a participant in this study, I realize that environmental justice should also be included as an objective.

To finalize the set of statements used in this analysis, I took several steps. First, I selected the most compelling and clear statements in each of the 15 categories representing various perspectives. I edited some statements to decontextualize them so they would not be readily attributable to the source. The purpose of this step was to ensure that none conjure emotional reactions unrelated to the content of the statement and that the ideas could be applied to other watersheds. I also edited statements for clarity and greater specificity. My goal was to make sure that each statement could be readily understood by anyone with a non-expert working knowledge of stormwater issues. Although the statements are meant to be interpreted differently by different participants (Webler et al., 2009), I avoided ideas with too much room for misinterpretation. For example, a statement such as "stormwater capture and groundwater recharge has great potential" is too vague for this exercise because it offers no specifics about these objectives could be achieved and does not offer much room for disagreement. I conducted two pilot rounds of interviews to reduce 41 statements to a final set of 25 (i.e., the Q-set). This helped eliminate confusing statements such as "the outcomes of infrastructural projects should…create civic programming," where the concept of "civic programming" was not commonly understood terminology. However, common understanding was not always desirable in statements (Webler et al., 2009). For example, I included several statements about "green infrastructure" that indirectly allowed the participant to demonstrate how they define or feel about the concept. I chose statements that portray different benefits of green infrastructure for which the participant can react and prioritize to self-define the concept. Notably, I opted for a smaller statement set since the statement sorting exercise and interviews were conducted virtually. Q-method studies might average about 40 statements, ranging from 15-65 statements (Lundberg et al., 2020).

2.2 Interviews and statement sorting research design

I conducted 18 semi-structured interviews over three months in late 2020. For efficacy in the narrative analysis, the total number of participants should be no greater than the number of statements and no less than half (Watts & Stenner, 2005). Participants were selected through purposive sampling with names found through the initial step of gathering statements or first-hand knowledge of key people involved in stormwater management or community organization. Although the selection of participants through purposive sampling can introduce researcher bias, this is a critical step to ensuring the quality of data collected for analysis will enable theoretically-sound interpretation (Dairon et al., 2017). Occasionally, further participants were identified through referral. The participants (i.e., the P-set) represent various entities involved in stormwater management or issues surrounding the Ala Wai watershed. The selection of participants was also based on evenly representing sector affiliations. There were four participants from government positions, five from consulting or research roles, five from community or advocacy groups, and four representing organizations dedicated to outreach or education. In inviting each person to participate in this study, I identified their role or position related to the Ala Wai watershed. Each participant was willing to respond from the position specified even though some participants identified multiple roles that might affect their responses. I assigned each participant to one of the four sector affiliations post-interview and followed up with participants with the opportunity to provide feedback. Although I did not explicitly collect demographic data, I interviewed a demographically diverse set of participants in gender, age, race, geographic relation to the watershed, and career backgrounds.

All interviews were conducted virtually via videoconference due to public health concerns imposed by the COVID-19 pandemic. For the statement sorting exercise, I used the Q-Method Testing and Inquiry Platform (Q-TIP)[8] provided by the University of Wisconsin-Madison Geography Department. Each participant was asked to arrange the 25 statements according to the ranking arrangement shown in Table 13, which is referred to as the "Q-sort." The Q-sort creates a forced prioritization of statements relative to one another, with the greatest number of statements prescribed to a neutral ranking (i.e., neither agree nor disagree). The statement order was randomized. However, the Q-TIP platform did not allow for the initial step recommended by Q-methodologists of sorting the statements into three piles of "agree," "neutral, and "disagree." Instead, the participants immediately sorted the statements into the Q-sort arrangement and were encouraged to re-arrange statements throughout the sorting exercise. The Q-sort exercise was followed up by a semi-structured interview to understand the rationale for statement rankings (Block, 2008).

Table 13. The research design for sorting 25 statements relative to one another, from most disagreeable (-4) to most agreeable (+4), with neutral in the middle (0).

Q-study sorting scheme									
Statement rank	–4	–3	–2	–1	0	+1	+2	+3	+4
Number of statements	*1*	*2*	*3*	*4*	*5*	*4*	*3*	*2*	*1*

2.3 Narrative analysis

Q-method employs data reduction techniques to determine a small set of narratives from the Q-sorts (i.e., the prioritized statement sets of each participant) collected during the interview process by identifying similarities between them as variables. Essentially, the analysis process takes the 18 Q-sorts and reduces them down to 2 to 5 narrative groups, or "average" Q-sorts (Webler et al., 2009). I use the *Ken-Q Data* open-source code[9] to conduct the narrative analysis. I use Principal Component Analysis (PCA) along with the "varimax rotation" technique to ensure principal components have meaning and are interpretable (Akhtar-Danesh, 2017); these are explained further below. The combination of PCA and the varimax rotation offers a mathematically unique solution (Ramlo, 2016). The principal components determined through the mathematical procedures are then interpreted into narratives using the semi-structured interviews. Even with a mathematically unique solution, there are multiple ways to approach the narrative analysis. Therefore, Watts and Stenner (2012) recommend approaching the narrative analysis with clear analytical aims, where the results are not necessarily 'expected' but should be 'suspected' based on researcher knowledge gained through the interview process. In other words, it is possible to have a mathematically optimal procedure that does not optimally capture the underlying participant perspectives. Therefore, researcher knowledge provides a critical analytical check during the narrative analysis process.

Principal Component Analysis

Principal Component Analysis (PCA) is a linear transformation method used to reduce the dimensionality of a dataset by maximizing the variance (i.e., capture the most amount of

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[8] https://qtip.geography.wisc.edu/#/

[9] https://shawnbanasick.github.io/ken-q-analysis/index.html

information) in the first principal component, and minimizing the variance in the last principal component (Figure 10). PCA uses eigendecomposition to transform the data linearly (Abdi & Williams, 2010). Eigenvectors and their corresponding eigenvalues are calculated by:

$$\mathbf{Av} = \lambda\mathbf{v}$$

Where $\mathbf{A}$ is an n-by-n matrix, $\mathbf{v}$ is a non-zero n-by-1 vector called an eigenvector, and λ is a scalar that is known as the eigenvalue of $\mathbf{A}$. As the equation implies, the eigenvalue produces a scalar transformation of the original matrix, $\mathbf{A}$, that can be recomposed with the eigenvector. Principal components are the eigenvectors found using the correlation matrix of the variables (i.e., Q-sorts). Because square matrices can have as many eigenvectors as dimensions (i.e., n number of eigenvectors), there will be as many principal components as there are dimensions in the data. However, the objective of PCA is to prioritize the principal components by the amount of information they retain.

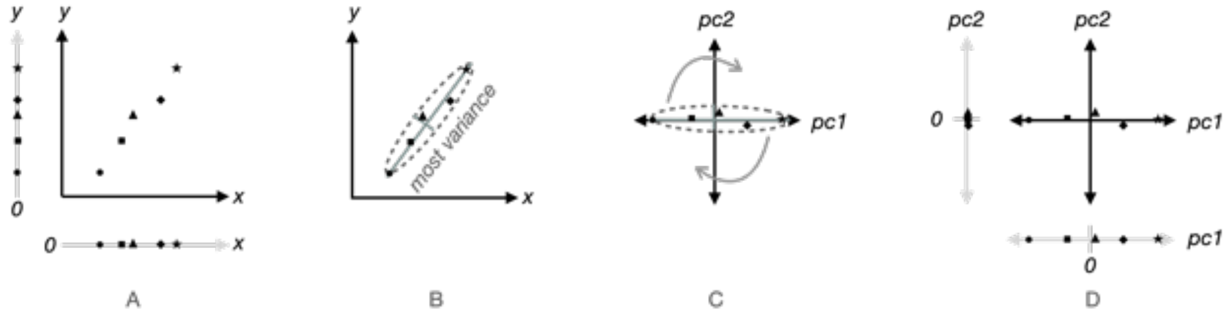

Figure 10. A conceptual example of how Principal Component Analysis (PCA) reduces a 2-dimensional dataset into a 1-dimensional dataset while preserving most of the information in the dataset. (A) Consider points plotted on an x,y plane. (B) PCA identifies a new coordinate system such that the first principal component (pc1) is some combination of the x- and y-values that maximizes the variance in the data. The second principal component (pc2) is orthogonal to pc1 and contains the least amount of variance. (C) PCA is often accompanied by a rotation method for ease of interpretation. (D) Most of the dataset's information can be captured by pc1, and pc2 can be eliminated with minimal information loss.

The first step to prioritizing the principal components is to order the eigenvalues. A larger eigenvalue represents a greater spread in the data (i.e., variance). Thus, the first principal component will capture the most amount of information contained in the data, and the last principal component will contain the least amount of information (i.e., smallest variance). Each subsequent principal component is orthogonal to the first such that there is no correlation between the principal components (i.e., the principal components are independent). Each principal component increases the percentage explained variance. The cumulative percentage of explained variance of the retained principal components reflects the amount of information retained. As a general rule, principal components with eigenvalues less than one can be eliminated since correlation values of the input matrix will be no greater than one (Watts & Stenner, 2005).

The resultant transformation of the data will yield correlation values of the variables (i.e., Q-sorts) to each of the principal components. However, in its raw form, the correlation values are an expression of a subspace where most variables correlate highly to the first principal component with many non-zero weights on subsequent principal components that make it difficult to interpret. Therefore, rotation methods are used to capture more meaning from the data and for ease of interpretation (Akhtar-Danesh, 2017). Orthogonal rotation techniques are commonly used in Q-methodology because it retains the assumption of independence between principal components (Addams, 2000). Varimax is an orthogonal rotation technique that maximizes the individual variable variance and minimizes the shared variance between principal components. That is, varimax aligns the transformed coordinate system so that any given variable correlates highly with one principal component and near-zero with the other principal components to the extent that the data will allow. The result is a more discrete representation of how the variables correlate with each principal component without losing the original data structure. Each defining variable (e.g., in this study, determined at $p < 0.05$) of a principal component will provide a weighted value based on its correlation to the principal component that will be used to calculate the "average" Q-sort for that principal component. The "average" Q-sorts are reconstructed based on the Z-score values of the 25 statements (i.e., the statement with the highest Z-score value is assigned +4 ranking, and the lowest Z-score is assigned -4 ranking). The Z-scores also allow for comparisons of statements between the narratives. The statistics gathered from the mathematical procedures enable the analytical process to interpret the narratives present from the principal components.

3. Results

3.1 Participant loadings on components

In total, I analyzed 18 Q-sorts (i.e., the prioritized statement sets of each participant) for this narrative analysis. Three principal components that explained 51% of the variance with eigenvalues greater than one were included in the analysis. I explored the results of retaining 2-6 principal components, and decided to retain three for interpretation based on how well they aligned with interview conversations. Of the 18 participants, 17 loaded on (i.e., correlated to) the three principal components with $p < 0.05$, as shown in Table 14. Component 2 was considered a bipolar component and split into two effectively opposite narratives (i.e., components 2a & 2b). Component 1 has six defining variables (i.e., participant Q-sorts) and four distinguishing statements ($p < 0.05$) with a composite reliability (i.e., a measure of the internal consistency of the principal component) of 0.96 and a standard error of component Z-scores of 0.20. Component 2a has eight defining variables and five distinguishing statements with a composite reliability of 0.97 and a standard error of component Z-scores of 0.17. Component 2b has one defining variable and four distinguishing statements with a composite reliability of 0.80 and a standard error of component Z-scores of 0.45. Component 3 has two defining variables and three distinguishing statements with a composite reliability of 0.89 and a standard error of component Z-scores of 0.33. There are four consensus statements between all principal components that do not distinguish between any pair of components ($p > 0.01$). There was no strong alignment between affiliations of participants and loading on components.

Table 14. Principal component (PC) loadings by participant. Bold loading values represent correlations to PCs of $p < 0.05$ that also indicate the defining variables for each PC.

Sector affiliation	PC 1	PC 2a	PC 2b	PC 3
Consulting/Research	**0.817**	0.171	-0.171	0.143
Community/Advocacy	**0.766**	0.033	-0.033	-0.293
Government	**0.750**	-0.007	0.007	0.395
Education/Outreach	**0.708**	0.003	-0.003	0.065
Education/Outreach	**0.689**	0.323	-0.323	0.113
Government	**0.488**	0.107	-0.107	-0.153
Community/Advocacy	0.452	**0.565**	-0.565	-0.123
Consulting/Research	0.344	**0.595**	-0.595	0.061
Consulting/Research	0.192	**0.618**	-0.618	-0.315
Community/Advocacy	0.174	**0.732**	-0.732	0.078
Education/Outreach	0.106	**0.519**	-0.519	-0.394
Government	0.074	**0.431**	-0.431	-0.066
Consulting/Research	-0.008	**0.634**	-0.634	0.180
Government	-0.200	**0.665**	-0.665	0.328
Community/Advocacy	0.364	-0.513	**0.513**	0.007
Consulting/Research	0.119	0.338	-0.338	**0.628**
Community/Advocacy	0.091	-0.201	0.201	**0.699**
Education/Outreach	0.578	-0.172	0.172	-0.560
% Explained Variance	22	19	19	11
Defining Variables	6	8	1	2
Composite Reliability	0.960	0.970	0.800	0.889
S.E. of PC Z-scores	0.200	0.173	0.447	0.333

3.2 Narrative interpretations of components

Narrative 1: "Stormwater solutions are strongly connected to land use and stewardship."

This narrative is characterized by a strong connection between land use and land stewardship as critical causes of current issues in the watershed and key factors to stormwater management solutions. Ideas prioritized in this narrative are natural features restoration, valuing and managing stormwater as a resource rather than a hazard, and green infrastructure. Ideas that were de-emphasized in this narrative include space as a limitation to green infrastructure and the centralization of stormwater management projects. Table 15 summarizes the notably ranked statements for this component compared to other components.

Participants who correlated to this principal component favor decentralized solutions and emphasize the need for a holistic, watershed-level approach to stormwater management. One participant, in particular, pointed to statements 16 ($p < 0.05$, d*), 11 ($p < 0.01$, d**), and 13 as interchangeable concepts. Statement 13, however, ranked relatively low for this narrative because of the general feeling among other participants that land ownership and urbanization is too large of an obstacle for implementing Hawaiian land and water management practices in the Ala Wai watershed specifically. Emphasizing decentralized solutions, another participant offered the thought experiment dividing $200 million (approximating the then-cost of the USACE

Project) amongst landowners to build rain gardens and hold rainwater on their property. There was a general sense that spending money on stormwater management would be fruitless unless through collaboration between the community and government.

Table 15. Summary of notable statements for Narrative 1.

Statement	**Statement Rankings per Narrative**			
	1	**2a**	**2b**	**3**
Highest ranked statement for Narrative 1				
16. The restoration of wetlands and other ecological features throughout the watershed is critical to successful environmental management.	+4*	+1	+2	0
Statements ranked higher for Narrative 1 compared to other Narratives				
11. We need to value and manage stormwater as a resource rather than a hazard. This means finding methods to keep and use water in-place as much as possible, rather than building systems to remove water as quickly as possible.	+3**	+1	–3	–1
12. Agencies should actively reach out to and seek input from residents and businesses in neighborhoods affected by stormwater management projects.	+3	0	+3	+2
2. Green infrastructure is a cost-effective approach to improve water quality and help communities stretch their infrastructure investments further by providing multiple environmental, economic, and community benefits.	+2	+2	–1	1
20. Removing impervious surfaces to increase the absorption capacity of the watershed is among the most basic and effective strategies that can be employed in the urbanized areas.	+2	0	+1	–2
10. Stormwater capture can contribute to water conservation efforts and increase the efficiency and productivity of water use.	+2	0	0	–1
18. Resiliency includes promoting opportunities for social cohesion (e.g., opportunities to work together and build community networks) in watershed projects.	+1	–3	+1	–1
1. Funding operations and maintenance into perpetuity is the most important consideration when planning any stormwater management project.	+1	0	–1	–1
7. Private landowners should be responsible for managing and minimizing stormwater runoff from their property.	0	0	–1	0
Statements ranked lower for Narrative 1 compared to other Narratives				
25. Stormwater should be held and used on-site as much as possible.	0	+1	+1	+1
17. We need better parks and public spaces that can also function as flood parks designed to retain water and reduce flash flooding.	0	+1	+2	+1
23. Retrofitting urban areas with distributed solutions like green infrastructure and low impact development should be encouraged through regulation or incentive programs.	0*	+2	+2	+2
13. Restoring Hawaiian cultural water and land practices, such as lo‘i kalo, can help us address some of our most pressing challenges.	–1	–1	+4	0
22. Government agencies should seek private-public partnerships to cover the capital costs of stormwater infrastructure projects.	–2	–1	0	+1
14. Community-driven approaches to stormwater management will be more effective than data-driven approaches.	–3	–2	+3	–2
6. Space is a significant limitation to scaling up green infrastructure-type solutions to meet the magnitude of the problem cost-effectively.	–3	–2	–2	0
Lowest ranked statement for Narrative 1				
15. Our stormwater issues are potentially so substantial that larger centralized projects for handling and capturing stormwater are more effective and cost-efficient than trying to treat it at thousands of small sources.	–4	–1	0	–4
Distinguishing statements: underlined rankings indicate Z-score is higher or lower than all other narratives at $^*P < 0.05$ and $^{**}P < 0.01$.				

This narrative's lowest ranking statements represent a rejection of reasons often used against green infrastructure, ecological restoration, and decentralized solutions. In particular, one younger participant attributed statements 15 and 6 as outmoded, rejecting them as "old school thinking" that is cause for the problems currently faced in the watershed. Seemingly counterintuitive to this narrative's emphasis on decentralized solutions, statement 23 ($p < 0.05$, d*) ranked low. One participant de-prioritized statement 23 with the rationale that stormwater management should be done for the intrinsic value of the ecosystem and not through incentives or regulation. Another participant was skeptical that regulation would motivate private landowners to implement best practices if not already doing so. At the same time, another suggested that blanket implementation of regulation or incentives would lead to uneven benefits where some areas of the watershed are better suited for stormwater runoff management than other areas. There was also general skepticism the private industry's role and whether a private venture would be in the public interest rather than a company's bottom line.

Narrative 2a: "Stormwater management as an essential government service."

This narrative is characterized by prioritizing funding and moving forward with the implementation of stormwater management projects, though not necessarily the USACE project. A summary of notable statements is provided in Table 16. Many of the ideas prioritized in this narrative emphasize distributed green infrastructure solutions alongside prioritizing the need for funding sources and a collaborative government agency effort for climate change adaptation strategies. Because the Ala Wai watershed receives ample rainfall, considering droughts as much as major storms was generally de-prioritized as a "common sense practice" rather than a priority issue. Generally, participants who correlated to this component emphasized the role of stormwater management as a public service that the government offers and prioritized other ideas around that central idea. This includes rethinking land use zoning policies to integrate stormwater management better and finding ways to minimize stormwater runoff in current spaces. Many of the participants comprising this narrative who do not currently hold a government position either work closely with the government in their current role or worked in a government position in the past.

Although not clearly reflected in this narrative's rankings, many of the participants who loaded on this component expressed the importance of building trust between the community and government. Several participants referenced the USACE project as providing a strong lesson in the need for community involvement in stormwater planning and management. They suggested that stormwater management in Honolulu should evolve accordingly. Often, participants referenced periphery benefits of implementing distributed solutions to foster trust between government and community when projects are successful and visible. Some of these projects have a clear way of bringing in the community as an actor. For example, one participant referenced "depaving parties" as an idea that can be adopted in the Ala Wai watershed, where community organizations can spearhead prioritization efforts to remove impervious surfaces in highly visible public spaces as a way to be involved in stormwater management. Such projects can demonstrate the government's commitment to action. However, in this framework of government having a central role, this narrative stops short of suggesting that stormwater management projects should promote social cohesion opportunities, such as projects that include a recreational component.

Similar to narrative 1, this narrative de-prioritizes statement 13 regarding restoring indigenous cultural practices based on the sentiment that the Ala Wai watershed is too urbanized to address the "most pressing challenges" of stormwater management. Across the board, no participant fundamentally disagreed with the concept of the statement. However, those who ranked this statement lower tended to feel that the statement was too strongly worded and interpreted the statement literally. However, one participant ranked the statement highly, referenced indigenous infrastructure as "the original public works." There was a considerable variation in the prioritization of this statement among participants and between components because of the various interpretations spanning from literal to philosophical.

Table 16. Summary of notable statements for Narrative 2a.

Statement	**Statement Rankings per Narrative**			
	1	**2a**	**2b**	**3**
Highest ranked statement for Narrative 2a				
24. Develop dedicated, local funding sources for stormwater management, such as stormwater fees.	–2	+4	–4	+3
Statements ranked higher for Narrative 2a compared to other Narratives				
9. Given the chance of a major storm, it is more prudent to spend money now to address urgent stormwater issues than await potential economic devastation.	–1	+3	–3	+2
5. We need a collaborative agency effort to implement proactive climate change and sea-level rise adaptation strategies.	0	+3	–1	+3
3. Stormwater planning and services should be better integrated with land-use zoning and planning.	+1	+2*	0	0
23. Retrofitting urban areas with distributed solutions like green infrastructure and low impact development should be encouraged through regulation or incentive programs.	0	+2	+2	+2
2. Green infrastructure is a cost-effective approach to improve water quality and help communities stretch their infrastructure investments further by providing multiple environmental, economic, and community benefits.	+2	+2	–1	1
25. Stormwater should be held and used on-site as much as possible.	0	+1	+1	+1
7. Private landowners should be responsible for managing and minimizing stormwater runoff from their property.	0	0	–1	0
Statements ranked lower for Narrative 2a compared to other Narratives				
12. Agencies should actively reach out to and seek input from residents and businesses in neighborhoods affected by stormwater management projects.	+3	0	+3	+2
13. Restoring Hawaiian cultural water and land practices, such as lo‘i kalo, can help us address some of our most pressing challenges.	–1	–1	+4	0
18. Resiliency includes promoting opportunities for social cohesion (e.g., opportunities to work together and build community networks) in watershed projects.	+1	–3*	+1	–1
21. Systems built for stormwater should serve the dual purpose for recreation and aquatic habitat.	+1	–3**	+1	+4
Lowest ranked statement for Narrative 2a				
19. We should think about droughts as much as major storms.	–1	–4**	0	–2
Distinguishing statements: underlined rankings indicate Z-score is higher or lower than all other narratives at *P < 0.05 and **P < 0.01.				

Narrative 2b: "Stormwater management by and for the community."

Principal component 2b is the practical inverse of component 2a, meaning this narrative prioritizes many of the ideas that component 2a de-prioritizes and vice versa. Table 17 shows a summary of notable statements for component 2b. This narrative centers stormwater management around the community, acknowledging that it is a public service provided by the government that should be community-driven. While most participants in this study took issue with the wording of statement 14, wanting instead to see community- and data-driven approaches working hand-in-hand, this narrative prioritizes the concept. The participant who correlated with this narrative prioritized the statement because the community can help direct and prioritize what data are critical to understanding the needed approaches. This narrative also prioritizes distributed and soft infrastructure solutions and generally considers social issues on equal footing as natural systems restoration. For example, the concern over developing dedicated funding sources such as stormwater fees stems from the high cost of living in Honolulu and skepticism around funding being spent on hard, centralized infrastructure. This narrative bears some similarities to component 1 in that these narratives envision a self-sustaining system if stormwater is managed correctly. Table 17 summarizes notable ideas for this narrative. Although it is typically better for analysis for more than one variable to correlate to a principal component, it is not a requirement (Watts & Stenner, 2005). It may be a limitation of the purposive sampling that I was not able to interview more participants who might correlate to this narrative.

Table 17. Summary of notable statements for Narrative 2b.

Statement	Statement Rankings per Narrative			
	1	2a	2b	3
Highest ranked statement for Narrative 2b				
13. Restoring Hawaiian cultural water and land practices, such as lo‘i kalo, can help us address some of our most pressing challenges.	–1	–1	+4**	0
Statements ranked higher for Narrative 2b compared to other Narrative				
12. Agencies should actively reach out to and seek input from residents and businesses in neighborhoods affected by stormwater management projects.	+3	0	+3	+2
14. Community-driven approaches to stormwater management will be more effective than data-driven approaches.	–3	–2	+3**	–2
17. We need better parks and public spaces that can also function as flood parks designed to retain water and reduce flash flooding.	0	+1	+2	+1
23. Retrofitting urban areas with distributed solutions like green infrastructure and low impact development should be encouraged through regulation or incentive programs.	0	+2	+2	+2
18. Resiliency includes promoting opportunities for social cohesion (e.g., opportunities to work together and build community networks) in watershed projects.	+1	–3	+1	–1
25. Stormwater should be held and used on-site as much as possible.	0	+1	+1	+1
15. Our stormwater issues are potentially so substantial that larger centralized projects for handling and capturing stormwater are more effective and cost-efficient than trying to treat it at thousands of small sources.	–4	–1	0	–4
19. We should think about droughts as much as major storms.	–1	–4	0	–2
Statements ranked lower for Narrative 2b compared to other Narratives				
3. Stormwater planning and services should be better integrated with land-use zoning and planning.	+1	+2	0	0
1. Funding operations and maintenance into perpetuity is the most important consideration when planning any stormwater management project.	+1	0	–1	–1
2. Green infrastructure is a cost-effective approach to improve water quality and help communities stretch their infrastructure investments further by providing multiple environmental, economic, and community benefits.	+2	+2	–1	1
5. We need a collaborative agency effort to implement proactive climate change and sea-level rise adaptation strategies.	0	+3	–1	+3
7. Private landowners should be responsible for managing and minimizing stormwater runoff from their property.	0	0	–1	0
9. Given the chance of a major storm, it is more prudent to spend money now to address urgent stormwater issues than await potential economic devastation.	–1	+3	–3	+2
11. We need to value and manage stormwater as a resource rather than a hazard. This means finding methods to keep and use water in-place as much as possible, rather than building systems to remove water as quickly as possible.	+3	+1	–3*	–1
Lowest ranked statement for Narrative 2b				
24. Develop dedicated, local funding sources for stormwater management, such as stormwater fees.	–2	+4	–4*	+3
Distinguishing statements: underlined rankings indicate Z-score is higher or lower than all other narratives at *P < 0.05 and **P < 0.01.				

Narrative 3: "Stormwater management as a collaborative effort."

This narrative characterizes stormwater management as an issue that requires collaboration, community contributions, and financing. Similar to all others, this narrative prioritizes soft, decentralized infrastructure ideas. However, unlike narratives 1 and 2b, these participants convey the need for capital financing of projects through private-public partnerships. Similar to component 2a, this narrative believes that private landowners should pay into stormwater management as a public service. However, opposite component 2a, this narrative prioritizes statement 21 as a means to bring attention to stormwater issues and create community buy-in on projects. The participants who correlate to this component emphasized the need for approaching stormwater management holistically but tended to view each idea in the context of local politics. Thus, these participants prioritized based on weighing politics alongside their perception of the stormwater management needs. For example, one participant felt that funding operations and maintenance should not be an impediment to moving forward, but acknowledged that this is a realistic obstacle to implementing City projects. Table 18 summarizes the notable statement rankings for this narrative.

Table 18. Summary of notable statements for Narrative 3.

Statement	**Statement Rankings per Narrative**			
	1	**2a**	**2b**	**3**
Highest ranked statement for Narrative 3				
21. Systems built for stormwater should serve the dual purpose for recreation and aquatic habitat.	+1	–3	+1	+4*
Statements ranked higher for Narrative 3 compared to other Narratives				
5. We need a collaborative agency effort to implement proactive climate change and sea-level rise adaptation strategies.	0	+3	–1	+3
23. Retrofitting urban areas with distributed solutions like green infrastructure and low impact development should be encouraged through regulation or incentive programs.	0	+2	+2	+2
25. Stormwater should be held and used on-site as much as possible.	0	+1	+1	+1
22. Government agencies should seek private-public partnerships to cover the capital costs of stormwater infrastructure projects.	–2	–1	0	+1
7. Private landowners should be responsible for managing and minimizing stormwater runoff from their property.	0	0	–1	0
6. Space is a significant limitation to scaling up green infrastructure-type solutions to meet the magnitude of the problem cost-effectively.	–3	–2	–2	0
Statements ranked lower for Narrative 3 compared to other Narratives				
16. The restoration of wetlands and other ecological features throughout the watershed is critical to successful environmental management.	+4	+1	+2	0
3. Stormwater planning and services should be better integrated with land-use zoning and planning.	+1	+2	0	0
10. Stormwater capture can contribute to water conservation efforts and increase the efficiency and productivity of water use.	+2	0	0	–1
1. Funding operations and maintenance into perpetuity is the most important consideration when planning any stormwater management project.	+1	0	–1	–1
20. Removing impervious surfaces to increase the absorption capacity of the watershed is among the most basic and effective strategies that can be employed in the urbanized areas.	+2	0	+1	–2**
8. Entrepreneurship should be encouraged to find technological solutions for some of the issues faced in the watershed.	–1	–2	–2	–3
4. Moving forward requires identifying one or two pilot areas where innovative solutions to stormwater management can be prioritized, rather than trying to solve everything all at once.	–2	–1	–2	–3
Lowest ranked statement for Narrative 3				
15. Our stormwater issues are potentially so substantial that larger centralized projects for handling and capturing stormwater are more effective and cost-efficient than trying to treat it at thousands of small sources.	–4	–1	0	–4
Distinguishing statements: underlined rankings indicate Z-score is higher or lower than all other narratives at *P < 0.05 and **P < 0.01.				

3.3 The consensus-disagreement spectrum

In this analysis, I found four consensus statements—statements 25, 8, 17, and 7—where the principal component Z-scores are not significantly distinguishable between any pair of components. This means that rankings were similar amongst all narrative groups. The consensus statements include a general agreement that stormwater should be held and used on-site as much as possible, that entrepreneurship should not be prioritized to find technological solutions, that parks and public spaces should be designed to retain water and reduce flash flooding, and neutrality (i.e., neither prioritized nor de-prioritized) over whether private landowners are responsible for minimizing stormwater runoff from their property. On the other end of the spectrum, rankings are highly variable between narrative groups around developing dedicated funding sources for stormwater management such as stormwater fees, moving forward to spend money now rather than facing potential economic devastation from a major storm, and managing stormwater as a resource rather than a hazard. In particular, statements 11 and 24 regarding developing dedicated funding sources for stormwater management and valuing stormwater as a resource rather than a hazard, respectively, are statistically distinct in two or more narratives ($P < 0.05$).

Table 19 shows all statements by Z-score variance in ascending order to show the spectrum of consensus to disagreement among statements. Statements consistently prioritized at or above a zero ranking (i.e., neutral) among all narratives are highlighted in green, and statements consistently de-prioritized at or below a zero ranking are highlighted in orange. Green highlighted statements tend to show a desire to incorporate stormwater management and green infrastructure in current distributed spaces through better integration of stormwater management into built and natural land features. The nature of the ideas emphasizes the government's role in providing stormwater management as a public service alongside prioritizing agencies actively reaching out to seek input from affected residents and businesses. Orange highlighted statements tend to show the opposite. Ideas that are de-prioritized include privatizing the role of stormwater management, approaching the solution incrementally, and centralized solutions.

Table 19. Statements by Z-score variance. Green highlighted statements show ideas that rank at or above zero for all principal components and orange for those that rank at or below zero, where zero is neutral.

Statement	**Statement Rankings per Narrative**				**Z-Score variance**
	1	**2a**	**2b**	**3**	
25. Stormwater should be held and used on-site as much as possible.	0	+1	+1	+1	0.03**
8. Entrepreneurship should be encouraged to find technological solutions for some of the issues faced in the watershed.	–1	–2	–2	–3	0.07**
17. We need better parks and public spaces that can also function as flood parks designed to retain water and reduce flash flooding.	0	+1	+2	+1	0.093*
7. Private landowners should be responsible for managing and minimizing stormwater runoff from their property.	0	0	–1	0	0.1*
23. Retrofitting urban areas with distributed solutions like green infrastructure and low impact development should be encouraged through regulation or incentive programs.	0	+2	+2	+2	0.155
3. Stormwater planning and services should be better integrated with land-use zoning and planning.	+1	+2	0	0	0.182
4. Moving forward requires identifying one or two pilot areas where innovative solutions to stormwater management can be prioritized, rather than trying to solve everything all at once.	–2	–1	–2	–3	0.183
10. Stormwater capture can contribute to water conservation efforts and increase the efficiency and productivity of water use.	+2	0	0	–1	0.231
6. Space is a significant limitation to scaling up green infrastructure-type solutions to meet the magnitude of the problem cost-effectively.	–3	–2	–2	0	0.249
22. Government agencies should seek private-public partnerships to cover the capital costs of stormwater infrastructure projects.	–2	–1	0	+1	0.249
12. Agencies should actively reach out to and seek input from residents and businesses in neighborhoods affected by stormwater management projects.	+3	0	+3	+2	0.268
2. Green infrastructure is a cost-effective approach to improve water quality and help communities stretch their infrastructure investments further by providing multiple environmental, economic, and community benefits.	+2	+2	–1	+1	0.29
1. Funding operations and maintenance into perpetuity is the most important consideration when planning any stormwater management project.	+1	0	–1	–1	0.321
18. Resiliency includes promoting opportunities for social cohesion (e.g., opportunities to work together and build community networks) in watershed projects.	+1	–3	+1	–1	0.435
16. The restoration of wetlands and other ecological features throughout the watershed is critical to successful environmental management.	+4	+1	+2	0	0.456
20. Removing impervious surfaces to increase the absorption capacity of the watershed is among the most basic and effective strategies that can be employed in the urbanized areas.	+2	0	+1	–2	0.493
5. We need a collaborative agency effort to implement proactive climate change and sea-level rise adaptation strategies.	0	+3	–1	+3	0.695
19. We should think about droughts as much as major storms.	–1	–4	0	–2	0.707
15. Our stormwater issues are potentially so substantial that larger centralized projects for handling and capturing stormwater are more effective and cost-efficient than trying to treat it at thousands of small sources.	–4	–1	0	–4	0.805
13. Restoring Hawaiian cultural water and land practices, such as lo‘i kalo[10], can help us address some of our most pressing challenges.	–1	–1	+4	0	1.145
14. Community-driven approaches to stormwater management will be more effective than data-driven approaches.	–3	–2	+3	–2	1.226
21. Systems built for stormwater should serve the dual purpose for recreation and aquatic habitat.	+1	–3	+1	+4	1.4
11. We need to value and manage stormwater as a resource rather than a hazard. This means finding methods to keep and use water in-place as much as possible, rather than building systems to remove water as quickly as possible.	+3	+1	–3	–1	1.533
9. Given the chance of a major storm, it is more prudent to spend money now to address urgent stormwater issues than await potential economic devastation.	–1	+3	–3	+2	1.636
24. Develop dedicated, local funding sources for stormwater management, such as stormwater fees.	–2	+4	–4	+3	2.472
Consensus statements that do not distinguish rankings between any pair of narratives, non-significant at ** P > 0.01 and * P > 0.05					

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[10] Lo‘i kalo is an indigenous wetland taro farming and terracing practice.

4. Discussion

4.1 Comparing Across Narratives

This study shows a coalescence around several ideas related to stormwater management. First, there is strong agreement over the need for green infrastructure-type solutions, showing a movement away from hard infrastructure characteristic of the twentieth century towards softer solutions to stormwater management. Along similar lines, there is broad agreement that stormwater management solutions need to be distributed rather than centralized. Narratives also tended to promote infrastructure ideas that offer secondary natural systems benefits, such as water quality improvement or increased infiltration. There was less tendency towards agreement on infrastructure that directly provides civic benefits, such as recreational options and opportunities to create social cohesion. However, narratives tended to suggest better use of space for stormwater management, such as in parks or through better integration of stormwater planning with land-use zoning. Overall, there was general affirmation of stormwater management as a public service provided by the government.

However, views around stormwater management diverge around responsibilities, funding, and underlying planning approaches. In particular, there was a wide extent of opinions regarding what citizens contribute, whether monetary, labor, or ideas. Generally, individual labor contribution (e.g., being responsible for runoff from one's property) was not a high priority. However, there was a split in narratives over whether citizen contribution should be in the form of paying into services or contributing ideas to the management process. No narratives suggested that the private sector should have a role in stormwater management. Participants tended to have a strong negative reaction to the word "entrepreneurship," suggesting that they did not see a role for profit-driven enterprises in stormwater management. The phrase "private-public partnerships" tended to conjure up similar reactions. One participant suggested that there were too many bad examples of private-public partnerships. Along similar lines, there was no strong indication that technological solutions or innovation would solve stormwater problems. Narratives tended to focus on either retrofitting the current system or restoring ecosystem functions. Fundamental views over long-term planning needs also varied significantly. There was no strong agreement over whether long-term needs are infrastructural, institutional, or monetary in nature. The USACE project shaped many participants' views on this front. For example, one participant expressed the perception that there is money for stormwater management, just not for the right types of projects. Overall, no strong pattern was revealed regarding affiliation; generally, affiliations were mixed between all narratives.

4.2 Characterizing competing views on stormwater governance

Stormwater management and planning are inherently multi-dimensional, and adding to the dimensionality are the various views of how stormwater should be governed. Here, I summarize the spectrum of viewpoints around various aspects of stormwater governance in a framework to show the dimensionality of the choice set. This framework covers the potential differing viewpoints in stormwater infrastructure approach, responsibilities, and planning approach.

Stormwater infrastructure approach

Concepts often associated with gray infrastructure versus green infrastructure are often viewed as opposing. Figure 11 describes the spectrum of choices in approaching stormwater infrastructure solutions. Gray infrastructure—also “hard” infrastructure—is frequently associated with engineered solutions that control the environment (e.g., canals to drain the land and convey water, basins to retain water). These solutions tend to be large, centralized, and can require sizable capital investments. Because of the singular purpose of such infrastructure, gray infrastructure often results in adverse consequences requiring mitigation. On the other hand, various ecologically-oriented engineering tactics such as green infrastructure and natural functions restoration focus on reducing runoff while retaining the water’s benefits as a resource. Green infrastructure—also “soft” infrastructure—usually include multiple objectives and focuses on creating positive ancillary outcomes (e.g., civic space, water quality improvement). Green infrastructure is frequently associated with engineered solutions that restore or mimic natural functions and may include distributed solutions such as low-impact development. Because green infrastructure tends to require greater upkeep and maintenance, it is often associated with greater labor demand.

In major cities built based on twentieth-century flood control principles, the legacy is often that of hard infrastructure, on which cities must retrofit new solutions. Therefore, achieving redefined outcomes for stormwater management built on legacy systems might include a wide array of often competing ideas to reconcile the concept of a new design with the constraints of an old system. Transitioning away from infrastructure built for the sole purpose of flood protection to adaptive, multi-functional infrastructure is a long-term, multistep process. As Porse (2013) describes, realistic constraints on the natural and built environments tend to force actual implementation options towards the middle or some hybrid combination of options. As is detailed in the planning approach framework below, I associate this hybridization of infrastructure to a pragmatic approach to planning. In this study, I found a tendency in narratives to favor distributed, soft solutions that achieve positive outcomes but a lack of strong opinions around resource base.

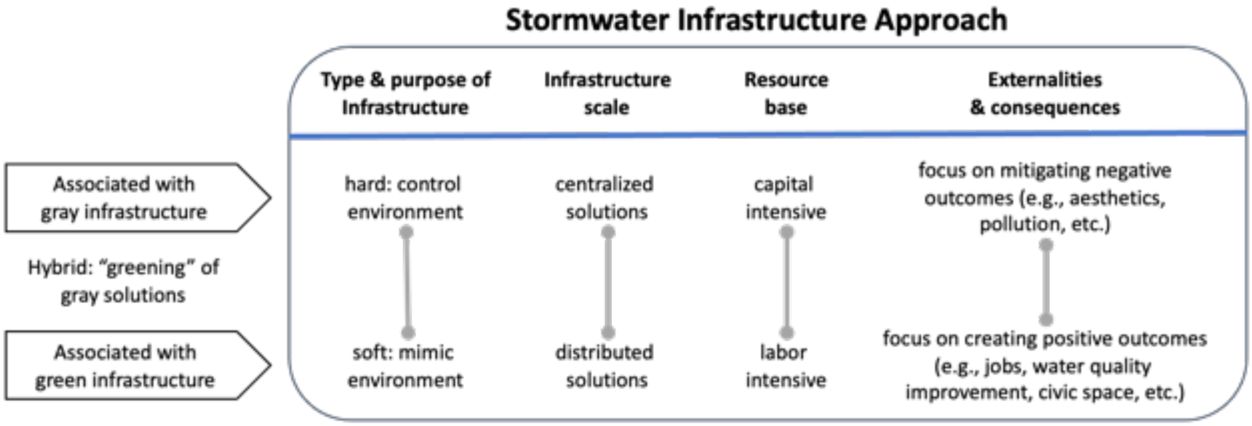

Figure 11. A framework to understand the spectrum of choices to approach stormwater infrastructure. Most current infrastructure projects might fall in the middle. Adapted from Porse (2013).

Stormwater Management Responsibilities

Jurisdictional purview may be clearly defined for some aspects of stormwater management, but not all. For example, water quality parameters in natural water bodies are regulated by the Clean Water Act, and therefore discharges from public stormwater conveyance systems require permitting. On the other hand, non-point source pollution (e.g., landscaping chemicals or oils and heavy metals from cars) and total runoff is more challenging to manage because of the dispersed land jurisdictions from which runoff comes. Figure 12 illustrates the various spectra of responsibilities over stormwater management. Managing stormwater can be considered the government's commitment, the individual landowners where rain falls, or some combination of both. Because stormwater management is a public service, it necessitates some degree of citizen contribution, which may be monetary, labor, or ideas. Defining expert roles and the functions of various expertise for stormwater management is also critical to understanding responsibilities over stormwater management. Conflict may arise over differing views of responsibilities, especially where those roles are not clearly defined. This study showed that most narratives consider stormwater management to be strongly within the government's responsibility and mixed thoughts about the role of individuals and the community in stormwater management. In general, there was no strong agreement over what citizens contribute to the process, but there was strong agreement that the private sector should have a minimal role.

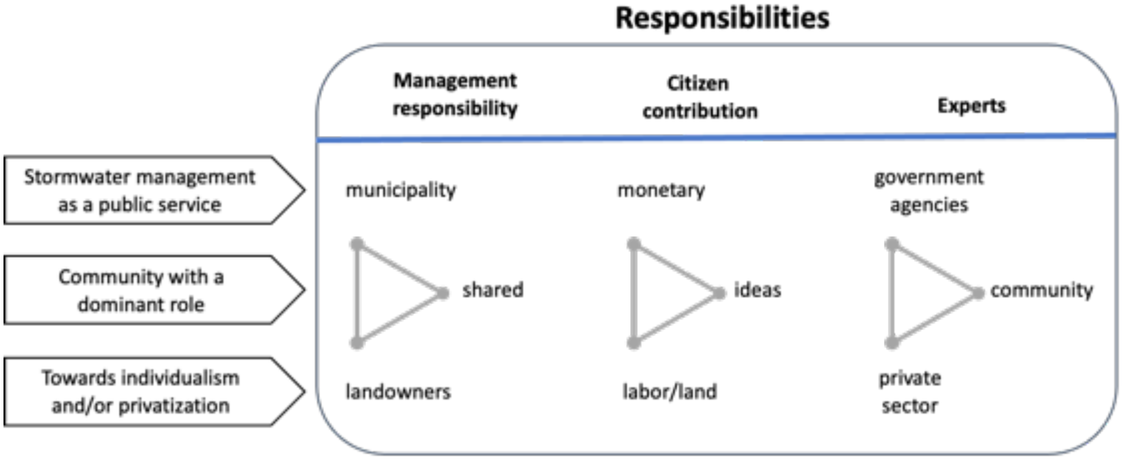

Figure 12. A framework to understand aspects stormwater management responsibilities and roles.

Stormwater Planning approach

Dialogue around stormwater management may include individuals whose approaches to planning come from fundamentally different visions, motivations, and ideas about long-term needs. These viewpoints are often explicitly unspoken, although they may bubble to the surface indirectly in conversations around infrastructure. Figure 13 shows a range of approaches to planning that can be considered antithetical. A pragmatic approach to implementation is often the practical default for projects because of the realities of timelines and budgets. Pragmatism here represents a pull towards a middle-of-the-road approach that is often motivated by urgency. Urgency may come out of some form of necessity (e.g., a shock) or perception of need (e.g., chronic stressor). As Finewood (2016) discusses, just as there is a "greening" of gray infrastructure, there can be a loss of a more democratic process in stormwater management through this middle-of-the-road approach. Therefore, urgency can take away from radical change and moving towards environmental justice or from a holistic vision of ecosystem function restoration. Innovation or technical solutions can be considered as opposite of ecosystem function restoration. I consider these incremental because technological solutions can rarely address sweeping problems with stormwater. For example, to avoid more difficult discussions and larger capital investments, installing pump stations to deal with nuisance flooding from sea-level rise is an incremental solution using technology to maintain the status quo. The viewpoints in this study tended to stay away from innovation and technology as solutions but were wide-ranging around other aspects of vision and motivation.

Views of long-term needs may also change people's foundational planning approach to stormwater management. This may be a perception that either infrastructure, institutions, financing, or some combination of the three need planning attention. If planning needs are infrastructural, then the built environment would be the focus of a planning effort. Institutional planning efforts may include measures to enact policies or regulations around stormwater. Monetary needs would shift the focus of planning efforts towards seeking mechanisms for financing. These concepts are not mutually exclusive and can work in tandem. For example, policies can create funding sources, or regulations can lead to infrastructure changes. In this study, there was a spread of viewpoints around the long-term needs, and participants tended to acknowledge the interlinkages between long-term needs. This framework represents generalities, and viewpoints may map differently in other contexts.

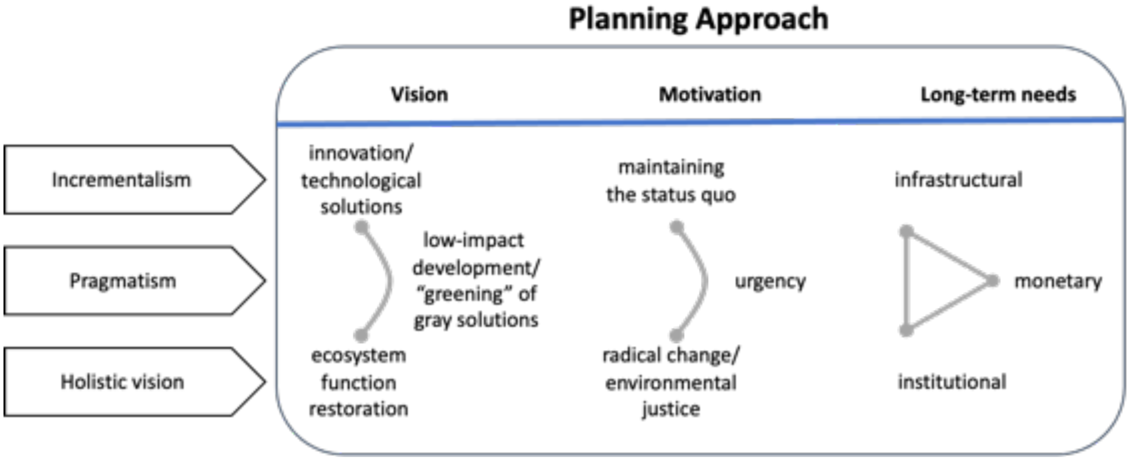

Figure 13. A framework to understanding various approaches to stormwater planning.

5. Conclusion

Dialogue is a fundamental means of shaping desired outcomes in planning. Coming to a common or acceptable understanding of "desired outcomes" can be challenging when a wide range of viewpoints exist around an inherently multi-dimensional problem. This study uses Q-methodology to elucidate specific narratives within the broader discourse about stormwater management in relation to a contentious USACE Flood Risk Management Study. The uprising of the community in response to the opaque, top-down process used by the USACE Study is indicative of a cultivation of distrust. When trust between the government and community is lost, it is both difficult to regain and conduct good faith dialogue to find desired outcomes, even if a project has merit. Q-methodology is a means to understand individual priorities by asking participants to rank various ideas according to a structure that forces few ideas to be prioritized and de-prioritized. The outcome of the Q-method is to interpret the social narratives that comprise the public discourse. Through the narrative analysis, specific points of agreement and disagreement to initiate dialogue and start rebuilding trust through authentic dialogue.

This study finds four narratives that describe differing priorities for stormwater management. The first narrative describes a strong connection between land stewardship and stormwater solutions. There is a clear emphasis on restoration of natural function and green infrastructure in the first narrative, paired with a strong rejection of centralized solutions. This narrative also prioritized community involvement in decision making as part of holistic water management, with the belief expressed by participants that successful holistic, natural functions restoration and community involvement will be a self-sustaining solution that costs less in the long-run. The second and third narratives are effectively opposite and might represent narratives that dominate the news and social media. The second narrative affirms stormwater management as an essential government service, and prioritizes financing mechanisms and integrated management. This narrative also emphasizes the urgency of taking action, while de-emphasizing the need to explicitly incorporate civic benefits into project solutions. Whereas, the third narrative focuses on the role of the community in stormwater management as a major priority. Finally, the fourth narrative emphasizes collaborative aspects of stormwater management, including inter-agency collaboration and collaboration between community and government.

Although the issues surrounding the USACE Flood Risk Assessment of the Ala Wai Canal can easily be perceived as polarized (e.g., community vs. government, upstream vs. downstream, residents vs. tourists) through news reports and social media, this analysis shows there is much greater nuance in the discourse. Most participants expressed that there were very few or no statements to which they were fundamentally opposed. All four narratives tend to agree that there should be more distributed soft infrastructure solutions that provide secondary benefits. Community engagement in projects often revolves around infrastructure solutions, however, narratives tend to diverge around responsibilities, funding, and underlying planning approaches. In other words, people largely agree on the what the infrastructure outcomes, but underlying differences in the “how-to” lead points of contention. These differences suggest that more discussion around responsibilities and planning approaches could alleviate misunderstandings that are often misattributed to infrastructural solutions. Notably, there was no discernable pattern in the participants’ affiliations and the correlations to narratives, which suggests an optimistic outlook for authentic dialogue through proper engagement of the community in stormwater management.

Article 3 —
On Issues of Fairness and a Stormwater Fee

Abstract

Combined challenges of aging infrastructure, land use change, climate change, and water quality degradation create a mounting imperative to ensure success in stormwater services. Increasingly, municipalities are establishing stormwater utilities (SWUs) that assesses a fee from service beneficiaries and encourages distributed stormwater runoff reduction practices. While communities expect effective stormwater management as a public service, there tends to be resistance to paying additional fees, especially where there is a perception of unfairness. This study creates a framework for understanding fairness as defined through both economic efficiency and concepts of equity. Through a systematic review of literature, I examine how these concepts manifest in stormwater financing, programs, and services. To illustrate how context is critical to shaping perceptions of fairness, I use Oʻahu's recent effort to develop a SWU as a case study. In the exploration of establishing a SWU, community members continually ask about aspects of fairness in the administration of a stormwater fee and credit system. In this study, I examine two perspectives of fairness. The first considers the concept of distributive equity in the context of a proposed hardship relief component. I find a high-degree of correlation between poverty rate and renter-occupied housing, suggesting that the exclusion of renters from hardship relief is a significant omission in an effort to create greater equity. For the second, I develop an illustrative stormwater model to estimate stormwater runoff based on total impervious area (IA). The findings challenge common assumptions around the economic efficiency of assessing a tiered fee solely based on a property's total impervious area (IA). I propose a rainfall multiplier as a simple mechanism to reduce the economic inefficiencies and to better-match the incentive of on-site practices to the accrued benefits.

1. Introduction

Cities across the United States and internationally face the converging challenges of aging stormwater management infrastructure and the uncertainties posed by climate change (Cesanek et al., 2017; Milly et al., 2008; Postel, 2010). Inadequate stormwater management and infrastructure results in public health and safety threats (Gaffield et al., 2003; Kessler, 2011; Sanders & Grant, 2020), water quality concerns for receiving waterbodies (Rodak et al., 2019; Zhou, 2019), and issues of equity in resource allocation, accrued benefits, and adverse impacts (Elshall et al., 2020; Wilfong & Pavao-Zuckerman, 2020). Concepts that re-envision stormwater as a resource rather than a hazard incorporate multi-purpose solutions built on sustainable, closed-loop stormwater management systems that address these and other challenges (Brown et al., 2009; Crosson et al., 2020; US Water Alliance, 2016). These stormwater management solutions often include low-impact development, green infrastructure, or other multi-benefit soft infrastructure that moves away from singular-purpose hard or gray infrastructure (Dhakal & Chevalier, 2017; Prudencio & Null, 2018; Pyke et al., 2011; Wang et al., 2020). In addition to a large share of stormwater impacts originating from private lands, funding and capacity issues have long been a barrier to implementing forward-looking solutions in stormwater management (Stormwater Infrastructure Finance Task Force, 2020).

Even though pollution in stormwater runoff is the leading cause of water quality degradation in the U.S., investment in stormwater management often lags behind drinking water purveyance and wastewater management (Stormwater Infrastructure Finance Task Force, 2020). Unlike drinking water and wastewater, which are conventionally governed by utilities, stormwater management programs have often competed with other municipal public works programs for funding and prioritization when there is no dedicated stormwater enterprise fund. In response, municipalities are adopting stormwater utilities (SWU) or stormwater fees, which create a designated revenue source for use on stormwater-related infrastructure, management, or maintenance. Currently, there are more than 1,700 SWUs across the U.S. and Canada (C. W. Campbell, 2019; Kea et al., 2016). Having a dedicated fund for stormwater systems ensures that property owners directly pay to address a ubiquitous issue, raising awareness of the problem. Moreover, incentives or credit systems can encourage individual landowners to adopt behaviors and practices that reduce runoff from their property.

However, municipalities often face conflicting demands from citizens, where communities expect more and better public service but are resistant to paying more taxes (Grigg, 2019). Perceptions of fairness are a key part of the SWU discourse to build political feasibility for SWUs. Often, concepts of "equity" and economic efficiency are conflated in the literature and by SWUs. For example, the concept of everyone paying into the service they receive is commonly couched as "more equitable." Rather, the notion of paying for public goods is rooted in economic efficiency. Another example is the way fees are assessed. The most prevalent method by which stormwater fees are calculated is based on a measure of total impervious area (IA) as a key driver of surface water runoff (Kea et al., 2016). This is often referred to as an "equitable" way to charge a fee. However, this again is rooted in economic efficiency and paying individual impacts to society. The viability of charging all property owners user fees and for charging fees based on IA is set in precedent by several U.S. court cases (National Association of Clean Water Agencies, 2014). Nonetheless, understanding the anatomy of fairness is critical to dissecting the discourse around SWUs and stormwater management.

In this study, I explore concepts of economic efficiency and equity in stormwater financing and management as a framework for understanding "what is fair" in various contexts. This paper is broken out into two parts. Part I is a deep-dive into structures of stormwater financing, economic efficiency, and a systematic literature review of equity concepts in stormwater. This provides a framework to define perceptions of fairness in the context of SWUs, stormwater program outcomes, and stormwater planning processes. Part II is an illustrative example about how context can shape perceptions of fairness. I use the example of a proposed tiered stormwater fee based on IA for the island of Oʻahu (also the City and County of Honolulu). I use the fairness framework developed in Part I to understand some of the issues raised by the community about fairness. I challenge some of the assumptions behind the City's framing of certain aspects of the proposed stormwater fee as "more equitable." I begin with a correlation analysis to understand whether spatial overlaps exist between socioeconomic parameters and variables that drive stormwater runoff. Then, using the computational methods of the U.S. EPA's National Stormwater Calculator, I test the assumption that IA alone is a sufficient variable for pricing runoff. I conclude with a discussion about "fairness" in implementing a stormwater fee in a place like Oʻahu with highly variable rainfall and how to consider the co-benefits of reducing runoff and increasing infiltration in SWU programming.

Part I – Defining “fairness” in stormwater financing and management

In Part I of this paper, I conduct a systematic literature of two nascent strands in the literature. The first review focuses on peer-review literature on stormwater utilities, fees, or credits (Section 2). I then situate financial concepts in welfare economic theory to better understand the roots of the terms “externalities” and “economic efficiency” used in the literature as applied to stormwater management. The second review covers peer-reviewed papers related to concepts of equity and how the literature approaches them (Section 3). Figure 14 shows the Web of Science publication results for the two literature searches with number of peer-review publications and the number of citations per year of the papers found. For the stormwater equity literature search, I followed PRISMA methods for systematic reviews and meta-analyses (Moher et al., 2009). I found 136 publications published from 2000-2021[11]. For the screening step, I read through abstracts to find studies that conducted an analysis or developed a method of analysis relevant to furthering concepts of equity in stormwater management or related stormwater issues. I kept 40 articles for a full-text review. At this step, I looked for deep discussion of equity or justice-related issues in stormwater management, definitions of equity or justice in terms of stormwater management, an analysis of issues of equity or justice in relationship to stormwater management, or a discussion of stormwater utilities, fees, credits, willingness-to-pay for stormwater management. In total, I included 28 papers in a review of methodology and equity concepts related to stormwater. The purpose of Part I of this paper is to create an analytical framework for approaching concepts of “fairness” around establishing a SWU.

Search terms
-stormwater or “storm water”
& utility or utilities
or fee or fees
or credit or credits
or finance or financing

Search terms
-stormwater or “storm water”
& justice
or equity or equitable
or socioeconomic or socio-economic
-“stormwater fee” or “storm water fee”
or “stormwater utility” or “storm water utility”
& efficient or efficiency

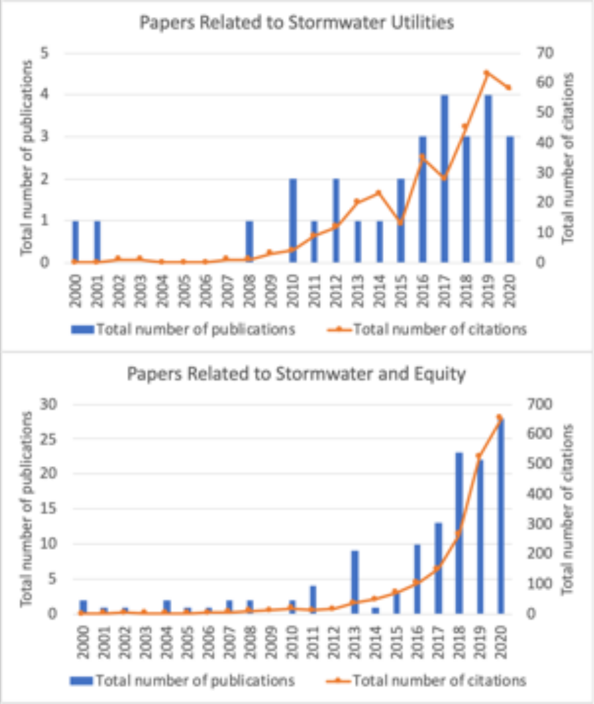

Figure 14. Meta-analysis of literature related to stormwater utilities and concepts of equity in stormwater and the respective search terms used for the literature search.

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[11] I also searched prior to 2000, but found the number of papers to be sparse and not directly relevant to the purpose of this literature analysis.

2. Stormwater Financing

Funding is often a major barrier to updating stormwater infrastructure and providing effective services while also meeting federal water quality regulations (Stormwater Infrastructure Finance Task Force, 2020). Under a traditional public works financing model, stormwater systems and management are funded through taxpayer sources, such as the general fund or road fees, and compete with other priorities for a proportion of the monies. In the face of increasingly deteriorating infrastructure, climate change impacts, federal regulations and water quality standards, land use change, and competing public works budgeting, many municipalities are establishing SWUs to create a separate revenue source for stormwater management services (Brisman, 2002; Grigg, 2013; Zhao et al., 2019). SWUs create enterprise funds that allow municipalities to establish a dedicated and predictable revenue source for proactive stormwater management services (Abebe et al., 2021). McDonald & Naughton (2019) find SWUs to be an effective means for increasing per capita funds for stormwater services. The most popular stormwater utility model uses an Equivalent Residential Unit (ERU) to determine the fee based on the average impervious surface area of a single-family residential parcel (C. W. Campbell, 2019). Non-residential properties are then charged based on the ratio of the impervious area of the parcel to the ERU. Other models include flat fees, water usage-based fees, and tiered fees, as described in Table 20. Many municipalities also offer credit systems that provide fee breaks for property owners that implement runoff reduction practices on their property (e.g., rain gardens, rain barrels, downspout disconnections) (Doll et al., 1998; Gmoser-Daskalakis, 2019; Hawaii Pacific University & One World One Water, 2017).

Table 20. SWU funding mechanisms found in the U.S. (adapted from Kea et al., 2016).

Funding Mechanism	Description
Equivalent Residential Units (ERUs)	Uses an average total IA for residential properties (ERU = total residential impervious area/total number of residential parcels) as a basis for charging user fees. Each property is assessed a fee based on ERU utilized. The use of this method can also create distinct stepped fees between typical residential properties and commercial properties.
Flat fee	All properties connected to the stormwater conveyance system are charged the same rate. Sometimes there may be a rate difference between residential and commercial properties.
Tiered fee	Properties a charged a fee based on categories. For example, total IA is often used to assess fees.
Water meter or usage	Some SWUs tie their user fee to potable water usage.

A number of factors might influence a SWU's decision about which fee structure to adopt. Administrative burden and available capacity can be a major limiting aspect for incorporating greater complexity into a stormwater fee (Fedorchak et al., 2017). For example, a flat fee is an administratively undemanding means of charging a stormwater fee, but may appear to be "unfair" because property characteristics are not taken into account (Tasca et al., 2017). Data availability can also be limiting and create greater administrative burdens. ERU-based fees attempt to reduce the data acquisition and administrative burden, while taking into account some degree of property characteristics. The amount of revenue needed can also play into the decision of how to structure stormwater fees (Fedorchak et al., 2017; Zhao et al., 2019). Enforcement is also an issue for a SWU that differs from other utilities. Therefore, it is useful to tie the stormwater fee to water or power billing to have a mechanism for enforcement (C. W. Campbell, 2019). This brings political feasibility into bear, which is shaped by public perception and trust. Issues of who bears the burden of costs overlaps with perceptions of fairness in the administration of a SWU and its benefits. In the next sections, I elaborate on what defines economic efficiency and where that does or does not overlap with perceptions of equity.

2.1 A Welfare Economics Framing

There are two theoretical framings that well-describe stormwater management systems and their financing (Lindsey, 1990). The first considers stormwater management services and infrastructure as a public good (J. W. Burnett & Mothorpe, 2018; B. S. Jorgensen, 2003). Public goods are defined as assets or services that are non-rivalrous and non-excludable. Meaning, everyone has access and no one's consumption reduces the usefulness to others. Public goods are also considered a market failure that limits the market from reaching a common good where no one is better off than anyone else. Under a public goods model for stormwater financing, there are two ways to fund services. The traditional method is based on bundling stormwater services as part of municipal public works and using tax revenue to prioritize all public works projects or services (National Association of Flood and Stormwater Management Agencies, 2006). With this financing model, there may be entities that benefit heavily from stormwater services but do not contribute to revenue to the funding pot, such as tax-exempt properties. Alternatively, stormwater services can be detached from public works and funded separately through user fees. This model would be akin to a SWU that charges a flat fee for all users connected to or who benefit from drainage service lines, and can obligate all service beneficiaries to pay a fee regardless of tax-exempt status.

While requiring everyone to pay into a SWU as a public good addresses one aspect of economic inefficiency, it does not yet capture the source of the stormwater issues that require management. This is where the second theoretical model of stormwater financing comes into play. This model of financing considers stormwater, and associated pollution, as an externality (Lindsey, 1990; Milon, 2019). A negative externality is an adverse effect to society created by individual activities. When rain falls on someone's property, it is first under the jurisdiction of that property owner. Water that exits the property as overland flow or through drainage systems becomes an externality. Stormwater runoff, and any contained pollution, that enters the drainage systems falls under the municipality's jurisdiction regardless of the contributor. Depending on the natural characteristics and the degree of land development, certain landowners may contribute more runoff than others. A stormwater fee can approximate the differential cost of stormwater runoff amounts as an externality. This would be akin to an ERU-based fee or a tiered fee. In welfare economic theory, externalities are a market failure. A common good entails no alternative that would leave anyone better off if there is a competitive equilibrium in pricing between the price-setters and price-takers. However, externalities violate this equilibrium because they cause costs to individuals that are not incorporated into the market price, and are thus a market failure. Charging a stormwater fee that approximates the cost of an externality follows the model of a Pigouvian price instrument, which is a method to correct for externalities as a market failure (Tasca et al., 2017). Such a pricing instrument is a mechanism for creating greater economic efficiency (i.e., eliminating or minimizing waste optimal production and distribution of resources).

The welfare economics definition of efficiency (i.e., Pareto efficiency) is an economic state where social welfare is maximized and all economic goods are optimally allocated across consumers and producers. Both public goods and externalities are market failures that lead to a sub-optimal market equilibrium, but have respective solutions. To avoid people benefiting from public goods but not paying (i.e., free riders), everyone is charged taxes or user fees for public goods and services. To correct negative externalities as a market failure, people are charged for the marginal costs of the impact they cause. These concepts reflect economic efficiency in theory, but do not necessarily reflect community ideas of "fairness" or politically feasible outcomes. In general, academic literature analyzing the social implications of stormwater utility fees and credits is limited (Tasca et al., 2017; Zhao et al., 2019), despite long-standing calls for studying equity and economic efficiency in stormwater utilities (Doll et al., 1998). The field of stormwater management is inherently interdisciplinary, and thus it is imperative to clearly define what might comprise fairness in the community's perspective through concepts of equity as well as economic efficiency.

3. A Systematic Literature Review of Equity Concepts in Stormwater

This section discusses definitions, methods, and analyses in the literature that functionally define what comprises ideas of "fairness" in the stormwater literature. Table 21 summarizes the concepts of economic efficiency and equity covered in the stormwater literature, which I refer to as constituting perceptions of fairness. As discussed in the previous section, externalities are a way to understand individual negative or positive impacts to the common good. An example of a positive externality in stormwater management might be the existence of a tree on one's property, which serves to capture rainwater that would otherwise become surface water runoff (Coville et al., 2020). Stormwater runoff resultant from land development (e.g., soil sealing: Laćan et al., 2020) or pollution sourced from an individual's property is a negative externality because there is an associated impact and cost to others associated with stormwater leaving the property. Capturing or reducing runoff through low-impact development or green infrastructure installations on individual properties is a means of reducing one's negative externality (e.g., Ando & Freitas, 2011; Sun & Hall, 2016). Minimizing economic inefficiencies entails using a pricing instrument to charge individuals for the externalities they produce, or by regulating externalities (e.g., Lu et al., 2013; Malinowski et al., 2020; William et al., 2017). Moving towards economic efficiency would also include charging taxes or user fees for stormwater systems as a public good and coordinating locations of green infrastructure that reduce negative externalities.

Economic efficiency and perceptions of equity can sometimes be overlapping and other times diverging. Although the literature does not make a clear distinction between economic efficiency and equity (e.g., Lindsey, 1990), I consider them here individually. The fundamental difference is that economic efficiency is meant to maximize an individual's utility function based on their private wealth and assets, but does not take into account differences between individuals and their respective environment if social costs are not taken into account. Therefore, inherent socioeconomic inequalities can be intensified in attempts to correct for economic inefficiencies. For example, higher income households that have the capital to invest in rain barrels (Ando & Freitas, 2011) or green infrastructure (Mandarano & Meenar, 2017) would gain potential benefit from stormwater fee reductions. This is not necessarily a bad outcome if the there is a higher total societal benefit and the outcomes serve to minimize economic inefficiency. However, such outcomes may raise questions about whether the distribution of benefits is equitable among households. Another example might be if a stormwater fee is based on total IA and lower income houses tend to have higher total amounts of IA (e.g., Laćan et al., 2020). This would increase the burden for lower income households that already inherently bear a higher burden as a percentage of household income with a stormwater fee compared to higher income households. On its face, it makes sense that those who produce externalities should pay for their impacts, however, there are clearly other considerations to take into account.

Perhaps most commonly conflated with economic efficiency is the concept of distributional equity. Distributional equity refers to the ways in which burdens or benefits are allocated. That is, how policies or plan implementation can affect the beneficial outcomes and allocation of resources. For example, distributive equity analyses that examine whether certain communities or groups of people benefit from parks, open space, and other types of green infrastructure are common in the literature (e.g., Baker et al., 2019; Chan and Hopkins, 2017; Li et al., 2020; Nyelele and Kroll, 2020; Wendel et al., 2011). Distributive equity is often discussed in the literature at a neighborhood- or municipal-scale. At the heart of these analyses is understanding where there are distributive inequalities, especially for those of lower income status (e.g., Nyelele & Kroll, 2020; Saywitz & Teodoro, 2021; Wendel et al., 2011). These inequalities can have consequences beyond the benefits that stormwater infrastructure provides. For example, people’s environment can shape how they understand and interact with green stormwater infrastructure, which can lead to low maintenance and community divestment (Meenar et al., 2020). To mitigate for distributive inequity, areas can be identified and prioritized for infrastructure investment (e.g., Li et al., 2020). Strategic investments can reverse typical trends related to income inequality. For example, in Portland densities of green stormwater infrastructure (Baker et al., 2019) and green streets and roofs (Chan & Hopkins, 2017) are found to have a negative relationship with income measures.

Although strategic prioritization and investment can help improve equality as a measure of outcomes, these solutions are often expert- or data-driven and may not necessarily comport with community needs or wants. Thus, procedural equity can be a critical component to a just process in stormwater planning. In addition to equity in outcomes, procedural equity or justice includes the community’s right to participation and transparency in the planning process (Finewood et al., 2019). Steps can be taken to reduce procedural inequalities. Community can help identify and prioritize problems or problematic areas that need particular attention. For example, interactive tools can be used to engage the community in identifying infrastructure or drainage problems (Hendricks et al., 2018; Meyer et al., 2018). Interactive tools and engagement methods can also be used to help community understand tradeoffs in outcomes (Heckert & Rosan, 2016, 2018; Meerow, 2019). Such decision support tools can help identify community needs and wants in the face of particular constraints. However, use of tools in the engagement process can help level the understanding between community and stormwater managers or planners. Still, they may not serve to engage communities or groups of people that may not be aware or committed to the process of stormwater planning (Mankad et al., 2015; Mason et al., 2019; Morison & Brown, 2011). Structural inequalities such as racism or historical injustices can also create systemic barriers to participation or can be propagated through the planning process (Heck, 2021).

Table 21. Literature coverage of issues related to equity and fairness. (IA = impervious area, GSI = green stormwater infrastructure, GI = green infrastructure, LID = low-impact development)

Author	*Concept*	*Method*	*Location*	*Description*
Negative or Positive Externalities (Parcel-scale)				
Ando & Freitas (2011)	Evaluate the distribution of technology adoption	Regression analysis	US – Chicago, IL	Analyzed factors related to the adoption of rain barrels. Found higher levels of purchase in higher-income neighborhoods and with the prevalence of owner-occupied housing.
Laćan et al. (2020)	Evaluate the distribution of IA	Regression analysis	US – San José, CA	Analyzed factors that related to front yard soil sealing. Found that areas of higher income relate to lower rates of sealing.
Sun & Hall (2016)	Simulate the effect of technology adoption	Survey & hydrologic modeling	US – Syracuse, NY	Simulated the reduction of runoff based on citizen-specified and government planned GI installation scenarios. Found only a modest reduction in peak flow and runoff volume.
Economic Efficiency				
Lu et al. (2013)	Evaluate the role of pricing instrument on technology adoption	Agent-based model	Simulated	Developed an agent-based model to understand incentives to adopt LID. Found that if developers must pay an impact fee for not using LID to build homes, it leads to a lower cost of living for apartment homes over single-family homes and therefore increased adoption of apartments.
Malinowski et al. (2020)	Evaluate the role of pricing instrument on technology adoption	Cost-benefit analysis	US – Charlotte, NC, Nashville, TN, Prince George's County, MD, Philadelphia, PA, & Seattle, WA	Cost-benefit evaluation of stormwater fees and credits for GI retrofits. Suggest that setting stormwater fee credits to cover the maintenance cost would encourage more adoption of GI retrofits.
William et al. (2017)	Simulate the effects of policy strategies on technology adoption	Game theory	US – Baltimore, MD	Simulated pollution effects of four scenarios using a game theory framework. Found the scenarios with the greatest reduction in pollutant loading were that of municipalities penalizing agents who do not adopt a threshold GI and a direct grant program for GI installation. According to their scenarios, the stormwater fee and credit scenario did not lead to a reduction in pollutant load.
Distributive Equity in Costs or Benefits (Municipal-scale)				
Baker et al. (2019)	Evaluate the distribution of outcomes	Regression analysis	US – Baltimore, MD & Portland, OR	Analyzed factors related to GSI density. Found a negative relationship with median income for Portland, and no relation for Baltimore.

Table 21. Literature coverage of issues related to equity and fairness. (IA = impervious area, GSI = green stormwater infrastructure, GI = green infrastructure, LID = low-impact development) (con't)

Author	*Concept*	*Method*	*Location*	*Description*
Distributive Equity in Burdens or Benefits (Municipal-scale)—con't				
Chan & Hopkins (2017)	Evaluate the distribution of outcomes and technology adoption	Correlation analysis	US – Portland, OR	Analyzed factors related to GSI density. Found a positive relationship between lower median income and green street densities, as well as green roof densities.
Li et al. (2020)	Identify priority areas for distribution of green infrastructure	New method or tool	Belgium – Ghent	Identified areas lacking existing green spaces as a measure of environmental justice in a multi-criteria prioritization method.
Mandarano & Meenar (2017)	Evaluate the distribution of outcomes and technology adoption	Correlation analysis	US – Philadelphia, PA	Analyzed factors related to GSI, voluntary GI adoption, and mandated GI investment. Found a positive correlation between income inequality and mandated GI investment, and a negative correlation between voluntary GI adoption and poverty.
Meenar et al. (2020)	Evaluate the distribution of outcomes	Field survey	US – Philadelphia & Camden, PA	Conducted field investigation of the appearance, context, and public perception of GSI. Suggest that lack of information can lead to low maintenance and social divestment in GSI.
Nyelele & Kroll (2020)	Evaluate the distribution of outcomes	Correlation analysis	US – Bronx, NY	Analyzed the coincidence of tree cover and other ecosystem services with socioeconomic variables. Found that disadvantaged communities receive disproportionately lower ecosystem services.
Saywitz & Teodoro (2021)	Evaluate the distribution of outcomes	Regression analysis	US – Houston, TX, Seattle, WA, Virginia Beach, VA	Analyzed adopt-a-drain programs and their relationship to sociodemographic variables. Found socioeconomic status to be a bigger predictor of participation than flood risk.
Wendel et al. (2011)	Evaluate the distribution of outcomes	Spatial analysis	US – Tampa, FL	Conducted a comparative analysis of the quantities of green space and access between two communities with different socioeconomic characteristics.
Procedural Equity				
Finewood et al. (2019)	Evaluate the planning process and engagement	Qualitative analysis	US – Pittsburgh, PA	Conducted semi-structured interviews of stormwater practitioners, government officials, and activists to understand the politics and discourse around GI.
Heckert & Rosan (2016, 2018)	Interactive tool to engage stakeholders in planning process	New method or tool	US – Philadelphia, PA	Developed an equity index as a tool to engage stakeholders in the GI planning process.

Table 21. Literature coverage of issues related to equity and fairness. (IA = impervious area, GSI = green stormwater infrastructure, GI = green infrastructure, LID = low-impact development) (con't)

Author	*Concept*	*Method*	*Location*	*Description*
Procedural Equity—con't				
Hendricks et al. (2018)	Interactive tool to engage stakeholders in planning process	New method or tool	US – Houston, TX	Developed a public participation tool to assess neighborhood-level infrastructure.
Mankad et al. (2015)	Evaluate awareness and interest in technology adoption	Qualitative analysis	Australia – Adelaide	Explored psychological and policy-related factors relating to community acceptance of managed aquifer recharge of urban stormwater. Found perception of fair distribution to be among the key factors for acceptance.
Mason et al. (2019)	Evaluate awareness and interest in technology adoption	Regression analysis	US – Knoxville, TN	Examined the awareness and interest in backyard GI investment based on a survey conducted. Found no significant relationship between income and either awareness of or interest in GI.
Meerow (2019)	Interactive tool to engage stakeholders in planning process	New method or tool	US – New York, NY & Los Angeles, CA Philippines – Manila	Created a model that maps spatial tradeoffs and multiple desired benefits. Extended the model as a decision-support tool that allows user input of criteria weights.
Meyer et al. (2018)	Interactive tool to engage stakeholders in planning process	New method or tool	US – Houston, TX	Created a smartphone application to allow stakeholders to assess infrastructure and indicate drainage issues.
Morison & Brown (2011)	Evaluate the planning process and engagement	Mixed methods	Australia – Melbourne	Conducted surveys, interviews, and document reviews to understand the implementation of Water Sensitive Urban Design (WUSD) by municipalities. Found coastal municipalities with 50% or more natural vegetation tended to have stronger commitment to WUSD, as well as wealthier communities.
Structural or Institutional equity				
Heck (2021)	Racial capitalism: contending with structural racism and historical injustices in infrastructure planning	Qualitative Analysis	US – St. Louis, MO	Conducted ethnographic and archival research on a wastewater redevelopment project. Found that redevelopment relies on "geographies of racial capitalism" without assessing benefits beyond cost savings and stormwater retention.

What constitutes perceptions of “fairness” is critical to creating policy, outreach programs, and planning processes that is responsive to real, on-the-ground issues. Here, I define fairness in terms of both economic efficiency and concepts of equity. Distinguishing an economic efficiency framing of fairness from perceptions of equity in driving fairness is crucial to the discourse around what a SWU can expect from community and what the community can expect from a SWU. Although these terms may not be properly adopted in the discourse, as they can be cumbersome to define and distinguish in everyday conversation, better care can be taken in the literature to use these terms properly.

Part II – An illustrative example of the ambiguity of “fairness”

4. Establishing a Stormwater Utility for Oʻahu, Hawaiʻi

For Part II of this paper, I examine the community and stakeholder scoping process for establishing a Stormwater Utility (SWU) for the island of Oʻahu, which is also the City and County of Honolulu. I consider various aspects of “fairness” raised by community members during a round of outreach, and how they fit into concepts of economic efficiency and equity discussed in Part I. As would be expected for outreach meetings held to provide information on the potential establishment of a SWU, the community questions centered around cost aspects of both economic efficiency and distributive equity. Meaning, there was concern over how the SWU would define who would pay the fee, how the fee and credit system would be calculated, and how it would affect the cost-of-living. In my analysis, I investigate whether a fee based on impervious area (IA) alone evenly distributes the potential costs of runoff produced (i.e., whether the externalities are priced correctly) given the wide variability in rainfall by location. I also explore the relationship between drivers of stormwater runoff and socioeconomic variables. This example showcases how the context of a place is critical to understanding and addressing various equity issues raised by the community.

4.1 Study context

Following a bill passed by the Hawaiʻi State Legislature in 2015 enabling counties to establish and charge user fees to create and maintain stormwater systems and infrastructure, the City and County of Honolulu began exploring the establishment of a SWU for the island of Oʻahu in 2019. The exploration is headed by the City Department of Facility Maintenance (DFM), which is responsible for maintaining stormwater quality standards, flood control systems, and streams, among other City assets. A SWU would create a dedicated fund for stormwater programs that ensures year-to-year consistency in revenue. Currently, revenue from property taxes (i.e., the General Fund) contributes approximately 75% of funds for stormwater management programs, and the remainder comes from the Highway Fund (AECOM et al., 2020). The process for exploring a SWU has involved extensive conducting community and stakeholder outreach. This includes two months of community outreach with 18 meetings held at various locations across the island, and other community touch points, such as booths at community events. In addition to the community process, DFM has convened a Stakeholder Advisory Group to provide expertise and input on technical and political aspects of the SWU and fee development.

In the consideration and justification of a SWU, several reasons are cited for why a SWU increases equity (AECOM et al., 2020). First, the SWU enables all landowners to pay into the benefits provided by stormwater management. Currently, under a predominantly property tax-based revenue system, tax-exempt or tax-advantaged properties (e.g., government, non-profits) effectively do not contribute significantly towards the municipal general fund. Second, the calculation of a fee based on IA increases equity between land use by sectors. For example, 85% of all property owners are residential. Yet, residential properties make up only about 44% of the total IA compared to the U.S. Government and Military owning 5% of all property and 18% of the IA. Non-taxable properties comprise about 25% of the total IA, which includes the U.S. Government and Military. Third, using a tiered fee system based on total IA and providing credit opportunities is cited as an approach that increases equity by being a closer approximation to runoff generated. The tiered fee system is preferred to an ERU-based funding mechanism because parcel size varies widely among residential properties. Finally, hardship relief is part of the set of recommendations to mitigate the potential disproportionate burden on the cost-living for low-income households. Notably, the proposed hardship relief would only apply to property-owning households and not to renters or lessors (Jacobs, 2020). The third example is the main subject of exploration of this paper.

During a round of focused community outreach across the island, issues, mainly described as “fairness,” were continually raised about the implications of a stormwater fee.

Table 22 shows some example questions and comments from community meetings, as documented in Kearns West et al. (2020), that I have categorized according to the concepts concerning fairness defined in Section 3 of this paper. Given the nature of the community meetings, the most common questions relate to the economic efficiency in administering a stormwater fee by capturing the externalities. Community members from various geographic locations repeatedly asked whether and how the fee would account for rainfall differences in different parts of the island. It is widely known that the distribution of precipitation for the island of Oʻahu varies widely by location (Akana & Gonzalez, 2015; Giambelluca et al., 2013). The distribution of average annual rainfall is shown in Figure 15b. This corresponds with the recharge estimates of the island, as shown in Figure 16. Questions about the impact to cost-of-living and affordability were also raised during the community meetings. These concerns raise several other questions about the underlying socioeconomic and biophysical heterogeneity of Oʻahu and how they interplay with a potential stormwater fee. Figure 15c shows neighborhoods that fall above the area median income (AMI) level of $96,000 and those that fall below. The counterargument used by the City in regards to the fairness of who pays often points back to the idea of paying for IA as a driver of stormwater runoff and the availability of fee discounts for runoff reduction or demonstrated hardship. However, other factors that drive stormwater runoff, such as slope (Figure 15a) and soil characteristics, vary widely throughout the island and were among the questions raised by community members about fairness. Figure 15d shows the potential corresponding monthly fee for single-family (or similar detached dwelling) residential properties[12] throughout Oʻahu, based on the currently proposed 8-tier fee system.

Another key aspect to the current SWU planning is their community education and outreach efforts. While this is critical to bringing community on-board in implementing a stormwater fee, there is also a chance for edification on the multiple benefits that households can provide through

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[12] This is an underestimate of total IA for properties, as it only includes permitted building area, and does not account for other impervious surfaces such as parking lots or driveways. The SWU would include these types of impervious surfaces in their fee calculation.

individual efforts beyond implementable practices that would earn stormwater fee reductions. Several questions that the community has raised during meetings about the SWU offer the ability to educate community beyond the scope of what decides a stormwater fee. Beyond answering questions and comments in terms of IA and runoff, they present a chance to explain infiltration loss. Incorporating touchpoints about infiltration can point to practices that may already exist on a landowner's property that provide some hydrologic benefit, rather than a sole focus on the problem that their IA creates.

Table 22. Some example questions and comments documented from community meetings about establishing a SWU regarding fairness of a fee and credit system.

Negative Externalities • Too many impervious surfaces • Monster houses & large parcel areas - city should regulate • Pesticides used for ant, termite, and cockroach control • Sediment. Impacts to marine environment. • Run off on steep slopes - Wilhelmina, etc. • People throw stuff in the drains
Positive Externalities • I have also installed small infiltration basins that are not visible from the air.
Market Efficiency • Would people with differing levels of rainfall pay the same rate? • How much revenue would be generated and would it be enough to address the problems? • What about properties that don't contribute to city storm drain system? • I especially think it is critical for tax- exempt properties to pay for impervious surface. I appreciate the opportunity to create incentives for best practices.
Distributive Equity - burdens • Have any studies been done on the true cost to a property owner due to trickle-down effects? • Don't break the people who have low finances • Make town pay (location based) this tax. Communities that have their water taken for the rest of the island should receive compensation.
Distributive Equity - benefits • Rational nexus between fee and the impact, and how will fee come back to community • Would like to know what plans, systems are going to be designed to build green infrastructures. Ways to absorb rain water - mitigate runoff, i.e. classes on rain gardens, catchment systems, etc.
Procedural Equity • Will there be a way to prioritize issues? Can the list of issues be shown publicly? Will there be a hotline for SW concerns? • Who will regulate the fee structure? • Do not make the meetings start at 5 PM if you want people to be able to attend. People should be able to attend meetings on this important topic.
Structural or Institutional Equity • Water is disproportionately taken from our Moku and we are not compensated. Funds will be collected and Ko'olauloa is always last for services.

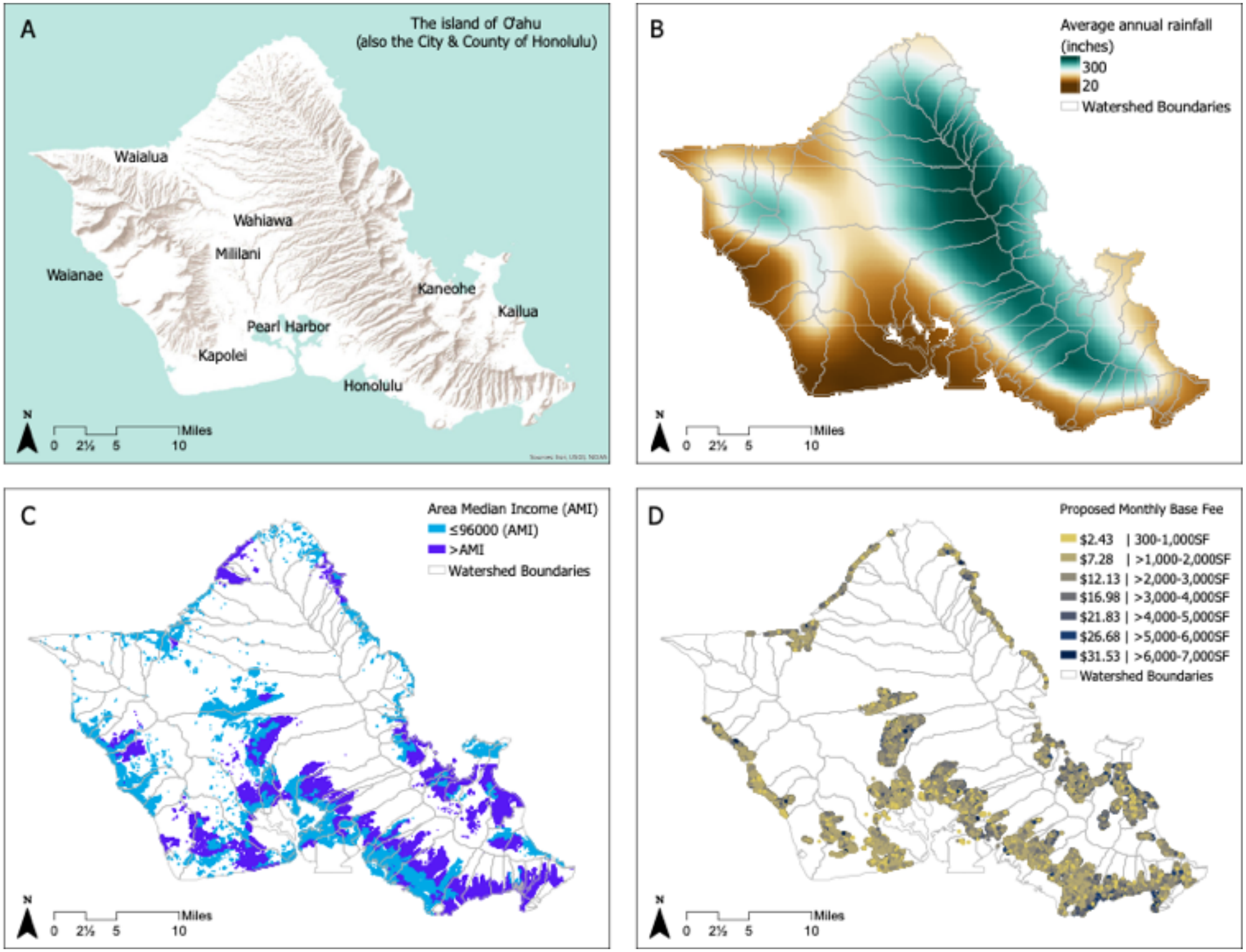

Figure 15. Maps of the heterogeneity of communities across the island of Oʻahu. (A) A relief map showing the location of some key communities on the island. (B) A map of average annual rainfall. (C) The distribution of neighborhoods above the area median income (AMI - $96,000) and at or below AMI. (D) A map of the potential monthly stormwater fees for residential properties (i.e., single-family housing) as currently proposed.

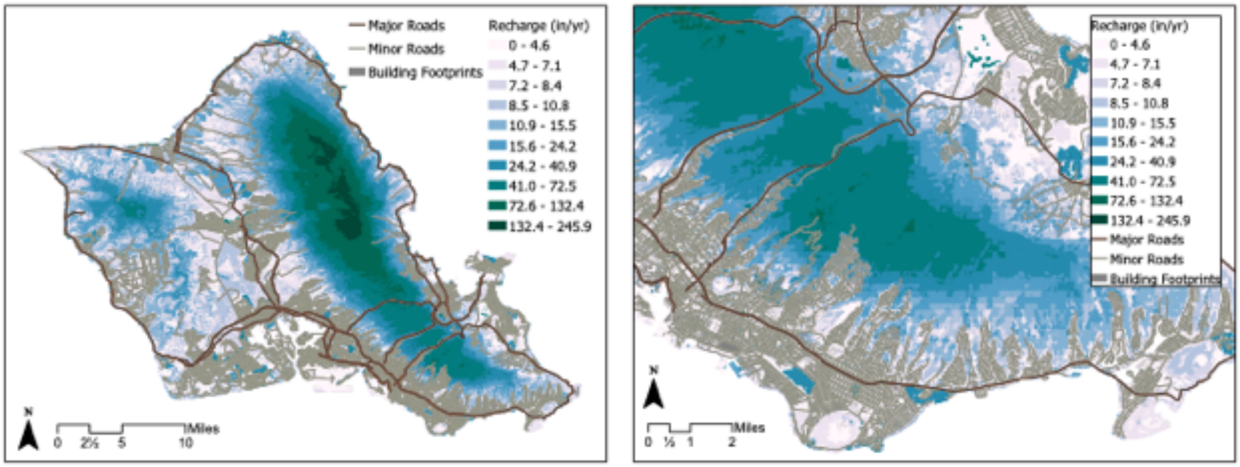

Figure 16. Recharge estimates based on land cover for O‘ahu and a zoomed-in view of East Honolulu (Engott et al., 2017).

4.2. Case Study Methods

4.2.1 Socioeconomic correlation analysis

To understand whether baseline patterns exist between physical drivers of stormwater runoff and socioeconomic characteristics of neighborhoods, I conduct a spatial correlation analysis. Correlation analyses are commonly used to find associations between socioeconomic variables and physical variables (refer to Table 21). Differences in spatial and temporal scales between socioeconomic and physical variables can define the reasonable extent to which the data can be used. I calculate the Pearson correlation coefficient to understand the relationship between median income, poverty rate, and renter-occupied housing percentage (U.S. Census Bureau, 2019) as socioeconomic variables and average annual rainfall (Giambelluca et al., 2013), slope, and building area (Hawaii Statewide GIS Program, 2016) as variables that drive stormwater runoff. I selected poverty rate and renter-occupied housing as variables to explore aspects of the hardship relief, including potential qualifiers who are experiencing poverty, as well as those who would not qualify because they are renting housing. I chose to include median income to determine whether there is any spatial correlation with building area, average annual rainfall, or slope as drivers of surface runoff. Building area is a proxy for what a property would be charged for total IA, but is likely an underestimate as it does not include driveways, pavement, parking lots, or unpermitted structures. Rainfall and slope are drivers of surface runoff, as described in the Manning’s equation in the section below. I run this analysis for low-, medium-, and high-density apartment and mixed-use apartment zoned land, as well as residential (i.e., single-family or similar detached dwelling) land use zones, with lots sizes of 3500, 5000, 7500, 10000, and 20000 square feet (SF).

4.2.2 Estimation of the impact of impervious area (IA) on parcel hydrology

To estimate the impact of IA on a parcel of land in any given location on O‘ahu, I use the computational methods employed by the U.S. EPA National Stormwater Calculator, which employs the same computational methods as the U.S. EPA Storm Water Management Model (SWMM) (Rossman, 2015; Rossman & Bernagros, 2019). Over a defined land parcel, the

National Stormwater Calculator estimates surface runoff from conservation of mass. Thus, the change in depth per unit time is determined by the difference between inflow and outflow of the defined parcel, as follows,

$$\frac{\partial d}{\partial t} = i - e - f - q$$

where d is the depth of water on the land surface, t is time, i is the rainfall rate, e is evaporation rate, f is the soil infiltration rate, and q is the surface runoff rate.

Since a stormwater fee based only on IA as a driver for runoff assumes uniformity in other stormwater drivers. I consider two scenarios of uniformity. First, I consider spatially uniform rainfall to calculate the total surface runoff (Q) and the corresponding total loss of infiltration (F) per unit IA for all residential parcels on the island. Second, I consider uniform parcel scenarios to compare the average annual volume of runoff at various locations across the island. The values estimated for these scenarios should only be used to understand how IA might impact the hydrology at any given site. This analysis is based on the methodology and assumptions used in the National Stormwater Calculator, which is considered a screening-level analysis tool.

2.1.1 Spatially uniform rainfall

To calculate potential runoff and infiltration loss, I consider three different 4-hour storms, as shown in Table 23. Calculating these parameters using identical storms for properties across the entire island allows for comparison of the influence of IA without the variability in rainfall seen throughout the island. The estimation of potential runoff provides an analysis of how land surface slope drives runoff, while the potential infiltration loss allows for the comparison of soil characteristics. Because single-family households are at the center of the concerns over fairness, I limited the area of interest to residential-zoned areas of the island. The calculated values per parcel are meant to be scalable to any size area within the parcel and are independent of any inflows from surrounding areas. Therefore, the values should be treated as an assessment of how much runoff might be produced in a unit area of IA and the associated loss of infiltration.

Table 23. Hypothetical storms used to estimate the impact to hydrology by impervious surface area.

Hour	*Storm 1*	*Storm 2*	*Storm 3*
1	0.2	0.5	1
2	0.5	1	1.8
3	0.2	0.4	0.6
4	0.1	0.1	0.1
Total Rainfall	**1-inch**	**2-inch**	**3.5-inch**

Potential surface runoff

First, to consider the potential runoff caused by impervious surface, I assume no infiltration $(f = 0)$. Thus, the depth of runoff (q) from impervious surfaces can be calculated using Manning's equation for each discrete time step. Surface water runoff can be estimated by,

$$q_t = \frac{1.49 W S^{1/2}}{An}(d_{t-1} - d_s)^{5/3}$$

$$d_{t-1} = i_{t-1}$$

$$Q = \int_0^t q_t$$

where W is the width of the parcel outflow face, S is the slope of the parcel, A is the parcel area, n is the Manning's roughness coefficient, d_s is the depression storage, d_{t-1} is the residual water depth from the previous time period, and the 1.49 coefficient is based on feet per second. Runoff is given in depth per unit area ($A = 1\ ft^2$). For impervious surface, I use n = 0.01 and d_s = 0.05 inches. The width of the outflow face is set to 150 feet, which is a conservative estimate of the maximum distance over which sheet flow can occur for a nominal 10-acre site. The equation and values here come directly from the National Stormwater Calculator's computational methods (Rossman & Bernagros, 2019). Runoff is only generated if $i > d_s$. For this analysis, it is assumed that no evaporation is occurring during the storm events.

Potential infiltration loss

To calculate the potential infiltration loss, I estimate the soil infiltration rate (f) of bare ground, or 0% impervious surface. The assumption of infiltration loss is based on the idea that creating impervious surface at any given location would eliminate infiltration. Therefore, the potential infiltration loss is the infiltration capacity lost by going from bare ground to impervious surface. I use the Mein-Larson modification of the Green-Ampt model to calculate soil infiltration rate, which uses a two-step calculation that governs the infiltration rate before and after the top layer of soil becomes saturated (Mein & Larson, 1971, 1973).

For the first step of the model when the soil surface layer is unsaturated, the infiltration rate is equal to the rainfall rate,

$$f_t = i_t$$

$$F = \int_0^t f_t$$

This is the case when the rainfall rate is less than or equal to the saturated hydraulic conductivity (K_s), i.e., $i \leq K_s$. When the rainfall rate is greater than the saturated hydraulic conductivity, then the above equation for the infiltration holds until the soil surface reaches saturation. The point of saturation is calculated by

$$F_s = \frac{\psi(\phi - \theta_0)}{(i/K_s) - 1}$$

where F_s is the surface saturation (i.e., the cumulative infiltration at the time when saturation occurs), ψ is the suction head at the wetting front, ϕ is the soil porosity, and θ_0 is the initial soil moisture content. The infiltration capacity is a function of the soil moisture, which increases according to,

$$\theta_t = \theta_{t-1} + \frac{f}{L_u} = \theta_{t-1} + \frac{f}{4/\sqrt{K_s}}$$

where L_u is the layer depth that can be calculated by $4/\sqrt{K_s}$ when L_u is given in inches and K_s is in inches per hour (Rossman & Bernagros, 2019).

When the top layer of soil becomes saturated, runoff is generated and the infiltration rate is governed by the equation,

$$f = K_s\left(1 + \frac{\psi(\phi - \theta_{t-1})}{F}\right)$$

where F is the cumulative infiltration depth. The values for K_s are from the Hawaii Soil Atlas (Deenik et al., 2014). The suction head parameter (ψ) is based on the empirical relationship (Rossman, 2015),

$$\psi = 3.23{K_s}^{-0.328}$$

Infiltration occurs as long as the soil moisture is less than the porosity, i.e., $\theta < \phi$. For this analysis, I use an initial soil moisture of zero, an average porosity of 0.45, and only consider soil moisture during the storm's duration.

2.1.2 Site-specific runoff estimations

To understand the role of rainfall variation in runoff generation, I compare the runoff generated at various locations on the island using actual rain gage data. I use the U.S. EPA National Stormwater Calculator to estimate the average annual runoff volume for a uniform 5,000 square-foot (SF) property. This exercise is meant to better understand community concerns over rainfall differences across the island and how that impact is priced. I calculate the runoff for four scenarios: 100% IA, 60% IA with 40% lawn, 40% IA with 60% lawn, and 100% lawn. For a 5,000 square-foot (SF) parcel, the associated stormwater fee costs are shown in Table 24. Note that the existence of lawns are not included in the calculation of the stormwater fee. To consider the locational generation of runoff, I use 6 residential community locations across the island, as shown on the map in Figure 17. These sites were chosen based on proximity to a weather station with at least a 20-year record of both rainfall and evaporation, and for their diversity in location and total annual rainfall. Table 25 shows the soil, terrain, and climate characteristics of each site. Using these runoff estimates, I can compare the estimated annual average runoff volume generated at each site and the associated cost.

Table 24. Proposed monthly costs for the O‘ahu SWU for an 8-tier and 4-tier pricing structure.

IA per scenario	8-tier monthly cost	4-tier monthly cost
5,000 SF (100% IA)	$21.83	$22.22
3,000 SF (60% IA/40% lawn)	$12.13	$16.36
2,000 SF (40% IA/60% lawn)	$7.28	$6.84

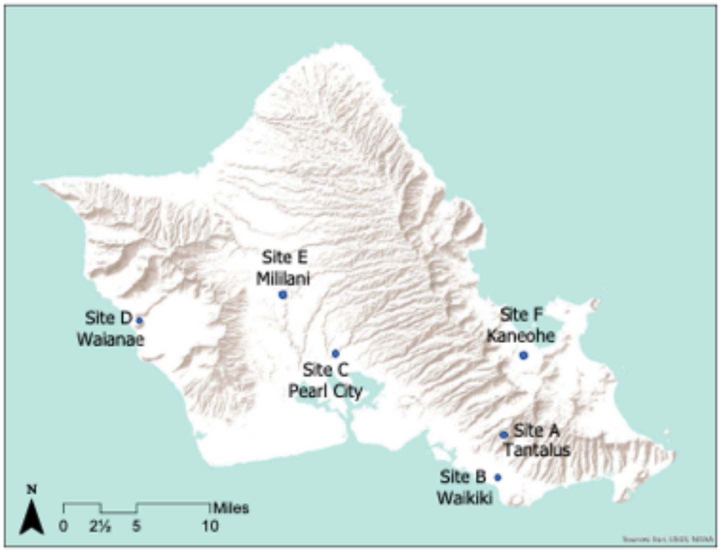

Figure 17. Map of locations for stormwater runoff calculations.

Table 25. Example sites with locational characteristics.

Location	**Site A Tantalus**	**Site B Waikiki**	**Site C Pearl City**	**Site D Waianae**	**Site E Mililani**	**Site F Kaneohe**
Soil Type	low runoff potential	low runoff potential	moderately low	moderately low	moderately low	moderately high
Soil Drainage (in/hr)	0.924	1.104	0.276	0.108	0.110	0.276
Slope	>15%	5-10%	5-10%	0-2%	2-5%	2-5%
Avg. Evaporation (in/day)	0.20	0.32	0.35	0.30	0.35	0.25
Avg. Annual Rainfall (in)	99.10	23.33	31.71	20.71	35.75	55.01

3. Results

3.1 Stormwater drivers and socioeconomics

Some notable relationships exist between socioeconomic variables and drivers of runoff. Correlation coefficients for land parcels zoned for apartments are shown in Table 26. There is a high degree of correlation between rainfall and both median income (r = –0.53) and the percentage of renter-occupied apartments (r = –0.51). There is also an strong inverse relationship between the percentage of apartments that are renter-occupied and median income (r = –0.86). There is a moderate positive correlation between average rainfall and poverty rate (r = 0.39), and a low degree of correlation between total building area and both median income (r = –0.15) and rainfall (r = 0.17). For residential-zoned parcels, shown in Table 27, there is a strong negative correlation between median income and the percentage of renter-occupied houses (r = –0.53). There is a moderate correlation between the percentage of renter-occupied houses and poverty rate (r = 0.43). Finally, there is a small correlation between parcel slope and income (r = 0.26). As expected, income is inversely related to poverty rate and rainfall and slope are positively related in both datasets.

Table 26. Correlations between physical drivers of stormwater runoff and socioeconomics for apartment land use zones only. All values included are significant ($p < 0.01$).

Variable	*Median Income*	*Poverty Rate*	*% Renter Occupied*	*Average Rainfall*	*Average Slope*
Poverty Rate	0.74				
% Renter Occupied	–0.86	0.74			
Average Rainfall	–0.53	0.39	0.51		
Average Slope	-	–0.05	0.04	0.50	
Total bldg area	–0.15	0.09	–0.01	0.17	0.08

Table 27. Correlations between physical drivers of stormwater runoff and socioeconomics for residential (i.e., single-family or similar detached dwelling) land use zones only. All values included are significant ($p < 0.01$).

Variable	*Median Income*	*Poverty Rate*	*% Renter Occupied*	*Average Rainfall*	*Average Slope*
Poverty Rate	–0.43				
% Renter Occupied	–0.53	0.43			
Average Rainfall	0.08	–0.03	0.13		
Average Slope	0.26	–0.14	–0.14	0.47	
Total bldg area	0.08	0.02	–0.03	0.04	0.05

3.2 Uneven hydrologic impacts

A stormwater fee structure based on IA assumes that impervious surface is the most significant driver of runoff and the runoff (as well as any pollution contained within) is the externality that the fee is capturing. The slope of a property will change the rate at which water runs off the land, where properties with steeper slopes will create stormwater runoff faster than flatter properties. However, the total amount of rain that falls on IA (assuming no evaporation) will become runoff. In this regard, a stormwater fee for O‘ahu that prices runoff would be more economically efficient in the unlikely case of spatially uniform rainfall. However, the loss of infiltration is another aspect of IA impacts. Even under spatially uniform rainfall conditions, the loss of infiltration differs by location. These differences are based on soil characteristics and the intensity of the storm. Figure 18 shows the potential infiltration loss for the three storm scenarios. For the 1-inch storm, most of the rainfall island-wide would infiltrate into the ground (Figure 18a). On average, 1 inch of infiltration is lost per parcel, ranging from 0.4 to 1.0 inches of infiltration lost for the 1-inch storm. The infiltration amount as a proportion of the rainfall is reduced as the storm size increases, and the surface soil becomes saturated at the beginning of the storm. For the 2-inch storm, an average of 1.5 inches of infiltration is lost per parcel, ranging from 0.7 to 2.0 inches per parcel (Figure 18b). For the 3.5-inch storm, the average infiltration lost per parcel is 1.7 inches, with a range of 1.0 to 3.4 inches per parcel (Figure 18c & d). Although there is no clear spatial pattern to infiltration loss, this analysis shows that infiltration loss is an unevenly spatially distributed externality associated with IA. This analysis indicates how critical the process of infiltration is for reducing runoff.

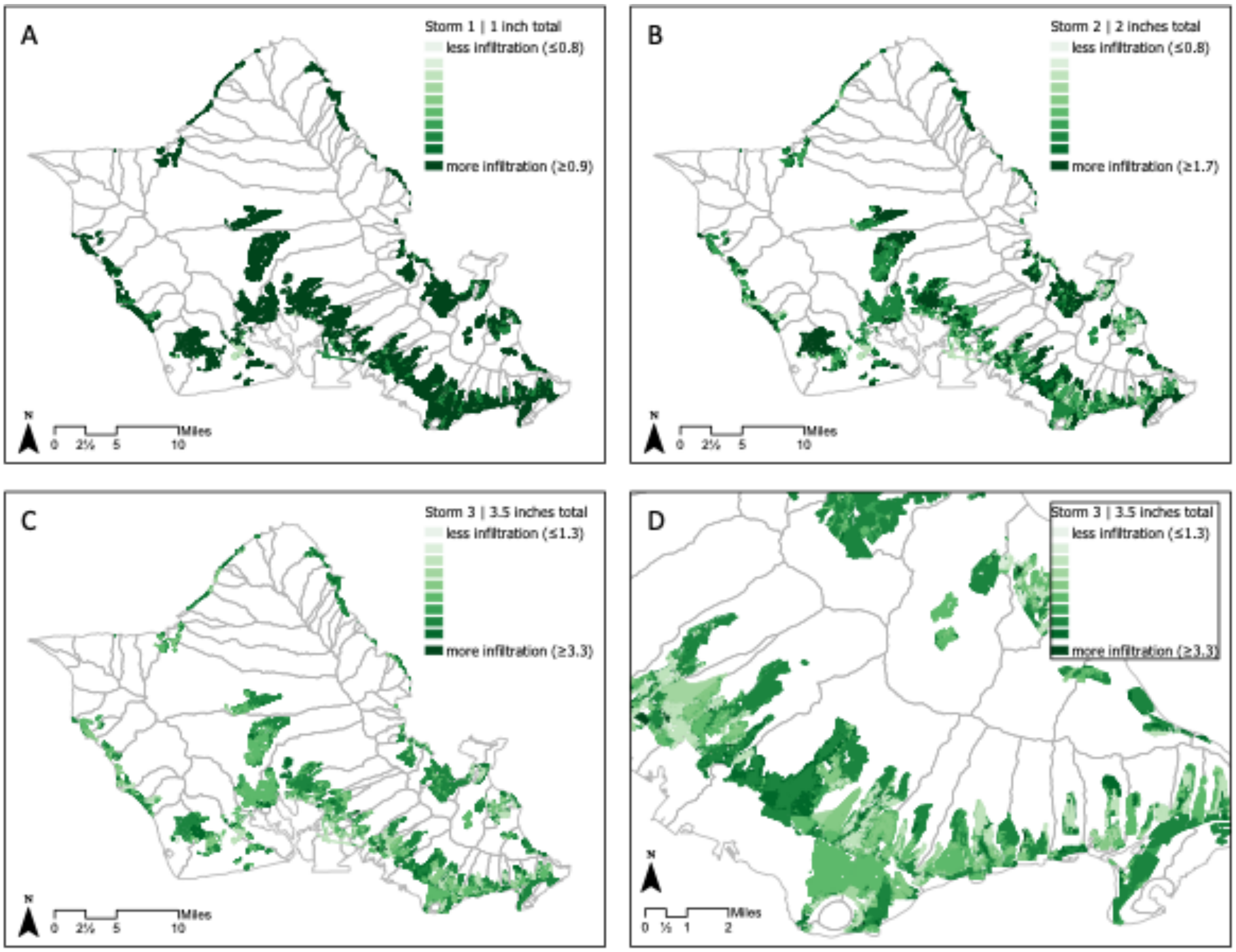

Figure 18. Maps of the estimated loss of infiltration for various storm scenarios: (A) a 1-inch storm, (B) 2-inch storm, (C) 3.5-inch storm, and (D) a zoomed-in view of East Honolulu for the 3.5-inch storm.

Adding the spatial variation in rainfall amplifies the impacts of IA. Figure 19 shows the average annual runoff volume for a 5,000-SF parcel of land with 100% IA, 60% IA, 40% IA, and 0% IA (bare ground). For the Tantalus location with 99.1 inches of average rainfall, the runoff depth for the bare ground is 0.4 inches and increases to 84.4 inches with 100% IA, a 221% increase in runoff. At the location downstream in the same watershed, Waikiki, the average annual rainfall is 23.3 inches with 0.04 inches of runoff for the bare ground scenario and 17.6 inches for the 100% IA scenario, a 55% increase. The runoff depth for the location in Pearl City with an average rainfall of 31.7 inches increases 10% from 2.5 inches to 26.2 inches for the bare ground and 100% IA scenarios, respectively. For the location in Waianae, where the average rainfall depth is 20.7 inches, the runoff depth increases 3% from 4.1 to 17.3. The runoff depth increases from 7.2 to 30.3 inches, or 3%, in Mililani where the average annual rainfall is 35.8. Finally, the runoff depth for the location in Kaneohe with an average rainfall of 55.0 inches increases 8% from 4.9 inches to 43.1 inches for the bare ground and 100% IA scenarios, respectively. Figure 19 shows that rain has a more distinct influence on runoff generation than total IA and that infiltration plays a critical role in reducing runoff.

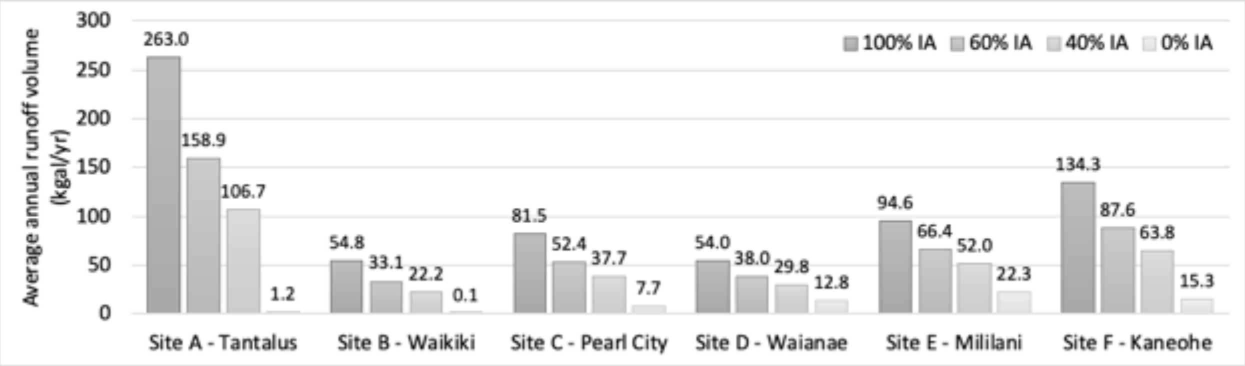

Figure 19. Estimated average annual runoff volume from various sites across O‘ahu for a 5,000 SF parcel with 100% impervious area (IA), 60% IA, 40% IA, and bare ground.

The monthly cost based on the currently proposed 8-tier and 4-tier pricing structure would be the same for each location based on IA. Therefore, the price per volume of stormwater can be calculated per location. Table 28 shows the cost per volume runoff for the proposed 8-tier fee structure, the current preferred rate structure (AECOM et al., 2020). Waianae and Waikiki, which have the lowest rainfall amounts of these select locations, would pay the most per thousand gallons. With the highest rainfall amount of the sites selected, Tantalus pays the least per volume of runoff produced. Tantalus is also the site with the highest increase in runoff generated per square-foot IA.

Table 28 shows the price of stormwater volume for the 4-tier fee structure as well. The price decreases per location going from the 4-tier to the 8-tier fee structure for the 5,000 and 3,000 SF IA scenarios, ranging from a $0.02 to a $0.09 and a $0.32 to a $1.53 decrease respectively. Whereas the price increases for the 2,000 SF IA scenario, ranging from a $0.05 to a $0.24 increase. Notably, the levelized the price of stormwater runoff by the square-footage provided in these examples show that the 5,000 SF IA scenario is paying the least per square-foot for their runoff. This is because the model scenarios for the 3,000 SF IA and 2,000 SF IA include 40% and 60% lawn per parcel, respectively. This reflects the current fee structure being based on total IA, and not considering any pervious area of a parcel.

Table 28. The estimated average annual price of stormwater runoff per thousand-gallons for each location and scenario with the proposed 8-tier and 4-tier fee structures for a 5,000 SF parcel of land.

		Site A Tantalus	Site B Waikiki	Site C Pearl City	Site D Waianae	Site E Mililani	Site F Kaneohe
Estimated cost per volume runoff ($/kgal) - 8-tiered fee structure							
5,000 SF IA	*$261.96 per year*	$1.00	$4.78	$3.21	$4.85	$2.77	$1.95
3,000 SF IA	*$145.56 per year*	$0.92	$4.39	$2.78	$3.83	$2.19	$1.66
2,000 SF IA	*$87.36 per year*	$0.82	$3.93	$2.32	$2.93	$1.68	$1.37
Estimated cost per volume runoff ($/kgal) - 4-tiered fee structure							
5,000 SF IA	*$266.64 per year*	$1.01	$4.86	$3.27	$4.94	$2.82	$1.98
3,000 SF IA	*$196.32 per year*	$1.24	$5.93	$3.75	$5.17	$2.96	$2.24
2,000 SF IA	*$82.08 per year*	$0.77	$3.69	$2.18	$2.76	$1.58	$1.29
Estimated cost difference between 8- and 4-tiered fee structure							
5,000 SF IA	*Ann. diff. -$4.68*	-$0.02	-$0.09	-$0.06	-$0.09	-$0.05	-$0.03
3,000 SF IA	*Ann. diff. -$50.76*	-$0.32	-$1.53	-$0.97	-$1.34	-$0.76	-$0.58
2,000 SF IA	*Ann. diff. $5.28*	$0.05	$0.24	$0.14	$0.18	$0.10	$0.08

4. Discussion

Concepts of fairness can manifest in various ways within stormwater financing, planning, and outcomes. The concept of economic efficiency in welfare economics provides a good starting point for thinking about fairness in terms of paying for stormwater services as a public good and for one’s marginal contribution to collective impacts, or externality. Economic efficiency is defined in terms of achieving a common good where no one is better off than anyone else. Still, economic efficiency does not necessarily imply equity. Equity itself comes in different forms. Distributive equity entails an equal allocation of burdens or benefits across communities or groups of people. Procedural equity is defined by a just planning process that incorporates a community’s right to participation and information access. Structural equality acknowledges that historical injustices and institutionalized racism need to be corrected systematically. Economic efficiency and the various classifications of equity are critical aspirations. However, administrative realities, political feasibility, and planning expediency often create barriers to achieving these objectives. As a result, the narrative is often flipped such that the goal of stormwater financing, planning, and outcomes is to find ways to reduce economic inefficiencies or inequalities in the process or the outcomes. A nascent literature explores these concepts in the context of stormwater.

4.1 Examining “fairness” in context

The example of O‘ahu shows that conversations about “fairness” are expressed in terms of externalities, economic efficiency, distributive equity, procedural equity, and structural equity. Stormwater service is a public good that everyone serves to benefits from, whether they live upstream or downstream in a watershed. Stormwater fees based on IA alone operate with the assumption that the total IA is the key driver of runoff as the externality. The analysis of stormwater runoff in six communities of O‘ahu shows two major shortcomings to this assumption. First, the variability in rainfall patterns can significantly influence the total runoff generated by location. The concept of "equity" based on IA used by many SWUs to establish fee structures is based on the assumption of spatially uniform rainfall. This assumption does not hold for O'ahu, where wide variations in average rainfall throughout the island show that rainfall is a greater driver of runoff. Second, the loss of infiltration due to IA is also an externality in addition to runoff (and pollution) that should be considered in decisions about programmatic costs and benefits. Currently, the fee only captures a parcels IA and does not account for undeveloped or pervious areas of a land parcel. Although runoff control is a critical aspect of SWUs, there are crucial co-benefits to encouraging the preservation of land for infiltration that fit a more integrated water management model towards which the City is moving.

Realistically, a fee that truly captures the marginal costs of runoff as an externality would be cumbersome and expensive to administer. However, taking rainfall into account is a simple step to reducing inefficiencies in the stormwater fee charge. This would better capture the climatological effects of runoff generated and account for some of the impact to recharge caused by infiltration loss. Given there is only a very low degree of positive correlation between rainfall and median income for residential properties, it would be unlikely that a rainfall multiplier would serve to greater amplify income disparities currently exist. This might also serve to discourage the slight positive correlative trend shown between total building area and rainfall. However, there is concern to note over renters that are not currently included in the proposed hardship relief. For both apartments and houses, there is a strong positive correlation between renters and poverty rate. Moreover, there is a slight positive correlation between renters and rainfall for houses, and a stronger correlation for apartments. Apartment complexes would likely develop their own system to pass the stormwater fee to occupants. However, any stormwater fee passed on from housing owners to renters with no possibility of hardship relief for the occupants would likely be a significant marginal increase in cost-of-living for those experiencing poverty.

In the process of exploring a SWU for O'ahu, equity has been pitched in terms of IA as the key variable to estimate the runoff amount from properties, with an 8-tier fee structure identified as the preferred structure to promote equity (AECOM et al., 2020). Truly capturing runoff costs as an externality would be achieved if the price per volume runoff were roughly equivalent per location. However, this analysis shows that this is not the case. A cursory analysis with an rainfall multiplier lessens the variation in the price per volume runoff between locations. Figure 20 shows the example rainfall multiplier map with 0.5 for drier and 1.5 for wetter regions of the island. Table 29 shows the updated prices per location with its multiplier factor. The justification for a multiplier fee is based on both the spatial differences in runoff reflecting known rainfall patterns for the island and the associated impact to infiltration. Higher rainfall areas are more critical to aquifer recharge and thus IA has a more significant impact on the hydrology in the upper parts of the watershed than towards the coast. In implementation, boundaries would need to be finetuned within communities. For example, Kaneohe straddles both the 1.0 and 1.5 multiplier in this map, and thus both values are shown in Table 29. These multipliers could also apply to credits, where a household implementing a runoff reducing practice in a wetter area would earn 1.5 times the credit and 0.5 times the credit in a drier area. This would better match the costs to the property owner and the benefits accrued by the SWU (Kertesz et al., 2014). Further financial analysis would be needed to capture a multiplier that enables greater fairness in fees while meeting the revenue requirements, which is the basis for the proposed fee structure. There is also currently no benefit built into the fee structure to discourage the total amount of IA coverage of one's parcel, other than paying more for the IA. That is, because the fee is structured based on total IA, it does not serve to encourage pervious or other vegetated space on a parcel except through earning a fee reduction off of the total IA. For example, a new development might build to maximize their fee reductions rather than minimize their total IA.

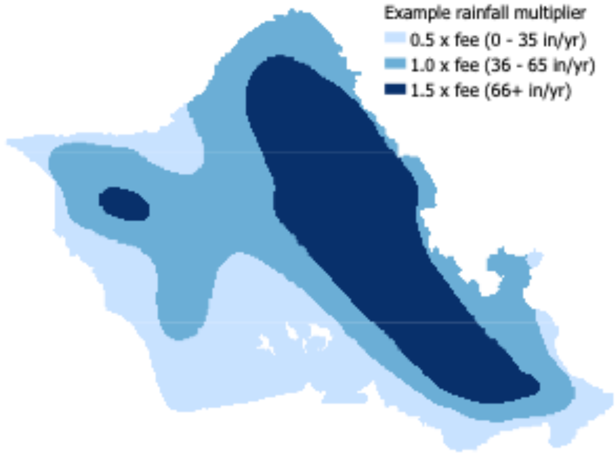

Figure 20. An example method of accounting for spatial differences in runoff generation and infiltration loss based on average annual rainfall.

Table 29. An updated estimate of the average annual price of stormwater runoff with the proposed 8-tier and 4-tier fee structures and the rainfall multiplier for a 5,000 SF parcel of land.

	Site A **Tantalus**	**Site B** **Waikiki**	**Site C** **Pearl City**	**Site D** **Waianae**	**Site E** **Mililani**	**Site F (1.0)** **Kaneohe**	**Site F (1.5)** **Kaneohe**
Multiplier	1.5	0.5	0.5	0.5	1.0	1.0	1.5
Updated cost per volume runoff with multiplier ($/kgal) - 8-tiered fee structure							
5,000 SF IA	$1.49	$2.39	$1.61	$2.47	$2.77	$1.95	$2.93
3,000 SF IA	$1.37	$2.20	$1.39	$2.58	$2.19	$1.66	$2.49
2,000 SF IA	$1.23	$1.97	$1.16	$1.38	$1.68	$1.37	$2.05
Updated cost per volume runoff with multiplier ($/kgal) - 4-tiered fee structure							
5,000 SF IA	$1.52	$2.43	$1.64	$2.47	$2.82	$1.98	$2.98
3,000 SF IA	$1.85	$2.96	$1.87	$2.58	$2.96	$2.24	$3.36
2,000 SF IA	$1.15	$1.85	$1.09	$1.38	$1.58	$1.29	$1.93

4.2 Emphasizing the co-benefits (co-impacts)

Although IA alone is an insufficient metric for determining total runoff (Lim, 2016), it remains the established basis for determining stormwater fees across the U.S. (Kea et al., 2016). A stormwater fee that takes precipitation into account, for example, has no established precedent. While stormwater fees are occasionally challenged in court cases, the primary source of litigation faced by SWUs is to test whether a stormwater fee is a tax in disguise (National Association of Clean Water Agencies, 2014). Many of these cases are decided based on whether the authority to charge a fee has been established and evidence that benefits provided through services funded by the revenue match the rationale for the fee (Grigg, 2013). The suite of programmatic benefits offered by a SWU might include drainage, flood control, pollution control, and city enhancement (Grigg, 2019). However, focusing solely on these conventional benefits that are associated with hard infrastructure serves to maintain a status quo in how stormwater is managed, even when there are attempts to integrate green infrastructure solutions (Finewood et al., 2019). Although most SWUs have not faced litigation, the threat of litigation exists (Hawaii Pacific University & One World One Water, 2017). Nonetheless, this should not be cause for taking a conservative route in establishing a SWU based on a precedent with outcomes that may not leave the City and community better off.

For Oʻahu, the establishment of a SWU is a critical juncture to move away from the status quo and adopt infrastructure and management solutions that emphasize co-benefits and cost efficiencies. The authority for the City and County of Honolulu (the island of Oʻahu) to charge a user fee for stormwater services was established by the State of Hawaiʻi in 2015. Furthermore, the Act focuses on the impacts of IA to recharge to justify the authority to create a SWU. It begins with a statement about the effects of climate change and land use change on drinking water supply, followed by encouraging "the adoption of best practices and infrastructure investment by the counties to capture and retain rainfall in Hawaii for potable water before it becomes stormwater runoff that results in pollution to streams, wetlands, and near-shore ocean areas will save the public significantly in the long run" (Hawaiʻi Act 042, 2015). Furthermore, the City enacted a "One Water" policy in 2020 that establishes a mechanism for City agencies to collaborate on water management and climate change adaptation (Honolulu Ord. 20-47, 2020). The One Water policy establishes an inter-agency panel tasked with tackling multi-jurisdictional water-related infrastructure problems with greater capacity and financial efficiency. These converging opportunities provide a chance for the City to move away from establishing a SWU based on the siloed agency model of stormwater runoff pollution control and towards a multi-benefit model with greater efficiencies across agencies.

4.1.1 Programmatic services designed for co-benefits

Programmatic services provided by a SWU should reflect the multiple impacts of IA, including runoff generation, water pollution, and infiltration loss. In the current structure of Honolulu City and County's governance, the Department of Facility Maintenance (DFM)—the agency spearheading the SWU effort—is responsible for stormwater quality and stream maintenance, among many other duties. As such, DFM's mission and responsibilities tend to focus on maintenance, which leads to work that is narrow in scope compared to the breadth of the problems faced. Without any current City governance over stormwater quantity or proactive, preventative stormwater planning, there is a risk that this gap will be propagated into the SWU. Building a SWU under such a framework means that property owners will be charged for creating runoff and the bulk of the funds will be used to mitigate problems caused by runoff and maintain the federal water quality standards. While this is a critical piece of stormwater management, establishing a SWU presents a considerable opportunity to fill known governance gaps and re-focus on services, infrastructure, and programs that provide multi-benefits.

There is a suite of projects and programs that could provide system-level multi-benefits for the SWU to consider moving forward. Upper watershed preservation is a beneficial activity to promote recharge and should be incorporated for drinking water protection. Still, there are also opportunities within the urban core and rural areas to rethink how built spaces can provide multiple stormwater benefits. Transportation corridors and parks are among the City assets that offer ample possibilities for on-site infiltration, stormwater retention, and water quality improvement. For example, current efforts around planning Transit-Oriented Development should consider ways to minimize stormwater runoff through permeable pavement, trees, bioretention, and other low-impact development solutions. There are creative ways that development designs can enhance the community experience in interacting with stormwater infrastructure. Incorporating funding for and promoting indigenous infrastructure is also a critical opportunity for interfacing with community in water retention, infiltration, and water quality improvement opportunities. Furthermore, drainage systems are part-and-parcel to climate change adaptation efforts where there is a vital need for proactive planning in current and expected nuisance flooding areas due to sea-level rise. A stormwater master plan that prioritizes critical multi-benefit programs and projects is key to ensuring the SWU steps out of the status quo role that stormwater management currently holds in City governance.

5. Conclusion

This paper frames notions of "fairness" in terms of economic efficiency and concepts of equity. Economic efficiency and equity are often conflated in the literature, as well as in the discourse concerning SWUs. Whereas both can be important components of achieving a fair SWU model, I argue that the distinction between economic efficiency and equity is crucial to the setting the right expectations around responsibilities of what a SWU offers the community and what the SWU can expect from property owners and the community. Ideas of economic efficiency and equity are theoretical ideals that often have real-life interconnections, so it is understandable that these ideas can become mixed. Even though everyday conversation might not compartmentalize the various concepts of economic efficiency and equity, it is critical that these conceptions are carefully defined in the literature. Because these concepts are theoretical ideals, much of the literature discusses minimizing economic inefficiency or minimizing inequality in outcomes, resource allocation, processes, or structures rather than achieving true economic efficiency or equity.

The illustrative case of Oʻahu shows that stormwater fees based on total IA assume spatially homogeneous rainfall, which falls far from achieving economic efficiency. A simple rainfall multiplier could be adopted to address issues of fairness repeatedly raised by the community. Taking precipitation into account is crucial step towards minimizing economic inefficiencies in the stormwater fee structure, since using total IA as the singular metric for runoff generation creates significant disparities in the price per volume runoff generated in various locations. This paper suggests a three-prong multiplier for drier, average, and wetter regions, but further research would be needed to ensure that the revenue requirements are met with such an approach. The same multiplier could be applied to credits offered so that the cost to the SWU of a runoff reduction practice better matches the benefit. A rainfall multiplier would not likely amplify the economic disparities that currently exist. However, the stormwater fee as currently proposed excludes renters from participating in hardship relief. More research is needed to understand how stormwater fees will impact renters, especially for those living in poverty.

In addition to runoff, infiltration loss is another impact of IA on a system's hydrology. As such, infiltration loss should be considered as part of the programs, projects, and outreach that the SWU conducts, rather than focusing solely on runoff and pollution. At the parcel level, the fee structure currently does not reward any area of a landowner's parcel kept vegetated or with no impervious surface. This might serve to encourage new developments to maximize their fee reductions without minimizing their total IA. On a regional scale, establishing a SWU offers an ideal opportunity to break free of the traditional siloed approach to water management and seek out projects that offer multiple benefits. These might include funding upper watershed protection, as well as finding opportunities for infiltration and runoff reduction in built spaces, such as roads, parks, and new development. Climate change adaption will also be an essential function of the SWU but will require filling a current gap within City governance around proactive stormwater planning.

Conclusion

This dissertation presents three articles that address contemporary water management issues faced by the City and County of Honolulu (also the island of Oʻahu) related to community interactions with water systems. These articles focus on designing water governance systems around the community as both beneficiaries of outcomes of water management and participants in the planning and policy-making processes. Article 1 analyzes factors related to reduced residential water use and adds to the intention-behavior gap literature on water conservation, where few studies use actual water use to understand people's expressed intention to conserve water. The local context motivating this research is Hawaiʻi state's sustainability goal of reducing water use per capita by 15% by 2030 from a 2013 baseline. Article 2 considers the narratives around stormwater management to understand what key ideas comprise each narrative, which ideas are widely agreed upon across narratives, and which ideas garner wide disagreement. The local context of this research relates to a US Army Corps of Engineers Flood Risk Management Project for the Ala Wai watershed that galvanized the local community to promote and seek alternative solutions to stormwater management for this key Honolulu watershed. Finally, article 3 discusses and defines "fairness" in stormwater management and financing and is motivated by a recent exploration to establish a stormwater utility. The article first disambiguates concepts of equity from economic efficiency, which are often conflated in the literature. It then explores the concepts of fairness in the context of the proposed stormwater utility for Oʻahu.

Socio-hydrological Planning Considerations

Towards Integrated Water Management for Oʻahu

Several converging opportunities exist for Oʻahu to progress towards integrated water management that reaffirms the integrated nature of ahupuaʻa management and positions the island communities to adapt to challenges imposed by climate change. In December 2020, the City and County of Honolulu enacted a "One Water" policy that establishes a City collaboration for water management and climate change adaptation. The One Water policy sets an inter-agency panel which aims to tackle multi-jurisdictional water-related infrastructure problems posed by climate change impacts. This effort builds on the City's efforts to actively address climate change issues by establishing the Office of Climate Change, Sustainability and Resiliency, and an advisory Climate Change Commission. With these efforts, the City has made progress in establishing needs and goals that arise from climate change impacts. However, it has yet to develop and implement concerted adaptation efforts. From the research conducted for this dissertation, I reflect on three general considerations in moving towards integrated water management solutions to address climate change impacts and legacy water management problems based on the research conducted for this dissertation.

Financing is a sticky subject, but fairness is critical

In article 2, I find that any idea related to financing or values garners widely different priorities and thoughts between narrative groups. I find that even though public discourse tends to be about infrastructure solutions, underlying disagreement lies more in how to get to those solutions rather than the solutions themselves, with financing being part of the "how-to." In the exploration of establishing a stormwater utility for O'ahu, there is an opportunity to have critical discourse about financing needs for stormwater management. The Department of Facilities Maintenance, which is leading this effort for the City, has so far conducted an inclusive effort with critical stakeholders and community outreach to further the discourse about stormwater financing. Community outreach meetings have shown that perceptions of fairness are top-of-mind to the community. In article 3, I disentangle what constitutes fairness in stormwater financing and management. I find that economic efficiency is a particularly critical concept to perceptions of fairness in stormwater financing; however, it is often conflated with equity terminology. In particular, I distinguish economic efficiency from distributive equity as distinct concepts that constitute community perceptions of fairness in stormwater financing and management. The focus of community comments and questions around their observed environments suggests the importance of listening to community concerns and incorporating local context into management decisions. Having mountain-to-coast jurisdiction over all watersheds of the island can help discourage the uneven implementation of policies and plans. However, it can also prevent needed contextual adaptation in policy and plan implementation according to a localized setting that serves to contribute to perceptions of fairness.

Land-use planning and public spaces can help shape social norms about water

Urban environments present ample opportunity to shape how people interact with water in the environment and view water use and management. In article 1, I show that there is an intention-behavior gap in water conservation. That is, people's expressed intention to conserve water is not reflected in their water use. However, factors related to reduced water use include participating in water conservation programs and installing water-saving fixtures. In the article, I use the Theory of Planned Behavior to understand why these actions might relate to reduced water use, whereas expressed intention to conserve water does not. This theory suggests that information about water use and social norms can play a role in closing the intention-behavior gap. Urban design, land-use policies, and public spaces can be critical hidden drivers of residential water use and can shape the social norms around how land and water interact. In O'ahu, location matters where highly variable rainfall across the island might influence the successful outcome of implemented solutions.

Factors such as vegetated land cover, housing density, and lot size, that are influenced by land-use planning decisions, can impact aggregate residential water use. These factors can also affect stormwater runoff, sometimes in competing ways. For example, vegetated land cover on a parcel may serve to increase water use if watered, however, it would create less stormwater runoff than if that same area were covered with impervious surface. As article 2 shows, people tend to agree that land use planning and stormwater management should be better integrated. This could easily extend to considerations over how land-use planning decisions influence water use. Outside of planning, water conservation programs and stormwater management practices that provide co-benefits might be critical to bridging these competing needs. For example, in article 1, I find that the presence of rain barrels or rain catchment systems in households relates to lower water use. These would provide the co-benefit of reducing stormwater runoff from a property, as discussed in article 3. Xeriscaping is also an example of providing the benefits of vegetated space without requiring excess water use for upkeep. The Honolulu Board of Water

Supply's Halawa Xeriscape Garden is a noteworthy model for members of the community to interact with and learn about how to use low-water landscaping techniques.

Public space can also play a critical role in shaping social norms around water use and management. In article 2, I find that while people tend to disagree over where citizen responsibilities lie in stormwater management and financing, people tend to affirm stormwater management as a public service. There is also widespread agreement that parks and public spaces can function as flood parks to retain water and reduce runoff in urban areas. With the expectation that individual actions can help decrease the total water demand and reduce the total amount of stormwater runoff, the City must consider the use of public spaces and buildings as demonstrative of a commitment to action on these fronts. Otherwise, official buildings and public spaces that visibly do not implement best practices suggested of individual landowners (e.g., conserving water or implementing runoff reduction practices) can discourage the individual land owner adoption of such measures. Overall, messaging (through both information and physical spaces) a positive framing around tangible actions that lead to increased water productivity could create a more palatable shift in cultural norms around water use and management.

Emphasizing and ensuring multi-benefits will better position projects to succeed

The findings of article 2, as well as the interviews conducted for that research, suggest that people agree with more than they disagree with in stormwater management. In particular, there is a coalescence around wanting to see more decentralized, green infrastructure-type solutions that provide multiple benefits. Current governance structures tend to discourage multi-benefit projects, where individual agency missions and responsibilities often emphasize a siloed role and function of water management. The establishment of the One Water policy presents a key window of opportunity to move projects that offer multiple benefits and cost efficiencies forward. Furthermore, the stormwater utility could be an essential vehicle for implementing such solutions that emphasize various benefits, as discussed in article 3. There are also opportunities within the urban core and rural areas to rethink how built spaces can provide multiple water management benefits. Creative urban design of transportation corridors, parks, and other public spaces can offer ample possibilities for on-site infiltration, stormwater retention, and water quality improvement, as well as serving a more abstract function of shaping social norms around how people interact with water.

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