Title
Decision Support for Multi-Benefit Urban Water Infrastructure

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Publication Date
2018

Peer reviewed|Thesis/dissertation

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By

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A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

in

Energy and Resources

in the

Graduate Division

of the

University of California, Berkeley

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Fall 2018

Abstract

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Urban water systems in the United States are poised for massive change. Water infrastructure built in the 20th century has promoted public health and has protected ecosystems from pollution. However, much of this infrastructure is now coming to the end of its design life, and requires substantial investments to keep it functional. Our water systems also face new challenges from shifting precipitation patterns, sea level rise, and contaminants of emerging concern, among others. Modernizing our nation's aging water infrastructure is imperative – and to meet 21st century challenges, we must do better than simply repairing it.

The next generation of urban water infrastructure can also provide other societal benefits like resource recovery from sewage, increased wildlife habitat, and improved resilience to climate change effects in addition to water supply and wastewater treatment. Yet there still is little guidance for how water managers can include broader societal goals for multi-benefit infrastructure into what have historically been singular fields of engineered water supply and wastewater treatment. Without a better understanding of how public policy ties in to water infrastructure goals, improvements may only be made in moments of crisis, and the opportunity to create multi-benefit water systems will be lost.

This dissertation seeks to support decision-makers in designing and implementing more equitable, holistic, and environmentally-sound urban water infrastructure. Chapter I assesses historical precedents for recycling sewage into drinking water in California to contextualize current concerns and challenges. Water recycling has had a rich and varied history in California; currently, potable water reuse is on the rise. Chapter II develops a legitimacy framework for potable water reuse in California, which facilitates decision-making about technologies that fit into the unique social, political, and cultural contexts of a particular locale. Chapter III provides a popular science look at the practice of potable water reuse, which is unfamiliar to many people and has faced stark public opposition in some areas. Chapter IV focuses on stakeholder perspectives to identify goals and strategies for multi-benefit wastewater treatment, as well as analyzes barriers to achieving these goals. Chapter V employs a quantitative multi-criteria decision analysis paired with stakeholder analysis and scenario planning to evaluate potential nutrient management options for the San Francisco Bay Area in uncertain future conditions.

Acknowledgements

To the wonderful people who helped bring this dissertation to fruition: thank you! The Energy and Resources Group (ERG) students and professors inspired me with their unwavering dedication to making the world a better place. Thank you for making the journey through graduate school fun, and for supporting me in following my academic interests. Special thanks to ERG's Water Group and Dr. Isha Ray, for building such a strong community of scholars, thinkers, and activists.

Dr. David Sedlak and the Engineering Research Center for Re-inventing the Nation's Urban Water Infrastructure (ReNUWIt) have introduced me to the world of environmental engineering and water infrastructure design. Thank you for welcoming me into your research circles and for challenging me to translate my work into practically useable findings. Thanks also to my collaborators at EAWAG, Dr. Christian Binz and Dr. Judit Lienert, for your generosity with your time and your patience for working across continents and time zones. I gratefully acknowledge the financial support from ReNUWIt and the National Science Foundation's Graduate Research Fellowship Program during my graduate studies.

My family has had boundless faith in my abilities to shape my graduate education into the experience I wanted. Thank you for always believing in me, encouraging me, supplying me with food, and hooking me up with a sweet place to live. I owe my sons, Ezra and Ruben, credit for helping this dissertation actually getting finished: thank you for motivating me to actually work during my work hours so that I could play with you the other times, and for helping me keep this project in perspective. My deepest gratitude to Felix Ratcliff, whose generosity, humor, support, R-brilliance and all-around wonderfulness enabled me to work on this project for the duration.

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Introduction

During my time in graduate school, California has experienced one of the most severe droughts in recorded history (Griffin and Anchukaitis, 2014). After a brief respite of a wet year in 2016, Sierra snowpack in January of 2018 was again nearing record lows, at 27% of normal depth and only 14% of normal water content for this time of year (Gustin, 2018). Climate models predict increased drought in many parts of California, and state and local water managers are looking for appropriate ways to respond (California Natural Resources Agency, 2016). California's drought has been equated to "a magnifying glass, revealing that California's water supply system is brittle and inflexible" (Lassiter, 2015). Drought is a powerful reminder that we need to pay attention to improving our state's systems for managing water resources. With 'drought' a household term, how we get our water and what we do with our wastewater are urgent concerns for Californians.

Many of the attitudes and institutions that determined decision-making about California's urban water systems in the past sprung from an earlier era of water abundance, fewer environmental regulations, and less regard for the well-being of non-urban residents (Hundley, 2001). Historically, water management followed a "take, make, waste" mindset of consumption (Daigger, 2009). Today's conditions of a changing climate, a growing population, and increasing environmental awareness require new modes of decision-making and new tools to support them (Brown, 2008; Gleick, 2003).

These concerns and patterns are not unique to California. Arid and semi-arid regions around the world are encountering challenges with traditional water management techniques that rely on past assumptions of water abundance and reliable rainfall; Cape Town and Rio de Janeiro's recent scares about running out of drinking water are notable examples (Watts, 2015; Welch, 2018)). Furthermore, much of our nation's water infrastructure is antiquated and in need of repair (American Society of Civil Engineers, 2012). Urban water systems are poised for massive change.

In addition to concerns about means of obtaining water supply, traditional paradigms of wastewater treatment are under scrutiny for their ability to meet 21st century challenges of water management (Guest et al., 2009; National Research Council, 2009). As our nation's urban water infrastructure stands on the brink of change, some water managers are already making the shift to adopting new technologies and preparing for new paradigms in water and wastewater management. These include finding ways to put treated sewage to productive use, and integrating management of drinking water, storm water, and wastewater (Daigger, 2009). There is a growing awareness of the need for collaboration between stakeholders and the traditionally stove-piped fields of water quality, water supply, wastewater treatment, groundwater management and stormwater control (Guest et al., 2009). There is also an increasing desire to incorporate managed natural systems and multi-beneficial solutions into traditional water infrastructure (Hering et al., 2013).

Yet transitioning to innovative technologies and more sustainable modes of water and wastewater management remains a challenge, despite the development of innovative technological options (Fratini et al., 2012). In particular, adapting social, regulatory, and bureaucratic institutions to a broader, more integrated role in water management requires attention and support (Brown, 2008; Brown and Farrelly, 2009; Ferguson et al., 2013; Hering et al., 2013; Van de Meene et al., 2011). In California, even as long-term statewide and regional water planning documents like the California Water Plan Update 2013 and the San Francisco Bay Area's Integrated Regional Water Management Plan tout the utmost importance of integrating water management with climate projections and habitat protection plans (California Department of Water Resources, 2014; *San Francisco Bay Area Integrated Regional Water Management Plan*, 2013), there is a dearth of information for water managers and engineers tasked with designing the next iteration of California's water infrastructure for how to effectively collaborate across agencies and organizations, and successfully juggle all of these concerns.

Traditionally, water infrastructure planning in the United States has been relegated to civil and environmental engineers. Using a linear approach to infrastructure planning – what urban planning scholar Judith Innes terms a "Decide, Announce, Defend" (DAD) mode of decision-making (Innes and Booher, 2010) – they have made many important public health gains, including making safe drinking water accessible in most cities, preventing devastating flooding, and quickly and efficiently removing sewage from homes. Yet some of these solutions have led to other environmental concerns, like destruction of sensitive habitat, intensive energy consumption, and vulnerability of water infrastructure to rising sea levels.

This dissertation aims to provide decision-support tools for policy makers and water managers to enable them to consider multiple, and sometimes conflicting, objectives for urban water infrastructure. It highlights ways in which water infrastructure design ties in to concerns about climate change, habitat creation/loss, energy use, and environmental justice, and how water infrastructure can be designed with an eye towards co-benefits for climate change mitigation, sea level rise, habitat creation, and environmental stewardship.

In particular, this dissertation focuses on providing decision support for water managers concerned with two emerging water-related issues: 1.) potable water reuse, which is the practice of treating sewage and deliberately returning it to the drinking water supply, and 2.) nutrient removal from wastewater effluent. It considers water reuse and nutrient management in their social, technological, and environmental contexts in order to better evaluate decision alternatives and support decision-making around these complex issues in the future. While this research focuses on Californian case studies, these issues were chosen because they are pressing concerns not just in California but in many parts of the globe.

Water reuse is part of a shifting paradigm for wastewater treatment – for many researchers and practitioners, wastewater treatment plants should not only protect human health and receiving water bodies from pathogens and other compounds in sewage, they should also recover resources from sewage like water, nutrients, and energy (Daigger, 2009). Potable water reuse is one way of recovering useable water from sewage, and it has been touted by engineers as potentially cost-effective because it doesn't require the construction of a new set of pipes as non-potable reuse does (Leverenz et al., 2011; Tchobanoglous, George and Raucher, Robert, 2014). Yet although technology exists for treating sewage to federal U.S. drinking water standards (National Research Council, 2012), there has often been public opposition to potable water reuse (Dolnicar and Hurlimann, 2011; Hurlimann and Dolnicar, 2010; Nancarrow et al., 2008; Po et al., 2003).

The first section of my dissertation research sheds light on the challenges facing potable water reuse through examination of the history of water reuse in California (Chapter I) and through an analysis of California case studies of water reuse to inform a legitimacy framework for understanding why some cities have adopted potable reuse while others have not (Chapter II). The historical lens on water reuse in California serves to contextualize today's attitudes towards water reuse, of which California has a rich and varied tradition (Harris-Lovett and Sedlak, 2015). The legitimacy approach to understanding adoption of potable water reuse applies a sociological lens to California case studies, and draws conclusions about the need for inclusion of diverse elements of a legitimacy portfolio. The results are applicable to water reuse in other regions and to other innovative water management strategies (Harris-Lovett et al., 2015).

Although many water professionals and practitioners are enthusiastic about potable water reuse (Tchobanoglous et al., 2011), concerns remain about the characterization, monitoring and chronic health effects of contaminants in the treated water (National Research Council, 2012). Though the health risks from potable water reuse are considered comparable or better to those of existing water supplies (National Research Council, 2012), public perceptions and concerns about potable reuse can make or break planned projects (Dolnicar and Schäfer, 2009; Hartley, 2006; Marks, 2006). To address these concerns, I wrote a popular science piece (Chapter III), published in the magazine Undark, explaining potable reuse technology and concerns relating to it (Harris-Lovett and Pickett, 2017).

The second section of my dissertation centers on decision-making about nutrient management, with a focus on a case of the San Francisco Bay. Nutrient control in coastal ecosystems is a concern across much of the nation and world-wide (Howarth, 2008; Howarth et al., 2002; Smith, 2003). Yet many traditional technologies for point-source nutrient control are expensive and energy intensive (Corominas et al., 2013), while providing the sole service of reducing nutrient load in wastewater effluent. Interest in a new paradigm of water management, in which infrastructure can provide multiple benefits, extends to nutrient management in the Bay Area case. My research clarifies the multiple objectives that Bay Area stakeholders want nutrient management to fulfill, analyzes the barriers to planning and implementing multi-benefit infrastructure, and details strategies to overcome these barriers (Chapter IV).

To support decision-making about multi-benefit water infrastructure, my research employs multi-criteria decision analysis (MCDA) combined with planning for uncertain future scenarios and stakeholder analysis in the Bay Area case of nutrient management (Chapter V). This project delineates how MCDA can support regional water infrastructure planning by elucidating areas of agreement and disagreement amongst stakeholders, assessing the potential of innovative technologies, and clarifying the effects of technical and future uncertainty on nutrient management outcomes.

These research projects on potable water reuse and nitrogen management reveal several challenging aspects of transitioning to multi-benefit urban water systems. They demonstrate that water infrastructure solutions must be context-specific by catering to local needs, history, culture and stakeholder goals. This implies that decision support tools should be broad enough to use across contexts while detailed enough to facilitate informed decision-making in any given region.

In addition, multi-benefit water infrastructure interfaces by nature with land management, city planning, and ecological stewardship, among other professional fields. This suggests that water professionals must be trained to do *more* than solely have technical expertise in their field. They must also be able to communicate broadly across professional roles, meaningfully collaborate with diverse groups of people and incorporate different viewpoints into decision-making, and assess technical interventions in their historical and cultural contexts.

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Chapter I: Historical precedents for multi-benefit wastewater treatment: California's history of recycling sewage

Preface

Deliberately re-using the water in sewage – a practice called by many different names including water reuse, water recycling, and wastewater reclamation – is becoming more common as an integral part of water supply solutions in the United States (National Research Council, 2012). Water reuse can take many forms: recycled water can be used for agricultural irrigation or landscaping, for cooling power plants, to replenish underground aquifers, to augment streamflow or drinking water reservoirs, or can be piped directly into drinking water treatment systems (Asano et al., 2007).

Advances in technologies for treating sewage for water reuse over time have progressively opened more potential uses for recycled water. What started with raw sewage application to farm fields and orchards has progressed to a high-tech industry that can treat sewage to suit its intended use, a process known as fit-for-purpose water treatment (Chhipi-Shrestha et al., 2017). Currently, technologies to purify wastewater have reached the level where they can clean sewage water to federal drinking water standards (National Research Council, 2012), though concerns about chemical contaminants and fostering antibiotic-resistant bacteria in drinking water remain (State Water Resources Control Board, 2018).

Although there has been a resurgence of public policy support for recycled water in recent decades (California State Water Resources Control Board, 2013; United States Environmental Protection Agency, 1998), recovering resources like water from sewage isn't new. Re-using water from sewage has a long and varied history in the United States and worldwide. Where did ideas about water reuse in the United States come from, and how have they evolved over time? This chapter examines this question through the lens of the history of water reuse in California.

Methods

Analysis of historic newspaper articles, scientific journal articles, magazine articles, and other documents from was conducted using the Proquest Newspapers database from 1881 – present (1881 was chosen as the start date because it was the first year the Los Angeles Times is included in the Proquest database). Search terms included combinations of "water reuse", "water recycling", "water reclamation", "sewage", and "California". Once major trends and projects were identified (i.e. sewage farms, irrigation of Golden Gate Park, Water Factory 21), these terms were included in searches.

A visit to Orange County Water District and tour of their facilities in 2013 was conducted to inform the more recent history of water reuse in California. Oral histories with some of the staff who have worked at Orange County Water District for more than a decade and seen the evolution of their Groundwater Replenishment System also informed searches for more recent documents, webpages, and projects about water reuse in California.

Excerpt from: 'The History of Water Reuse in California' by Sasha Harris-Lovett and David Sedlak. Published in Lassiter, Allison, ed. *Sustainable Water: Challenges and Solutions from California*. University of California Press, 2015.

A concrete building in one of Orange County's suburban neighborhoods has a small sign at the entrance reading Orange County Water District. Behind this sign is one of the region's vital organs: the mechanical kidneys that process and disinfect wastewater from 2.4 million residences, then pump the treated effluent back into the water supply.

This is Orange County's water recycling plant, known as the Groundwater Replenishment System. It is world-renowned for making treated sewage clean enough to add to the region's drinking-water aquifer, which the utility has been doing for over 30 years. In this semi-arid part of California, reuse is a cost-effective way to provide water for a growing population in the face of rising costs of imported water, over-drafted groundwater basins, and shrinking snowpack.

Water reuse and recycling, which are defined in this chapter as intentional reuse of treated municipal wastewater, are becoming more popular across the Golden State. Recycled water is used for irrigation of agricultural crops and urban landscaping, for industrial cooling and boiler systems, and in some cases, as in Orange County, for potable use. California utilities reused over 890 million cubic meters (724,000 acre-feet) of water in 2012 (National Research Council, 2012) enough to meet the yearly needs of approximately 3.2 million people (calculated from (Hanak, 2011)).

Despite its great promise, water reuse comes with its share of technical, social, and philosophical challenges. The technical challenges, like how to remove residual chemicals from wastewater, or how to assure that the technology is functioning properly at all times, may be the easiest to solve. The social challenges, like how to address public perceptions related to the reuse of wastewater, are a bit more complex. But at the core, the most difficult challenges associated with water reuse are philosophical: What do water reuse technologies reveal about humans' relationship to the environment and notions of waste?

Tracing the story of water reuse in California's history provides insight into many of these challenges. This chapter chronicles the changing technologies and attitudes toward water reuse in California, from the use of raw sewage on crops in the early 1900s to today's technologies for augmenting drinking-water supplies with treated wastewater. Historically, Californians kept wastewater "out of sight, and out of mind." This mindset continues to influence some water reuse projects across the state. During the past decade, more sensitive methods for detecting trace chemicals and pathogens have challenged the old "out of sight, out of mind" paradigm of sewage treatment. Today, as water reuse practices trend toward recycling treated wastewater for drinking-water supplies, a new guiding philosophy is needed for urban water systems. Instead of considering water "waste" after one use, it must be treated as a valuable resource. New policies and technologies to prevent toxic chemicals from entering sewage and for monitoring water quality are necessary to ensure the safety of water reuse as part of urban water supply portfolios.

Dealing with the “Obnoxious Matter” of Sewage: Wastewater before 1930

The story of water reuse in California intertwines with the story of wastewater management. Californians have long used water to get waste out of their homes and thoughts. George Davidson, an engineer tasked with redesigning San Francisco’s sewage system in the late nineteenth century, summed up the prevailing philosophy about waste: “We must simply but effectually get rid of the obnoxious matter in the shortest and cheapest manner” (Davidson, 1886). For the cities in California (and most other parts of the developed world), this meant flushing waste away with piped freshwater, instead of waiting for the rain to wash it away. Wastewater utilities built pipes to contain the odors emitted by sewage (which were believed to be toxic) and to carry the waste away from homes.

In coastal areas, pipes transported sewage to the sea, where it would be diluted enough not to offend people with its smell (Grunsky et al., 1899). However, this was not possible for many of California’s inland communities. An alternative to dilution was imperative for getting sewage out of sight.

In 1900, the inland city of Pasadena managed their sewage by reusing it for agricultural irrigation. They purchased a 120-hectare (300-acre) plot of land outside the city, called it the Pasadena Sewer Farm, and piped their raw sewage there to water crops. The farm produced walnuts, pumpkins, hay, and corn. Sewage farming was a profitable business. In 1903, the walnut crop alone paid for all the farm’s expenses and accrued an additional $2,400 (about $63,000 in 2013 dollars) in profit for the city (Holder, 1904).

Other Southern California cities turned to sewer farms as a way to make a profit on human waste while getting it away from homes. In 1909, residents of the coastal city of Redondo Beach voted down a proposed sewer outflow to the ocean and instead insisted that their city adopt the sewer farm model for reuse (Barkley, 1909). Sewage, to them, was a source of water and nutrients that could make the dry landscape of Southern California produce useful crops. This wasn’t a new idea; several decades earlier in Europe, Karl Marx had criticized London’s plan to pipe its wastes directly into the nearest large body of water: “Excretions of consumption are of the greatest importance for agriculture. So far as their utilisation is concerned, there is an enormous waste of them in the capitalist economy. In London, for instance, they find no better use for the excretion of four and. a half million human beings than to contaminate the Thames with it at heavy expense” (Marx, 1906)

While sewer farms in California ultimately didn’t survive, due to concerns about odors and health risks associated with putting raw sewage on farm fields, the Farm Bureau continued to support the idea of sewage reuse (Los Angeles Times, 1921a). The engineers who designed San Francisco’s sewer system in the 1920s acknowledged the value of nutrients and water in the city’s sewage to nearby farmers, but decided that water reuse was not feasible given the cost of pumping the sewage uphill to nearby agricultural areas (Grunsky et al., 1899).

Instead of using sewage to grow commercial food crops on agricultural land, San Francisco diverted sewage from its inner-city neighborhoods to irrigate Golden Gate Park (which was then on the outskirts of the city), making it possible to grow lush, verdant meadows where before only sand dunes existed (Hyde, 1937).

Around the same time, in 1921, Los Angeles voters nixed a proposal to enlarge their city's sewage system because they thought sewage should be used for fertilizer rather than squandered in the Pacific (Knowlton, 1928). Even after Los Angeles eventually built an upgraded sewer outflow to the ocean in the 1920s, the *Los Angeles Times* ran an article condemning the city government for "wasting the valuable fertilizing elements in its sewage by dumping it in the sea" instead of reusing it (Los Angeles Times, 1921b).

In this era, a need for fertilizer spurred part of the enthusiasm for reusing sewage in agriculture. Many farmers in the United States relied on dwindling imports of Peruvian guano to fertilize their crops (Smil, 2004). Sewage was also nutrient-rich, and cheaper than South American bat droppings. After World War II, a German company commercialized the Haber-Bosch process for converting atmospheric nitrogen to liquid ammonia for fertilizer (Erisman et al., 2008). This synthetic nitrogen quickly supplanted organic waste as fertilizer.

Getting Rid of the Smell: Early Technologies for Sewage Treatment

`As California's urban populations expanded, the practice of piping sewage away proved to be insufficient for getting rid of the smell. Coastal areas reeked. In 1922, Los Angeles responded to the stench by screening its sewage and burying the captured solids in the sand dunes before sending the remaining wastewater into the Pacific Ocean (Knowlton, 1928).

In inland cities, sewer farms smelled bad and attracted flies. In Fresno in 1924, the city council decided to apply wastewater to the surface of the ground outside the city, where it would infiltrate back into the aquifer. To make the wastewater percolate quickly, they lowered the level of the groundwater by building nine additional extraction wells (City of Fresno, 2018a). Because groundwater was the primary drinking-water supply for the city (City of Fresno, 2018b), this project for getting sewage out of sight (and smell) essentially created the state's first planned potable water reuse system.

In San Francisco, the city grew to surround Golden Gate Park. New neighbors voiced serious complaints about the odors of sewage used for landscape irrigation. In response, in 1932 the Park Commission built a state-of-the-art activated-sludge treatment plant near the park. The new technology bubbled air through the wastewater so bacteria could break down the sewage. Chlorine killed any pathogens remaining in the effluent, so it could be used for irrigation. The treated water was also used to create an artificial brook and chain of lakes running through Golden Gate Park (Hyde, 1937), reinforcing the planners' ideal of a lush environment in a naturally semi-arid area.

Quenching Californians' Thirst: Early Water Supply Solutions

Settlers in the semi-arid regions of Southern California originally relied on local surface water and groundwater to meet their needs for drinking, bathing, and irrigation. Farmers and cities drilled wells into the aquifers underneath what are now Los Angeles and Orange Counties, where abundant water bubbled out of the wells day and night (San Francisco Chronicle, 1900).

Towns were named Fountain Valley, Santa Fe Springs, and Artesia in recognition of the bountiful springs.

But as more people tapped southern California's groundwater, they depleted the supply. By the 1940s in Orange County, residents withdrew the coastal groundwater basin to five meters below sea level, causing the seawater to flow inland through the porous sand underground (Orange County Water District, 2013a). Seawater contaminated the groundwater, making coastal wells too salty to use. Southern California needed new water supplies if it wanted to encourage agricultural and suburban growth.

In response, the local, state, and federal governments funded massive infrastructure projects to satisfy the water demand of the burgeoning cities on the California coast and of the farmland reclaimed from the desert. Over the following three decades, politicians and engineers devised a network of aqueducts, reservoirs, and pumping stations to transfer water to Southern California. These water transfers occurred, in some cases, at the expense of the ecosystems and rural communities that had previously relied upon that water for survival.

Yet, imported water wasn't enough to meet demand. During World War II, Los Angeles became the manufacturing center for wartime aircraft and other military supplies. The population soared (Kling et al., 1995). All these new Californians needed water.

After World War II, newspaper articles touted technology as critical for economic progress and for solving the nation's problems (New York Times, 1956). Water shortages were no exception. When Southern California found itself short of water, it turned to technology to increase the supply.

The vast Pacific Ocean would provide an endless supply of water for California's coastal cities, if only scientists could find ways to remove the salt. Across the country, researchers began studying desalting technologies. Electrodialysis and distillation both proved technically feasible, but extremely expensive.

Though using the ocean as a water supply was the original intention, scientists soon found that the same technologies worked far more efficiently in desalting less salty water, like the brackish groundwater in many of the state's wells. In 1959, the Central Valley town of Coalinga, where the groundwater was too salty to use, invested in the first demonstration desalting plant in the United States. The new plant in Coalinga provided a small amount of drinking water (enough for about 140 people) at a fraction of the cost of bringing it in by tanker trucks, by using electrodialysis to separate the salts out of their brackish groundwater (Los Angeles Times, 1958a).

With technologies available for converting seawater and salty groundwater to freshwater, anything seemed possible. Even wastewater was considered a potential source of supply, given these new technologies to transform previously inaccessible sources into fresh water (Los Angeles Times, 1958b; Phillips, 1949). An engineering company's report to the California State Water Resources Control Board indicated that reusing wastewater could be the answer to the state's future water needs. The report predicted that water recycling would "save California and other States of the thirsty Southwest from economic dehydration" (Los Angeles Times, 1955). More water would ensure growth in the driest regions of the state.

To make water reuse feasible on a larger scale, excess salt—caused in part by water softeners, detergents, and household wastes—needed to be removed more cheaply. Distillation and electrodialysis were expensive, but a promising new product—plastic—had recently come on the market. Technophiles hyped plastics as making better, cheaper products, from dolls to concrete (New York Times, 1955; Washington Post, 1952). If plastics could improve dolls and concrete, why not desalting technologies? In 1959, two graduate students at UCLA, Sidney Loeb and Srinivasa Sourirajan, employed a synthetic plastic membrane in a new desalting technology called reverse osmosis, making the process cheaper than ever before (Loeb, 1981). Reverse osmosis worked by forcing water molecules across a membrane, thus separating them from most of the salts, nutrients, and pathogens.

The city of Coalinga, which had installed the small electrodialysis plant seven years earlier, built the nation's first reverse-osmosis treatment system in 1965 to desalt their groundwater (Loeb, 1984). Though it could only produce enough freshwater for about thirty people per day, this demonstration plant proved that reverse-osmosis technology was much cheaper if used on groundwater than on seawater (Loeb and Manjikian, 1965; Loeb and Selover, 1967; Rosenfeld and Loeb, 1967; Stevens and Loeb, 1967).

The U.S. federal government took an active role in advocating a "world-wide cooperative effort" to solve global water shortages through desalination (Udall, 1965). In 1961, President Kennedy gave a rousing speech to Congress about water reuse, which was reprinted in full in the *New York Times*. He said that "to meet all needs—domestic, agricultural, industrial, recreational—we shall have to use and reuse the same water, maintaining quality as well as quantity." He also allocated $75 million (1961 dollars) in federal funds to the Office of Saline Water (a program of the Department of the Interior) for increased research into technologies for reclamation of wastewater and seawater (MacGowan, 1963).

Just six months later, construction began on a water reclamation plant in Los Angeles, at Whittier Narrows. The plant processed sewage and sent the treated wastewater to a sandy basin next to the facility. The treated wastewater, along with any pooled stormwater runoff, infiltrated into the groundwater. The water district then pumped the groundwater to the surface, where it became part of the local drinking-water supply. Though inland cities like Fresno infiltrated treated wastewater back into the groundwater, Whittier was the first to publicly advertise what they were doing as *water reuse*, rather than just a convenient means of waste disposal (Nelson, 1961).

Wastewater reuse in California soon became a source of water for recreational purposes. In 1965, a community in inland San Diego County called Santee began using treated wastewater to fill man-made lakes used for fishing and swimming. For Santee, water reuse was cheaper than connecting their sewage pipes to San Diego's metropolitan sewage system (Hill, 1965). They used activated-sludge technology to treat the sewage, then percolated it through 120 meters (400 feet) of soil for additional treatment before pumping it to the surface, chlorinating it, and releasing it into the lakes (City of San Diego, 2005).

Before, treated wastewater was quietly reused out of the public eye for groundwater recharge or for outdoor irrigation. But in Santee, swimmers had full body contact with reclaimed water. Media accounts touted water reuse as "an inevitable fact of life as water demands increase" (White, 1965). In 1968, a front-page article in the *Chicago Tribune*, titled "A Pattern for the Future: Using Water Over and Over Again," characterized water recycling as the norm for American cities, and cited Santee as a model for future development (Bukro, 1967).

In arid parts of California, many communities realized that reusing wastewater was an economically feasible option for both enhancing water supply and curtailing sewage pollution. By 1970, over 123 million cubic meters (100,00 acre-feet) per year of recycled water were being used for agricultural irrigation in California—nearly a third of the capacity of Hetch Hetchy Reservoir. An additional 24 million cubic meters (20,000 acre-feet) per year were used for urban landscape irrigation in California (California State Water Resources Control Board, 2009a), or enough water to submerge the island of Manhattan to a depth of two feet. Building on this momentum, San Diego built a reverse-osmosis facility to desalinate wastewater effluent for landscape irrigation (Los Angeles Times, 1970a). Water recycling in Southern California garnered national attention and a positive review in a front-page article in the *Wall Street Journal* in September 1971 (Graham, 1971).

The following month, Orange County announced its plan to build a new "water factory," known as Water Factory 21. The recycled wastewater produced there would keep saltwater from intruding into coastal aquifers near Newport Beach, and at a lower cost than the alternatives. For over a decade, Orange County and other water districts along the Southern California coast had bought imported freshwater to inject underground to prevent seawater from migrating inland and contaminating groundwater (Orange County Water District, 2003; West Basin Municipal Water District, 2018). The injected freshwater formed a barrier underground, raising the level of the aquifer at the coast and providing enough pressure to keep the seawater out of the drinking-water supply (Pryor, 1971).

Water Factory 21 began operating in 1976, treating over 56,000 cubic meters (46 acre-feet) of wastewater a day (Orange County Water District, 2003), enough to fill 22 Olympic-sized swimming pools. To create an effective hydraulic barrier against saltwater intrusion, engineers at Water Factory 21 realized that they needed to remove many of the salts from the treated wastewater. They treated half the waste stream with reverse osmosis, which was expensive but could remove salts; this marked the first use of reverse-osmosis technology with wastewater. They passed the other half of the wastewater through layers of anthracite coal, sand, garnet dust, and granular activated carbon (the stuff of modern-day Brita filters) to remove some of the residual chemicals in the water. Then they chlorinated the water to kill pathogens, before injecting it into the aquifer (Hammer and Elser, 1980). The interior secretary, Rogers Morton, touted Water Factory 21 as an example for California and the rest of the world (Boettner, 1972; Los Angeles Times, 1972).

Calls for Caution: Risks of the Unknown

Even as water recycling grew more common in California throughout the 1960s and 70s, some people called for restraint. The growth of potable water reuse coincided with a nascent awareness of the harmful impacts of some of the synthetic compounds that had been enthusiastically used after World War II. Rachel Carson's seminal work, *Silent Spring*, alerted the public to the unintended health and environmental consequences of the synthetic pesticide DDT (Carson, 2012). Less than a decade later, in Southern California, the Montrose Chemical Company gained notoriety for sending DDT down the sewers into Santa Monica Bay (Dreyfuss, 1971). Sewers in California had long carried waste out of sight and out of mind. As household and industrial chemicals became more ubiquitous after World War II, these potentially toxic chemicals were also thrown "away" down the drain without a second thought.

But in Santa Monica Bay, DDT did not become nontoxic when it went down the drain. Instead, it devastated the region's brown pelican population. The public worried that human health would suffer as the chemical bioaccumulated up the food chain. A 1970 *New York Times* article about the DDT in Santa Monica Bay stated, "Most humans are now believed to have DDT in their bodies. Its effects are not known, but some scientists have suggested it may cause cancer" (New York Times, 1970).

Given this context, it is not surprising that some Californians worried that existing wastewater treatment processes could not protect them from chemicals in sewage if the water were reused (Bengelsdorf, 1965). To them, water reuse was a Pandora's Box that could wreak havoc if it allowed synthetic chemicals and viruses to make their way into water supplies by way of recycled water (Harris, 1977). Citing the groundwater-recharge project at Whittier Narrows as an example, critics suggested that water reuse was harmful to the American public. The media suggested that "the nation—some say legislators and a horde of Public Health Service scientists—is rapidly poisoning its drinking water" (Mulligan, 1963).

These concerns were not unfounded. Industrial, agricultural, and household chemicals passed through activated-sludge treatment plants and polluted surface waters. In many cases, these rivers supplied water for cities downstream. A 1975 study by the Environmental Protection Agency found synthetic carcinogenic chemicals in the drinking water supply of 79 of the 80 cities tested (Bukro, 1975).

The California Department of Public Health voiced concerns about the safety of reused water. Henry Ongerth, then chief of the state's Sanitary Health section, said to a reporter in 1977, "Sewage is an infectious waste that has to be treated properly to protect the health of the people. . . . Health considerations—disease transmission and control—are a limiting factor [in water reuse]" (Harris, 1977).

In contrast to Ongerth's perspective, engineers working for water utilities called for complete water reuse. They claimed that technologies to purify sewage to drinking-water standards already existed. While this claim was technically true, drinking-water standards assumed that sources were relatively pristine—not city sewers. At the Second National Conference on Complete Water Reuse in 1975, chairman Lawrence Cecil declared, "The technology [for complete water reuse] is here. All we have to do is do it" (Anderson, 1975).

Since the advent of membrane technologies, no research had shown people getting acutely ill from reclaimed water (Pryor, 1971). A 1977 study by the Los Angeles Sanitation District demonstrated that many of the common water-reuse technologies could remove 99.999 percent of the viruses from wastewater (*Pomona Virus Study*, 1977). Reverse osmosis, though originally designed to remove salts, was also found to remove the vast majority of dissolved solids, color, pesticides, nutrients, and pathogens from water (Asano et al., 2007). In Southern California, scientists found reclaimed water to be cleaner, on the basis of existing measurement techniques, than the imported water from the Colorado River on which Southern California cities had typically relied (Lee, 1965).

Concerns about the health effects of reclaimed water use were pushed aside as California plunged headlong into a severe drought in the mid-1970s. Using membrane technologies to reuse wastewater continued to gain steam as California cities pursued growth in their semi-arid region.

By 1976, the State Water Resources Control Board proposed an amendment to the state water code stipulating that recycled water must be used if available. The new code, reprinted in the *Los Angeles Times,* stated that "failure to reclaim water or use reclaimed water could constitute a waste or unreasonable use of water" (Dendy, 1976). By 1977, over 200 different sites in California, including golf courses, power plants, and municipal buildings, used reclaimed water (Harris, 1977).

Dr. Daniel Okun, an environmental engineering professor at the University of North Carolina, Chapel Hill, continued to urge caution throughout the 1980s. He acknowledged that state-of-the-art treatment technologies for water reuse could reliably remove most pathogens and prevent acute infectious disease if the treatment systems worked properly. But he wasn't convinced that existing technologies could protect the public from chronic diseases like cancer from long-term exposure to the traces of chemicals in reclaimed water.

In Okun's estimation, the unknown health risks posed by under-studied chemicals or by newly minted synthetic chemicals were grave enough that recycled water was best reserved for non-potable purposes, like flushing toilets, watering lawns, and washing cars. In his 1980 address to the Environmental Protection Agency at their symposium on protocol development for potable reuse, he said, "It may very well be that, just as with radiation and asbestos, many decades will pass before the full impact of these organic chemicals . . . is understood" (Okun, 1980).

Studies of the health effects of trace chemicals in recycled water were nearly impossible, because measurement tools were not sensitive enough to detect them. Researchers from Stanford University noted the "great difficulty of detecting analytically significant differences in the removal of trace organic materials [in Water Factory 21], which is attributed to . . . the general lack of sufficient analytical precision" (McCarty et al., 1979). What they could measure, however, met current drinking water standards.

Ongerth, then chief of the Bureau of Sanitary Engineering of the State Health Department, echoed Okun's concerns: "Studies show that the ability to control most synthetic organic compounds to current limits of detectability is good. It is recognized, however, that the majority of organic compounds in advanced wastewater treatment effluents are unidentified and of generally unknown significance" (Ongerth and Ongerth, 1982).

Instead of putting recycled water back into the drinking water supply, Okun advocated for new pipes to carry recycled (nonpotable) water separate from drinking water. These dual distribution systems would allow for year-round water reuse for air conditioning, firefighting, and industrial cooling with minimal health risk (Okun, 1997). The downside of dual distribution is the expense of laying thousands of miles of new pipes. Costs for installing dual-distribution systems in Northern California range from $600,000 to $1.9 million (2010 dollars) per kilometer of pipe. This price tag constitutes a major barrier to increased water recycling (Bischel et al., 2012). In some places, adding new pipes to the already-crowded infrastructure below the street is not physically feasible.

And even dual-distribution systems for reclaimed water are not risk-free. Studies of several such systems in the United States and Australia have documented unintentional cross-connections between the pipes for drinking water and for nonpotable reclaimed water, sometimes occurring for more than a year before they were noticed. In each of these cases, multiple households were affected, and people reported an increase in diarrheal illness and other acute infectious disease (National Research Council, 2012).

Water Reuse, Expanded

By the mid-1970s, water reuse projects occurred across the state, spurred by suburban expansion's competition with agriculture for water. In the agricultural Salinas Valley, extensive water withdrawals depleted groundwater supplies. Seawater intruded into coastal aquifers at a rate of nearly 150 meters (500 feet) per year (Crook and Jaques 2005), which made the groundwater suitable for irrigating only the most salt-tolerant crops, like artichokes. A water reuse program could provide the necessary low-salt water for growing fruits and vegetables. As a result, the Monterey Regional Water Pollution Control Agency built a water reclamation facility that distributed reclaimed water to farmers for irrigation (Crook and Jaques, 2005).

Concerns about the safety of using recycled water on agricultural crops, many of which would be consumed raw, prompted a seven-year study to test the safety of this practice. Federal, state, and local funds provided the $7.2 million necessary to undertake a comprehensive research program, called the Monterey Wastewater Reclamation Study for Agriculture (Asano, 1998).

The results of the study, which were released in 1987, indicated that reclaimed water was "safe and acceptable" for crop quality, crop growth, crop marketability, soil quality, and groundwater quality (Sheikh et al., 1990). The results of the study in the Salinas Valley gave the green light for increased reuse of water in irrigation of food crops across the state.

The media portrayed water reuse as the "green" thing to do (Los Angeles Times, 1970b). The new term *water recycling* for the practice, which had previous been referred to as *water reuse* or *water reclamation*, helped solidify it as part of a solution to the environmental crisis. The California Water Recycling Act, signed into law in 1991, touted water reuse as "a cost-effective, reliable method of helping to meet California's water supply needs." The act also clarified the potential environmental benefits of water reuse in California, including "a reduced demand for water in the Sacramento-San Joaquin Delta which is otherwise needed to maintain water quality" (*Water Recycling Act of 1991*, 1991). It set goals of reusing 863 million cubic meters (700,000 acre-feet) per year of water in the year 2000 and 1.2 billion cubic meters (a million acre-feet) per year by 2010, though neither of these goals were met (see Figure 1).

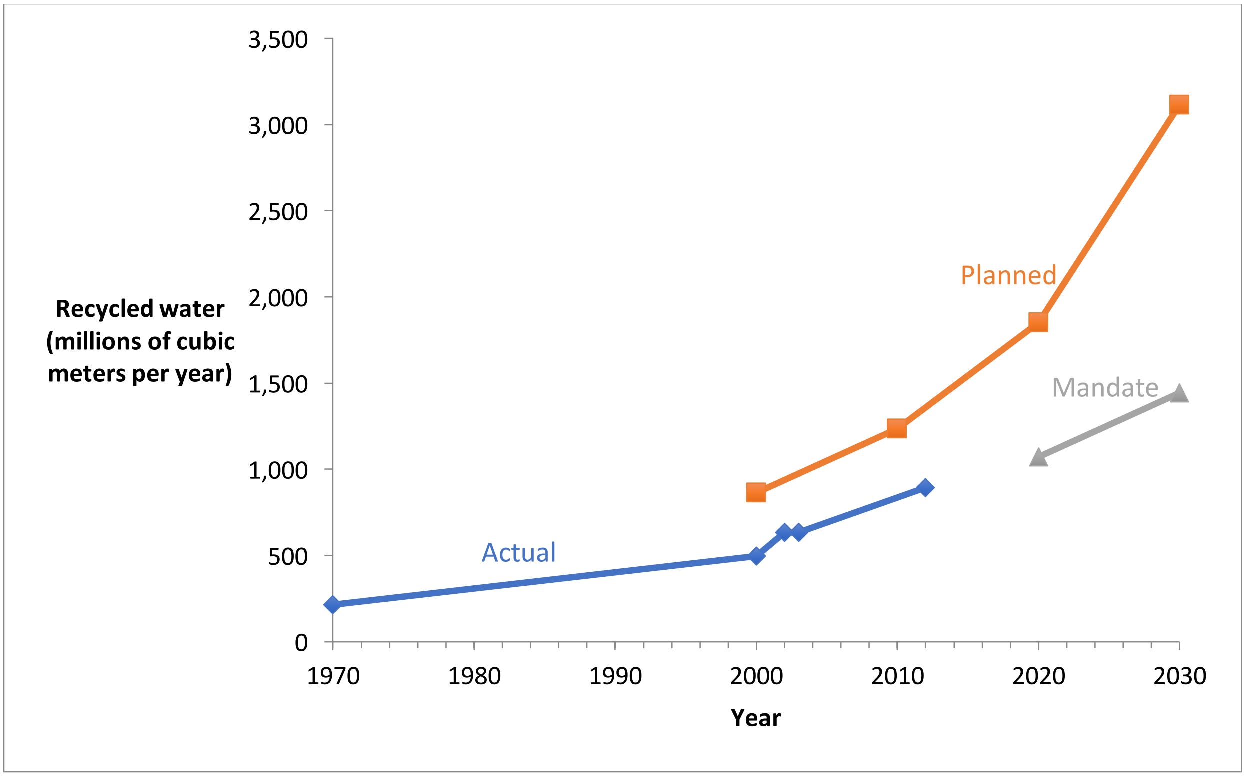

Figure 1. California water reuse, goals, and mandates. Data from (California Department of Water Resources, 2003; California State Water Resources Control Board, 2013, 2009b, 2009a; National Research Council, 2012)

Given California's growing interest in water recycling, several professional organizations developed in the early 1990s to share information, fund research, and lobby the government for regulations amenable to water reuse. The National Water Research Institute, WateReuse Association, and WateReuse Research Foundation funded research, held professional conferences, and created materials for educational outreach (WateReuse Association, 2013). As the need arose for more information pertaining to water reuse, from the chemistry of treatment processes to the marketing of new systems, these professional organizations supported water utilities as they moved forward with water reuse projects.

At West Basin Water District, just north of Orange County, water engineers pioneered the concept of "tailored water," which involves treating wastewater to different standards depending on the end use. In 1995, West Basin's facility opened and began providing water for groundwater augmentation, for landscape irrigation, and for industrial cooling systems (West Basin Municipal Water District, 2018). Utilities across the state looked to West Basin and Orange County as examples of successful potable water reuse projects.

In 1998, the National Research Council, an independent body of preeminent research scientists, issued a new report on potable water reuse that challenged the "out of sight, out of mind" mentality of sewage management. The report noted that *unintentional* potable reuse of wastewater was common around the nation. It cited over twenty-four drinking-water facilities drawing from rivers consisting of over 50 percent wastewater at some times of year, and implied that potable water reuse would continue in the United States whether or not it was planned

(National Research Council, 1998). The media noticed that over 200 sewage treatment plants drained into the Colorado River, from which southern California imports much of its drinking water (Cannon, 1997). Despite the generally supportive content of the report with respect to planned water reuse, the report's executive summary stated that potable water reuse should be considered an "option of last resort," given risks from chemicals and waterborne pathogens (National Research Council, 1998).

Not everyone in California was on board with the notion of water reuse, especially if recycled water was slated to become part of the drinking-water supply. In the late 90s, just after the National Research Council report came out, planned potable water reuse projects in San Diego, Dublin-Pleasanton, and the San Gabriel Valley ground to a halt. A combination of factors likely influenced public opposition to these projects, including city politics, critical media coverage (which labeled the projects "toilet-to-tap"), lack of trust in government agencies, and lack of public outreach on the part of the utilities (Harris-Lovett et al., 2015; Sedlak, 2014). Some residents said reusing treated sewage for potable purposes was disgusting, a phenomenon social scientists dubbed the "yuck factor" (Hartley, 2006). In 2002 in Redwood City, a suburb of San Francisco, a small group of residents even opposed a nonpotable water reuse plan to direct reclaimed water through a separate distribution system. They were concerned about children ingesting the water from sprinklers at parks and schools (City of Redwood City, 2013).

Residents of regions that did accept increased water recycling for potable purposes, like Orange County and West Basin, had long seen water reuse as a way to curb the problem of saltwater intrusion into their groundwater. Although engineers working for the utilities knew that groundwater recharge effectively meant augmenting potable water supplies underground with treated wastewater, the utilities' public-outreach materials emphasized the saltwater-intrusion barrier over the drinking-water-augmentation aspect of the project (Boettner, 1972). Furthermore, utilities in these regions spent decades building trust between citizens and water utilities through education campaigns and research programs to address health concerns (Po et al., 2003).

In general, reclaiming water for nonpotable uses and distributing it through separate pipes didn't attract as much controversy as projects that slated reclaimed water for potable use. To encourage more water recycling, Irvine Ranch Water District invested in a new set of pipes to bring recycled water to their customers.

Though a dual-distribution system worked well for the city of Irvine, other cities found new pipes for reclaimed water to be too expensive. In San Jose, California, in the late 1990s, the water utility wanted to distribute nonpotable water to their customers for irrigation but they were stymied by the cost of constructing pipes to the residents in their 780-square-kilometer (300-square-mile) service area (Sedlak, 2014).

California at a Crossroads

Orange County's indirect potable reuse project went smoothly until the year 2000, when a potent carcinogen, N-nitrosodimethylamine (NDMA), was detected in the groundwater (California State Water Resources Control Board, 2011). To the water utility's dismay, it seemed that a significant fraction of the chemical was actually being produced during the advanced wastewater treatment process (Mitch and Sedlak, 2002). The utility could detect as little as onebillionth of a gram of NDMA per liter in their water, and they knew that even this tiny amount of the substance increased their customers' cancer risk (Mitch et al., 2003). After consultation with the state health department, the water district decommissioned some of the drinking-water wells that were close to the water recycling plant (California State Water Resources Control Board, 2011).

The Orange County Water District responded to this problem by adding ultraviolet light with hydrogen peroxide to their treatment process, a technology that was previously used to treat groundwater at hazardous-waste sites (Huang et al., 1993). This technology would destroy the NDMA produced at the water reuse facility before the reclaimed water was introduced into the aquifer. It would also treat some other chemicals, like 1,4-dioxane, a common industrial solvent, which slips through reverse-osmosis membranes (Bellona et al., 2004).

Despite this technological mishap, the public's confidence in Orange County's drinking water remained strong, thanks in part to the water utility's proactive response to the detection of NDMA and its sophisticated media communications strategy (Harris-Lovett et al., 2015). In 2008, Orange County Water District expanded the facility to produce 265,000 cubic meters (215 acre-feet) of reclaimed water per day, and renamed it the Groundwater Replenishment System (Markus and Deshmukh, 2010) . Three and a half decades of operating experience had convinced Orange County residents that they would not get sick from drinking their tap water, which was part recycled water. The utility's outreach materials began to openly tout their project as "the world's largest advanced water purification system for potable reuse" (Orange County Water District, 2013b).

Today, many of California's water engineers think increased water recycling will be critical to meeting the demand for water in the state. California's population is growing by over 300,000 people per year (California Department of Finance, 2018), stressing existing water supplies (CDM Smith Consulting, 2015). The state's water supply is likely to diminish in the coming decades, because climate change is predicted to cause more precipitation to fall as rain rather than as snow. Scientists project a 25-percent loss in the state's average snowpack by 2050 (Andrew, 2015). Considering that over 20 million Californians rely on snowmelt for part of their water supply, these changes could cause severe shortages if other sources of water are not developed (Kiparsky and Gleick, 2003).

In response to the challenges of climate change and population growth, the California Water Board's current policy is to increase recycled water use in the state in the coming decades. The policy includes the goal to substitute "as much recycled water for potable water as possible by 2030." At a minimum, the Water Board's policy mandates that California use an additional 247 million cubic meters per year of recycled water by 2020 (over 2013 levels), and 370 million more by 2030 (California State Water Resources Control Board, 2013). The WateReuse Association and the National Water Research Institute advocate increased potable water reuse (WateReuse Association, 2013), because the technology to treat sewage to drinking-water standards exists and has been tested for decades by water utilities like the Orange County Water District and the West Basin project.

In 2009, the WateReuse Association announced its Direct Potable Reuse Initiative, which aimed to identify and eliminate any barriers to direct potable water reuse in California (Smith, 2010). They raised over $6 million in three years from water utilities and engineering firms to support lobbying and research efforts (Smith, 2013). As a result, the California state legislature passed a bill requiring the Department of Public Health to develop regulatory criteria for groundwater recharge with treated wastewater by December 2013, to develop rules for augmenting surface water reservoirs with treated wastewater by 2016, and to assess the feasibility of implementing a policy that sets criteria for direct potable reuse—that is, sending highly treated wastewater directly into a drinking-water treatment plant—by 2016 (Pavley, 2010).

In parallel with these efforts, the Water Board adopted the first monitoring standards for chemical contaminants in recycled-water projects in January 2013. The monitoring standards addressed constituents of emerging concern (CECs—e.g. pharmaceutical compounds, personal care products, and hormones), a group of compounds that had raised concerns among regulators and community members when prior potable water reuse projects had been proposed. The Water Board acknowledged the need for more research on the potential presence of these substances in the drinking-water supply because many have unknown health effects. The policy read, "The state of knowledge regarding CECs is incomplete. There needs to be additional research and development of analytical methods and surrogates to determine potential environmental and public health impacts" (California State Water Resources Control Board, 2013).

The new legislation will improve the state of knowledge of the presence of chemical contaminants, but it does not guarantee that chemical contaminants will never be detected in recycled water. According to the new regulation, potable water reuse utilities in California must test twice a year for a suite of regulated drinking-water contaminants and eight chemicals that are known to be present in sewage but are not included in state or federal drinking-water standards, including caffeine, DEET (a mosquito repellent), and triclosan (an antimicrobial). The eight chemicals were selected to provide an indication of the treatment plant's ability to remove chemicals commonly present in wastewater, not comprehensive information about all chemicals that could pose health risks. There are no repercussions apart from continued monitoring requirements if the concentration of the chemical detected in recycled water is less than 100 times the "monitoring trigger level," which is a health-based screening level developed by a scientific advisory panel (California State Water Resources Control Board, 2013). Although no chemical contaminants have been detected in recycled water at concentrations that pose potential health risks since the Orange County Water District detected NDMA in 2000, it is possible that some future discovery could reopen the discussions about health risks associated with chemical contaminants in recycled water.

California's Twenty-First-Century Water

In a system where wastewater is treated and then returned to the water supply, sewage is no longer flushed away and forgotten. Instead, water sent down the drain is a resource that can enable Californians to meet their own needs without compromising the needs of future generations (by overdrawing groundwater supplies) or the needs of other species (that rely on having water in streams).

Going forward, potable water reuse may require California to expand its notions of water stewardship. Regulations for watershed protection, for example, may need to be extended to include city sewers. To avoid future surprises regarding chemical contaminants in recycled water, policymakers may need to focus on preventing toxic substances from going down the drain, especially those chemicals that are difficult to remove in advanced wastewater treatment plants. In an era of water reuse, "out of sight, out of mind" can no longer be a guiding philosophy for waste disposal.

A more appropriate philosophy for Californians' relationship with water and waste might be "We're all in this together." In this framework, Californians acknowledge that whatever enters the sewer will need to be removed before the water returns to the drinking-water supply.

Though water reuse is becoming increasingly important, it is not clear exactly what form it will take in California's future. Options for integrating centralized water reuse into California's cities include expanding nonpotable reuse through dual-piped distribution systems, augmenting groundwater supplies or surface reservoirs with highly treated wastewater, and piping recycled water directly into the drinking-water system. Though the state's current institutions and regulations lend themselves to the centralized solutions mentioned above, other options for recycling water exist. For example, decentralized wastewater treatment systems have strong public support in some communities (Woelfle-Erskine, 2015). In these systems, households reuse potable water on site for "cascading" uses, as in using water from the clothes washer to irrigate gardens or flush toilets. To facilitate expansion of these practices, research is needed to assess the possible health risks as well as to develop ways to reduce the current high costs of treatment.

In the future, Californians may decide to invest in dual-distribution systems for non-potable water reuse, to turn to potable reuse of wastewater effluent, or to invest in household-scale water reuse systems. These options are not mutually exclusive. Different cities are likely to develop their own portfolios of water reuse systems that are appropriate for their topography, community values, and existing urban form. Whatever paths the state chooses, water reuse in California will continue to expand. Done correctly, with measures to prevent difficult-to-remove contaminants from entering sewers and to continually monitor water quality, water recycling will be an important part of California's toolkit for meeting the water challenges of the twenty-first century.

Conclusion

Contextualizing California's current trends towards increased water recycling within its long history of wastewater reuse provides several insights. Sewage has long been seen as a resource by some Californians. The urge to recover nutrients and water in sewage comes not just from a recognition of the value of these resources and a desire not to waste them, but also from an exploration of possible options for sewage disposal. These motivations still exist today. In addition, the push-pull of mixed emotions about recycling sewage into useable water is not new: there have long been proponents and detractors of water reuse. Even as engineers and water managers recognize the potential for resource recovery from sewage, public health officials and others have cautioned about the risks of water reuse for irrigation and for drinking.

The following chapter analyzes case studies of California cities who have embraced and opposed potable water reuse in more recent times. This analysis allows for a richer understanding of the conditions which lead to adoption or rejection of the technology.

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Chapter II: Adoption of innovative water technology: The case of potable water reuse

Preface

Using sewage water for irrigation and fertilizer, as documented in the previous chapter, has a long history in California. Yet currently, reusing sewage for agricultural irrigation and fertilizer is not always practical because of the geographic distances between where most sewage is produced (cities) and where most agriculture takes place (rural areas). If the sewage from cities is to be recycled, finding uses for the water inside of city limits would be much more practical. Most American cities use drinking-quality water for all purposes (indoor use, cooking, and outdoor irrigation). This leaves some water managers and engineers wondering about the possibility of purifying sewage to the extent that it can be used for drinking water.

Worldwide, planned direct potable water reuse (deliberately purifying sewage for human consumption as drinking water and piping the recycled directly into the drinking water supply) has been employed in Namibia and Singapore. Many more countries worldwide, including parts of the United States, use purified sewage to recharge groundwater aquifers, which may contribute to drinking water supplies (Binnie and Kimber, 2008), a practice called indirect potable reuse.

Many water resource managers in the United States tout the potential of potable water reuse to provide a reliable, local source of drinking water in water-scarce regions (Cain, 2011; Daigger, 2009a; Leverenz et al., 2011; Schroeder et al., 2012). Despite data documenting the ability of advanced treatment technologies to treat municipal wastewater effluent to meet existing drinking water quality standards in the United States, many utilities face skepticism from the public about potable water reuse (Marks, 2006a).

Prior research on this topic has mainly focused on marketing strategies for garnering public acceptance of the process (Dishman et al., 1989; Nellor and Mark Millan, 2010; Ruetten, 2006). This study takes a broader perspective on the adoption of potable water reuse based on concepts of societal legitimacy, which is the generalized perception or assumption that a technology is desirable or appropriate within its social context (Suchman, 1995).

To assess why some potable reuse projects were successfully implemented in the United States while others confronted fierce public opposition, we performed a series of 20 expert interviews and reviewed in-depth case studies from potable reuse projects in California. Results show that a legitimated potable water reuse project in Orange County, California engaged in a portfolio of strategies that addressed three main dimensions of legitimacy, while other proposed projects that faced extensive public opposition relied on a smaller set of legitimation strategies that focused near-exclusively on the development of robust water treatment technology. Widespread legitimation of potable water reuse projects, including direct potable water reuse, may require the establishment of a portfolio of standards, procedures and possibly new institutions.

Excerpt from: 'Beyond User Acceptance: A Legitimacy Framework for Potable Water Reuse in California'. By Sasha Harris-Lovett, Christian Binz, David Sedlak, Michael Kiparsky, and Bernhard Truffer. Published in *Environmental Science & Technology* 49, no. 13 (2015): 7552-7561.

Introduction

Limited water resources and increasingly complex societal demands require water managers to develop innovative solutions to water challenges (Brown et al., 2009). However, changing practices in the water sector is notoriously difficult because the social and institutional contexts, including the rules, norms, and conventions that govern decision-making, often hinder diffusion of innovative technologies or new systems of governance (Kiparsky et al., 2013). Water recycling, and in particular recycling for potable water reuse, illustrates the ways in which social and institutional concerns can affect technology adoption (Binz et al., 2016; Bischel et al., 2012). Potable water reuse is defined here as the practice of intentionally returning highly treated municipal wastewater to the public water supply (National Research Council, 2012, 1998).

Some water resource managers and consulting engineers tout the potential of potable water reuse to provide a local, reliable water supply in water-scarce regions (Cain, 2011; Daigger, 2009a; Leverenz et al., 2011; Schroeder et al., 2012). Potable water reuse can be less costly than alternatives, such as desalination or importing additional water, and can meet or exceed existing water quality standards (National Research Council, 2012). However, these factors are not always sufficient for obtaining public support (Hurlimann and Dolnicar, 2010). Proponents of potable water reuse have mainly framed this issue as one of a lack of public acceptance (Macpherson and Slovic, 2011; Nellor and Mark Millan, 2010; Wade Miller, 2006), which can be defined as the public's passive acquiescence to the expert knowledge of water managers and engineers (Stenekes et al., 2006).

Previous research has addressed the lack of public acceptance of potable water reuse by focusing on the benefits of selecting positive terminology to describe the practice, development of communication strategies, characterizing populations that accept potable water reuse, and development of public education campaigns (Dolnicar and Hurlimann, 2011; Dolničar and Saunders, 2006; Dolnicar and Schäfer, 2009; Haddad et al., 2009; Hurlimann et al., 2009; Hurlimann and Dolnicar, 2010; Khan and Gerrard, 2006; Nellor and Mark Millan, 2010). This research has yielded an improved understanding of the language and strategies for marketing potable water reuse. Nonetheless, in several high-profile cases, technologically-sound potable reuse projects have floundered when actors outside of the control of the project's advocates used terminology that was unfavorable(Hurlimann and Dolnicar, 2010).

Research based on public acceptance does not incorporate the full complexity of the issues surrounding new technology adoption (Nancarrow et al., 2008), and may overestimate the ability of project proponents to affect community support by targeting individual perceptions of water reuse (Marks, 2006b). Previous studies have shown that water authorities and developers tend to approach public acceptance in terms of persuading the public to accept water reuse by means of provision of more technical information. This occurs despite evidence that members of the public are interested in a broad range of information about the project including social and environmental costs and benefits, institutional structure, risk comparisons to other activities, regulatory systems, and analysis of alternative solutions (Russell et al., 2008). Previous research suggests a public acceptance paradigm for understanding perceptions of potable water reuse is too narrowly framed, but stops short of proposing an empirically-grounded, comprehensive framework (Bell and Aitken, 2008; Stenekes et al., 2006). Other scholars place a public acceptance mode of expert outreach for water management, in which experts choose what they perceive as the most desirable solution and convince the community of its relevance and importance, as a hallmark of an old paradigm of unsustainable water systems that is no longer useful in the twenty-first century (Pinkham, 1999).

A more robust framework for engaging the public in issues of potable water reuse based on societal legitimacy (Markard et al., 2016) may address some of the shortcomings in public acceptance research. Legitimacy - a key concept in sociology and innovation studies - acknowledges that creating widespread trust in an innovation depends on strategies that not only target individual psychology, but that also address aggregate sectorial and societal rules, norms and conventions (Geels and Verhees, 2011; Markard et al., 2016; Suchman, 1995). Sociology scholars define legitimacy as “a generalized perception or assumption that the actions of an entity are desirable, proper, or appropriate within some socially constructed system of norms, values, beliefs, and definitions”(Johnson et al., 2006). In its sociological definition, legitimacy can be assessed by the “taken-for-grantedness” of a particular technology, implementing organization, or process (Suchman, 1995).

Establishing legitimacy involves the process of embedding a new technology in the shared social belief systems, moral standards and cultural conventions of a given group (Lawrence et al., 2011; Scott, 2008; Suchman, 1995), through a set of strategies that go beyond traditional public relations or educational outreach. Establishment of legitimacy may require the institutions responsible for the technology, also known as the implementing organizations, to undergo fundamental changes. Some of these changes may challenge the traditional authority of water providers, as they may require sharing power through collaborative decision-making and consideration of heterogeneous public values. Water utilities cannot build legitimacy for potable water reuse based on hollow promises. Superficial interventions undertaken to approximate the legitimacy framework presented in this paper and manipulate public perceptions of legitimacy will likely not create stable legitimacy, but rather foster mistrust in the management’s true intentions. Because legitimation is a societal process, it is most stable when it is established in public discourse.

It is important to note that establishment of legitimacy for a particular technology, like potable reuse, may not be possible in places where the technology does not mesh with the values and social beliefs of a given community. A deeper understanding of legitimacy and the legitimation process can, however, help water engineers find solutions for water supply and wastewater disposal that are most appropriate for a given community. It can also help prevent investment in technological infrastructure that will encounter stark public opposition.

The case of potable water reuse in California illustrates the process of legitimation, which has relevance to a wide range of emerging environmental technologies. California has a long history of potable reuse (Harris-Lovett and Sedlak, 2015), from which we draw and examine examples of both successful and unsuccessful attempts to legitimize the practice. We extend the sociological definitions of legitimacy to include innovative technologies and the institutional systems surrounding them (Markard et al., 2016) and define a comprehensive analytical framework for the legitimation process of potable water reuse and innovations in general (see Table 1). The present paper complements another publication, which focuses on a detailed process account of technology legitimation in an innovation system context (Binz et al., 2016).

Analytical Framework for Legitimacy

Legitimacy is a multi-dimensional phenomenon that can be differentiated into several key types. Suchman's comprehensive framework (1995) divides legitimacy into three generic types: pragmatic, moral and cognitive (Suchman, 1995), which we term Type 1, Type 2, and Type 3 legitimacy, respectively. Each of these types can be further grouped into several distinct dimensions. Table 1 illustrates our application of legitimacy concepts to innovative technologies in general and potable reuse in particular.

Pragmatic Legitimacy (Type 1 Legitimacy) is based on the end user's self-interested calculations about the direct benefits that can be derived from the innovation (Suchman, 1995). Its first component, *exchange legitimacy*, is derived from the end user's perceived gain of a good or service from the innovation (e.g., support for a water reuse project based on the notion that adoption of the technology may provide a means for maintaining golf courses without restrictions on water use). The second component is *influence legitimacy,* which occurs when end users perceive an implementing organization to be responding directly to their personal interests (Suchman, 1995) (e.g., support of a potable reuse project arising from the participation of community members on the project's advisory board). The third component, *dispositional legitimacy*, occurs when an innovation is managed by an established, trustworthy entity (e.g., faith in a water utility with a professional reputation to responsibly manage a potable reuse project).

Moral Legitimacy (Type 2 Legitimacy) is established when an innovation corresponds to societal values and broader societal welfare (Suchman, 1995). The first component, *consequential legitimacy,* occurs when proponents of an innovation demonstrate that it has a strong record of providing beneficial outcomes for society (e.g., support for potable water reuse systems that have operated for a long time without problems). The second component, *procedural legitimacy,* is defined by the quality and validity of the procedures and protocols used to implement the innovation (e.g., trust in potable water reuse systems based on end user's awareness of consistent, comprehensive water quality monitoring). The third dimension, *structural legitimacy,* is related to the physical attributes of the innovation that enhance its safety and reliability (e.g., endorsement of a reuse project based on the presence of a state-of-the-art water quality lab). The final component of Type 2 legitimacy, *personal legitimacy,* is related to the perceived trustworthiness and integrity of the implementing organization's leadership.

Cognitive Legitimacy (Type 3 Legitimacy), is not based on conscious evaluation, but rather on compliance with taken-for-granted routines and cultural beliefs ("the way we do things") (Scott, 2008; Suchman, 1995). It includes two main components: The first, *comprehensibility*, occurs if an innovation fits into prevailing cultural assumptions and daily-life habits of end users (e.g., support for bottled recycled water if it looks and tastes like established bottled water brands). The second component, *taken-for-grantedness*, occurs when the innovation meshes with end users' deep cognitive frames that are not consciously questioned (e.g., people familiar with solid waste recycling may think of potable water reuse as another desirable form of recycling).

Table 1: Definitions of key dimensions of legitimacy and corresponding strategies in potable reuse

Legitimacy types	Dimension	Definition	Legitimation strategies in potable water reuse
Type 1. Pragmatic Evaluation based on self-interest	1.1 Exchange	Support for an innovation based on its perceived value to the end user	Public outreach campaigns, explaining the innovation's benefits to different users
	1.2 Influence	Support of an implementing organization because it shares decision-making power with end users	User involvement in planning and management, focus groups and surveys, user representatives on decision-making bodies
	1.3 Dispositional	Support for an implementing organization based on a belief that the organization is acting in the end user's best interest; has 'good character'	Transparent information policies, cooperation with external evaluators and regulators, developing a 'quality brand' for the proponent utility
Type 2 Moral Evaluation based on norms / societal values	2.1 Consequential	Support based on evaluation of the implementing organization's accomplishments	Publicizing data indicating consistently high water quality, building a success story about the innovation
	2.2 Procedural	Support based on an evaluation of the implementing organization's specific procedures	Adopting strict quality control and monitoring procedures, standardized emergency intervention plans, and professional training for operators
	2.3 Structural	Support based on an evaluation of the implementing organization's physical characteristics	Having advanced water treatment technology, water quality management department, 24/7 monitoring technology, and emergency shut-off valves
	2.4 Personal	Support based on an evaluation of an implementing manager's charisma	Water utility managers talking directly to the end users
Type 3 Cognitive Evaluation based on deeply held customs & beliefs	3.1 Comprehensibility	Support because an innovation meshes with the end user's daily life experiences and cognitive frames	Organizing water tastings, providing bottled recycled water, developing comprehensible vocabulary
	3.2 Taken-for-grantedness	Support based on seeming inevitability, in which alternatives are "unthinkable"	Relating potable reuse to other taken-for-granted activities (e.g., recycling)

Source: Adapted from Suchman (1995)

An innovation is considered wholly legitimized when a majority of the population takes it for granted, and any opponents are no longer able to achieve a serious response from community members. Nonetheless, individual projects may lose credibility even after legitimacy is established for the sector if they do not continue to employ legitimation strategies for their specific project (Suchman, 1995).

Achieving legitimacy for new technologies requires development of all three types of legitimacy: if only Type 1 legitimacy is established, as is often done in acceptance-based public outreach campaigns, the project might be accepted temporarily, but legitimacy will likely erode when end users start questioning whether or not the Type 2-related procedures and institutional structures that support the innovation are legitimate. Similarly, if only Type 2 legitimacy is emphasized, the public may trust that the innovation is managed with competency, but end users may question the usefulness of the innovation to the community. Complete legitimacy thus requires a comprehensive portfolio of legitimation strategies that address each of these dimensions.

We hypothesized that the more complete the legitimation portfolio of a utility involved in potable water reuse projects, the more likely the project will be to avoid organized public opposition or rejection by the community. We assessed the legitimation portfolio of California's potable water reuse projects—and identified gaps therein—to provide insight into the ways in which communities' support or reject technological innovation in the water sector.

Methods

To address the legitimacy of potable water reuse we examined a case study of legitimated potable reuse, and compared it with cases of several other projects in which California water utilities failed to implement potable water reuse.

The Orange County Water District (OCWD), in Orange County, California, was chosen as a case of legitimate potable water reuse. The water district has practiced potable water reuse since 1976, when it began to inject highly treated municipal wastewater into the region's groundwater aquifer (Allen and Elser, 1979; Argo, 1985; Harris-Lovett and Sedlak, 2015; Orange County Water District, 2013). This system was expanded from 15 MGD (57,000 m^3/day) to 70 MGD (265,000 m^3/day) in 2008. The present advanced treatment system configuration, called the Groundwater Replenishment System (GWRS), sources municipal effluent from a nearby wastewater treatment plant, then uses microfiltration, reverse osmosis and an advanced oxidation process to further treat the water. The treated water is then pumped into recharge basins and injection wells, where it mixes with local groundwater (Markus and Deshmukh, 2010). The GWRS contributes to drinking water supplies for more than 2 million people (Markus and Deshmukh, 2010). There has been no organized public opposition to GWRS (Interview 19). The GWRS is considered a best practice in the potable water reuse community and serves as the basis for the technological design of several other potable water reuse projects (Binz et al., 2016).

Other cases considered include the Dublin-San Ramon Services District's proposed potable reuse project, which failed due to public opposition after the facility was built; San Diego's water recycling project, which the public vehemently opposed in the 1990's; and the Santa Clara Valley Water District's proposed potable water reuse project.

We conducted in-depth semi-structured interviews with 20 key, expert stakeholders who were deeply involved with implementing potable water reuse in California (as well as nationally and globally). Interviewees included managers and executives of water and wastewater utilities, public relations consultants, regulators, academics, and engineering consultants. We used respondent-driven sampling techniques (Heckathorn, 1997), including snowball sampling (Atkinson and Flint, 2001), to identify and interview the small group of people who have been most influential in the development of potable water reuse systems in California. We designed interview questions to elicit responses about the legitimation strategies applied in single projects as well as in the wider potable water reuse community (see Supporting Information, section 1). We transcribed interviews, then codified them using MaxQDA qualitative data analysis software and analyzed them for mentions or allusions to dimensions of legitimacy. We triangulated interview data with relevant reports and white papers, utility public outreach information, scientific publications, and newspaper articles (see Supporting Information, section 2). We grounded the case studies in historical research regarding local experiences with and attitudes towards water use and reuse. We used perspectives presented in local news articles and editorials as well as the presence or absence of organized public opposition groups as proxy measures for user opinion (Ching and Yu, 2010). Both are standard proxy measures for user legitimacy in institutional sociology literature (see e.g. Geels and Verhees 2011). Cases like San Diego, where several opposition groups and intense, controversial newspaper coverage emerged, indicate limited societal legitimacy. Cases like Orange County that never triggered organized public opposition and mostly positive newspaper coverage, would in turn indicate stable end-user legitimacy. These measures were used because many of the cases occurred in the past, so it was not possible to interview users directly.

Results

Orange County Water District's Potable Water Reuse Program

Since it began its first potable water reuse program in 1976, OCWD has employed a diverse portfolio of legitimation strategies. Some of these strategies were deliberate attempts to foster trust in potable reuse, while others emerged during the development of their potable water reuse system. Each dimension of the project's legitimation portfolio is summarized below and in Table 2.

Type 1. Pragmatic Legitimacy

OCWD's management team invested considerable time and resources into explaining how potable water reuse was in the public's best interest (Interview 17), which resulted in the creation of *exchange legitimacy* for the GWRS. The utility targeted community and business group leaders within their 2.4 million customer service area and informed them about the benefits of the potable water reuse system in simple language (Interview 4) with more than 1,200 presentations (Interview 19) that were translated in Spanish, Vietnamese, and Chinese (Interview 17). The talks were targeted to the interests of their specific audience, and emphasized the idea that the technology would guarantee a safe, reliable water supply into the future, which was a key interest of all inhabitants of Orange County (Interview 19).

"We would just go out and talk about what the water district does, what the need was for future needs. And how this project, the Groundwater Replenishment System, meets those needs." (Interview 17)

OCWD established *influence legitimacy* by soliciting and accepting feedback from the public through citizen's advisory committees, focus groups and in discussions with community leaders (Interview 16). OCWD relied on the citizen's advisory committees to inform certain aspects of the project, including improvement of the project's outreach materials:

"We had a Citizens' Advisory Group, made up of community leaders… So all of these different groups were working together to make sure that needs were met, that we were on point, that we were spending money wisely, and that we were meeting the needs of the community." (Interview 17)

While OCWD carefully planned the above legitimation strategies, others emerged as a result of the district's responses to technical challenges. In particular, in the year 2000, OCWD detected N-Nitrosodimethylamine (NDMA), a potent carcinogen, in their treated water(Mitch et al., 2003), and realized that some of this compound had actually been created in their water treatment process. Though this situation could have threatened the legitimacy of OCWD's potable reuse efforts (Interview 6), the response of the utility to the incident ultimately enhanced its dispositional legitimacy: Instead of hiding the problem, the management decided to publicly disclose it, and proved to both regulators and the public that they were competent in dealing effectively with the contamination (Interview 5).

"We were actually causing the problem in the water we were injecting. Some of us on the water quality end of the business wanted to get answers to the problem. See what can we do to fix it, first. [The public relations specialist] said no, that we needed to talk to the public, we needed to actually call the media in and do press briefings… His instincts were right. If the media and the public perceive you as having nothing to hide, if you've got something that goes wrong, you're going to tell them about it. […] I think that really earned us a lot of trust." (Interview 19)

In a press conference, OCWD representatives explained what had happened and how they were working to address the problem. They also set the NDMA exposure in context by explaining how people are routinely exposed to the compound in food and beverages (Interview 17).

As a result of the utility's transparent communication strategy, the media described the story as a minor incident that was in the process of being fixed, rather than as a severe threat to public health. In describing the NDMA problem, the Los Angeles Times reported:

"NDMA […] is a ubiquitous chemical that occurs naturally, but also is a byproduct of chlorinating water supplies to disinfect them. It is found in rocket fuel, pesticides, lubricants, cosmetics and all kinds of food, from bacon to beer and at far higher levels than turned up in local water tests... There is believed to be no threat to public health, district officials said."(Mehta, 2000)

Overall, OCWD's Type 1 legitimation activities addressed all relevant sub-dimensions. They successfully educated people about the need for potable reuse and convinced them potable water reuse would meet their needs more effectively than the alternatives; they engaged community members in improving outreach by addressing public concerns about potable reuse; and they proved that the OCWD was transparent and proactively engaged in serving the public interest (Interview 2).

Type 2. Moral Legitimacy

Many of OCWD's activities promoted Type 2 legitimation by embedding potable water reuse into wider moral belief systems. First, OCWD used its long experience with potable water reuse (through injection of treated wastewater into the aquifer) and its reputation in the community to establish consequential legitimacy, or faith in the organization's capacity to responsibly conduct potable reuse (Interview 12). When the utility introduced plans to expand their potable reuse system in the late 1990s, they could show the public a three-decade-long track record of safe and reliable operations:

"[OCWD] already had that plant running, they were operating it, they were doing all the monitoring. They had developed a reputation. They developed the confidence of the community… Once they wanted to expand, they were expanding on a base of success and reputation." (Interview 20)

Regular testing for a suite of contaminants at OCWD also became an important element of creating procedural legitimacy. When confronted with a complex, new technology the public often forms opinions about it by asking whether the organization running it is applying the right procedures to guarantee safety (Suchman, 1995). OCWD was addressing this issue by establishing strict water quality testing procedures and monitoring for 335 chemicals, instead of just the 122 compounds required of them by the regulator ("Water Quality and Laboratory Operations," n.d.).

In addition, OCWD developed standard operating procedures for their water reuse system. They established protocols for routine operating conditions and in the event of an upset and explained these to end users in tours (Interview 1). In addition to providing clarity to the plant's operators, this further improved procedural legitimacy of the organization.

Third, OCWD consistently emphasized that it had the right physical infrastructure in place to guarantee safe operations (structural legitimacy). Other professionals were impressed with how the utility maintained cutting-edge technologies for water treatment and source control, employed more than 200 staff, operated 24/7 and built a state-of-the-art water quality laboratory directly on-site (Interviews 1, 2, 15). Interviews reveal the existence of a lab inside the utility was effective in signaling structural legitimacy to the general public (Interview 17).

OCWD's management staff also reinforced personal legitimacy by personally speaking to the public in outreach campaigns:

"It wasn't the consultants who did the speeches. It was staff or board members. We found that the people, the general public, gravitate much more to the personal touch, when it's someone actually affiliated with the project." (Interview 19)

In doing so, OCWD managers established themselves with members of the public as trustworthy and competent experts (Interview 16) who could handle the complex water reuse system.

Type 3. Cognitive Legitimacy

OCWD's worked to deliberately establish Type 3 legitimacy. OCWD's choice of name for their potable water reuse technology, the "Groundwater Replenishment System," made the public associate what the utility was doing with Orange County's half-century-long practice of augmenting groundwater with fresh water in order to prevent saltwater intrusion into the aquifer, rather than with a new, unfamiliar technology (Interview 12). The name "Groundwater Replenishment System" had positive cognates to protecting groundwater from contamination and ensuring a safe water supply, and was a familiar reference to end users, thus improving the comprehensibility of the project. West Basin Water District also adopted this strategy to enhance comprehensibility, calling the agency that injected recycled water back into the aquifer the "Water Replenishment District" (Interview 4).

Second, OCWD tried to mesh the idea of potable water reuse with frames (Lakoff, 2010) that were taken-for-granted by their constituents. Use of the term "water recycling" exemplified this effort; framing the GWRS as potable 'reuse' and water 'recycling' (Interview 4) allowed OCWD to enlist the support of environmentalists who were favorably disposed toward recycling in general:

"The first groups to be supportive were environmental groups. I think they saw recycling as just making good environmental ethical sense, so they were supportive early on." (Interview 19)

Table 2: Summary of OCWD's legitimacy portfolio for potable reuse

Legitimacy Type	Dimension	Strategies
Type 1: Pragmatic	1.1 Exchange	+ Targeted outreach and education campaigns
	1.2 Influence	+ Elicited feedback from community leaders
	1.3 Dispositional	+ Demonstrated the utility's trustworthiness
Type 2: Moral	2.1 Consequential	+ Consistent track record of high water quality
	2.2 Procedural	+ Emergency intervention and quality monitoring plans
	2.3 Structural	+ State-of-the-art technology, sophisticated laboratory
	2.4 Personal	+ Management personally involved in outreach work
Type 3: Cognitive	3.1 Comprehensibility	+ Serving visitors purified water from a tap
	3.2 Taken-for grantedness	+ Framing potable reuse as recycling, groundwater protection

(+ traits contributing to legitimacy portfolio, - traits detracting from legitimacy portfolio)

As a result of these comprehensive efforts, potable water reuse reached a level of legitimacy in Orange County that made it improbable that voices of opposition would gain traction within the community (Binz et al., 2016). Available evidence suggests that local media is not particularly interested in the OCWD's water reuse project anymore because it has become routine (Interviews 19, 20).

OCWD is one of a limited number of utilities that have successfully introduced potable water reuse. Other utilities that have achieved a similar level of legitimacy include the West Basin Municipal Water District and Inland Empire Utilities Agency (National Research Council, 2012). When managers of West Basin Municipal Water District began their potable water reuse project, they mimicked both OCWD's technology and outreach approach, which they institutionalized by hiring some of OCWD's experienced personnel (Interviews 4, 10).

Legitimation portfolio of other utilities in California's water reuse sector

Despite the legitimacy of the potable reuse projects in Orange County, West Basin, and the Inland Empire, public opposition has halted similar projects at the Upper San Gabriel Water District, the City of San Diego, Dublin-San Ramon Services District (DSRSD), and the City of Los Angeles. In response to these failed projects, an advocacy coalition of utilities, consulting engineering firms, academia and NGOs has emerged to work towards legitimizing potable water reuse in general (Binz et al., 2016; Ruetten, 2006, 2004) Internal networks like the WateReuse Association and the National Water Research Institute (Binz et al., 2016) increasingly coordinate legitimation strategies and recently began lobbying the state government to streamline the implementation of direct potable water reuse policies (i.e., potable water reuse without an intervening natural barrier like an aquifer or a lake) (Tchobanoglous et al., 2011). In the following section, we use the legitimacy framework to analyze the legitimation strategies that have been used by failed potable reuse projects as well as by the coalition of proponents of potable water reuse.

Type 1. Pragmatic Legitimacy

The cases of several proposed potable reuse projects that were halted by public opposition in the 1990s show that a lack of *exchange legitimacy* can spur public resistance to potable water reuse (Interviews 7, 20). An illustrative example is a potable reuse system in Dublin-San Ramon Services District (DSRSD) that was halted by public opposition. In retrospect, experts close to the project believed that DSRSD's board made a mistake by advertising their potable reuse project as a wastewater management strategy, rather than as an improvement in drinking water supply (Interviews 12, 20). The result was a lack of exchange legitimacy for water users—only wastewater managers, and not the general public, could see a direct benefit from the potable water reuse system.

In addition, what water managers touted as a benefit of the recycled water in the Dublin-San Ramon area—that it would enable economic growth and suburban development, an argument that seemed to have worked in Orange County—was not favorably received in the Northern California social context (Interview 20). Public opposition quickly emerged in the Dublin-San Ramon area as groups questioned whether there was an actual need to make the public 'drink wastewater'. A local newspaper, the Pleasanton Weekly, reported:

> *"DSRSD representatives said they need to have a way to dispose of treated wastewater if and when it exceeds the capacity of the LAVWMA pipeline. "We're not in love with injection," said DSRSD board director Georgean Vonheeder-Leopold, "It's just that it makes the most sense... and it's economical that way. We just don't want to put it in the creek or irrigate with it."* (Ericson, 2000)

Potable water reuse advocacy coalitions subsequently funded several research projects on ways to improve exchange legitimacy for potable reuse (Interview 7) (Ruetten, 2006). Research results suggested that framing planned potable reuse as an improvement over existing water supplies, many of which employ *de facto* reuse (i.e., a practice in which water from a municipal wastewater treatment plant discharges into a river or lake that is used as the drinking water source for a downstream community) (National Research Council, 2012) was an effective means of increasing exchange legitimacy and public support (Ruetten, 2004; WateReuse Research Foundation, 2012). In conjunction with the research projects, the WateReuse Association created an educational video, called "Downstream," to explain *de facto* water reuse and try to create exchange legitimacy for the broader potable water reuse sector (WateReuse Association, 2012; WateReuse Research Foundation, 2012).

Some water agencies have begun to integrate elements of *influence legitimacy* into outreach campaigns. Recent potable water reuse projects in West Basin, San Diego and Santa Clara employed focus groups to address public concerns (Interview 4). Despite these efforts, many water utilities only have limited public involvement in planning and decision-making. Water managers often lack a commitment to implementing suggestions raised by focus group participants (Interview 7), effectively negating their efforts to establish influence legitimacy for potable reuse projects.

"[Water utility managers] talk about public involvement. They don't really want involvement, because they know what they want to do, and they want to just go do it and want everybody to like it." (Interview 16)

Many water utilities also did not focus on *dispositional legitimacy* as part of their legitimation strategy. For example, opposition to Dublin-San Ramon Services District's proposed potable reuse project cited a lack of trust in the organization's integrity and the utility's "maverick" reputation, which stemmed from its perceived support of a controversial suburban expansion project (Interview 20). A passionate editorial in the local newspaper about the ballot measure to implement potable reuse further demonstrates this lack of trust in the utility:

"Why would we trust the stewardship of our most precious resource to a sewer company?…The proponents of this measure have intentionally tried to mislead the public into thinking this is a vote for recycling. Their slick propaganda campaign has been less than straightforward … Why would we trust them to be forthcoming if an accident or human error occurred that permanently contaminated our groundwater basin?"("Vote on Measure J: Pleasanton not ready for RO treatment," 2000)

To address the poor image of water and wastewater utilities like DSRSD, advocates for potable water reuse in Southern California began collaborating to improve water and wastewater agencies' reputation, and thereby their dispositional legitimacy, by creating a 'utility branding network' in 2007 ("Utility Branding Network homepage," 2008). The network's activities focused on competitive branding strategies at the regional potable water reuse sector-wide scale (Ruetten, 2008) in an attempt to show utilities how to avoid the type of resistance which DSRSD met. Building trust in a utility is a long-term process and it is difficult to assess whether the utility branding network has improved dispositional legitimacy for water and wastewater utilities in California.

Type 2. Moral Legitimacy

Several projects with long-term track records like Orange County and West Basin have shown that potable reuse systems can be operated to meet water quality regulations and provide benefits in terms of water supply and wastewater disposal to communities, resulting in *consequential legitimacy*. Proponents of water reuse often reference these examples. However, existing water reuse advocacy coalitions and many water and wastewater utilities in California did not emphasize other key dimensions of Type 2 legitimacy.

Procedural legitimacy is a case in point: Water utility managers and consultants have invested in research and development related to the operation of specific engineered treatment trains, but few resources have been devoted to developing sector-wide procedures to assure safe water reuse operations. Experts within the potable water reuse sector have identified the need for a number of sector-wide procedural standards (Hultquist, 2013), including regulatory oversight (Crook, 2010), operator training (Interview 1), source control (Interview 4), and emergency procedures (Interview 5). Currently, responsibility for developing these procedures falls on individual water utility managers on an ad-hoc basis (Interviews 6, 14). To address this apparent shortcoming, the WateReuse Foundation has recently initiated a project to develop training and certification schemes for utilities that run direct potable reuse plants.(*WateReuse Research Request for Proposals: Development of Operation and Maintenance Plan and Training and Certification Framework for Direct Potable Reuse (DPR) Systems*, 2014) The development and diffusion of such standards may improve procedural legitimacy for potable water reuse.

Structural legitimacy, in contrast, has recently become a strong current focus of the potable water reuse community. Experts in academia, engineering consulting groups and industry have been working to develop cutting-edge technologies to improve treatment processes, monitor systems online, or engineer buffers that extend response time in case of system failures (Drewes, Jorg, 2006; Ruetten, 2004; Serna, Marc et al., 2014; Tchobanoglous et al., 2011; Trussell, R. Rhodes, 2012; Wade Miller, 2006). Currently, no clear structural standards exist for potable reuse systems. Due to the lack of public opposition to its project, OCWD's treatment train for potable reuse has developed into an unofficial sector-wide best practice (Interview 1), which has been replicated in several new projects.

Personal legitimacy, finally, was not an important element in many contentious potable reuse projects. In some cases, the managers of the utility lacked the public speaking experience or interest in serving as public communicators about potable reuse (Interview 16). In an attempt to get charismatic leaders to speak publically about potable reuse projects, some utilities attempted to enlist local politicians to speak in support (Interview 8)—yet this strategy sometimes backfired when politicians neared the ends of their terms and actively tried to garner votes by appealing to public sentiments against potable reuse (Interview 18).

Type 3. Cognitive Legitimacy

Following public opposition to potable reuse projects in the 1990s, advocacy coalitions for potable reuse have begun to address *comprehensibility* by improving education activities and adapting them to different audiences (Interview 7). Some water agencies strategically dispatched people to conduct outreach programs whose racial background matched that of the communities they spoke with:

"There are [utilities] who hire a Latino consultant to work with the Latino community, hire an Asian-American consultant to work with the Asian-American community, hire an African-American consultant, because then people are hearing this from people who look like them, who've had similar experiences." (Interview 16)

Advocates for potable water reuse also developed vocabulary and imagery that related potable reuse to positively connoted cognitive frames like 'recycling,' and attempted to standardize these terms across engineers and utilities advocating for potable reuse (Interview 7) (Macpherson and Slovic, 2011). While environmentalists tend to oppose desalination projects

(Dolnicar and Hurlimann, 2010), in part because of a perception that creating new water sources in arid regions will encourage growth in areas that ecologically cannot support an increasingly large population, they tend to support water recycling because it ties in with their ideals of living in closed-loop systems—though potable water reuse projects also effectively create a new water source that could have the same growth effect in water-scarce regions (Interview 11).

In addition, the WateReuse Foundation employed surveys and focus groups to understand which vocabulary words and images would resonate well with cognitive frames of water users. They found that wording related to the origin of the water (i.e., wastewater, sewage, treated wastewater) resonated poorly, whereas terms that emphasize the high quality of the produced water (e.g., purified water) were more acceptable (Macpherson and Slovic, 2011). However, proponents of potable reuse at different water utilities continue to use a variety of terms to describe the practice (Interviews 7, 11).

Most potable water reuse projects in California have not reached a *taken-for-granted* level of legitimacy. Advocacy coalitions for potable water reuse have begun to implicitly address this issue, mainly through describing potable water reuse as part of the natural water cycle (Interview 7), and by framing potable reuse as "water recycling," which associates the practice with the taken-for-granted frame of converting something used into something new and fresh.

Table 3: Legitimation portfolio of other California potable reuse projects (+= traits contributing to legitimacy portfolio, - = traits detracting from legitimacy portfolio)

Legitimacy	Dimension	Examples
Type 1: Pragmatic	1.1 Exchange	+ Outreach campaigns to establish controlled potable reuse as an improvement over *de facto reuse*
	1.2 Influence	+/- Weak public involvement in planning and decision-making about potable reuse
	1.3 Dispositional	- Little proof of the sector's 'good character', despite branding efforts
Type 2: Moral	2.1 Consequential	+ Successful track record with indirect potable reuse systems in some places
	2.2 Procedural	- Incomplete procedural standards for water reuse plants
	2.3 Structural	+ Research on infrastructure and technology development
	2.4 Personal	+/- Few knowledgeable spokespersons for potable reuse
Type 3: Cognitive	3.1 Comprehensibility	+ Development of vocabulary that meshes with cognitive frames - Inconsistent use of terminology
	3.2 Taken-for-grantedness	+/- Relating potable reuse to the water cycle

Discussion

Several key observations stand out when comparing legitimacy of potable water reuse at OWCD and other potable water reuse projects in California. First, a legitimacy framework for assessing potable water reuse projects, in combination with an understanding of the history and values of local residents in the project area, appears to be useful in explaining adoption of potable water reuse. OCWD's success in establishing legitimacy for potable water reuse cannot be ascribed purely to its innovative technological approach or to its constituents' passive acceptance of expert opinion. OCWD employed a comprehensive portfolio of legitimation strategies both deliberately and by chance, which fostered public trust in the utility and in the practice of potable reuse.

When the practice of potable water reuse began to spread beyond OCWD, many engineers assumed building structurally sound treatment and monitoring systems would suffice for establishing public trust in potable reuse. This approach did create structural legitimacy, but this attribute could not compensate for other shortcomings in the legitimacy portfolio such as the lack of community representation in decision-making and the lack of trust in the utility's ability to manage risk. These experiences show that potable reuse projects seeking societal legitimacy cannot establish it by simply copying the treatment train from OCWD; they must also adopt a comprehensive legitimation portfolio approach.

In contrast to OCWD, many other potable water reuse projects in California have had substantial gaps in their legitimation portfolios. Overall, proponents of potable reuse have often categorized opposition to potable water reuse in a narrow technology-focused and social-marketing-based "public acceptance" paradigm. Important gaps in the legitimation portfolio occur if this paradigm is used—dispositional and procedural legitimacy, and to a lesser degree influence and personal legitimacy, are usually absent. Sociological theory and our interviewees identified the importance of covering these dimensions if potable reuse is to attain a 'taken-for-granted' level of legitimacy. This need becomes even more pertinent when considering the recent advocacy efforts for direct potable reuse, which is likely to provoke wider attention and therefore additional questions on whether the current industry is "right for the job."

For potable water reuse to be legitimate, potable water reuse projects must demonstrate how they will benefit the end users of the water (*exchange legitimacy*), strengthen public involvement in planning and decision-making (*influence legitimacy*), incorporate transparent communication procedures and develop an organizational reputation for high quality (*dispositional legitimacy*), and have reliable risk management procedures and emergency intervention procedures in place (*procedural legitimacy*). The legitimacy portfolio also requires involvement of experienced utility managers in public outreach (*personal legitimacy*) and relation of potable reuse to established social practices (*taken-for-grantedness*).

The current lack of standardized operational procedures for potable water reuse systems is especially striking. Training and certification programs specific to potable water reuse operators, with creation of a sector-wide standard, could be useful for establishing *procedural legitimacy*. A promising strategy might be to emulate risk management and emergency procedures from similar low-probability, high-risk industries like aviation. The oversight of an independent, possibly governmental organization to investigate system failures, similar to the

Federal Aviation Administration and the National Transportation Safety Board, could be beneficial for establishing procedural legitimacy. This would make the innovation more understandable by relating it to standards and procedures that have already gained legitimacy in other established sectors.

The legitimacy portfolio perspective presented in this paper is relevant beyond the Californian potable water reuse case. It can be applied to potable reuse systems world-wide, to other innovations in the water sector (e.g., point-of-use treatment or on-site water recycling) or potentially to innovation in other sectors, like energy or transportation. Our findings suggest that establishment of legitimacy for an innovation like potable water reuse relies upon a balanced and comprehensive portfolio of strategies that address all three types of legitimacy. These legitimation strategies include elements like collaborative public engagement in planning and decision-making, which are outside the realm of the 'public acceptance' paradigm traditionally employed in water projects. A fourth type of legitimacy, regulatory legitimacy (Scott, 2008), has not been explicitly separated in this research from the other three types. The role of regulatory legitimacy in potable water reuse merits future research.

These findings do not imply that there will never be opposition to potable water reuse projects if all legitimacy dimensions are addressed. In fact, potable water reuse may turn out not to be legitimate in some communities, especially if it does not satisfy the community's criteria for meeting all three aspects of legitimacy, and other options for water supply and/or wastewater disposal may be more appropriate. Rather, the broader the legitimacy portfolio, the lower the probability that potable water reuse projects will move forward to a level of financial investment in physical infrastructure in places where opposition to the project will prevent it from coming to fruition. These results also show that many dimensions of legitimacy cannot be created by changes in vocabulary or promotional campaigns alone, which are hallmarks of marketing in a public acceptance paradigm. Establishing legitimacy may require wide-ranging structural, procedural or institutional changes – which ideally emulate pre-legitimized practices from other sectors.

It is important to note that ideas of legitimacy are culturally specific. What constitutes exchange legitimacy in one place may not be considered valid elsewhere. For example, having more water to enable suburban growth was legitimate in southern California but it helped create opposition to the Dublin San Ramon water reuse project in northern California. Also, this analysis focused on legitimacy among members of the general public-- mainly in an attempt to complement existing acceptance studies. Legitimation strategies to engage other groups (e.g. politicians, regulators or experts) might be equally important and should be addressed in future studies. Future research to survey potential potable water reuse users with regards to pragmatic, moral, and cognitive legitimacy in contemporary cases of utilities considering implementation of potable water reuse would be useful to supplement the historical perspective given here. Finally, the present case studies should be complemented with research in other sectors like energy or transportation to improve the concept's generalizability.

Conclusions

Recovering useable water from sewage fits into the emerging paradigm that sewage treatment should do *more* than just purify sewage for safe release into the environment – it should also be able to recover resources like water, nutrients and energy from wastewater (Daigger, 2009b; Guest et al., 2009; Miller, 2006). Though using treated sewage water for irrigation is widely considered acceptable in the United States, consuming water intentionally extracted from sewage is considered revolting to many people (Haddad et al., 2009). The "yuck-factor" related to drinking water derived from sewage is one problem that can inspire public opposition to potable water reuse projects (Hurlimann and Dolnicar, 2010).

Because of this social stigma, proponents of potable water reuse have worked hard to make the practice legitimate in society (Binz et al., 2016). They have done so by engaging in political advocacy for potable reuse (e.g., lobbying politicians and crafting regulations), developing common vocabulary for the new technology, developing friendly panels of experts to provide external favorable assessment to potable reuse projects, and by developing prestigious prizes and awards to professionals working in the field of potable reuse (Binz et al., 2016).

Though proponents of potable water reuse are prominent within the water industry, there remains concern that potable water reuse could be detrimental to public health (Okun, 1980). After all, the "yuck-factor", or revulsion, to consuming water derived from sewage is a healthy instinct, based in the premise of avoiding contagions and toxins that are unhealthy for our bodies (Haddad et al., 2009).

Technologies for potable water reuse like reverse osmosis and advanced oxidation processes can purify sewage water to higher standards than required by the Clean Water Act (Tchobanoglous et al., 2011), and are considered as clean or cleaner than many existing water supplies (National Research Council, 2012; Rice et al., 2015, 2013). But there are still many unknowns about the public health implications of potable water reuse (Ong, 2016). Among these are valid concerns about the chronic effects of very low doses of chemical contaminants present in sewage and only partially removed by treatment, the risks of chemical spills or microbial outbreaks that could cause a pulse of contaminants in the product water, and the difficulties of real-time monitoring of water quality to ensure system reliability (National Research Council, 2012).

Much of the communication to the public about potable reuse has appeared as marketing materials by proponents of the technology, for example as a promotional video (WateReuse Association, 2012). Finding solutions to water challenges requires informed deliberations and the participation of communities to engage in planning and choosing the alternatives that are most appropriate for them (Marks, 2006b)—and to do so, there is a critical need for informative, non-propaganda explanations of potable water reuse technologies and processes. The following chapter helps meet this need by detailing the tensions about potable reuse and explicating both its potential as a water supply and its potential risks, in a magazine article format.

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Appendix to Chapter II: Supporting information for 'Beyond User Acceptance': A Legitimacy Framework for Potable Water Reuse in California (Harris-Lovett et al., 2015)

Figure S1. Interview guidelines

Interview with: _______
Date: ________
Type of organization: (I.e. Utility, regulator, consultant) ________

Introduction

- Introduction of interviewer(s) and explanation of aim of the interview: 1.) Reconstructing the process leading up to implementation of direct potable reuse in California's water code, 2.) Understanding current challenges to potable reuse, 3.) Understanding advocates' and critics' arguments and actions, 4.) Understanding potential solutions to innovation barriers.
- Definition of 'direct potable water reuse' (from the California water code/Senate Bill 918): injection of treated wastewater effluent directly into a drinking water distribution system or directly upstream of drinking water plant, with no natural buffer.

- Permission for audio recording

- Information about interviewee: Briefly describe your professional background. Which roles/jobs/positions have you had in your career? How do you see your role in California's water reuse scene?

History of direct potable reuse

- From your perspective, how did the story of water reuse in California unfold? What were important steps between 'not considering this technology at all' towards 'implementing it as a goal in California's water code'?

  Follow-ups
  - When did you first hear about potable reuse? What did you think of it?

- How did the discussion on potable reuse unfold? What were the different phases of development? How can they be characterized?
- What were important milestones in developing the idea of potable water reuse?
- Was the advance of potable water reuse ever particularly endangered? What happened? When?
- Was there ever competition between potable water reuse and alternatives like desalination, water transfers, or non-potable water reuse?
- Is there is a need to pursue potable water reuse? Why or why not?

Organizational role

What was your organization's role in developing potable water reuse?

- When did your organization get involved in potable water reuse? Why? Who was advocating for it?
- What were crucial milestones in the internal discussions on potable water reuse? When? Why?
- Did you team up with partners in pushing potable water reuse? Who? Why? What joint projects were formulated?

Other actors

- Which other actors were important in pushing potable water reuse? What did they do specifically? Did you cooperate with or try to influence them?
- Who is actively opposing potable water reuse? Why?

Networks

- What potable water reuse networks and associations does your organization participate in? Why?
- Are existing networks effective in developing solutions for the sector? Why (not)?
- Did your organization create potable water reuse-specific networks? Why (not)? With whom?

Regulatory institutions

- What kind of policies pushed/hindered potable water reuse? Regional differences across the state?
- Did your organization influence regulation/policies (e.g. Senate Bill 918)? How?

Public involvement/participation

- Do you feel that potable water reuse is well-accepted in society? Why (not)?
- How did your organization influence the public perception of potable water reuse? What were your organization's core strategies? Based on what key arguments? Did your organization have success/failure? Why?
- Do people trust your organization's potable water reuse activities? Did you create new management/communication tools for potable water reuse? What exactly? Why?

- What happens in case of system failures? Have you experienced emergencies in the past with your potable water reuse system? Were problems communicated to the public? Why or why not?

Current challenges/future perspective

- From your perspective, what are currently key challenges for the further development of potable water reuse? How could they be overcome?

Public acceptance/involvement

- What prejudices exist about potable water reuse in the public? Does your organization address them? How? Does anyone else address them?
- Does anyone show/showed resistance to potable water reuse? What did they do and say specifically? How did your organization address public resistance/fear?
- Were there moments of concentrated media attention on potable water reuse? How did your organization react? How did others react? With what effect?
- Does your organization have a specific communication strategy on potable water reuse?
- Are standardized public involvement/participation programs developed in California's potable water reuse scene?

Finances

- Where does the money for potable water reuse projects come from?
- What problems exist in finding financial resources for potable water reuse? How could the situation improve?

Technologies

- Why didn't other technologies get implemented more broadly (e.g. desalination)?

Influence from outside California

- Did best practices from outside CA / the US play a role in developing CA's potable water reuse (Windhoek, Singapore, Big Springs TX, Cloudcroft NM)? When, in what project?
- Did failure stories from other projects influence California's potable water reuse story? (Toowoomba AUS, others?) How exactly?

Regulation, policy

- How to overcome the unclear regulatory responsibility on potable water reuse?
- How does the process for defining potable water reuse standards/regulation work? Who is involved? Is standardization also pushed at a federal level? Why (not)?
- How could dispersed regulation of potable water reuse be simplified? Who is crucial in a simplifying process?

Final questions

- Did we miss an important topic that is relevant?
- Is there further documentation or sources of information that might be useful?
- Are there other people you suggest we should interview?
- What is the best way to follow-up? Do you want to comment on the interview transcripts?

Table S1. List of interviewees

Professional Role	Type of Organization	Interview
Company president and consultant	Water engineering and policy consulting company	1
Water engineering consultant	Water engineering consulting company	2
Senior Vice President and Chief Technology Officer	Engineering consulting company	3
Assistant General Manager	Municipal water district	4
Professor, expert panel member	University	5
Environmental engineering consultant	Regulatory: Public health	6
Company founder and consultant	Public relations and communications consulting company	7
General Manager	Municipal groundwater management district	8
Executive Director	Research and advocacy non-profit	9
General Manager	Municipal water district	10
Director and owner	Water engineering consulting company	11
Water Reuse Chief Technologist and Associate Vice President	Engineering consulting company	12
Managing Director of the California section	Water reuse advocacy organization	13
Former Principal Engineer	Regulatory: Public Health	14
Professor emeritus	University	15
Executive Vice President	Strategic communications consulting company	16
Head of Public Relations	Municipal groundwater management district	17
Founder and General Manager	Environmental engineering company	18
Assistant General Manager	Municipal groundwater management district	19
Retired director	Municipal water and wastewater district	20

Table S2-A. Orange County Water District case study, additional quotes from interviews to support framework

Legitimacy types	Dimension	Quotes
Type 1. Pragmatic Evaluation based on self-interest	1.1 Exchange	"It was a 10-year effort to just educate the public and gain their trust. And educate them about what the project would mean." (Interview 17) "We had materials in different languages." (Interview 17) "I think the main reason that they accepted [Water Factory 21] was that we were trying to prevent a much greater harm. We had a serious seawater intrusion problem." (Interview 19) "I think we really managed to kind of stay on track with the community about what they were worried about, and how we were going to address their concerns, and how we would need, in terms of our outreach materials, the way we presented, the kind of language that we used, all of that was, I think, crafted around the kind of feedback that we had gotten from the focus groups and the surveys. So when we heard something from them, we learned something about what language not to use, what language to use, and how we can-- well what they were most concerned about and how we can speak to those concerns." (Interview 19) "I can show you this water is better than my other sources. So I have a number of choices to put water in the ground. Which one is my best? It's the recycled water. It's a pretty good story." (Interview 19) "This plant is producing better quality, we've already talked about that, it's the best available, it's reliable, we control it, and it's cheaper. What's not to like?" (Interview 19) "It costs less, and one of the things the environmental folks love, it's about half the energy. Taking water from Southern California from Northern California, you have to lift it about 4,000 feet over the catch basin. This takes less energy than lifting the water 4,000 feet, basically." (Interview 19) "The business groups saw, you know, what's good for business is a reliable predictable water supply. So the business groups were supportive." (Interview 19) "The ground water recharge program then was packaged in a way to support growth and so those who were already questioning the policies of growth were able to attack the ground water recharge." (Interview 20)
	1.2 Influence	"We created an opportunity for a lot of input. So it wasn't very insular or it wasn't just our folks making the decisions." (Interview 17) "We actually did surveys and focus groups to find out what the public was concerned about." (Interview 19)
	1.3 Dispositional	"One reason Orange County is so successful is because mainly because-- well, not mainly, but their reputation, they've always done a very good job." (Interview 2) "If there's been a problem, they've identified it, made it available for the press or anyone else that wants to hear about it, and resolved the issue." (Interview 2) "Orange County had a very sophisticated and transparent approach." (Interview 7) "I think reputation and water quality from an agency who wants to do a project like ours is really critical to getting support for their project. It's about earning the public's trust." (Interview 17)

Legitimacy types	Dimension	Quotes
		"Without your reputation and your values, you have nothing." (Interview 17) "When we were doing the pilot project there was an issue with NDMA. And instead of burying...our heads in the sand, we worked with the regulatory and water quality staff in trying to put it in layman's terms what it meant, and we brought some of the local press in to talk about it so that they wouldn't hear it later on and claim, 'You're hiding this.' Transparency is probably the cornerstone of any good communications outreach plan, whether it's a really controversial project, or something that maybe doesn't even cost as much, it's just-- so transparency is what we continue to do. So if we do have a problem we're open and we talk about it." (Interview 17) "The media asks, the public asks, 'Well, I've been reading in the paper about pharmaceuticals, what do you do with pharmaceuticals?' Well, we test pharmaceuticals. We're not required to. We do because we know it's one of the things that the question comes up." (Interview 17) "They were open with the public about [the NDMA]. They got right on it and offered to treat the nearest well. They modified the design of their treatment plant so it would remove it, and they monitor it regularly." (Interview 18) "We had a problem, it was potentially a serious problem, because this is a very carcinogenic compound. But we gave the media some perspective on it. If people are exposed to NDMA from hot dogs and beer, and lots of other foods, and so the exposure through water wasn't going to give them significant doses of something that they weren't already getting from other sources. So they got some perspective, and then what are we going to do about it? Well we secured part of the plant, we shut down part of the plant, the GAC part of the plant.... The RO part of the plant, we added a treatment component after the RO, and that's where the UV first came in. With UV, we could destroy NDMA." (Interview 19) "So I think that that made it so that instead of losing public confidence, that we could do an even bigger treatment plant, to take even more recycled water, put it in the ground, that if anybody was going to be able to do it right, we would. So I think it helped to bolster public confidence that, if we ran into a problem, we were going to tell them about it, that we would be able to find solutions to any problem we ran into, that they could trust us." (Interview 19)

Legitimacy types	Dimension	Quotes
Type 2 Moral Evaluation based on norms / societal values	2.1 Consequential	"Mainly it is due to the track record that they haven't had any issues. There's no major outbreak. People are not falling over by the thousands. And they essentially accepted this as a viable way of augmenting drinking water supplies." (Interview 5) "We have the water quality data. We have been able to replicate year after year after year the same results. That's why others come here, others visit us and we share our data with them." (Interview 8) "It's not like [the Ground Water Replenishment System] arose from nothing. They did Water Factory 21 first." (Interview 11) "Now that we've been online now for over five years, people see that they can trust it. We have all of the data to back that up." (Interview 17) "We have the data that the water is safe. It exceeds most drinking water standards; meets or exceeds, and most of the different compounds it exceeds." (Interview 17) "We had a lot of data to refer to back then. Even though the purpose [of Water Factory 21] wasn't to directly replenish our groundwater supplies, because we were injecting it to prevent seawater intrusion, ultimately that water did make its way in the groundwater. And the quality, you know, we could show data that the quality was exceptional. So we had all of that to back us up, as well." (Interview 17) "Bottom line, it goes back to whoever-- if it's a public or private agency that's going to be building and operating the project, you need to speak to your history of what you do. And fortunately, we've had a really good long standing reputable history." (Interview 17) "Because we had Water Factory 21, we used it as a demonstration facility." (Interview 17) "When they built the demonstration project, it was still some form of an extension of Water Factory 21." (Interview 17) "This is really a key thing, and it can't be emphasized too much, that it was easier for us, in terms of garnering public support, because we had so much history with Water Factory 21. We had over 20 years of history with Water Factory 21, we showed people we could do it, and we showed them, that we had problems, that we could deal with the problems, and I think that really helped with public confidence." (Interview 19)
	2.2 Procedural	"They monitor for 400 elements and they don't find them." (Interview 1) "In Orange County-- they found, for example, that they were finding dioxane in the water. And so what they did was they then went to the community and they tried to find out who was using dioxane, who was discharging dioxane, and they found several of them, and they got them to agree to stop the discharge and such and so by doing that, which goes beyond what you would say is the pre-treatment requirements, provided some extra benefit, some extra protection." (Interview 1) "Orange County …actually had about a six-month training period to get their operators to get them very knowledgeable and very reliable to run the system. It's a much more complicated system than the typical water system and so they did that and that's great." (Interview 1)

Legitimacy types	Dimension	Quotes
		"They have a plan here called the operation maintenance and monitoring plan, OMMP. It is five inches thick and that's for an IPR plant. It's how to run this plant, everything from monitoring … everything soup to nuts, five inches thick." (Interview 9) "They have a wonderful source control program, they have every business on GPS. They know who's discharging what." (Interview 15) "If there's a problem with our system, we can shut down, and nothing else stops." (Interview 19) "I can compare, look at TDS, look at nitrates, look at pharmaceuticals, look at just about anything." (Interview 19)
	2.3 Structural	"They have a very good lab, a very advanced lab, very qualified people." (Interview 2) "In Orange County, operations staff is first class there. They've got maybe six or seven people who have been there since 1975, so who saw the first membrane and who have thirty years of working on an R.O. membrane." (Interview 4) "Orange County has two operators 24/7 plus a varying number of operators during each shift." (Interview 15) "Orange County has a huge staff, people devoted to microbiology, people devoted to source control, people devoted to pipe-- I mean, it's the entire system that makes direct potable reuse possible, not treatment technology." (Interview 15) "We have the water quality assurance laboratory, and having that on site has also been very instrumental in helping to earn the public's trust." (Interview 17) "We're one of only six different labs in the nation to analyze-- monitor and analyze emergent contaminants of concern that aren't regulated yet." (Interview 17) "We actually got the board to buy into the idea of building about a 40,000 or 39,000 square-foot lab, and that's what you see kind of on the northeastern corner of our site here. And it was, I think, a recognition by the board that they've got a really nice high tech facility here. It's very impressive. It's very 21st century. We needed to be able to show a similar commitment to our quality. So that's the nature of the laboratory investment by the board, was a recognition that if you take somebody through the treatment plant it's, "Gee whiz, this is really great technology," but you need that final bit of gee whiz to show them that we're doing everything we can to assure that the water is safe… It was essential for GWRS because it's part of the image." (Interview 17)
	2.4 Personal	"He championed it... He's the senior guy. He's been in Orange County politics a long time. He kept-- he knew a lot of the details, but he would say, "This is an important project to do. We have to support it." (Interview 4) "We didn't use the consultants in that way [to do outreach]. We always sent staff out, board members." (Interview 17) "The one area that we did utilize consultants to go and speak a lot were for multicultural communities. So Latino communities, Vietnamese, Chinese communities, that's where we did have some consultants who spoke those languages. But other than that it was all pretty much in house." (Interview 17)

Legitimacy types	Dimension	Quotes
		"One of the things that our district did was, as we talked to politicians and got them to nod yes, we got them to send a letter saying that they were in support of the project." (Interview 19) "What's most important is for the community leaders the leaders of the Kiwanis group, the leaders of religious groups, the leaders of medical groups. You want those people to have a good understanding of the project, first and foremost, because they're the ones that everybody else relies on." (Interview 19) "We did presentations with the public so we could speak to their concerns directly." (Interview 19)
Type 3 Cognitive Evaluation based on deeply held customs & beliefs	3.1 Comprehensibility	**"**One of the things that we found is that during these presentations when we talked about where natural water comes from and that all water's recycled, and then when we'd have the opportunity to tour people at our facility they'd see how it works and understand reverse osmosis, inevitably the next question that followed when we would taste the water was, "Well, why are we wasting our time putting it in the groundwater basin?" (Interview 4) **"**We were the spokesperson, because we're on the water side, as opposed to the waste water side, the dirty water side. So we wanted to put the emphasis more on water, the purified water and not reminding people of the source, which could have had negative connotation." (Interview 8) **"**[OCWD] had a really good consulting firm who just did multicultural consulting. And in Orange County that was primarily Vietnamese and Hispanic. They targeted in on those audiences and talked with them in a way they might need to be able to talk." (Interview 16) **"**When we first started, it was wastewater purification or wastewater treatment. Now, we use the word treatment just to talk about the wastewater before it comes here. So a sanitation district treats it to high levels. Here, it's purification. And it's not a wastewater purification facility. It's a water purification facility." (Interview 17) **"**Even today, we have people come and sample the water. And it's just kind of that last clincher. Like, they believe it. In fact, on the cup, it says, "Tastes like water because it is water." Because a lot of people that drink it go, "Hum, it takes like water." It is." (Interview 17) **"**A lot of people don't realize, especially in Southern California, we're downstream of other sources. So at some point, water's used. It's taken out. It's put back in. … So in some way or another, most of us are drinking recycled water. And once people get that, they understand and appreciate [the GWRS]." (Interview 17) **"**We've been a part of numerous studies where they have helped to create kind of, like, a glossary of words that are more effective." (Interview 17) **"**We've talked about bottling the water, similar to Singapore's water. And using it just as an educational tool, to take it to Sacramento to talk to our state legislators. Or to take it to Washington, DC." (Interview 17) **"**Hence the name of the laboratory, Advanced Water Quality Assurance Laboratory, so kind of like you'd have from a factory, you'd have an assurance, a quality assurance facility, and that's what we have at the lab." (Interview 17)

Legitimacy types	Dimension	Quotes
		"But because we put it back in Mother Nature, we put it back in the ground, it's like Mother Nature had it last. One person referred to it as, the kiss of Mother Nature. It's got the kiss of Mother Nature. And somehow that's improved the quality, the perception of the quality." (Interview 19)
	3.2 Taken-for-grantedness	"And so they're fearful of the change but once it gets up to a point, and I don't know what that curve is, but there's this plateau and now it's business as usual, the public doesn't-- you know, they don't get sick, they don't see anything, they don't smell anything, I mean if it continues to be operated well. And therefore you … get the Orange County Water District, it's routine." (Interview 12) "But after a while, you know, if we don't have anything controversial, if we're not discovering a new contaminant, it's not really a great story, right, the newspapers don't like it." (Interview 19)

Table S2-B. Other potable water reuse case studies in California, additional quotes from interviews to support legitimacy framework

Legitimacy types	Dimension	Quotes
Type 1. Pragmatic Evaluation based on self-interest	1.1 Exchange	"When the public understands the sources of their water, the fact that even natural water supplies oftentimes have a certain amount of treated effluent in them and they see the difference in the level of controlled and a technology that's applied that in fact people can have a preference for potable reuse compared to other water supplies." (Interview 3) "Unless it's a dire emergency, it's hard to convince people." (Interview 11) "It's letting the community understand why you're doing it, and what it's going to cost, and why it's the best cost for them. So in the case of Southern California now where potable reuse has been shown to be protective of public health, the discussion isn't any more about sea water intrusion. It's about this community's growing, the water that's coming from the Colorado River is drying up, the water that's coming from Northern California is going to dry up some and so you can decide to pay $3,000 an acre foot to pump water from who knows where to LA or you can decide to pay $1,200 an acre foot to do potable reuse, right?" (Interview 12) "The message to the public was, "We don't want to pay to do this so instead we're going to make you drink toilet water." (Interview 12) "You can't look at indirect potable reuse as a comparison to the water you have now. You have to look at it as a comparison to the water that you're going to need later, because it's clear that we don't have enough water later." (Interview 12) "One of the things that happened at first, we were in the middle of a drought or just coming out of one. People were really concerned about water, really, really concerned." (Interview 16) "The first time around they had a wastewater guy who could get things done and so they put him kind of in charge of [the potable water reuse project]. So then it looked like a wastewater solution, not a water solution." (Interview 16)

Legitimacy types	Dimension	Quotes
		"Everything's local, so you have to figure out, "Okay. What do these people want to do? How and when do they want to do it? What's the project? What's the benefit?" (Interview 16) "Focus groups are part of the researching. We always try to encourage our clients to do research. They don't all do it. But it's the best way. Focus groups, and then also telephone surveys. So they can see in a generalizable way how people feel about the issue. And then, so once you get in the focus group, that helps you develop your messages or know your messages are working, whether they need to be changed or whatever." (Interview 16) "We think about the different audiences. You've got the business community. They have certain interests. We need to approach them in certain ways. The environmental community, certain ways. Multicultural communities." (Interview 16) "The first time I went there, as I'm driving from the airport in Toronto to this place, it's like a jungle, for Gods sakes. You know, it's like green stuff everywhere, and I thought, "Why in the world do they need to do a reuse project?[…] Because if you've got a bunch of rain and things are all green, that's not like being in Southern California where we're at the end of all the pipelines and where we know that drought is a way of life." (Interview 16) "I'm working on a project now in Olympia, Washington. It's a wastewater agency, but they have a reclaimed water program and they also want to infiltrate the groundwater, reclaim water into the groundwater basin. But the groundwater is a source of drinking water, and people are asking, 'Wait a minute. Why do we want to do this?' Because it rains a ton up there. I swear, every time I've been up there it rains. It's raining. So you have-- okay. So now you got to figure out, "Well, what is the benefit here for these? Why are you doing this project?" Because that's what I mean. You really need to have the purpose and the need for the project clear for the particular place where you are. Because otherwise, nothing is going to happen." (Interview 16) "Every community's needs are slightly different." (Interview 17) "The driver in Southern California is drought." (Interview 18) "Winning public opinion, other than winning over the board, has never even been part of [water utilities'] management experience. Now, that's changing." (Interview 18) "They only did communication for a short time, and then they sort of backed off, and they got stung, I think, by the fact that they weren't constantly at communication, they weren't constantly telling people what they were proposing to do, why they were proposing to do it, and why it was going to be okay." (Interview 19) "What I heard them saying is, yeah, we want to go to potable, because it's cheaper. But you know what, to tell people, we want you to drink sewage rather than use it on your golf course, because it's cheaper, that's not really going to resonate well." (Interview 19) "If you want the public to embrace this, they have to see that somehow it's going to improve things." (Interview 19) "One of the things we'll have to be able to look at for the public, is how does this water compare to what else you have?

Legitimacy types	Dimension	Quotes
		If you can show people that it's better, it will be a lot easier to accept." (Interview 19) "This type of innovation is about water resource, that's the driver, our society needs a water resource. And so to promote these kinds of innovative projects, you need to look at what is going to be the acceptable driver. So here's water resource and everybody knows that you need adequate, reliable water supplies but the project was promoted as a wastewater discharge project which society doesn't accept as absolutely needed." (Interview 20) "He would bring up the Southern California experience, Orange County. 'Hey, this is done all the time, that this is the Southern California model,' and then the reaction is 'We don't want the Southern California model in Pleasanton. What the hell are you talking about? We don't need Orange County here.'" (Interview 20)
	1.2 Influence	"You have to continue to inform people, continue to involve them, continue to engage them." (Interview 7) "It works much better because you talk to them about, "We've got this project. What do you think? Do you like it? We need your support. If you don't like something, tell us." So when you have that type of conversation, it works much better than just going out and saying, "Hey, aren't we great? Look at all these things we do for you. You got water because of us."" (Interview 9) "We don't want to be just talking at people, we like to be in a conversation with them, because they may have questions or concerns about this new water source. And we know they will have questions and concerns, and we want to be able to address all of those." (Interview 16) "Probably the best way to go about it is if you actually go and talk to people about, "Here's our water, here's what we're facing, in terms of water supply. Here's all the options that we have. Here's how much they cost. Here's how independent they make us. Here's-- whatever. "Which ones do you think we should do?" That would be a wonderful thing to do. And then you would have people behind you from the get-go, because they helped you make your plan. But most water agencies don't do their planning that way. They go in a room and they do it and then they come out and say, "Here's what we're going to do. We're going to do this project."" (Interview 16) "Even if they give you the ideas, you're not going to do them, because you already know what you want to do. That's I think how many, if not most, water agencies or public agencies, any agency, operates." (Interview 16) "People set up advisory groups a lot. They really don't want advice. They already know what they want to do and they just want to be able to do it and have you like it." (Interview 16) "So you actually ask people. Sometimes they're going to give you some really good information. But if you ask them and they tell you that and then you say, "Thanks a lot," and then you paint all the roofs green when they said paint them pink, that's a bad thing." (Interview 16) "There's, I think, a general kind of perception that there's greater acceptance if the public feels like they've been engaged throughout the process." (Interview 19)

Legitimacy types	Dimension	Quotes
		"As the outreach was underway, there was an attempt, obviously, to find out what the public was concerned about, and we all responded to their concerns, so focus groups and surveys to say, all right, what are you guys worried about." (Interview 19)
	1.3 Dispositional	"You cannot create trust unless you're honest. And I think that that's one of the places in which we have been, as an industry, dishonest. We've tried to hide the reuse that already occurs because we don't want to make things worse." (Interview 7) "If you're trusted in your community then you're much more likely to be able to pull off these provocative projects" (Interview 9) "It failed because ...the public believed that the district was trying to fool them." (Interview 12) "You still have to reach out to the public and tell them what you're doing though, absolutely have to communicate with them and don't hide from the issue of this once was toilet water… however you say it, you have to say the origin of the water and what you're doing with it and how it's cleaned." (Interview 12) "It goes back to what I said before, your reputation and your trust. How many times before in your agency history have you had a snafu, or what pipelines have broken, or did you ever serve water that was not of the right quality. So that's when that scrutiny is going to go back to the agency that wants to do direct potable reuse." (Interview 17) "If another agency does it improperly, does it too fast, doesn't get the support built up, if they aren't transparent, if they find things and don't let other people know, then it can spread and--unduly to others." (Interview 17) "So when I said earlier how important it is to look at the institution that is sponsoring it, is what is their reputation because reputation precedes everything." (Interview 20)
Type 2 Moral Evaluation based on norms / societal values	2.1 Consequential	"Orange County here I think was very important, because they installed a lot of these things, and they got a lot of publicity worldwide as this showplace of high technology application in drinking water. And I think that created more general knowledge that it existed. It wasn't just something you would find in the technical literature. It was very public. And then people believed that it could be done, it was being done, and therefore "Okay, it's important." (Interview 1) "We've become pretty comfortable with IPR particularly with both groundwater recharge and surface water augmentation with very high levels of treatment like Orange County's doing." (Interview 2) "The work that had been going on at Orange County for at least a decade looking at membranes put the two things together and said, "We could do that." And went off to first demonstrate and then begin building new water plants." (Interview 3) "Once it's being done in a developed country like that and more than one place at fairly large scale that again those that have-- just have a gut-level rejection of this approach their logical arguments are going to begin to drop away." (Interview 3) "We have to make sure that we as operators can actually produce consistently high water-quality. And, again, I don't think that's a given. I think years of research are needed before we can get to that point." (Interview 4)

Legitimacy types	Dimension	Quotes
		"I think for us to really sell public confidence, we need a significant time running these projects." (Interview 4) "It started with the success of Orange County Water District bringing their plant online in 2008. When people saw that that worked and it delivered water and they could taste the water, and the fact that you could produce so much-- I think that had a significant impact on going from IPR to DPR." (Interview 4) "We have convinced people that [indirect potable reuse] is safe…because the ones that have been in use are safe." (Interview 11) "You explain the history. Now that you have this established successful operation, they don't really get much resistance down there now. There's project after project that's being planned and implemented, projects being expanded without concern now." (Interview 12) "Those of us in the reclamation field, the last thing we want to see is for somebody to really stub their toe badly, because if somebody messes up out there, it will reflect badly on all of us, because it will dampen public confidence that we can do it safely." (Interview 19) "Everything that we conceived in that period of the early 1990's is exactly what Orange County San District did, has done. So the whole technology, everything was exactly the same, it was take the wastewater, treat it with RO membranes, UV disinfection, that's the technology, put it in the ground water basin and therefore it's part of the water resource." (Interview 20)
	2.2 Procedural	"You should have adequate monitoring." (Interview 1) "There were no real criteria spelled out." (Interview 1) "They approved that technology, and it's running, but they didn't have any standard. They didn't have a regulation. They didn't have a standard procedure or anything else." (Interview 1) "Everybody knows that [operator training] is important and so what's the best way to do it? Probably some sort of accredited school that the operator can go for whatever time and learn." (Interview 1) "Nobody has the training for people to do reverse osmosis." (Interview 1) "I don't think we have online monitoring that's reliable for pathogens for example and its acute effects." (Interview 2) "What if something in the plant goes wrong? How are you going to make sure that it's safe?" (Interview 8) "So the question is something's going to break. Something's not going to work. Something's going to happen. What do you do? And we need to understand that. We need to be able to detect it. We need to have best practices on how to avert it." (Interview 9) "You have to do source control. The other thing is you have to do watershed protection." (Interview 9) "It's the right system, but how are they going to monitor for it? How are they going to run it? Who's the operator? Is he trained? I mean does he know how to run membrane plants?" (Interview 9) "Something will go wrong and if you don't have a plan for how to react and what to do, what are you going to do when something goes wrong?" (Interview 9)

Legitimacy types	Dimension	Quotes
		"I think we need a better program for source control. So the compounds that only pass through reverse osmosis, right, we need to find out the worst actors and the most ubiquitous of those compounds and look if we need to do a source control program to get them out of discharge to the sanitary and replace them with something." (Interview 10) "What operator training do you need? How do you monitor whether those operators are doing it right? How do you monitor your equipment? How do you-- do you maintain it differently? Do you have scheduled maintenance on it that you might not otherwise do?" (Interview 13) "One of the questions that comes up is, 'Well how do we develop standards for large and small communities?'" (Interview 15)
	2.3 Structural	"The technology is pretty well established." (Interview 3) "The biggest challenge is just the operations. I think it's the "How do we ensure there's enough fail-safes in there?" (Interview 4) "What types of instruments need to be developed to ensure that the process is safe or if there's a problem that we know immediately?" (Interview 8) "I was in a workshop [at another potable reuse project], and one of the questions came up and they said, 'Well, why are you using AOP if you don't have 1,4-dioxane?' … And they said, 'Well, we just copied what they did in Orange County.'" (Interview 8) "They said, "Hey, Orange County's doing it. Let's just put in their technology. We'll build a plant, we'll be done." That's what their approach was." (Interview 9) "We don't have a 24/7 water sensor for the unknowns. We don't have that, and we got to get something commercially available that's a 24/7 water sensor." (Interview 10) "Dublin San Ramon Services District built a beautiful advanced treatment facility for three million gallons a day." (Interview 12) "So I guess the challenge we face is staying vigilant on each of these processes that we put in, the little one million gallon a day facility that was, you know, that didn't have all the bells and whistles, those are the ones we've got to watch out for, right? We can't have a failure, we just can't." (Interview 12) "So you have to look at each of these processes and you have to define a monitoring method that guarantees you the barrier of each process." (Interview 12) "What we learned in that project, we brought in NASA and the nuclear industry and structural, people, where they're dealing with life threatening engineering problems. And really the biggest thing we learned on that whole thing was that you have to try to decouple systems. So you don't want one process to fail and to cause other downstream processes to fail." (Interview 12) "I think we have sufficient monitors right now but in my judgment, they're going to get much better. Lots of people are working on them, it's not as though we're-- just lots of people are working on them." (Interview 15) "Frankly, there's no project that has ever gone down because there's some problem with the technology. It's always the public. You know, the public acceptance." (Interview 16)

Legitimacy types	**Dimension**	**Quotes**
		"The technology has changed sufficiently and fundamentally…by every measure that we can measure the water is much cleaner than the water we're already drinking." (Interview 18) ""There will be some low molecular weight compounds that come through. Will they be harmful? Probably not…but it's not like there's no issue at all." (Interview 18) "I was idealistic in thinking that from a technology point of view if we did the best possible job on technology […] that that would prevail." (Interview 20)
	2.4 Personal	"You want to have all of the public officials and the opinion leaders formally supporting... we try to cover all of our officials and opinion leaders and other special-interest groups and try to get as many as we can officially-- an official statement that we support it. That's probably the best thing you can do, but it's got to be personal contact time. It can't be a bunch of ads. That doesn't work. Going out and put sweat equity into the program where you're actually one-on-one or one in a group talking to them, informing them, having a dialog and then asking them for a formal support letter, that's probably the most important thing you can do." (Interview 10) "Public relations is always tricky because the public sees you hiring a public relations firm not as an effort to communicate with them but as an effort to manipulate them." (Interview 18) "It should be the agency people who are out talking about their own project. We can help them. We can develop their presentation, we can schedule presentations, we can schlep the projector. You know, whatever needs to be done. But they need to be doing the talking." (Interview 16)
Type 3 Cognitive Evaluation based on deeply held customs & beliefs	3.1 Comprehensibility	"We produce water that we deliver to customers and then the water we put in the ground we sell to a separate groundwater management agency called Water Replenishment District... They are like the Orange County Water District... Then, on top of that, we don't actually inject it ourselves. We give that water to the county. The county government then injects that water." (Interview 4) "We shouldn't be talking about wastewater. Waste has a negative effect. People don't want waste. We should really get people to be involved in the discussion about water cycle. And we should call it used water." (Interview 7) "But we don't need to brand ourselves as wastewater because if we do, we're not going to get as far down the track with the public who will continue to say wait a minute. I don't like that thought. That's yucky." (Interview 7) "If we understand water's use and reuse, and if we understand how we put things into water, and how we take it out again to make it fit for purpose, it clears the mind for us to be able to understand this thing called potable reuse. It puts it into a context for us that allows us to be able to embrace it more holistically." (Interview 7) "Until the water industry speaks with one voice, we're doomed." (Interview 7) "I think the public needs to understand holistically what is use and reuse. Otherwise, they're going to think that this is all unfamiliar. This is unusual. And unusual things are things that we fear. And yet, water is ninety-five to ninety-nine percent of the population of the world is downstream of somebody else. We just don't know it." (Interview 7)

Legitimacy types	Dimension	Quotes
		“We all need to change the way we’re talking about this and talking about contextually. I have tried to get people to say instead of talking about water reuse, why can’t we all just agree to say water is reusable. And we reuse the water in different ways up to and including drinking water.” (Interview 7) “We created a visitor center that was transparent about the treatment technology that was a very complete visitor experience and showed the public the issue of water, the whole thing, the natural cycle, water’s use and reuse around the world, and then showed the technologies, and then at the end just let people leave and go back out into the environment. What we found is the people, as they went through that facility, were-- became more and more understanding of what the issue was. And when they left, they were much more accepting.” (Interview 7) “As an industry we have done a terrible job in explaining to people where their water comes from.” (Interview 8) “The environmental community loves recycled water. And they say ‘Why don't you do more recycled?’” (Interview 10) “Whatever engineering they do above ground, they’re going to somehow have to make it as palatable to the public as nature. Now how do you do that?” (Interview 11) “Bringing it all together with a focus just on the [water] cycle was really helpful.” (Interview 11) “[Environmentalists] support water recycling. They hate desal.” (Interview 11) “[Downstream] goes through and explains the whole cycle of water from the context of water reuse. It's not just the water falls on the mountains and goes into the beautiful pristine stream, there's no cows crapping in the water, sorry. The water cycle we learned in school is so perfect and then people drink it and then it goes to the wastewater plant and then it goes to the ocean, right? *Downstream* tells it like it really is but in a very gentle way.” (Interview 12) “One of the key research projects is come up with a communications plan so as a community we’re using consistent terminology working from a playbook, a plan for communicating with... we don’t have a unifying grand plan for how to communicate with key stakeholders at this point, and that’s what we need.” (Interview 13) “We have support from environmental groups. They want to see recycling increase.” (Interview 13) “Right now we're trying to craft some kind of language regarding recycled water and DPR and how we all communicate, because we all do use different words like reclaimed, recycled, advanced treatment, and we're confusing the heck out of the public when one agency says it one way and another.” (Interview 17) “There's a few agencies like ours that probably better positioned, maybe because we're one level removed from the retail customer, to be able to look at those kinds of options, and figure out how we can make our groundwater basins more reliable.” (Interview 19)
	3.2 Taken-for-grantedness	“People are mistrustful but once it gets up and running it’s so routine, it’s like it’s just a non-issue.” (Interview 20)

Chapter III: Communication of innovative technologies: The case of potable water reuse

Preface

Throughout my research on potable water reuse, I encountered two starkly different perspectives on the issue. People with these perspectives can be categorized as 'the Believers' and 'the Skeptics'. Believers had a strong faith in technology and great optimism about the potential of potable water reuse. Skeptics were not sure potable water reuse would be safe, and voiced the idea that "absence of evidence does not mean evidence of absence" with regards to negative health effects from drinking water that had been purified from sewage.

Many of the Believers included water engineers (including many managers of drinking water and wastewater utilities, as well as engineers at water infrastructure consulting companies), who were often strong advocates for potable water reuse. They touted the fact that potable water reuse would not require the construction of a new set of pipes (as opposed to recycling for irrigation, which would), the scarcity of new water sources in arid regions, the depletion of existing water sources due to changing environmental conditions (e.g., less snowpack) and stricter regulations to keep flows in-stream, and the notion that advanced wastewater treatment technologies can consistently produce water that has fewer contaminants than some traditional water sources (like rivers or groundwater) (Tchobanoglous et al., 2011).

Skeptics tended to be community members or public health experts. They often did not buy into the notions that potable water reuse was necessary or safe. Many of them were aware that scientific advances for better detection of trace organic chemicals have changed the metrics for 'clean' water. They knew that scientific understanding of the health effects of hormone-disrupting chemicals is still evolving (National Academies of Sciences, 2017). Many of them felt the prudent way to deal with unknowns about potable water reuse was to avoid it, and instead stick with non-potable water reuse for irrigation, or to reduce water demand through conservation measures rather than try to increase the supply.

Most people, however, are entirely ignorant of issues of potable water reuse. Even in Orange County, where potable water reuse has been practiced for nearly half a century, every person I spoke with on my research trip with who was not directly involved with the water system in some way (e.g., waitresses, taxi drivers, hotel staff) had no idea that their water utility recycled sewage into drinking water. In Silicon Valley, where the water utility has plans for potable water reuse, most citizens I spoke with (tech employees, yoga teachers, and parents, among others) had heard of water recycling for irrigation but were completely unaware that wastewater could be recycled into drinking water. They were very curious about the fact that their water utility had plans to do so in the not-so-distant future; many had a host of questions about the technology.

To reconcile these perspectives, as well as communicate the basics of potable water reuse to citizens who are unaware of the practice, I developed the following magazine article which was published as a feature in Undark magazine in 2017. The article also clarifies some of the questions about the need for potable water reuse – who needs it, and why? The article began in a science journalism class I took with Michael Pollen at the UC Berkeley School of Journalism, and the co-author Mallory Pickett was my peer editor in the course.

To research the article, I drew on interviews with water managers, researchers, citizens, and public health experts, as well as documents on potable water reuse (white papers, reports, and academic literature) and visits to wastewater facilities in Orange County and Silicon Valley. The fact-checking editor at Undark confirmed the quotes with the individuals in the article as well as the material in the article with the relevant documents. In the traditional journalistic style, references and citations were not publically provided with the article aside from the highlighted links.

Excerpt from "Return to Sender: Can Recycled Water Help Alleviate California's Water Woes?" (Harris-Lovett and Pickett, 2017)

In July 2014, in the middle of one of the hottest and driest summers in California history, Silicon Valley celebrated the opening of its newest water supply facility: a $72 million purification plant that can produce clean water from sewage. A small crowd of local and state officials stood on stage. Before them sat an audience of nearly 200, and behind them loomed the new Silicon Valley Advanced Water Purification Center. Its pipes and filters would take treated sewage effluent from San Jose's wastewater treatment plant across the street and turn it into fresh water to irrigate the landscaping at the new Apple headquarters, the Villages Golf and Country Club, and the new Levi's 49ers stadium in Santa Clara, among other sites.

The plant's completion was 10 years in the making, and officials on the stage planned to christen the opening of the plant with a symbolic watering of two potted peach trees. They lifted their beakers of water, which just days prior had been flushed down Silicon Valley's toilets, and held them high as if raising Champagne flutes for a toast.

But they didn't water the trees. Instead, taking everyone by surprise, they brought the water to their lips and drank.

Pam John, the center's senior engineer, clapped from the audience. She wasn't shocked at the board's decision to toast the facility with a drink — she'd tasted purified water from plants like this many times — but she knew most of the audience would be. After all, that water was extracted not just from sewage from people's homes, but also from the stuff flushed down the toilets and drains of hospitals, laboratories, and manufacturing plants.

While the event that summer was simply a demonstration, it was illustrative of much longer-term ambitions for the plant, which include using the water it treats to recharge groundwater basins in Santa Clara County and, if regulation is passed, to someday pipe the water directly to customers.

Reusing wastewater isn't a new concept. Many countries have long used recycled water for non-potable purposes like irrigation and landscaping. And some, including the United States, Israel and Australia, also treat recycled water so that it can added to groundwater supplies. This process, known as "indirect potable reuse," is supposed to help keep consumers safe — and it has been used in California for over 40 years. In theory, allowing this treated, recycled water to percolate through an aquifer's natural soil and rock filtering systems diminishes any remaining contaminants — and it also gives managers, water quality engineers, scientists, and technicians time to detect and respond to any potential hazards.

California's current regulations, enacted in 2014, require recycled water to stay underground for two months before it is withdrawn for drinking. Many water utilities seem not to mind: Drawing drinking water from an aquifer helps preserve the illusion that it's "natural," even if it was sewage just a few months ago.

But not every utility that wants — or needs — to recycle water has a handy aquifer beneath it. That leaves some areas, particularly those facing water shortfalls, looking hard at the prospect of what's known as "direct potable reuse." In short, that's sending sewage first for treatment, and then directly to your tap.

This method, which in 2013 was active in fewer than a dozen municipal water plants around the world, according to a report by the Australian Academy of Technological Sciences and Engineering, could be implemented more or less anywhere. Interest in direct potable water reuse is growing, particularly in arid areas like the Southwestern United States. In Texas, for example, severe drought drove the city of Big Spring to build the first direct potable reuse plant in the U.S. in 2013. The next year, the nearby city of Wichita Falls also implemented the process, though only as a temporary emergency measure which has since been taken offline. The city of El Paso, Texas is now preparing to use direct potable reuse to supplement their water supplies.

It's the sort of solution that a growing number of cities might be forced to consider. The United Nations estimates that water scarcity is already affecting more than 40 percent of the world's population, and the problem is only expected to get worse amid a changing climate. Although California is experiencing a welcome respite from its years-long drought, the state's water woes are far from over.

"California needs more high quality water, and recycling is one way of getting there," declared California Governor Jerry Brown's 2014 California Water Action Plan, the administration's signature response to the drought crippling the state. That year, the state government enacted regulations to govern additions of recycled water to underground drinking water sources. Since then, they have streamlined permitting processes, provided financial and technical support for water recycling projects, and convened an expert panel to create recommendations for regulations for recycled water.

The federal government is enthusiastic about water reuse too: A grant last year provided $30 million of funding to seven different recycled water projects in California.

Those projects, the largest of which is in Orange County, use indirect potable reuse. But once California water regulators establish standards for potable water reuse, the Silicon Valley plant is likely to become the state's first direct potable reuse project. Planning to purify millions of gallons of water per day, it would likely also be the largest in the country, though Zach Dorsey, director of communications at the trade organization WateReuse, said utilities with indirect potable reuse projects may come to decide that moving to direct makes sense.

While drinking water extracted from sewage may sound profoundly unappetizing, as the state continues to grapple with limited water resources, public health experts say there needs to be discussion of the potential risks and benefits of "toilet-to-tap" technology.

On a cloudless day in March 2015, four years into the drought and one year after Governor Brown declared it a state of emergency, Pam John was preparing to give a tour at the Silicon Valley Advanced Water Purification Center in San Jose, California. At 56, she's cheerful and energetic, with big sunglasses and a red-and-black jacket. Over 22 years working in the Santa Clara Valley Water District, John has witnessed the explosion of the region's economy and stretching of its water resources first-hand. And as one of the senior civil engineers who helped design the Advanced Water Purification Center, and the facility's manager from January 2015 until her retirement last May, she knows the place inside and out.

From the street, it doesn't look like much. A few low-slung buildings and some large tanks and pipes sit in an open field behind a chain-link fence. But this plant, set on the southern edge of the San Francisco Bay, is poised to become the first in Northern California to purify recycled sewage to replenish groundwater aquifers. It could also be the first to send the water directly to consumers if the state approves new regulations for direct potable use, with the potential to serve up to eight million gallons of drinkable water daily.

Though the water it produces is now used for non-potable purposes only, it's designed as a demonstration plant, John explains. "When we built this plant, we knew what we wanted," she says. She gestures animatedly as she speaks. "We wanted to get to potable reuse."

Here in the heart of Silicon Valley, water is in short supply. Santa Clara County, where the plant is located, is home to the state's booming tech industry. Growing businesses demand water, and John is determined to get them what they desire.

"We want to ensure that the economic engine keeps on churning," she says with a wide smile. The Silicon Valley Leadership Group, a powerful trade organization that includes corporations like Chevron, Google, and Intel, wrote a letter of support for the Purification Center when the Santa Clara Valley Water District applied for state grants to help fund the project.

About half of the water used in urban California is used outdoors, largely for irrigating lawns and gardens, and Silicon Valley is no exception. "We spend thousands of dollars on good backyards and front yards, and yet not to be able to maintain it…" John says. "We want to make sure that quality of life continues."

According to John, the water utility is doing everything it can to stretch existing supplies, which are imported from the Sierra Nevada Mountains, 150 miles away, and pumped from local groundwater. They're encouraging water-wise landscaping. They're giving rebates for high-efficiency appliances. They import water from the Sacramento-San Joaquin Delta. They capture rainfall and infiltrate it back into the groundwater basin. But when it doesn't rain, water capture doesn't help.

"We are entering the Fourth. Year. Of drought," John enunciates. Which leads us back to the sewer as an option of last resort.

She starts the tour by the pumps, where treated sewage from the wastewater treatment plant across the street enters the Purification Center. Silicon Valley's sewage, like all sewage, is nasty stuff. After standard sewage treatment, it still contains trace amounts of salt from bodily fluids and water softeners, bacteria from feces, pharmaceutical drugs and hormones we take and excrete, and chemicals we use around our homes. That's not all. Silicon Valley's treatment plant also accepts industrial wastewater, which contains a slew of different compounds used in processing and manufacturing. Since about 10,000 new chemicals are developed each year, a leading textbook on water reuse, published in 2007, states that knowing exactly which chemicals are in wastewater at any given time is an "unachievable goal."

When the wind blows just right, the smell of sewage wafts on the breeze from across the street.

John's low-heeled black boots clack on the cement as she heads to the next stop, a large warehouse. Another set of pumps bringing wastewater over to the Purification Center whir like airplane propellers. Everything looks spotlessly clean. The place is remarkably devoid of humans. Other than a water quality engineer crouched by one of the valves, a smartphone edging out of the back pocket of her jeans, everything is automated. If something goes wrong alarms will sound and the equipment will automatically shut down, John says reassuringly.

Poster-sized photos hang from the warehouse ceiling: a smiling woman with a full glass of water, a sprinkler on a sports field, freshly harvested produce. On the right are long banks of filters, standing nearly 8 feet tall, which strain out anything bigger than 0.1 micron, which is about 1/1000th the width of a human hair. On the left are stacks of pipes that house reverse-osmosis membranes.

Reverse osmosis works by pushing contaminated water against a semi-permeable membrane at high pressure. Ideally, only water molecules are forced through. Everything stuck on the wrong side of the membrane — that is, anything wider than 0.0001 microns across, including salts, microorganisms, viruses, and contaminants from most personal care products and pharmaceuticals — is sent back through the wastewater treatment plant across the street to either be recycled or treated again before being released into San Francisco Bay.

In reality, *mostly* only water molecules get through reverse-osmosis membranes. The technology filters out most contaminants but not all of them. Some especially small molecules, like acetone (the stuff in nail polish remover), 1,4 dioxane (an industrial solvent), or n-nitrosodimethylamine (formerly used to manufacture rocket fuel), can potentially slip right through.

How well reverse osmosis works to filter out other contaminants, like pharmaceuticals and pesticides, depends on the specific chemical and the amount of pollution in the water. The water reuse textbook states that reverse-osmosis membranes strain out 90 to 96 percent of the toxic pesticide atrazine, for example, and 85 to 95 percent of the poisonous element arsenic. Most of the time, this means there is a very small amount of these pollutants left in the water after reverse osmosis. But if there were an atrazine spill, and a lot of the pesticide was washed into the sewer, then a potentially harmful dose of the toxin could make it through reverse osmosis. The final step of treatment is a blast of ultraviolet light. If any germs or harmful chemicals make it through reverse osmosis, the UV light is supposed to scramble their DNA or shatter their molecular bonds. If the water is used for drinking, advanced oxidation processes will be added to break down any remaining toxic organic compounds. John declares these combined water treatment technologies "fail-safe." Yet even "fail-safe" engineered systems — like the Titanic or the Fukushima nuclear power plant — can malfunction under unusual circumstances.

Near the end of the tour, there's a table set up with several beakers of water on it. Each beaker holds water from a different part of the process. When the wastewater first enters the Purification Center, it's slightly cloudy, with a hint of a golden-brown hue. (One tries not to think about what made it that color.) By the time it leaves, it really is completely clear, and completely odorless (and tasteless, stripped of the minerals that normally flavor tap water). Then it's off to a massive holding tank before being sent out to customers through non-potable pipes — for now.

When John describes the process, she sounds like a preacher talking about redemption. “We don’t have to be stranded in a state where we’re at the beck and call of hydrologic cycles,” John says, her voice resonating. “Will it rain, will it not rain? Maybe we can change that paradigm.”

Improving on such hydrologic cycles is hardly a new idea in California. For nearly a century the state has been building dams and hundreds of miles of canals to transfer water and snowmelt from the wetter regions of California to its arid cities and farms. Based on the host of unforeseen ecological outcomes that arose from building dams, one can’t help wondering if water recycling will also have unexpected consequences.

Dr. Florence Bonvin studies the traces of chemicals that get through the advanced water treatment technologies the Silicon Valley Advanced Water Purification Center and similar facilities use. She is athletic, with an easy smile. Bonvin specializes in a set of tiny chemical molecules that aren’t dangerous, but that can leave a telltale smell in highly treated wastewater.

One of these chemicals is vanillin, the primary component in vanilla bean extract, which smells sweet and delicious. “But most of them are not as nice,” Bonvin said. “They’re musty, earthy, medicinal.” She knows that if recycled water smells bad, people won’t want to drink it.

Human noses are remarkably sensitive chemical detectors. “Even if we remove 99.9 percent of a specific compound during treatment, [that might] not be sufficient to have levels below the odor threshold,” Bonvin explains. The odor threshold is the lowest concentration at which 50 percent of a human panel can sniff out one of these chemicals. And for many of the chemicals she studies, the threshold is less than 10 parts per trillion. That’s like being able to smell one grain of wild rice in 3.4 million pounds of white rice.

Bonvin recently completed a stint as a postdoctoral researcher at UC Berkeley. (She now works in research for a private potable reuse company in Switzerland.) In the spring of 2015, she gives a tour of her lab on the second floor of a bulky concrete building on the Berkeley campus.

Bonvin moves gracefully through the lab to her workbench, where vials of perfectly clear water, with which she has spiked minute amounts of different chemicals, are lined up by on a lab bench, ready for analysis.

The instrument she uses for the analysis is topped by a little red box, which shakes rhythmically. It mixes the water in one of the vials around a thin wire, which sticks into the fluid and will trap chemicals on its surface. Those chemicals are injected into an instrument called a gas chromatograph, where they can be separated based on their different characteristics. By measuring their different masses, Bonvin is able to detect ever-lower concentrations of some of the smelly chemicals. But she concedes that there are many more potential chemical contaminants for which no measurement method has yet been developed.

And if there isn’t a way to test for them, they could make it past treatment.

The smelly molecules that come through wastewater treatment are only part of the problem. When these chemicals get through advanced treatment, it means that other, more dangerous, compounds have likely gone through as well. “On the one hand, you have the taste and odor, which are not dangerous to human health, but aesthetically, could alter public perception of the water," Bonvin says. "And then on the other side you have the solvents, which we can't really see or taste, but could have effects on human health."

Solvents are a class of chemicals used for a range of purposes from dry cleaning to paint thinning to manufacturing. Many of them are small molecules, so they can slide untreated through reverse osmosis. And many of them are poisonous to humans.

Solvents and other industrial chemicals that can disrupt hormones in the body's endocrine system are particularly worrisome. With a litany of dreadful health effects like cancer, birth defects, and infertility, these endocrine-disrupting chemicals can be extremely toxic even at the very low levels that could potentially get through even the most advanced water treatment, including reverse osmosis and advanced oxidation.

"It's not reassuring to me to hear that chemicals are present "only" at parts per trillion levels," said Ted Schettler, a physician and the science director of the non-profit Science and Environmental Health Network. "There are many chemicals that you would worry about at parts per trillion."

Parts per trillion is really tiny — like having one drop of poison spread throughout 20 Olympic-size pools. For some chemicals, we don't even have analytical methods that can accurately detect such low concentrations. Yet even such a minuscule amount can have an effect on our bodies. "Our bodies' hormone systems operate at low parts per trillion levels," Schettler explained. "The hormone receptors are exquisitely sensitive to even minor shifts in those concentrations."

The Environmental Protection Agency counts about 85,000 industrial chemicals registered for current use, but requires additional toxicity testing for only about 200 of them. Pesticides in home and garden products, which are regulated by the EPA's Federal Insecticide, Fungicide, and Rodenticide Act, can also make their way down the drain, as can FDA-regulated pharmaceuticals, which people excrete naturally after use.

This all means that tens of thousands of different chemicals may be present in sewage before treatment—and after treatment we still don't have a full idea of the range of chemicals that get through. "What you really need to do is figure out what's in the water, and at what levels," Schettler said.

But that's easier said than done.

No one knows exactly what's in sewage at any given time—people and businesses don't dump things down the drain on a regular schedule. It's very hard for a water scientist or public health official to know everything to look for. And since detecting tiny amounts of chemicals relies on identifying them by their unique characteristics, it's nearly impossible for them to recognize a chemical they weren't already looking for.

Of the contaminants that *are* detected in recycled water, many of them have unknown health effects. "There's a lot [of chemicals] out there, that show up in monitoring, but that we don't really know what the broad effects might be from them," said David Spath, the former Chief of the Division of Drinking Water and Environmental Management for the State of California. Even more troubling is that a combination of chemicals can be more toxic than the sum of their parts. It could be a big problem, according to Spath, "if you get three or four chemicals that are all endocrine disruptors that disrupt the same endocrine process, or if you have two or three chemicals that are all carcinogens that result in the same carcinogenic endpoint."

Only one major epidemiological study has documented the human health effects of drinking recycled water. Conducted by a private research corporation and commissioned by a water utility, the study is now more than 25 years old. ("The chemicals that they're now looking for weren't even in anybody's vocabulary at the time," Spath said.) The science was inconclusive: Because of confounding factors like smoking and alcohol consumption, researchers couldn't prove or disprove the notion that drinking recycled water caused cancer or heart disease. The fact that some chemicals could disrupt hormone functioning hadn't yet been discovered at the time the study was published.

"It is a difficult situation," Spath added. He sighed. "You've got the pressure to move forward, and in some cases the need to move forward with these types of uses, because of the water resources situation in California."

The timeline for sending Silicon Valley's recycled water directly into the drinking-water pipes is uncertain, pending the state's development of regulations for direct potable reuse, which are estimated to be completed in the next few years.

In the meantime, the water agency plans to stick with indirect reuse: send the recycled water back into the aquifer, and then pump it out for drinking. Garth Hall, Deputy Operating Officer of the Santa Clara County Water District, estimates Silicon Valley will be drinking this recycled water by 2020.

After Governor Brown mandated in early April 2015 that all California water districts cut their water use by 25 percent, Silicon Valley residents were limited to watering their gardens twice a week. Grassy medians turned brown. Burbling fountains fell silent.

But 750 sites in Silicon Valley were spared the water restrictions. These sites, ever lush and green, include various city parks, the Intel corporate campus, and the grounds of Great America amusement park. As customers of the South Bay Water Recycling Program, some of the water they use comes from the Silicon Valley Advanced Water Purification Center.

Walking through two of these city parks on a Sunday afternoon during the dry spring of 2015, most park-goers had no idea recycled water was currently used for irrigation or that Silicon Valley was planning to use recycled water for drinking in the near future.

"I think recycled water is a great thing," said LaRee Rouse of Santa Clara, as she watched her children climb on a play structure surrounded by the verdant lawns of Lick Mill Park. She paused, "But I don't know much about drinking recycled water, how good it is for you or not. For watering grass it makes sense."

For Ana Reyes, who recently moved to San José from San Antonio, Texas, people who live in an arid environment have to learn to be thrifty with water. "I can't believe y'all are just doing conservation efforts now," she said. But if it comes down to it, she says she would drink recycled water. "I'm fine with it as long as it's safe," she added.

Reyes isn't alone. In a 2014 poll from the non-profit National Resources Defense Council, 64 percent of the 1,000 Californians surveyed said "building local water-recycling plants is a very important water supply solution." But when it comes to the long-term health effects of drinking recycled water, no one really knows for sure.

California has since lifted its statewide water restrictions and allowed counties to set their own goals, but the Santa Clara Valley Water District is still aiming to cut water use by at least 20 percent. The state legislation is moving to develop regulations for the use of treated sewage as a drinking water supply. The recycled water unit chief for the State Water Resources Control Board, Randy Barnard, said in 2015 that the current advanced treatment technologies, like those at Silicon Valley's Advanced Water Purification Center, are covering all contaminants and that testing has found "no measurable health risk."

Knowing that there's no good data on the long-term health effects of ingesting trace amounts of countless chemicals and pharmaceuticals in recycled water, Spath, the retired Chief of the Division of Drinking Water, is wary. "I think prudence would argue for a slow, measured process that assesses the risk," he said. In his view, recycled water should be used for the lowest-risk purposes, like watering plants, first. Part of the discussion about integrating recycled water directly into our drinking water supplies should include "an understanding of the potential for future health consequences," he wrote in an email.

In December, 2016, California water regulators released a report to the State Legislature on the feasibility of developing state-wide criteria for direct potable water reuse, based on the recommendations of an expert panel and an advisory board convened by the state to evaluate direct potable reuse. They concluded that while creating regulations to recycle sewage into drinking water is feasible, there is a need for better methods to identify potential contaminants and to study their effects on our health.

After a draft of the report came out came out in September, Barnard took a more cautious stance. On October 3, 2016, he emailed that while direct potable reuse has great potential, there are "very real scientific and technical challenges that must be addressed before DPR can be consumed by public water system customers."

But state regulators aren't planning to wait for this research to be done before passing regulations to allow direct potable reuse; the report (which was supported by "significant time, effort, and investment" from water reuse advocacy groups) concluded that the research could be done concurrently with developing regulations. Barnard could not say when such regulation would be passed.

Silicon Valley, along with other California cities, continues to move forward with plans to use recycled water for drinking. During her tour, Pam John showed a map of Santa Clara County that gave a glimpse into the future. Different colored lines squiggled across the city streets, marking the current location of drinking water pipes in green and recycled water pipes in purple. John had delineated all the places where recycled water produced at the Purification Center could be connected directly to drinking water pipes.

"There are options," she said, smiling.

In the three years since the Silicon Valley Advanced Purification Center came online, Pam John has retired but the plant's ambition and influence have kept growing.

In keeping with its mission as a demonstration facility, the plant hosts visitors from water districts throughout the state and international guests who come to learn about their technology and their marketing. Last June, water officials from the City of Pleasanton, which is considering building a similar facility, came to discuss their options.

This time their host was a young engineer, Paolo Baltar, fresh out of graduate school but cool and confident, and Marta Lugo, the center's polished and knowledgeable outreach coordinator. The Pleasanton officials were just as keen on the details of the plant's public outreach as its technology. The Dublin San Ramon Services District, which provides wastewater treatment for the City of Pleasanton, had tried to implement an indirect potable reuse project years ago, an effort abandoned in the face of opposition from citizens disturbed at the prospect of drinking purified sewage. But that was before the drought. Baltar and Lugo assure them that things are different now. People understand the value of a reliable local water source, even if the source is a bit icky.

Water engineers frequently point out that in comparison to some other water supplies, like imported water from the Colorado River, recycled water actually contains fewer known contaminants, like nitrates or arsenic. Many people are already drinking recycled water treated much less thoroughly than what happens at the Santa Clara plant. Besides the aquifers in Orange County and the lake water in Texas, hundreds more are located downstream from sewage effluent, so residents' water supply contains wastewater that hasn't been treated to recycled water standards so much as diluted, what water officials call "de facto" or "unplanned" potable reuse.

"Do you tell people they've been drinking recycled water for 50 years?" one of the Pleasanton officials asked Lugo. "How much do you leverage that?"

"We don't focus too much on de facto recycled water," Lugo said. "We don't want to get them focused on 'Oh, what's in the Delta water?' or go down that path."

Instead, she says they remind their customers, "All water on Earth is recycled. There's no new fresh water anywhere."

Conclusion

One of the fascinating aspects of the phenomenon of potable water reuse is the decision-making process that leads to it. Who decides that potable water reuse is the solution? And what is the problem it is assumed to solve? Pam John, the engineer in Silicon Valley, articulates her perspective on some of these needs in the article: the need for more water to irrigate expensively landscaped gardens, the desire to be free from seasonal constraints of the water cycle. These goals may resonate with some Silicon Valley stakeholders and not with others.

As demonstrated in previous chapters, decisions about potable water reuse in the United States have been made historically by wastewater and water utility staff with little stakeholder input. This decision-making process is changing, with more recognition of the need for stakeholder involvement in the process (Marks, 2006). Other multi-benefit wastewater technologies, in addition to potable water reuse, are in a similar position with regards to decision-making.

Transitioning towards more public participation in decision-making about wastewater infrastructure is particularly interesting because wastewater has traditionally been treated in an 'out of sight, out of mind' manner by the public in the United States. Bringing wastewater treatment more into the public eye, in a way that is satisfying and appealing to members of the public, may be a substantial challenge.

The following section of this dissertation focuses on strategies to support decision-makers in articulating and clarifying goals for multi-benefit wastewater infrastructure systems. Project objectives that are clear, transparent and well-supported by stakeholders can help lead to water systems with broad community support for allocation of funds, and avoid investments in projects that will face steep opposition (Lienert et al., 2014). The following section focuses on a case study of planning for nutrient management in San Francisco Bay. It develops a stakeholder-informed method of identifying goals for multi-benefit infrastructure, reveals strategies for meeting multiple goals, and highlights the barriers to implementing multi-benefit water infrastructure projects.

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Chapter IV: Decision-making about multi-benefit wastewater treatment

Preface

Water and wastewater systems in the United States have historically been designed to solve a specific problem. In the case of potable water reuse described in the last chapter, this problem was conceived and articulated by the managing engineers in Silicon Valley: residents needed more water supply to maintain their expensive gardens, among other uses. After considering a set of options for solving the problem, like importing more water from the Sacramento-San Joaquin Delta, encouraging drought-resistant landscaping, and recycling wastewater into the drinking water supply, the utility conceived of a plan that involved all of these solutions.

Yet the definition of the problem, the desired project outcomes, and the range of possible solutions could have been different in the Silicon Valley case if the problem were defined differently, for example as, 'Silicon Valley's population has outgrown the region's natural resources, and water scarcity is compounded by unnecessary irrigation of status-symbol gardens.' The solution to this problem might entail a different set of potential solutions and would likely have different project outcomes to determine success. In this re-framed problem statement, potable water reuse may not have been a desirable solution, and it may have faced public opposition.

Thinking about water infrastructure systems in this way raises questions: who gets to define the problem? How is the success of a water project determined? What is the range of options under consideration to solve the problem, and how do these options meet the project's goals?

This is a critical time to think about these questions, because many wastewater treatment systems across the United States currently need expensive upgrades to address challenges posed by pollution, population growth, and climate change (Du et al., 2014; Heberger et al., 2009; National Research Council, 2009; Scott et al., 2012; Tafuri and Selvakumar, 2002; Vidal-Dorsch et al., 2012a). Researchers, practitioners and members of the public have expressed concerns that solutions to individual problems may miss opportunities to create more effective and sustainable systems (Hering et al., 2013). For instance, if investments required to control nutrient discharges to sensitive ecosystems could also improve wildlife habitat, enhance drinking water supplies and save energy, it might be worth spending more money to build and operate the project. Such multi-benefit projects are not well-supported by current planning and decision-making processes.

In addition, water projects conceived and implemented without transparent intentions and in the absence of public support tend to face public opposition (Hurlimann and Dolnicar, 2011, 2010; Marks, 2006). This implies a starkly different need from traditional decision-making modes in the water sector, where the public tended to rely on and implicitly trust water engineers' definitions of the problem as well as range of potential options to solve it (Hundley, 2001). With multi-benefit water projects, an inherently wider range of stakeholders is implicated in the problem definition (Hermans et al., 2007). Articulating clear, stakeholder-informed objectives for water infrastructure projects and being able to clearly delineate how different options meet these objectives also helps support for funding these projects (Hämäläinen et al., 2001).

To support stakeholder-informed, multi-benefit designs for wastewater treatment this chapter considers efforts to protect the San Francisco Bay from excess nutrients in sewage. The research identifies stakeholders' broad goals for a wastewater infrastructure project, and highlights management strategies that can help reach these goals. We identify and analyze the social, institutional, and technical impediments to planning and implementing multi-benefit wastewater infrastructure projects and identify strategies to overcome some of these challenges.

Excerpt from 'Towards a New Paradigm of Urban Water Infrastructure: Identifying Goals and Strategies to Support Multi-Benefit Municipal Wastewater Treatment' by Sasha Harris-Lovett, Judit Lienert, and David Sedlak. *Water* 10.9: 1127. (2018)

Introduction

Throughout the world, researchers and practitioners have expressed the need to move towards a more sustainable paradigm for wastewater treatment and water management (Daigger, 2009; Farrelly & Brown, 2011; Grant et al., 2012; Gregory et al., 2006; Guest et al., 2009; Hering et al., 2013; Larsen et al., 2016; Makropoulos et al., 2008; Miller, 2006; National Research Council, 2009; Pahl-Wostl et al., 2011; Smith, 2009; Wilsenach, et al., 2003). This new paradigm entails a shift in goals and expectations for municipal wastewater treatment by encouraging the recovery of water, energy and nutrients from sewage; by employing natural systems for water treatment; and by coordinating among agencies managing different facets of water systems. The implication is that wastewater treatment plants should do *more* than meet their traditional objectives of protecting receiving water quality by removing organic matter, nutrients and pathogens from sewage.

In the United States, much of the municipal wastewater infrastructure is nearing the end of its design life (United States Environmental Protection Agency, 2016). In the next two decades, hundreds of billions of dollars will be needed to maintain wastewater systems, amounting to an investment of approximately $830 per person in the United States (American Society of Civil Engineers, 2017; United States Environmental Protection Agency, 2016; US Census Bureau, 2018). In addition, population growth, sea level rise and concerns about impacts of nutrients and trace organic contaminants in wastewater may require additional investments in existing wastewater treatment systems (Du et al., 2014; Heberger et al., 2009; National Research Council, 2009; Scott et al., 2012; Tafuri & Selvakumar, 2002; Vidal-Dorsch et al., 2012a).

Traditional approaches, in which problems are solved separately through the installation of additional treatment systems, may not be sufficient for transitioning urban water systems to a more sustainable course (Ferguson, Frantzeskaki, & Brown, 2013; Truffer et al., 2010). Instead, institutional shifts that embed regulatory and political support for multi-benefit infrastructure early in the planning process may be more effective (Werbeloff, Brown, & Cocklin, 2017). Furthermore, cooperative regional approaches to water management are often less expensive and more efficient (Zeff et al., 2016), particularly in preparation for uncertain future conditions (Herman et al., 2014).

Transitions to more sustainable water systems require clear articulation of a long-term vision (Malekpour, Brown, & Haan, 2017). Yet the development of this shared vision is often assumed or overlooked, even in cases that take a deliberative approach to multi-benefit infrastructure (e.g, (Cohon & Marks, 1973; Everard & McInnes, 2013). In addition, many institutional impediments exist to implementing multi-benefit water infrastructure (Brown & Farrelly, 2009).

To characterize and develop the specific, regional goals that underlie a more sustainable vision of wastewater infrastructure, we analyzed a case study of planning for nutrient management in the San Francisco Bay Area, California. Our research aims to identify strategies for fulfilling multiple goals by analyzing the social, institutional, and technical impediments to planning and implementing multi-benefit wastewater infrastructure. It examines the ways in which current institutional structures and modes of decision-making help or hinder the transition to a new paradigm for urban water systems. It investigates the possibility of new institutions, relationships, or processes that can support these objectives. By demonstrating a mixed-methods approach for eliciting these context-specific goals and strategies with local stakeholders, including stakeholder analysis, multi-criteria weight elicitation, and secondary document analysis, we provide a replicable example to support other multi-benefit water resources planning initiatives.

Materials and Methods

Case Study Background

The southern reach of San Francisco Bay receives approximately 34,000 kg of nitrogen each year, primarily from municipal wastewater treatment plant discharges (Bay Area Clean Water Agencies, 2016; McKee & Gluchowski, 2011; Novick & Senn, 2014). Domestic sewage is the main source of nutrients in municipal wastewater in locations such as the San Francisco Bay where industrial discharges are small (Lienert & Larsen, 2007b). Eleven municipal wastewater treatment plants discharge into this portion of the Bay (see Figure 1), making it one of the most heavily nutrient-laden estuaries in the nation in terms of concentration in Bay water (Glibert et al., 2010).

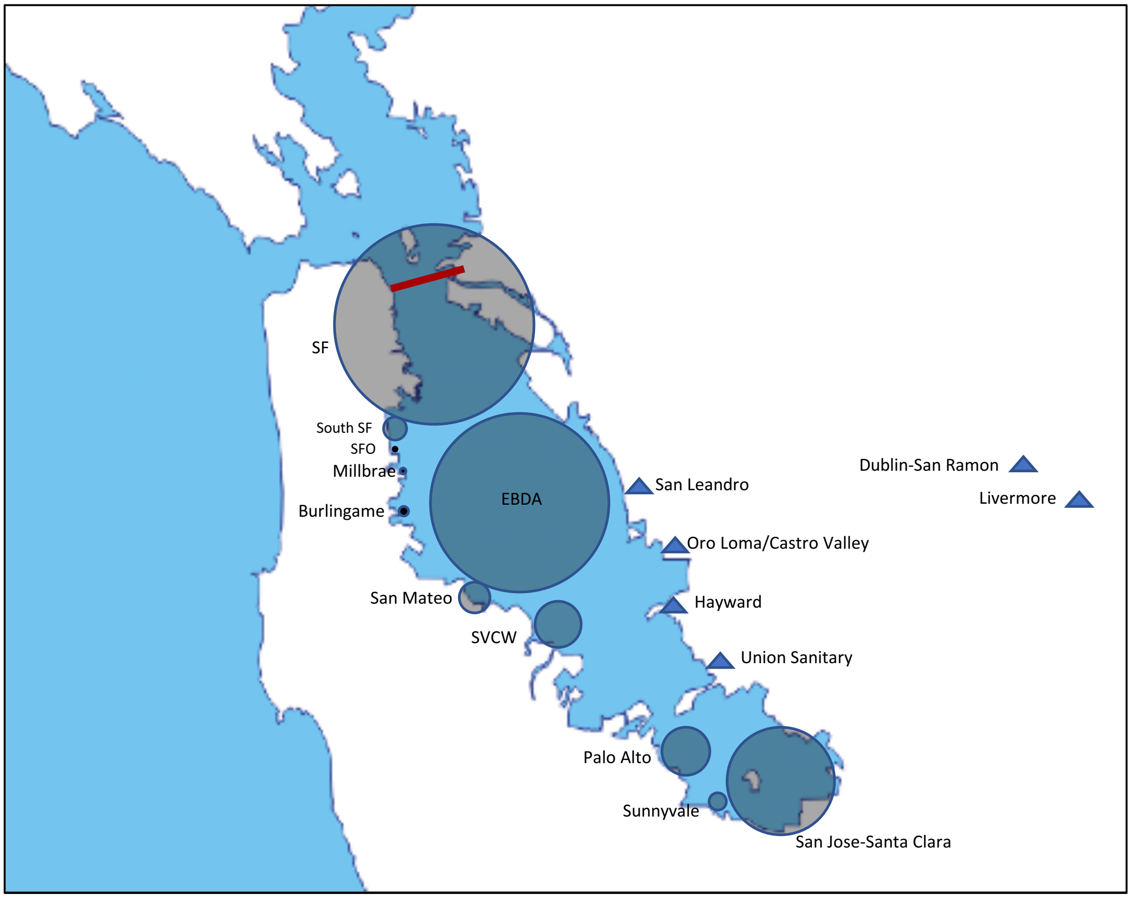

Figure 1. Locations of wastewater effluent discharges in the southern reach of San Francisco Bay. Dot size corresponds to average daily mass of total nitrogen discharged. Triangles mark locations of wastewater treatment facilities that discharge effluent via the East Bay Dischargers Authority (EBDA) outfall pipe. The *line marks the San Francisco Bay Bridge, which delineates the southern reach of the Bay. (Base image © d-maps.com/Wikimedia Commons/2017)*

During the second half of the 20th century, primary productivity in the San Francisco Bay was limited by sunlight penetration. As a result, the Bay showed very little sign of the eutrophication that is common in other nutrient-rich aquatic ecosystems (Glibert et al., 2010). However, water managers are concerned that current nitrogen loads could soon result in poor water quality and impairment of the Bay's beneficial uses, due to shifting environmental conditions like increasing water clarity, potential for longer water stratification periods, and declining populations of invasive bivalves (Cloern & Jassby, 2012; Glibert, 2010; Kimmerer & Thompson, 2014; Lehman et al., 2013; Sutula & Senn, 2015).

Wastewater treatment facilities have traditionally enacted plant upgrades in response to regulatory concerns about effects of pollution on receiving waters. For nutrient control, these upgrades are generally energy intensive and expensive (Butt & Brown, 2000; Corominas et al., 2013; Malone et al., 1993). Upgrades frequently consist of nitrification and denitrification or biological nutrient removal (Tchobanoglous, Burton, & Stensel, 2002). Despite large capital investments, nutrient reductions do not always result in immediate improvements in conditions if water quality is already severely impaired, as in the case of the Chesapeake Bay (Butt & Brown, 2000).

In the Bay Area, water managers are proactively addressing nutrient problems before the ecological situation deteriorates. Dischargers, regulators, baylands stewards and scientists in the region have established a stakeholder working group to address nutrient pollution and reduction strategies. This group consists of a steering committee, a stakeholder advisory group, a technical working group, and a science team (San Francisco Bay Nutrient Management Strategy, 2016).

In 2014, the local regulator, the San Francisco Bay Regional Water Quality Control Board, implemented a watershed-wide nutrient-related permit for dischargers. This permit, which is valid until 2019, mandates that dischargers monitor and report loads of nutrients in their effluent and annually fund scientific studies to assess effects of nutrients on Bay ecology. Dischargers also must identify opportunities for treating and removing nutrients from wastewater effluent (San Francisco Bay Regional Water Quality Control Board, 2014). In addition to examining the potential for treatment plant upgrades to lower concentrations of nutrients in wastewater effluent, the permit also specifies, "Dischargers may evaluate ways to reduce nutrient loading through alternative discharge scenarios, such as water recycling or use of wetlands, in combination with, or in-lieu of, the upgrades to achieve similar levels of nutrient load reductions." (San Francisco Bay Regional Water Quality Control Board, 2014)

The language in the 2014 permit reflects the local sentiment that next-generation wastewater treatment could achieve more than safe discharge of effluent. A regulator at the San Francisco Regional Water Quality Control Board explained in an interview:

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

By proactively addressing nutrient loading in the Bay, Bay Area water managers have more leeway to be visionary and to consider new paradigms for multi-benefit wastewater infrastructure than if they were reacting to acute impairment of water quality.

Nationally, there has been a push in recent years to address excessive nutrient loading into surface waters (Beauvais, 2016). After the complicated and costly experience of trying to control nutrients in the Chesapeake Bay (Butt & Brown, 2000; Malone et al., 1993), many water managers across the country are looking to the Bay Area for guidance on how to proceed. According to a regulator at the Environmental Protection Agency Region IX (EPA),

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

Therefore, the case of Bay Area nutrient control offers insight into nutrient management strategies nationwide, as well as highlighting opportunities and obstacles to transitioning to a new paradigm of multi-benefit urban water infrastructure more broadly.

Data collection process

To assess stakeholder perspectives, we conducted two rounds of stakeholder interviews. The first round of interviews focused on elicitation of goals for good nutrient management and the second focused on eliciting the relative importance of these goals to decision-making. Analysis of regional planning documents (e.g., (Association of Bay Area Governments and the Metropolitan Transportation Commission, 2017; *San Francisco Bay Area Integrated Regional Water Management Plan*, 2013) as well as strategic water management plans at the utility and city scale (City of Livermore, 2016; City of Palo Alto Utilities, 2016; Dublin San Ramon Services District, 2016; GHD, 2016; San Francisco Public Utilities Commission, 2016; Santa Clara Valley Water District and City of San Jose, 2014) was also conducted to contextualize and triangulate interview responses. Findings from the document analysis are presented in the discussion in relation to the results of stakeholder interviews.

Data collection to elicit goals

First, in-depth, semi-structured interviews were conducted with 32 stakeholders using open-ended questions to elicit information about their goals for "good nutrient management" in San Francisco Bay. "Good nutrient management" was chosen as the primary objective based on a previous study of sustainable water infrastructure planning in which stakeholders described goals for "good water supply and wastewater disposal infrastructure" (Lienert, Monstadt, & Truffer, 2006; Lienert, Schnetzer, & Ingold, 2013). The phrase "nutrient management" (rather than an alternative like "nutrient control") was chosen to reflect the language in the regional Nutrient Management Strategy (San Francisco Bay Nutrient Management Strategy, 2016).

Stratified sampling and snowball sampling were combined (Lienert et al., 2013) to select stakeholders for first-round interviews. Stakeholders were initially identified based on their professional interest in nutrient loading to San Francisco Bay, specifically whether they were involved with decision-making or would be affected by decisions made (Grimble & Wellard, 1997; Reed et al., 2009) about nutrients in the Bay. The selected group included water managers, baylands stewards, researchers, engineers, regulators, urban planners, flood control managers, and advocates for coastal industry or environment at the local, regional, and federal scales (Kunz, Moran, & Kastelle, 2013). Individuals within organizations were selected based on their professional involvement with San Francisco Bay nutrient management, as evidenced by their authorship of documents or presentations pertaining to the issue. If no one in an organization was closely affiliated with nutrient management, the person with the most responsibility for strategic planning was contacted using publicly available professional email addresses. A set of stakeholders with diverse professional roles, who were operating on different scales (i.e, local, regional, and federal) were sampled.

Once interviews commenced, snowball sampling (Atkinson & Flint, 2001; Biernacki & Waldorf, 1981) was used to identify other stakeholders. Participants were asked to rate their own influence over decision-making as well as how much decisions made about nutrients would affect them, on a scale of 1-7. They also rated the influence and defined the extent to which others would be affected. This information was used to determine the set of stakeholders involved and to better characterize the local social networks (Lienert et al., 2013). Multiple stakeholders from a single organization were contacted when they had distinct roles in the decision-making process about nutrient management and when they were identified by other stakeholders in the snowball process. Several stakeholders represented more than one organization (e.g., one person served as director of an industrial advocacy group and also served on the board of a public wastewater utility). Of the 88 individuals contacted initially, 32 stakeholders (representing 29 different organizations) agreed to participate in an interview. They were categorized according to their professional role and their relevance to decision-making (see Supplemental Information, Table S1).

First-round interviews with stakeholders yielded more than sixty goals for "good nutrient management" in San Francisco Bay as a response to the questions "In your opinion, what are the most important goals for any nutrient management scheme or technology?" and "What are the most important goals for good nutrient management in San Francisco Bay?" (Table S2).

Responses included objectives for the process of managing nutrients (e.g., collaboration among people in different fields to develop a management plan, and basing regulatory limits on site-specific scientific evidence of effects) as well as goals that characterized the end result of nutrient management (e.g., building systems that are resilient to sea level rise or that result in good water quality in the Bay). To inform a multi-criteria decision analysis (MCDA) (see Chapter 5), goals were selected that characterized the end result of good nutrient management, based on the philosophy of "value focused thinking" (Bond, Carlson, & Keeney, 2010; Keeney, 1992, 1996; Keeney & Raiffa, 1993). To reduce the number of fundamental objectives for ease of mental processing for a MCDA (Belton & Stewart, 2002; Marttunen, Belton, & Lienert, 2018), similar goals were combined (e.g., "low costs" and "low initial capital investment") to yield 13 separate goals. Goals that were a means to a more fundamental objective (for example, "consider the low-hanging fruit for infrastructure upgrades" was deemed to be a means to "low initial capital investment") were eliminated (Eisenführ, Weber, & Langer, 2010). An objective the researchers deemed to be important, "ease of use of the nutrient control technology or system", was added, since decision-makers tend not to articulate all the objectives that are important to them for any decision (Bond, Carlson, & Keeney, 2008).

We categorized the final list of objectives into overarching categories, where the sub-objectives describe the scope of different goals in each category (Eisenführ et al., 2010) (see Figure 2). Although they were not included in the objectives hierarchy, the process-oriented goals stakeholders mentioned are characterized in the discussion section of this paper.

Data collection to elicit importance weights

Follow-up interviews were conducted with nine stakeholders and decision-makers (a subset of the original group of 32) who are closely involved in planning for nutrient management in San Francisco Bay. We chose the subset to participate in a second interview by performing a cluster analysis based on each stakeholders' stated goals for nutrient management in the first interview (see Chapter 5). From each of the seven resulting clusters, we contacted those stakeholders who we classified being most relevant to decision-making to participate in a second interview (on a scale of 1 to 4, with 1 being most engaged with or affected by decision-making about nutrient loading) (Table S1).

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

In the nine follow-up interviews, in-depth explanations of the importance of each of the sub-objectives was elicited, as well as their relative importance to decision-making from each stakeholders' perspective. Interviewees assigned points (from 0-100) for the importance of improving the measure of each of the objectives from its worst to its best state using the Swing method for elicitation (Mustajoki, Hämäläinen, & Salo, 2005; Schuwirth, Reichert, & Lienert, 2012), which is commonly used in MCDA (Eisenführ et al., 2010). These point values were then confirmed by comparison to an initial ranking of the importance of each of the objectives. Quantitative weights (on a scale of 0-1) were then calculated for each of the sub-objectives for each of the stakeholders based on the points they assigned. Weight elicitation requires the respondent to make trade-offs between achieving different objectives, which is cognitively demanding and subject to various biases (Montibeller & Winterfeldt, 2015). It is especially important to consider the range of the objectives, i.e. the best- and worst-possible outcome of each objective (Eisenführ et al., 2010), given the specific decision options, which were carefully prepared beforehand (see Harris-Lovett, in preparation).

First round interviews lasted 30-90 minutes and were conducted primarily one-on-one over the phone, with the exception of four individuals from one organization who asked to be interviewed in person together. These four individuals filled out surveys with open-ended questions first to elicit individual preferences and points of view, then engaged in group discussion for the remainder of the 2-hour interview. Second round interviews were conducted in person and took 60-120 minutes. Interview notes and recordings were transcribed, then coded using MaxQDA software.

The interview protocols were approved by the Institutional Review Board at the University of California, Berkeley.

Stakeholder/institutional analysis

Interview questions eliciting information about stakeholders' relative decision-making power and influence in the first set of interviews were triangulated with documents about decision-making modes and procedures for nutrients and for water quality in general, regionally and federally. For example, some respondents indicated that the regulators at the US Environmental Protection Agency (EPA) had ultimate power over decision-making about nutrients, which was confirmed by documents on EPA's power to promulgate water quality standards (US EPA, 2014). Interview questions in which stakeholders described their institutional roles and constraints in the first set of interviews were triangulated with official job descriptions, organizational websites and mission statements, and regional and organizational strategic planning documents. For example, a discharger's statement that they were obligated to evaluate different options for nutrient control was confirmed in the official nutrient watershed permit (San Francisco Bay Regional Water Quality Control Board, 2014). Responses about barriers to multi-benefit infrastructure and strategies to overcome them emerged in different parts of the interviews. Some of these were elicited by asking about the process of decision-making in the first set of interviews (e.g., "Tell me about the process of decision-making about nutrient management thus far. What have been some of the milestones in the process?"). Other barriers and strategies to overcome them emerged from elicitation of potential management options in the first set of interviews (e.g., "How are people in the field talking about solving the nutrient problem? What do you think should be done, if anything?"). Still other barriers and strategies to overcome them were offered in the second set of interviews during discussion of the objectives and potential management options.

Results

Fundamental objectives for good nutrient management

Thirteen fundamental objectives for "good nutrient management" in San Francisco Bay were developed and grouped into five overarching categories (Figure 2). These objectives were developed to be as complete as possible (i.e., they take into account the most important factors influencing the decision), without redundancies (i.e., objectives do not have overlapping meaning), and are measurable (as accurately and unambiguously as possible) (Eisenführ et al., 2010).

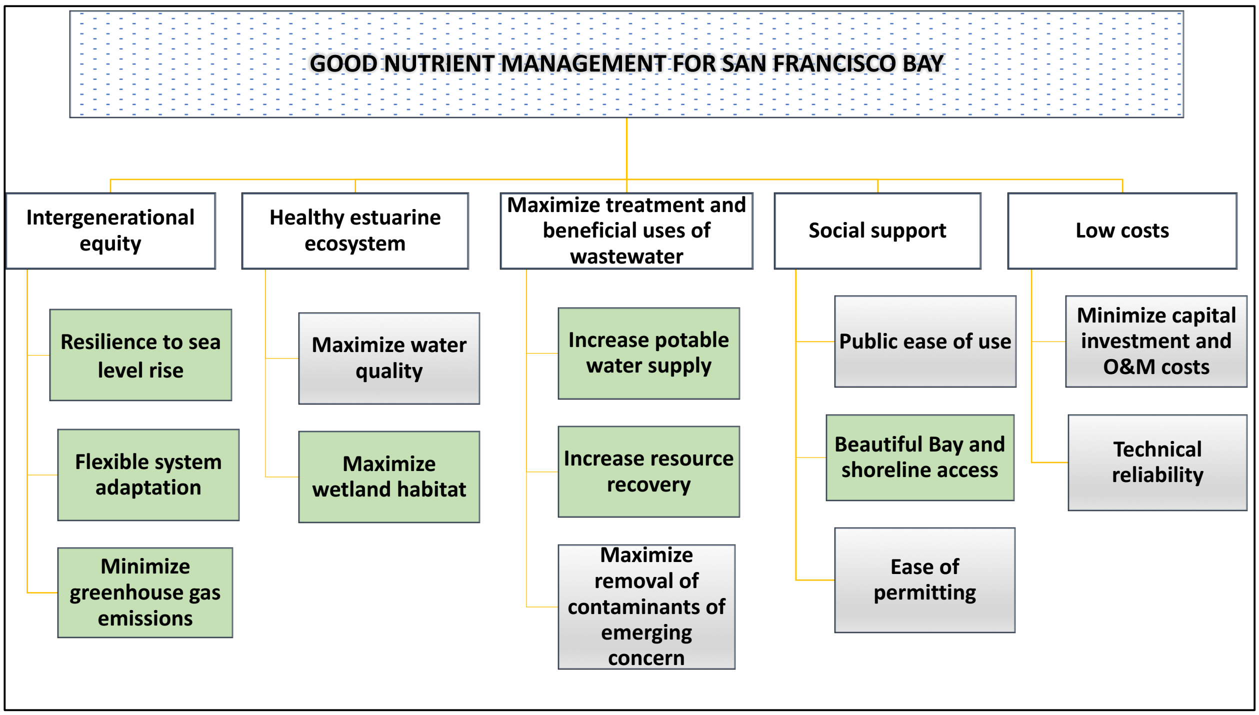

Figure 2. Objectives hierarchy for good nutrient management for San Francisco Bay, derived from interviews with 32 stakeholders. Objectives are color-coded by overarching categories (white background), objectives that are characteristic of traditional wastewater infrastructure upgrades (grey background), and objectives that are indicative of a new paradigm for multi-benefit wastewater treatment (green background). Reasons for the categorization are explained in the text.

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

Resilience to sea level rise: Much of the Bay Area's wastewater treatment infrastructure is located at the shore of the Bay and is vulnerable to sea level rise (Heberger et al., 2009), with estimates ranging up to 1.7 meters by the year 2100 (San Francisco Bay Conservation and Development Commission, 2017). Developing resilience to sea level rise while investing in wastewater infrastructure is a consideration for many stakeholders.

Flexible system adaptation: The ecological effects of nutrient loading on the Bay ecosystem are not fully understood, nor are the changes in external conditions that can contribute to nutrient over-enrichment known with much certainty (e.g., trends in water turbidity and salinity, temperature, and abundance of mollusks). This objective expresses the sentiment that good nutrient management should be able to adapt quickly and easily to shifting external conditions, to tightening regulations, and to other factors like population growth (or decline). If there is an indication that the Bay ecosystem is on the cusp of serious eutrophication, nutrient management strategies (both regulatory and technical approaches) should be able to quickly adjust accordingly. Having nutrient control options that can be flexible also would allow for adaptive management, which several interviewees expressed as being important.

Minimize greenhouse gas emissions: Bay Area water managers are concerned with the contributions of greenhouse gasses to the atmosphere associated with building and operating nutrient control systems. Though there are efforts to improve energy efficiency of wastewater treatment operations, some options for nutrient management are energy intensive or require energy-intensive materials (e.g., cement) in their construction, which embody large amounts of greenhouse gasses in the life-cycle of the system (Corominas et al., 2013; Stokes & Horvath, 2009).

Maximize Bay water quality related to nutrients: The original impetus for addressing nutrient loading in the Bay was concern about nutrient enrichment (and resulting eutrophication) and impairment of the Bay's beneficial uses. These uses include biological goals like fish habitat and spawning as well as human goals like recreation (California Regional Water Quality Control Board San Francisco Bay Region, 2017). This objective expresses the view that good nutrient management should prevent any deviation from ambient nutrient-related conditions that could impair beneficial uses.

Maximize wetland habitat: Increased wildlife habitat, particularly wetland habitat, was seen by several stakeholders as a relevant goal for good nutrient management. Wetlands provide habitat for rare, endangered and migratory species, as well as help increase shoreline resiliency to sea level rise (Kirwan & Megonigal, 2013; Monroe et al., 2016). Healthy wetland ecosystems are considered imperative for a thriving Bay ecosystem (San Francisco Joint Venture, 2018; Williams & Faber, 2001; Williams & Orr, 2002).

Increase useable water supply: After enduring a long drought between the years 2011-2017, water supply is at the forefront of many Bay Area water managers' thoughts. Stakeholders expressed opinions that as they address nutrients, wastewater utilities should concurrently be considering ways to augment water supplies through increased recycling of wastewater for irrigation or for potable uses (Miller, 2006).

Increase resource recovery: Removing nutrients from effluent is important for protecting the Bay ecosystem, but some stakeholders considered recovering them for reuse to be an even more desirable outcome. Though there is currently little economic incentive to recover and reuse nutrients, generating a potential revenue stream and contributing to a closed-loop nitrogen and/or phosphorus cycle by applying wastewater-derived nutrients as fertilizer to crops (Daigger, 2009) were viewed as goals of nutrient management.

Maximize removal of contaminants of emerging concern: Good nutrient management may also control other chemicals present in wastewater (e.g., pharmaceuticals, personal care products, pesticides), which are not completely removed by most secondary wastewater treatment systems (Vidal-Dorsch et al., 2012b). Although the health and ecosystem effects of many of these chemicals are still unknown, and the vast majority are not regulated, many stakeholders said that choosing a nutrient control option that also reduced concentrations of these chemicals in wastewater effluent would be prudent.

Public ease of use: The urban wastewater system is currently extremely easy for the public to use because properties are directly connected to a sewer system that requires little to no maintenance by members of the public. To assess potential responses to source-separating toilets designed to recover nitrogen-rich urine from wastewater (Lienert & Larsen, 2009), the researchers added the "public ease of use" objective. This objective helps to differentiate between the existing plumbing system and a urine-separating system that might require adjustments by members of the public (e.g., men might be required to sit when urinating, and source-separating toilets might require additional maintenance).

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

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

Minimize initial capital investment, operations and maintenance costs: By convention and due to the nature of public utilities, good nutrient management systems (like all urban water systems) should minimize costs. Public money funds wastewater utility upgrades and their operations, so many stakeholders were concerned that these funds be used prudently and wisely.

Technical reliability: Knowing with confidence that a wastewater treatment technology will perform in a reliable manner has historically been a leading decision criterion for wastewater engineers (Tchobanoglous et al., 2002). Technical reliability helps ensure regulatory compliance and keeps costs predictable.

These thirteen goals can be categorized into those that are in line with traditional wastewater infrastructure upgrades and those that are indicative of a new paradigm of increased expectations for multi-benefit wastewater treatment (Figure 2). These categorizations were made by analysis of documents as well as from interviews with stakeholders.

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

Of the goals that are indicative of a new paradigm of wastewater infrastructure, several fall within the mandates of professionals who are usually not responsible for planning municipal wastewater treatment plant operations, such as urban planners (beautiful bay and shoreline access), water supply agencies (increase potable water supply), and baylands stewards (maximize wetland habitat). In the San Francisco Bay case, some entities that operate municipal wastewater treatment plants are also responsible for the water supply (e.g., San Francisco Public Utilities Commission), and the region's nutrient stakeholder working group includes baylands stewards and scientists on its Steering Committee (San Francisco Bay Nutrient Management Strategy, 2016). Thus, entities responsible for the goals of increasing potable water supply and maximizing wetland habitat are involved in the Bay Area nutrient issue, but the staff members usually responsible for the issue work in different divisions of the organization and may not have the ability to allocate resources from one part of the agency to another to solve the problem.

Many of the goals stakeholders have for nutrient management do not specifically fall within the institutional mandates of the stakeholders, including flexible system adaption, resource recovery from wastewater, minimizing greenhouse gas emissions, shoreline access, and resilience to sea level rise (Table 1). That these goals (many of which are indicative of a new paradigm of wastewater infrastructure) are being considered by representatives involved with nutrient management is indicative of the individual resolve of stakeholders to enact their vision of next-generation wastewater infrastructure.

Table 1. Stakeholders institutionally mandated to fulfill stated goals for "good nutrient management"

Goal	**Institution mandated to achieve goal**
Resilience to sea level rise	None
Flexible system adaptation	None
Minimize greenhouse gas emissions	None (currently, but may fall on dischargers with passage of Assembly Bill 32 – California Global Warming Solutions Act)
Maximize water quality	Regulators, dischargers, baylands stewards, scientists
Maximize wetland habitat	Baylands stewards
Increase water supply	Water supply agencies
Increase resource recovery	None
Remove contaminants of emerging concern	None (though regulators must respond once they have evidence contaminants are detrimental to public or environmental health)
Public ease of use	None

Goal	Institution mandated to achieve goal
Beautiful Bay and shoreline access	Urban planners
Ease of permitting	Regulators, dischargers
Minimize initial capital investment, operations and maintenance costs	Dischargers
Technical reliability	Dischargers

Of the nine stakeholders who participated in the second interview, there were differing opinions about the relative importance of each of these goals to decision-making about nutrient management (Figure 3). The weights of these goals were elicited using a standard MCDA procedure (Swing) based on improvement from the worst to best-state of metrics that assess fulfillment of each objective (Eisenführ et al., 2010).

Overall, median values of the importance of maximizing water quality, flexible system adaptation to changing conditions, provision of wetland habitat, and technical reliability had relatively stronger weights in decision-making than minimizing greenhouse gas emissions, increasing beautiful Bay and shoreline access points, and public ease of use. However, even the latter, less-traditional goals for nutrient management still were important to most stakeholders. There was wide variation in the importance of incorporating resilience to sea level rise in decision-making, with some stakeholders listing it as the most important criteria and others assessing it of no importance (for specific point values assigned to criteria, see supplemental information, Figure S1, and for individual stakeholder weights for criteria, Figure S2).

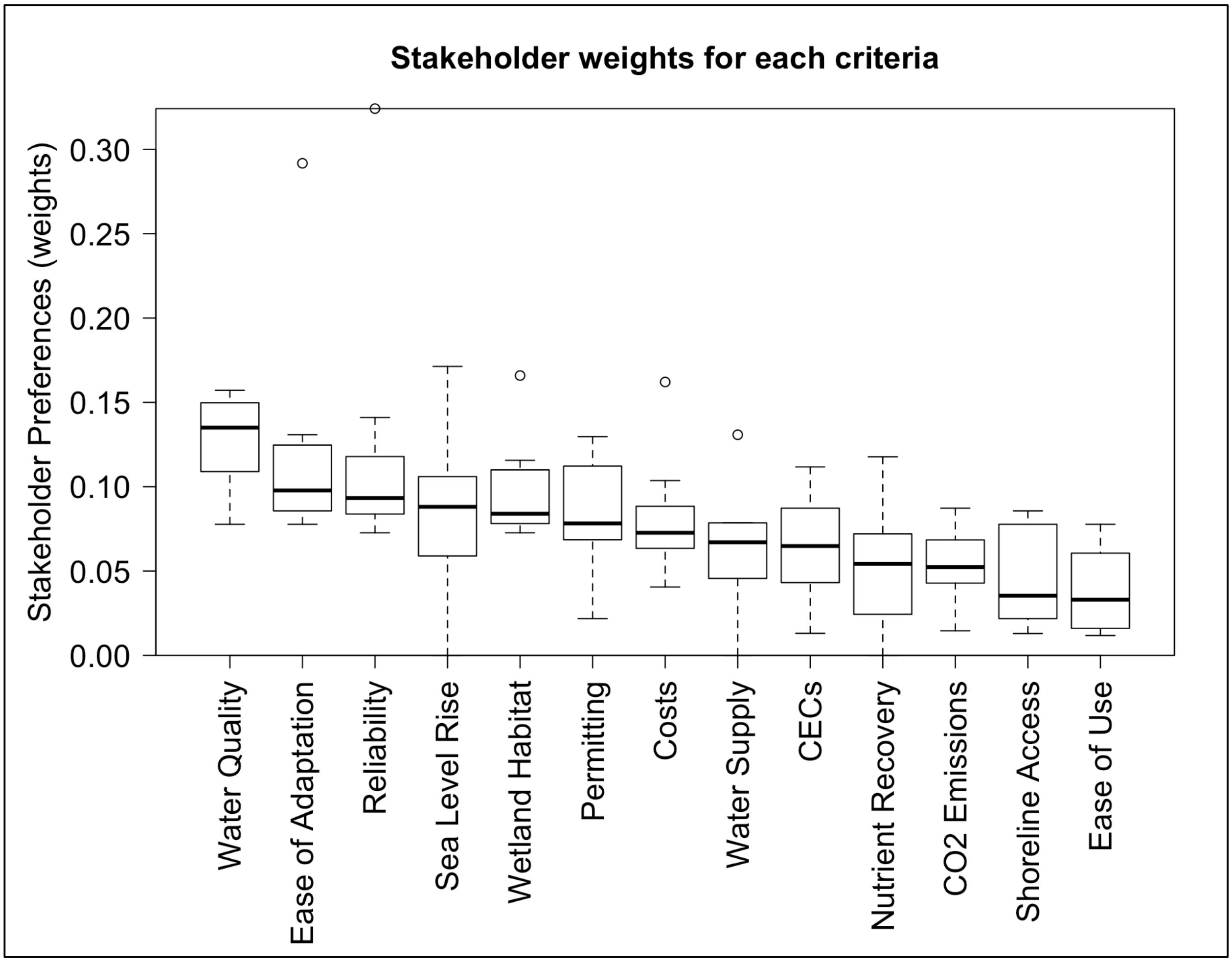

Figure 3. Relative weights of goals for Bay Area nutrient management, derived from interviews with nine stakeholders. Boxplot midlines denote median values of responses, boxes represent the interquartile range, and whiskers extend to 1.5x the interquartile range. Outliers are marked with a circle. Each stakeholders' total weights added to one.

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

Impediments to multi-benefit wastewater infrastructure planning and implementation

Despite strong sentiments amongst many stakeholders that nutrient control strategies should ideally provide other benefits in addition to prevention of adverse impacts from nutrients in the Bay, many stakeholders identified barriers to multi-benefit wastewater infrastructure planning and implementation. These perceived barriers fall into institutional, social, and technical categories (Table 3). Supporting quotations from stakeholders are included in the supplemental information, Table S4.

Table 2. Perceived barriers to planning and implementation of multi-benefit wastewater systems.

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

Category	Barrier	Primary concern	Description
		require user responsibility?	
Technical	**Effects on existing treatment**	How will new treatment options change the function of existing systems?	Concern that innovative technologies may change the composition of influent or effluent of existing wastewater treatment plants. For example, decentralized or satellite water recycling technologies might result in less influent to municipal wastewater treatment plants.

Strategies to overcome barriers to multi-benefit wastewater infrastructure

Many stakeholders provided practical suggestions for overcoming some of the barriers to multi-benefit wastewater infrastructure planning and implementation. Each of these suggestions requires a set of stakeholders from particular roles to take action to overcome these barriers (Table 3). Supporting quotations can be found in the supplemental Information, Table S5.

Table 3. Suggested strategies to overcome barriers to multi-benefit wastewater infrastructure in the San Francisco Bay Area. N/A: no interview responses addressed how to overcome this barrier.

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

Category	**Barrier**	**Strategies to overcome barriers**	**Stakeholders implicated for action**
	Public compliance	N/A	
Technical	Effects on existing treatment	N/A	

Discussion

Historically, the main drivers for water infrastructure planning have been regulatory compliance and low costs (Brown, Keath, & Wong, 2009). These drivers remain in the Bay Area, but our results suggest that in addition to objectives pertaining to the traditional role of wastewater treatment (e.g., good water quality, technical reliability, and low costs), other objectives related to the development of multi-benefit infrastructure are also prominent for many stakeholders. However, it is noteworthy that not all stakeholders are interested in a new paradigm of wastewater infrastructure. For example, one wastewater treatment plant manager we interviewed (SH3) primarily expressed goals related to traditional water infrastructure paradigms, and was strongly averse to goals that were outside that scope (e.g., they gave no value to resilience to sea level rise, recovery of nutrients from wastewater and water supply). Defining the role of wastewater treatment in response to issues beyond nutrient pollution may be necessary before stakeholders choose regional solutions for nutrient management.

Goals for nutrient management in their social and institutional context

San Francisco nutrient management stakeholders who expressed goals consistent with a transition to next-generation urban water infrastructure are not operating in a vacuum. Regional strategic planning documents for water, like the San Francisco Bay Area Integrated Regional Water Management Plan (IRWMP), mirror objectives that many stakeholders in the nutrient control case expressed. For example, the IRWMP aims to "Encourage implementation of integrated, multi-benefit projects", "Reduce energy use and/or use renewable resources", "Plan for and adapt to sea level rise", and "Increase recycled water use" (*San Francisco Bay Area Integrated Regional Water Management Plan*, 2013).

Some of the broader goals stakeholders mentioned could arguably be cast as prudent engineering. For example, flexible system adaptation is not a mandate for dischargers, but it is considered good practice to build a wastewater treatment system that will be useful throughout a design life of three or four decades. Likewise, removing contaminants of emerging concern from wastewater could preempt a need to build additional treatment systems if compounds are regulated in the future (Tchobanoglous et al., 2002).

Other less-traditional goals for nutrient management, like resilience to sea level rise, increasing wetland habitat, and reducing greenhouse gas emissions, may improve wastewater utilities' public image by explicitly aligning their actions with local pro-environmental values. Improving utilities' "brand" in this way may help make it easier for them to gain the support of the community and to raise funds for projects (Harris-Lovett et al., 2015).

Despite the benefits of achieving these broader objectives, it is notable that many of the goals reflective of a new paradigm of water infrastructure fall outside of stakeholders' institutional mandates. Dischargers are tasked with regulatory compliance and reliable service. Regulators must uphold state and federal rules for preventing impairment of water bodies, like the federal Clean Water Act and California's Porter-Cologne Act (California State Water Resources Control Board, 2018). To conceptualize and implement next-generation water infrastructure, stakeholders in the San Francisco Bay case may need to go beyond their professional and institutional mandates and think creatively about how to develop rules, collaborations, and decision-making processes that support their vision. In addition, regional, state or federal policy to indicate that multi-benefit water projects should take priority over single-purpose water systems when possible could help support the implementation of a new paradigm for water infrastructure.

In the Bay Area nutrients case, individuals with interest and motivation for development of multi-benefit infrastructure exist and have power within bureaucratic, historically slow-to-innovate regulatory agencies and wastewater utilities. Regional enthusiasm for multi-benefit approaches may stem from the overall pro-environmental culture of the Bay Area, as evidenced by recent passage of a bill to raise a Bay Area parcel tax to fund wetland restoration (Ting, 2015). The same enthusiasm may not exist elsewhere. At a national level, green infrastructure approaches are championed by the national Environmental Protection Agency (US EPA, 2015) but may not be reflected in the perspectives of stakeholders in any particular locale.

Critics of integrated water management and multi-benefit water infrastructure argue that the complexities of considering multiple goals in a single water infrastructure project are too difficult for one group or agency to master and that the hurdles of institutional collaboration are too great (Biswas, 2008). However, the Bay Area nutrient management case shows that even without formalized institutional collaboration, individuals with strong motivation for multi-benefit infrastructure have the capacity to lay the foundations for the necessary communications and teamwork, especially in a social culture like that of the Bay Area.

Lessons for planning and implementation of multi-benefit infrastructure

Stakeholders pointed to the importance of having existing connections, trust, and communication channels in place between water managers, regulators, and ecological stewards that can be drawn upon in a decision-making context. These connections provide the foundation for the collaboration necessary for multi-benefit projects to be successful. In the Bay Area, the Regional Monitoring Program for Water Quality in the San Francisco Bay, a partnership between regulatory agencies and regulated utilities that studies Bay water quality, has been important in this regard (Trowbridge et al., 2016).

Regional monitoring also supports multi-benefit projects because it provides an integrated assessment of the Bay's ecology, as opposed to the site-specific monitoring that is usually done to ensure regulatory compliance. The holistic view provided by regional monitoring, which tracks natural variability as well as cumulative impacts of human activity, also allows managers to prioritize regional management actions and goals (Kirchhoff & Dilling, 2016; Schiff et al., 2016).

Bay Area dischargers also collaborate on other aspects of regional environmental stewardship. Their relationship is formalized through an advocacy organization called Bay Area Clean Water Agencies (BACWA), which provides a unified voice for local wastewater utilities in regulatory and scientific settings (Bay Area Clean Water Agencies, 2018). In addition, regional regulatory permits for total maximum daily loads for polychlorinated biphenyls and mercury currently exist in San Francisco Bay, and another for selenium is underway (Trowbridge et al., 2016). All of these require communication and collaboration between dischargers to meet these limits.

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

This collaborative approach exemplifies an important step in moving towards more sustainable water infrastructure: the development of a coalition of diverse actors who share a common vision and trigger institutional change (Tàbara & Ilhan, 2008). The Bay Area's Nutrient Management Strategy is made up of broad set of actors, including nutrient dischargers (e.g., wastewater treatment plant managers, stormwater managers, and industrial dischargers), environmental advocates, regulatory organizations, and resource trustee agencies (e.g., Department of Fish and Wildlife) (San Francisco Bay Nutrient Management Strategy, 2016).

Another benefit of establishing these social networks is the possibility of collaboration between regulators and dischargers to support multi-benefit technologies. Traditional technologies are currently simplest for regulators to permit, because there is precedent for them and they fit neatly within institutional mandates. In contrast, multi-benefit technologies may challenge existing regulatory structures. For instance, constructed treatment wetlands may have seasonally variations in the removal of nutrients, and they may be subject to a variety of different rules based on their proximity to endangered species (Wren, 2017). Open channels of communication between technology developers/users and regulators may help to establish new policies, and navigate the complexities of existing policies, to facilitate the adoption of new multi-benefit technologies.

Technological fixes are not the only potential solutions to nutrient control. Strong networks and partnerships between dischargers and agencies can also lay the groundwork for innovative strategies to manage nutrients, like trading credits for nutrient discharge within the estuary (Bennett, Thorpe, & Guse, 2000).

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

Our research shows that water managers and decision-makers in the San Francisco Bay Area nutrient management case have addressed many of the barriers to sustainable urban water management addressed in the literature as summarized in the review published by Brown et al. (Brown & Farrelly, 2009)(Table 4).

Table 4. Barriers to sustainable water infrastructure management, adapted from a review by Brown et al. and the San Francisco Bay approach, as identified in stakeholder interviews and document analysis.

Barrier identified in the literature	San Francisco Bay case approach	Sources
Uncoordinated institutional framework	Coordination through the Nutrient Management Strategy and BACWA; single regulatory body (San Francisco Regional Water Quality Control Board) for water quality for the entire region	Interviews, documents (San Francisco Bay Nutrient Management Strategy, 2016; San Francisco Estuary Institute Aquatic Science Center, 2016)
Limited community engagement	Nutrient Management Strategy advisory board and steering committee to engage disparate stakeholders	Interviews, documents (San Francisco Bay Nutrient Management Strategy, 2016; San Francisco Bay Regional Water Quality Control Board, 2017)
Limits of regulatory framework	Regulators collaborate with dischargers to develop rules that would support multi-benefit infrastructure	Interviews
Insufficient resources	Dischargers contribute $880,000/year to scientific studies about nutrient effects on the Bay	Documents (Bay Area Clean Water Agencies, 2016; San Francisco Bay Regional Water Quality Control Board, 2014)
Unclear roles and responsibilities	Some delineation of roles through the Nutrient Management Strategy, but some lack of clarity remains	Interviews, documents (San Francisco Bay Nutrient Management Strategy, 2016; San Francisco Estuary Institute Aquatic Science Center, 2016)
Poor organizational commitment	Committed individuals within bureaucratic organizations	Interviews
Lack of information about integrated, adaptive management	Partnership with San Francisco Estuary Institute and academic researchers, but some uncertainty remains	Interviews, documents (San Francisco Bay Nutrient Management Strategy, 2016)
Poor communication	Foundations for communication laid with regional water quality monitoring	Interviews, documents (Schiff et al., 2016; Trowbridge et al., 2016)
No long-term vision or strategy	Long-term visions exist (e.g., San Francisco Bay Plan), but not specific to nutrient management	Documents (Monroe et al., 2016; San Francisco Bay Area Wetlands Ecosystem Goals Project, 2015; San Francisco Bay Conservation and Development Commission, 2008)
Technocratic path dependencies	Not addressed	Interviews
Insufficient monitoring or evaluation	May still be a problem, but partnership with Regional Monitoring Program will help alleviate the burden	Interviews
Lack of political and public will	Committed individuals within bureaucratic organizations	Interviews

Overcoming impediments to multi-benefit infrastructure implementation

Despite strong interest in multi-benefit wastewater infrastructure for nutrient control, substantial impediments to their implementation exist in the San Francisco Bay Area. While previous literature has focused on socio-institutional barriers (Brown, 2005, 2008; Ferguson et al., 2013; Sharma et al., 2016; Werbeloff et al., 2017), we found several technical barriers existed as well. Several of these technical barriers focused on reliability of innovative multi-benefit systems.

In particular, technologies that require changes in consumer habits (e.g., urine source-separation) face substantial challenges with their reliability because of increased user responsibility. Strategies stakeholders generated for overcoming barriers to multi-benefit wastewater infrastructure in this case failed to address the difficulties of reliability associated with urine-source separation, though studies in Europe show high enthusiasm for decentralized urine source-separation and treatment (Lienert & Larsen, 2009). This is a topic that merits further research, though some evidence shows that pilot projects help facilitate adoption of these technologies (Lienert & Larsen, 2007a).

Other types of innovative multi-benefit wastewater systems also could be less reliable than traditional systems because there is less experience with their performance. To counteract the risk of lower reliability, stakeholders mentioned that it would be essential to develop easily-implemented wastewater technologies that were simple to adapt to changing external conditions. These easily-implemented and adaptable technologies could be deployed if riskier multi-benefit wastewater systems did not achieve the desired water quality effects. In addition, regulatory or permitting structures to "pre-approve" or fast-track adaptive technologies for quicker implementation was identified as a useful approach to hasten implementation. Further research is needed to develop nutrient control technologies that can be easily and quickly adapted to changing conditions, such as population size, rising sea levels or tightened regulations.

Today's wastewater treatment systems are designed to essentially be 'out-of-sight, out-of-mind' for the public. Yet some stakeholders relayed the difficulties with this design: the public does not consider how wastewater is treated and is unwilling to invest in new infrastructure because there is often not public awareness of insufficiencies of existing infrastructure. Making wastewater treatment systems more visible to the public may serve to inspire respect for the systems that are employed to turn sewage into clean water, and may enable further investment in innovative, multi-benefit technology. Studies conducted in Europe have shown that people are more open to new water technologies if they see the environmental benefit (Lienert & Larsen, 2009), but more research needs to be done on this topic, particularly in the United States.

Many stakeholders also pointed out the lack of clear leadership as a barrier to planning and implementing multi-benefit infrastructure projects, and no strategies to address this problem emerged from interviews. In the absence of consolidation of decision-making (combining agencies that manage different aspects of water management and different wastewater treatment agencies), which is unlikely to happen, one solution may involve "value-focused thinking", an approach that guides a specific school of MCDA (Keeney, 1992, 1996). Multi-attribute value theory is a useful tool for understanding and defining stakeholders' values and objectives. This "visioning" step is one that a leader would take early on in a planning process. In the absence of a single entity in charge, coming to agreement about collective goals (and clarity about areas of disagreement) can help to fill that gap. Formation of a new agency or workgroup to facilitate this process may be necessary. Finding measures to assess fulfillment of these goals that are acceptable to stakeholders would also help clarify how to collectively judge the success of an infrastructure project.

The process of identifying goals for “good nutrient management” in the Bay Area and evaluating them for various nutrient control options also served to identify areas of agreement and disagreement amongst stakeholders. For example, for some stakeholders, developing infrastructure that is resilient to sea level rise was of utmost importance. For others, it was entirely unimportant. Coming to an agreement (either professional or regulatory) about the utility of developing wastewater infrastructure that is resilient to sea level rise – and clarifying whose institutional mandate includes adaptation to sea level rise, and at what point in time – will be an essential step in planning. For example, the American Society of Civil Engineers officially supports incorporation of the potential effects of climate change on building standards for engineered systems (American Society of Civil Engineers, 2015); a similar resolution from utilities, with necessary changes in allocation of funding, would provide clarity to the issue.

Identifying goals for nutrient control also sets standards for multi-benefit infrastructure projects – they need to actually meet the goals in order to truly provide multiple benefits. For example, if a constructed wetland is used to control nutrients based on the premise that it will also provide bird habitat and improve shoreline access, then these goals can provide additional guidelines and metrics for determining the success of the technology. Development of more pilot-scale projects to implement multi-benefit technologies, like treatment wetlands and resource recovery from urine, and monitoring how well they meet broader goals is necessary. In addition, research on how well these technologies operate under different conditions (seasonally, spatially, and with different influent characteristics) is needed, as well as assessment of whether they actually fulfill the various goals they are purported to meet.

Multi-benefit water infrastructure hedges against uncertainty

One of the most difficult features of nutrient management in the Bay Area case is that the effects of nutrients on the Bay’s ecosystem and beneficial uses are not entirely known. Although much scientific effort is being directed towards these ends, decisions about nutrient control infrastructure may need to be made before the complex relationship between nutrient loading and impairment are completely understood. Dynamic environmental conditions and the potential for ecological thresholds complicate decision-making. In this case, multi-benefit infrastructure for nutrient control serves as a way to hedge against the risks posed by future uncertainty. For example, even if nutrients end up not being a big problem for the Bay’s water quality in the future because environmental conditions shift in an unexpectedly positive way, a multi-benefit solution to address nutrient loading which provides wildlife habitat, freshwater supply, or resource recovery can still be seen by stakeholders as a net benefit overall.

Conclusions

Many stakeholders in the San Francisco Bay Area involved with managing nutrients view it as part of their professional responsibility to not only effect good water quality in the Bay, but also to develop infrastructure for nutrient control that provides additional benefits like resilience to sea level rise, creation of wetland habitat, or recovery of resources from wastewater. These views mirror a larger paradigm shift in wastewater infrastructure that envisions holistic systems that go beyond the traditional goals of removing organic pollutants from wastewater.

Enthusiasm for a new paradigm of wastewater infrastructure in the Bay Area has resulted in individuals' actions to build coalitions amongst disparate water management agencies. They also chose to engage proactively in nutrient management instead of waiting to respond to acute impairment of water quality. They must forge new relationships and modes of decision-making to support their vision for multi-benefit wastewater infrastructure, though they still face significant barriers. Many stakeholders are working beyond the scope of their institutional mandates, and many of their goals are not represented by the institutional mandates of any entity involved with the problem of nutrient control (or wastewater treatment in general).

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

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

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

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Appendix to Chapter IV: Supplemental information for 'Towards a New Paradigm of Urban Water Infrastructure: Identifying Goals and Strategies to Support Multi-Benefit Wastewater Treatment' (Harris-Lovett et al., 2018)

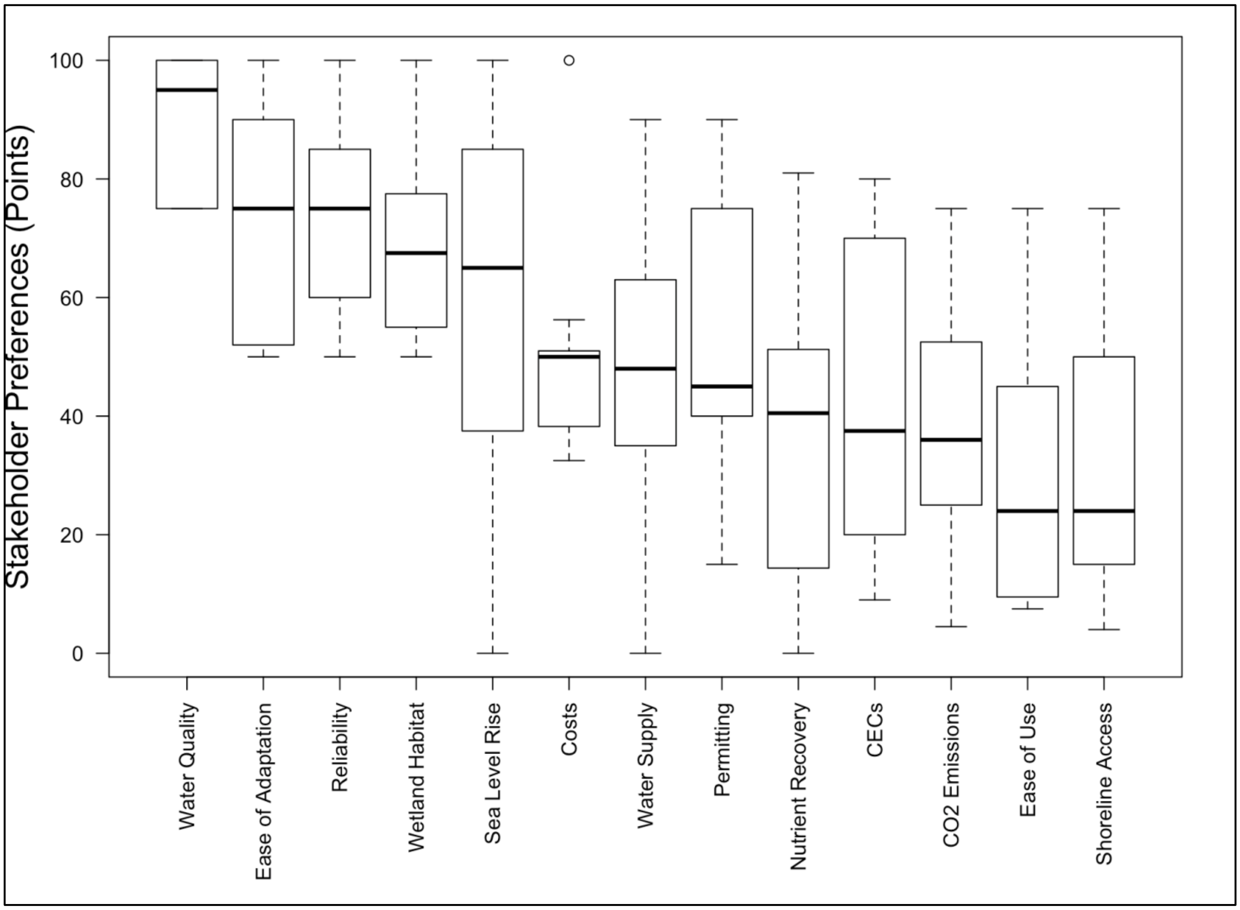


Figure S1. Stakeholder points for improvement of fulfillment of criteria for nutrient management from the worst to the best state, on a scale from 0 (not at all important) to 100 (most important).

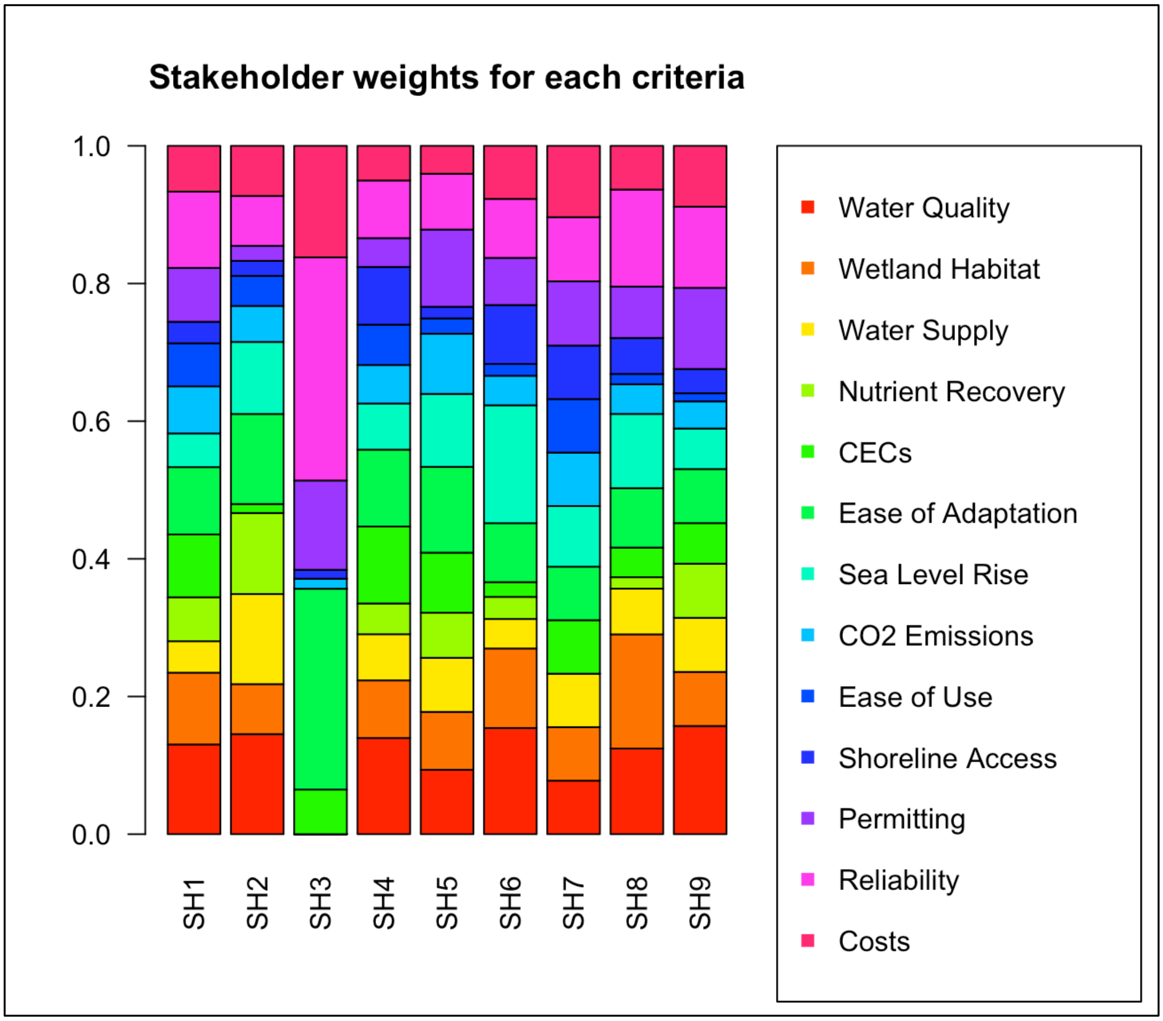


Figure S2. *Stakeholder weights for criteria for nutrient management, on a scale of 0 (not important to decision-making) to 1 (most important to decision-making).*

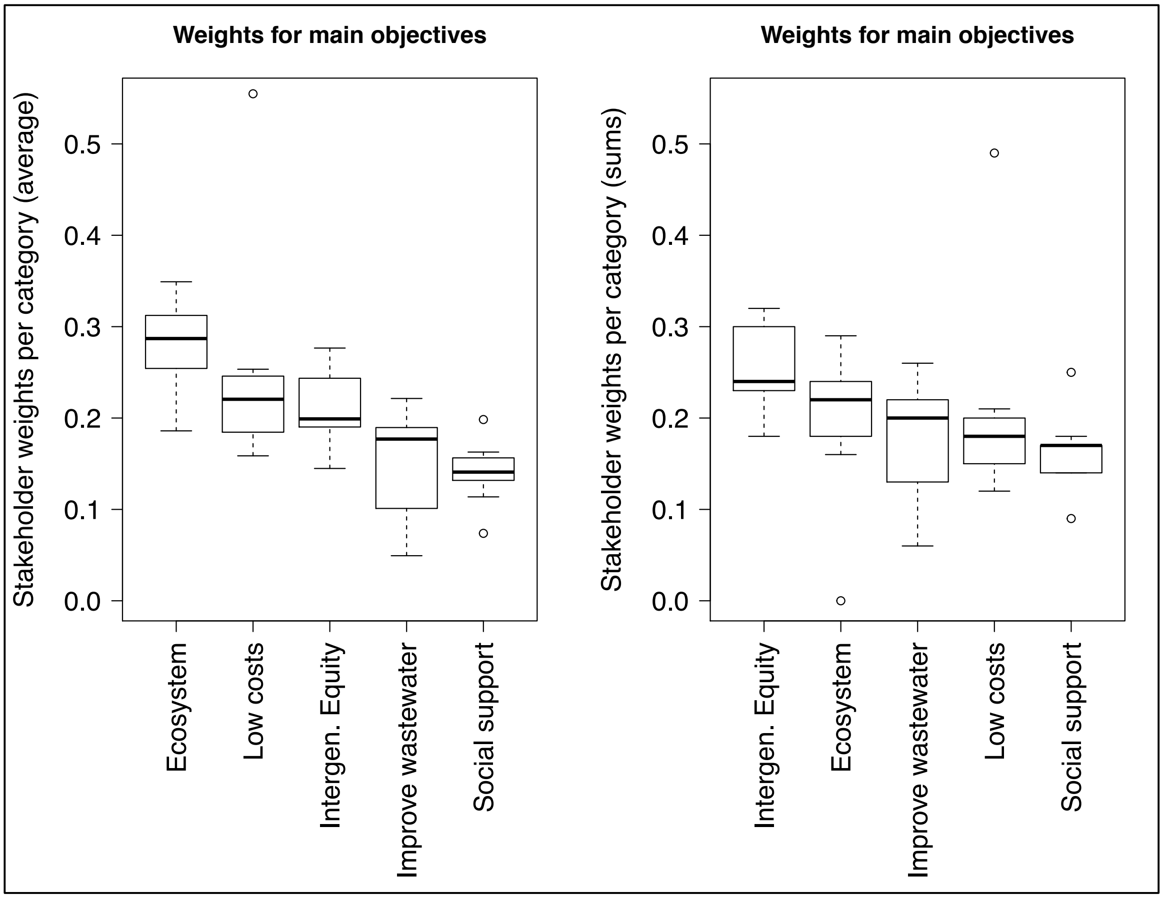


Figure S3. Stakeholder weights of main objectives for nutrient management. The figure on the left shows the average weight of sub-objectives per category, and the figure on the right shows the summed weight of sub-objectives within each category for the stakeholders.

*Table S1. List of stakeholders, their professional role, and their relevance to decision-making about nutrient management. Stakeholders marked with an * participated in a second interview.*

Professional roles defined as: Advocate = Supports the interests of a particular cause or group through legal means, public outreach, and/or political lobbying; Discharger = Part of an organization that discharges nutrients to the Bay from a point-source like a wastewater treatment plant, as specified in the 2014 nutrient watershed permit (San Francisco Bay Regional Water Quality Control Board, 2014); Engineer = Designs and builds technologies for wastewater treatment; Planner = Determines, designs, and/or controls construction and development of the Bay and shoreline areas; Regulator = Responsible for setting and enforcing legal regulations about environmental conditions; Researcher = Conducts scientific studies and analyses of ecological conditions in and around the Bay; Steward = Manages land and/or habitat area in and around the Bay; Water supplier = responsible for obtaining and distributing municipal water supply.

Relevance defined as: 1 = directly involved in decision-making; 2 = strongly affected by decision-making about nutrients, or with strong influence over those involved in decision-

making; 3 = affected by decision-making about nutrients but would not have to make fundamental changes to daily work, 4 = interested/concerned about nutrients, but not directly affected by decision-making.

Stakeholder ID	Professional role	Relevance to decision-making
SH1*	advocate	1
SH2*	discharger	1
SH3*	discharger	1
SH4*	regulator	1
SH5*	regulator	1
SH5*	steward	3
SH7*	discharger	1
SH8*	advocate	1
SH9*	regulator	1
SH10	regulator	1
SH11	planner	4
SH12	regulator	1
SH13	regulator	1
SH14	regulator	4
SH15	water supplier	4
SH16	regulator	2
SH17	advocate	4
SH18	researcher, advocate	2
SH19	discharger	2
SH20	researcher, steward	4
SH21	discharger	2
SH22	discharger	1
SH23	engineer	2
SH24	researcher	4
SH25	steward, researcher	3
SH26	water supplier	3
SH27	regulator	2
SH28	discharger	1
SH29	engineer, planner, regulator	4
SH30	discharger	2
SH31	engineer, planner, regulator	4
SH32	discharger	1

Table S2. Respondents' stated goals for good nutrient management, our research classification of goals, and how they informed the objectives hierarchy. (Note: where several respondents stated a goal in very similar or identical terms, it is only shown once here.)

Goal	Goal classification	Placement in objectives hierarchy
"Nimble, quick to change"	Ease of adaptation	Flexible system adaptation
"Adaptively manage all actions"	Ease of adaptation	Flexible system adaptation
"Regularly review and update science and actions"	Ease of adaptation	Flexible system adaptation
"Low sunk costs"	Ease of adaptation	Flexible system adaptation
"Balances not doing anything until it's conclusively proven and the precautionary principle. Those two can meet if done well, in an adaptive management framework"	Ease of adaptation	Flexible system adaptation
"Ability to upgrade nutrient removal from a low level of reduction to a higher level of reduction"	Ease of adaptation	Flexible system adaptation
"Understand ecological effects of nutrient loading in each subembayment"	Sound science	Outside the scope of the objectives hierarchy
"Get the loads right"	Sound science	Outside the scope of the objectives hierarchy
"Understand nutrient dynamics – what are the contributions from the benthic environment?"	Sound science	Outside the scope of the objectives hierarchy
"Understand all effects of management actions"	Sound science	Addressed by measuring attributes for all objectives in the MCDA
"Consider non-point sources in addition to point sources"	Sound science	Less relevant in the southern reach of the Bay, where the vast majority of loading is from point sources
"Set a realistic baseline of nutrient levels in the Bay"	Sound science	Outside the scope of the objectives hierarchy
"Avoid premature regulatory action"	Sound science	Outside the scope of the objectives hierarchy
"Use innovative technology based on research"	Sound science	Addressed by considering non-traditional technologies (e.g., wetlands for wastewater treatment, urine source-separation) in the MCDA
"Consider future conditions like climate change, other regulations, and population change"	Sound science/MCDA/Climate concerns	Addressed by considering effects of future uncertainties on MCDA results
"It should make sense to the public"	Public support	Public ease of use
"Should be natural looking and feeling"	Public support	Beautiful Bay and shoreline access
"A sense that the community is receiving the benefits of the investment"	Public support	Beautiful Bay and shoreline access
"Visible, tangible benefits to the people that are paying for it"	Public support	Beautiful Bay and shoreline access
"Doesn't disrupt the public's enjoyment of the shoreline"	Public support	Beautiful Bay and shoreline access

Goal	Goal classification	Placement in objectives hierarchy
"Should be well-funded"	Public support	Outside the scope of the objectives hierarchy
"Have a clear definition of the problem"	MCDA	Addressed in the stakeholder analysis portion of the MCDA process
"Understand a range of management alternatives"	MCDA	Addressed in the MCDA process
"Stakeholders should provide input"	MCDA	Addressed in the stakeholder analysis portion of the MCDA process
"Balance nutrients with other long-term planning"	MCDA	Addressed in the MCDA process
"Identify short term "no regrets" actions"	MCDA/Low costs	Addressed in the MCDA process
"Technology should be easy to operate"	Reliability/Low costs	Technical reliability/ Minimize initial capital investment and operations/maintenance costs
"Reliably achieves desired nutrient removal"	Reliability	Technical reliability
"Should be reliable, can decently meet our treatment requirements"	Reliability	Technical reliability
"Low cost"	Low costs	Minimize initial capital investment and operations/maintenance costs
"Consider low-hanging fruit"	Low costs	Minimize initial capital investment and operations/maintenance costs
"Is economically efficient by using funds regionally"	Low costs	Minimize initial capital investment and operations/maintenance costs
"Costs less to operate"	Low costs	Minimize initial capital investment and operations/maintenance costs
"Good water quality in the Bay"	Good water quality	Maximize water quality
"Results in the Bay being ecologically stable and resilient"	Good water quality	Maximize water quality
"Supports fish habitat"	Good water quality	Maximize water quality
"Protects public health"	Good water quality	Maximize water quality
"Maintains dissolved oxygen levels"	Good water quality	Maximize water quality
"Keeps harmful algal blooms down"	Good water quality	Maximize water quality
"Prevents Bay-wide eutrophication"	Good water quality	Maximize water quality
"Protects San Francisco Bay's beneficial uses"	Good water quality/wildlife habitat	Maximize water quality/Maximize wetland habitat
"Good wildlife habitat"	Wildlife habitat	Maximize wetland habitat
"Enhances wetland species richness and diversity"	Wildlife habitat	Maximize wetland habitat
"Done in a way to improve habitat use and ecosystem function of wetlands"	Wildlife habitat	Maximize wetland habitat
"Recovers endangered species"	Wildlife habitat	Maximize wetland habitat
"No effects on fish and wildlife"	Wildlife habitat	Maximize wetland habitat
"Removes other wastewater-derived contaminants"	Improve wastewater treatment	Maximize removal of chemicals of emerging concern
"Increases the water supply"	Improve wastewater treatment	Increase potable water supply

Goal	Goal classification	Placement in objectives hierarchy
"Maximize water recycling to reduce nutrient loading"	Improve wastewater treatment	Increase potable water supply
"Recover resources from wastewater, like nitrogen, phosphorous, or energy"	Improve wastewater treatment	Increase resource recovery
"Having beneficial reuse […] especially with drought and water demands, [increasing water recycling] is probably the biggest impact and biggest positive we could have"	Improve wastewater treatment	Increase potable water supply
"Not just wait and just use existing technology, but to test and help renew it"	Improve wastewater treatment	Addressed in MCDA option choice
"Actually capture [nitrogen] and use it as a resource"	Improve wastewater treatment	Increase resource recovery
"Increases climate resilience"	Climate concerns	Resilience to sea level rise
"Addresses sea level rise"	Climate concerns	Resilience to sea level rise
"Any facility upgrades should account for sea level rise"	Climate concerns	Resilience to sea level rise
"Minimizes greenhouse gas emissions"	Climate concerns	Minimize CO_2 emissions
"Avoids unnecessary energy use"	Climate concerns	Minimize CO_2 emissions
"Less energy-intensive"	Climate concerns	Minimize CO_2 emissions
"Making sure this is part of strategy development for sea level rise"	Climate concerns	Resilience to sea level rise
"Complies with regulation"	Getting permits	Ease of permitting
"Regulation should be phased in over time"	Getting permits	Ease of permitting
"Collaborative process across professional fields and regionally"	Collaborative process	Outside the scope of objectives hierarchy
"Collaborative process without litigation"	Collaborative process	Outside the scope of objectives hierarchy
"Do this with no attorneys. Meaning we maintain an actual collaborative all the way through, and everyone is giving and taking"	Collaborative process	Outside the scope of objectives hierarchy
"Regional cooperation"	Collaborative process	Outside the scope of objectives hierarchy

Table S3. Supporting quotations for objectives, based on interviews with 32 stakeholders. Stakeholder number is given in parentheses in third column (see Tab. S1).

Objective	Quotation	Stakeholder professional role
Beautiful Bay and shoreline access	[Improved shoreline access to beautiful parts of the Bay shore is important] "so when we're out explaining to our ratepayers why the rates need to go up [to control nutrient loads] it makes some sense."	Wastewater treatment plant manager (SH7)
	"At the local level, [it's important to have] a sense that the community is receiving the benefits of the investment. It gets very hard, for	Federal regulator (SH12)

Objective	Quotation	Stakeholder professional role
	example, for a community to invest and not have it be something visible or tangible.”	
	“Our [current wastewater infrastructure] is all out of sight, out of mind. That’s one of our challenges when we try to get people to support [wastewater infrastructure improvements], they’re like, “support what? Isn’t it all being taken care of?” I understand bringing that physical, human nature [of shoreline access] to understanding it. […] It’s a factor from my perspective.”	Local regulator (SH4)
Ease of permitting	“If there’s a way to minimize either the amount of time or the amount of money it takes to get a permit, or if there’s some assurances from one permit to the next, [it would improve the appeal of a nutrient management option] […] There’s real financial and resource implications.”	Wastewater treatment plant manager (SH7)
Flexible system adaptation	“How nimble could a [nutrient] management plan be, a plan of action be, if we saw an indicator [of bad ecological effects]? Because if we have to wait ten years to meaningfully change [nutrient] loading, that will likely be too late.”	Local regulator (SH4)
	[Good nutrient management should have an] “ability to upgrade nutrient removal from a low level of reduction to a higher level of reduction without sunk costs.”	Local regulator (SH16)
Increase useable water supply	“Are agencies taking advantage and creating synergies with water recycling during these upgrades?”	Wastewater treatment plant manager (SH22)
	“Having [nutrient control that includes] beneficial [water] reuse is probably my number one goal…If you just do a process [for nutrient control] and it doesn’t have any beneficial impact, then why are we doing it? To me, that’s the number one thing. There should be a beneficial impact. […] Especially with drought and water demands, [water reuse is] probably the biggest impact and biggest positive we could have.”	Wastewater treatment plant manager (SH32)
	“If we’re good at saving water and recycling it for productive uses we may both augment our water supply and reduce the need to discharge those pollutants into the Bay and its tributaries. So I think those different kinds of more holistic looks at these things are critical to an effective strategy.”	Federal regulator (SH9)
	“Any solution implemented [for nutrient control] should achieve multiple benefits. And you know, in California’s current state of drought and sort of the main threat that is climate change, I think reducing our reliance on imported water should be a big priority. And probably through recycled water.”	Water quality advocate (SH8)
Increase resource recovery	“Are agencies looking at cost-effective capture of nutrients, instead of removal of nutrients? To put nutrients back into the agricultural stream.”	Wastewater treatment plant manager (SH22)
	[It’s important to] “look at nutrients not as a problem but as a resource. Actually [considering] nutrients in wastewater as a resource, and to see that it presents opportunities for increased energy recovery, [and] resource recovery for things that can be repackaged and used.”	Federal regulator (SH5)
Remove contaminants of emerging concern	“There are other water quality drivers in the Bay Area that are of concern... Some other emerging contaminants. Endocrine disruptors, and things like that which might conceivably be of concern. And so it’s going to be important in looking at future infrastructure needs to consider not just a driver like nutrients and nutrient effects, but to see	Federal regulator (SH5)

Objective	Quotation	Stakeholder professional role
	how does that fit with these other pollutant concerns? To sort of try to figure out […] because you're only going to upgrade a wastewater treatment plant once every so often. You're not going to keep adding little widgets to wastewater treatment plants."	
	"It's not just nutrients, right? You can remove heavy metals, you can remove pesticides, you can remove all of the chemicals and drugs, and pharmaceuticals, personal care products. So it's removing from the waste stream lots of different things. […] It's not just for the nutrients. Now you've got five or six different priority issues that represent a longer-term need, that focus on our wastewater treatment plants."	Federal scientist (SH24)
Maximize water quality in the Bay	"The ultimate goal is to protect the Bay."	Wastewater engineer (SH23)
	"Our goal would be to be sure our discharge isn't creating a nutrient problem in the Bay."	Wastewater treatment plant manager (SH2)
Maximize wetland habitat	"[Nutrient management] also needs to very much think about longer and larger solutions that ideally would go above and beyond really any water quality threshold. What we tend to do nowadays […] is as a society we tend to protect the environment just to that point where we're protecting an endangered species, or a bright-line threshold that we know has an impact. But we tend not to go to the extra work to really do the work properly to have a healthy, functioning, non-impacted ecosystem."	Federal scientist (SH25)
	[Nutrient management should be] "done in a way to improve habitat use of and ecosystem function of, for example, wetlands."	Local regulator (SH5)
	[Everyone should be] "taking advantage [of planning for nutrient control] to look at things like shoreline resiliency and wetland restoration as part of these upgrades."	Wastewater treatment plant manager (SH22)
Minimize greenhouse gas emissions	[Good nutrient management should] "avoid unnecessary construction and energy use."	Local regulator (SH10)
	[Good nutrient management should] "minimize energy usage and greenhouse gases."	Local regulator (SH16)
	[It is essential for good nutrient management to] "do no harm – [cause] no significant increase in greenhouse gas emissions."	Manager at a wastewater utility (SH19)
Minimize costs	"What are the highest value stabilization strategies per dollar spent? I think that's probably the greatest challenge."	Manager at a wastewater utility (SH21)
	"What might be expected out of improving treatment at some of the wastewater treatment plants [to control nutrients] could be very costly, and probably not cost-benefit."	Federal regulator (SH5)
	"The more those costs come down, the better able communities can afford it, obviously–so that means we [should] implement [nutrient control] in a way that doesn't overburden our society with costs."	Drinking water utility manager (SH15)
	"We want a bang for every billion dollars spent."	Local regulator (SH4)
Resilience to sea level rise	"There are issues related to sea-level rise that we need to think about when we figure out what our 21st century wastewater treatment plant looks like."	Federal regulator (SH5)
	"With sea-level rise coming we know that a lot of our wastewater treatment plants that are down on the flats are going to either need to be protected or moved. So [nutrient management] might fit into a larger	Federal scientist (SH25)

Objective	Quotation	Stakeholder professional role
	overarching opportunity to get the San Francisco Bay on a few larger regional wastewater treatment plants that do a much better job--but up and out of the Baylands so that they don't have to have seawalls around them […] move them up and out well above high water marks you expect in 50 to 100 years."	
Technical reliability	[It is essential that good nutrient management options] "are reliable, and can decently meet our treatment requirements […] Because we want to make sure that we're consistently meeting our goals."	Wastewater treatment plant manager (SH7)
	"We want to make sure that when we're investing in big capital dollars [for nutrient control], that the technology is proven. It's going to work. It can be operated by operators reliably."	Wastewater utility advocate (SH1)

Table S4. Supporting quotations from stakeholders about barriers to multi-benefit water infrastructure projects. Stakeholder number is given in parentheses in the final column.

Category	Barrier	Supporting quotation	Stakeholder professional role
Institutional	Leadership	"What organization or agency would be the one to deal with an issue [of multi-benefit nutrient control] like that?"	Baylands steward (SH6)
		"Who is managing it [multi-benefit infrastructure for nutrient control]? And who is making the wise decisions? And who is resolving the natural disputes that are going to arise?"	Wastewater treatment plant manager (SH3)
		"What's your overriding goal?"	Wastewater treatment plant manager (SH3)
	Collaboration	"In our case, [water recycling for nutrient control] involves another agency. And I don't know how water recycling fits into [the water supply agency's] long-term supply strategy."	Wastewater treatment plant manager (SH7)
		[Multi-benefit nutrient control] "would also depend on relationships with other entities--like water supply district, or planning agencies, or the community and their receptiveness."	Wastewater utility manager (SH2)
	Permitting	"If [nutrient control] has multi-attributes, it's going to be harder [to permit] … It's when you try to meet multiple goals, then it gets harder."	Wastewater discharge manager (SH2)
		"In those new discharge scenarios: the unconventional stuff, where you say rather than discharge waste to the Bay, discharge to wetlands -- that does have some permitting challenges. I don't want to downplay that."	Local regulator (SH13)
	Risk tolerance	"Using something like wetlands or horizontal levees to try to treat nutrients? It may have some promise in the future, but I don't think anyone right now, including the regulators, would say this is the way to go. Because they don't know what the outcome is going to be or if there's going to be other challenges. Solve one problem, create two more down the road sort of thing."	Wastewater treatment plant manager (SH7)
		"There's a lot of aversion in the industry to new stuff. Until they've seen it happen – they're used to this high degree of reliability. It's almost unrealistically high. A lot of it has been driven by compliance considerations and enforcement."	Local regulator (SH4)

Category	Barrier	Supporting quotation	Stakeholder professional role
Social	Public opinion	"[Urine source separation and treatment] sounds insane. Just insane!"	Wastewater treatment plant manager (SH3)
		[People can adapt to urine source separation.] "Think about how we've adapted as humans. [Consider] seatbelts […] I was from a generation when you never used a seatbelt. The concept of a seatbelt was like, what? You've got to be kidding. It took me a while, but then you adapted and now you just do it."	Local regulator (SH4)
	Public compliance	"If you're going to depend on the public to actually do something [for nutrient control] – I don't think that's a good strategy."	Baylands steward (SH5)
		"It's hard enough to get people to recycle – so getting them to carry their urine in a bottle […] unless it was double piped and that would be really expensive."	Federal regulator (SH9)
		"We have a hard-enough time getting people to separate their food scraps [for compost], much less their pee from their poo."	Wastewater advocate (SH1)
Technical	Effects on existing treatment	"They want you to recycle more, but by recycling, they're removing the water that keeps my effluent diluted enough that I might possibly, barely meet the selenium and mercury regulations. That will be the repercussions of what they're doing. There will come a point where we'll be in constant violation unless we shut off the recycling things. If they do [more water recycling], I'm not sure I can meet the ridiculously low limits."	Wastewater treatment plant manager (SH3)

Table S5. Supporting quotations for strategies to overcome barriers to multi-benefit infrastructure. The stakeholder number is given in parentheses in the final column (see Tab. S1)

Category	**Barrier**	**Strategies to overcome barriers**	**Supporting quotation**	**Stakeholder professional role (SH number)**
Institutional	Collaboration	Establish networking relationships between different agencies, organizations and water managers *before* decisions need to be made	"Fortunately over the years there's been a more cooperative environment that's built up in the Bay Area anyway, in terms of water quality planning […] there's been a long-term cooperative monitoring program for San Francisco Bay into which a lot of the dischargers sort of pay into this rather than running their own monitoring programs. And I think there's been good experience with that, and that has led people to maybe be a little more open to this kind of approach [multi-benefit wastewater infrastructure]."	Federal regulator (SH9)
			"When you have, for example, the annual meetings of the RMP [Regional Monitoring Program], and you talk about data -- Having that group of scientists, and regulators, and dischargers, and NGOs have meaningful discussion around that data and what it means, and the fact that it requires something to be done, is a powerful way to have a foundation for doing something [with multiple benefits]."	Federal regulator (SH16)
		Structure permits regionally to force interaction and collaboration between dischargers	"Traditionally, we tend to look at wastewater permits sort of facility by facility. And oftentimes we do not do a great job looking at how they operate as a collective, in looking at their collective impacts – but also looking at them as a group of associated operations that might have the capacity to cooperate in doing work to address a problem of concern."	Federal regulator (SH9)
		Regulators, dischargers, and technology developers/scientists collaborate to develop regulations that support adoption of innovative technologies	"We don't want to wait and just be regulated towards the existing technology. We're looking for new [multi-benefit] technology."	Wastewater treatment plant manager (SH28)
	Permitting	Increased permit length	"Five years would be unreasonable [to plan and implement a multi-benefit wastewater infrastructure project], for sure. Just because of the money involved, and the time it takes to go	Wastewater treatment plant manager (SH2)

Category	Barrier	Strategies to overcome barriers	Supporting quotation	Stakeholder professional role (SH number)
			through all of the items I just discussed [different alternatives, technologies, costs, and environmental review]. A more reasonable timeframe would probably be something along the 10- to 15-year range."	
			"If there's a way to minimize either the amount of time or the amount of money it takes to get a permit [for a multi-benefit infrastructure project], or if there's some assurances from one permit to the next, because the target's always moving. Having a longer permit, having a 10 or 15-year permit, would make the process feel a little less painful, because you're making the investment for a longer period of time."	Wastewater treatment plant manager (SH7)
	Costs	Increased institutional funding for research	"Our public agencies are not set up as research institutions--and most of us don't collect any dollars for research. […] Maybe we should. Why wouldn't we be, just as in the private side--if you want to grow your business or you want to expand that, you have to spend money on research and development? We just don't do that as public sector. And it sorely is needed."	Wastewater treatment plant manager (SH28)
		Find ways to share costs	"[We need to] find a way to incentivize [multi-benefit infrastructure] through a cost-share program to say 'If we made this change, it would benefit you, but it would also benefit nutrient discharge.' You know, find a source of funding to offset those improvements or cost share. You can kind of get more progress with carrots than you can with a stick."	Baylands steward (SH25)
	Risk tolerance	Develop easily implemented and adaptable technologies	"Given that implementation of change in wastewater treatment is 5-10 years, are there things that could be implemented quicker, that are not full upgrades? Are there things that are readily available, when we need change, that could kick in? […] That's why I'm getting some interest in new technologies. Maybe are they quicker to implement than the full upgrade? [...] Rather than having a risk-aversion based approach [build proven traditional nutrient removal upgrades at wastewater treatment plants] that could be very costly, we're going to accept some risk [and try to implement	Regional regulator (SH4)

Category	Barrier	Strategies to overcome barriers	Supporting quotation	Stakeholder professional role (SH number)
			unproven technologies], as long as we can adapt reasonably quickly."	
Social	Public opinion	Make wastewater treatment more visible	"I was very much moved by […] how the Roman system was built with these public fountains, and it was reasonably well funded relative to the economy, and a big part of it was people knew what it was all about. Versus our [wastewater infra-] structure is all out of sight, out of mind. That's one of our challenges when we try to get people to support stuff [like multi-benefit wastewater infrastructure], they're like, "support what? Isn't it all being taken care of?"	Regional regulator (SH4)

Chapter V: Multi-criteria decision analysis to support regional decision-making about multi-benefit water infrastructure

Preface

Given the range of different objectives for multi-benefit water infrastructure demonstrated in the previous chapter, it is unlikely that water infrastructure projects will meet many of these objectives purely by chance. In addition, regional water infrastructure projects – which span multiple jurisdictions (e.g., of water or wastewater utilities, cities, and counties) are necessary for addressing many of these goals, since issues like water pollution, greenhouse gas emissions, and aesthetic improvements may span existing jurisdictional boundaries. These factors suggest that strategic planning for multi-benefit water infrastructure on a regional scale may be necessary.

Finding regional solutions for water infrastructure and other regional environmental management challenges requires coordination, communication, and a shared understanding amongst different stakeholders. This chapter develops and evaluates a mixed-methods approach to facilitating collaborative strategic planning for multi-benefit water infrastructure and other regional environmental management.

The approach integrates multi-criteria decision analysis, scenario planning, and stakeholder analysis, all of which have been used in various permutations in water management and environmental planning more broadly (Hajkowicz, 2008; Hermans et al., 2007; Kiker et al., 2005; Liu et al., 2008a; Scott et al., 2012a; Starkl et al., 2009; Wiek and Walter, 2009). These methods were deliberately chosen to resonate with water managers in different roles, since one of the aims of this chapter is to provide effective decision support for water managers. Due to this intended audience, the methods employed here intentionally integrate qualitative methods often used in regional planning and business (stakeholder analysis, scenario planning) with quantitative optimization approaches favored by engineers (multi-criteria decision analysis).

This combination of methods identifies agreements and conflicts between stakeholders, which can aid decision-makers in finding appropriate solutions (Gregory et al., 2001). In addition, it clarifies the extent to which different approaches could meet goals for regional environmental infrastructure and assesses relative effects of future uncertainties and technical uncertainties on outcomes. In combination, these methods can provide valuable insight into strategic planning processes for multi-benefit water infrastructure, as well as a framework for organizing regional decision-making.

Excerpt from 'A Mixed-Methods Approach to Strategic Planning for Multi-Benefit Regional Water Infrastructure', by Sasha Harris-Lovett, Judit Lienert and David Sedlak. In review in *Journal of Environmental Management*, 2018.

Introduction

There is increasing interest amongst researchers and practitioners in improving urban water management by transitioning from existing, segmented management approaches to integrated, multi-benefit approaches (Brown and Farrelly, 2009; Larsen and Gujer, 1997). Achieving this goal is socially, politically, and technically complex because water infrastructure affects many different stakeholders, lasts for multiple decades, and requires significant financial investment. Improved strategic planning processes can help facilitate this transition by allowing stakeholders to articulate their values and objectives, by providing a means of considering innovative options, and by explicitly accounting for uncertainties about the future (Truffer et al., 2010). They also can support major shifts in water infrastructure investment by allowing decision-makers to fully consider the long-term benefits of potential systems in ways that are not captured accurately by existing planning methods, which tend to result in incremental improvements to individual projects (Dominguez et al., 2009).

To facilitate transitions to approaches that support multi-benefit water infrastructure, decision-makers must engage with stakeholders who have historically been excluded from the decision-making process (Pearson et al., 2010). Researchers have developed qualitative strategic planning processes in which stakeholders describe uncertainties and qualitatively explore trade-offs amongst different management alternatives (Störmer et al., 2009; Störmer and Truffer, 2009). This process can include analysis of the social dynamics and long-term goals of stakeholders involved with infrastructure planning (Dominguez et al., 2011). Yet researchers suggest that decision-makers whose choices implicate large sums of money or influence many peoples' lives should use both qualitative and quantitative data to inform decision-making (Mays et al., 2005). Therefore a mixed-methods approach to facilitate decision-support is useful (Greening and Bernow, 2004).

As a result of the long design lifetimes of most water infrastructure projects, consideration of future conditions is an essential aspect of the decision-making process. Scenario planning, in which critical uncertainties about the future are considered in the development and analysis of potential management options, allows decision-makers to explicitly consider a range of ossible future conditions. This tool is becoming more popular among water infrastructure planning professionals (Kang and Lansey, 2012; Lienert et al., 2006) as well as other professionals concerned with environmental management (Mahmoud et al., 2009; Peterson et al., 2003).

Multi-criteria decision analysis (MCDA) can also guide management actions in environmental planning (Mendoza and Martins, 2006; Huang et al., 2011; Liu et al., 2008; Linkov et al., 2006; Reed, 2008), water resources management (Borsuk et al., 2001; Gregory et al., 2006; Hajkowicz and Collins, 2006; Kunz et al., 2013; Marttunen and Hämäläinen, 2008; Mutikanga et al., 2011), and water infrastructure development (Al-Kloub et al., 1997; Garrido-Baserba et al., 2016; Hauger et al., 2002; Kabir et al., 2014; Lienert et al., 2014, 2006; Scholten et al., 2015; Zheng et al., 2016). MCDA creates a structured framework for multiple objectives articulated by local stakeholders (Belton and Stewart, 2002; Keeney, 1992) (Figure 1). Participating in MCDA interviews can help decision-makers clarify their own objectives for any given decision (Gregory et al., 2001; Lichtenstein and Slovic, 2006; Marttunen and Hämäläinen, 2008; Payne et al., 1992). This clarity is especially important for infrastructure projects because it promotes transparency in uses of public funds (McDaniels et al., 1999). By identifying the topics of greatest agreement and disagreement amongst stakeholders, MCDA can help avoid later conflicts (Hajkowicz, 2008; Hermans et al., 2007).

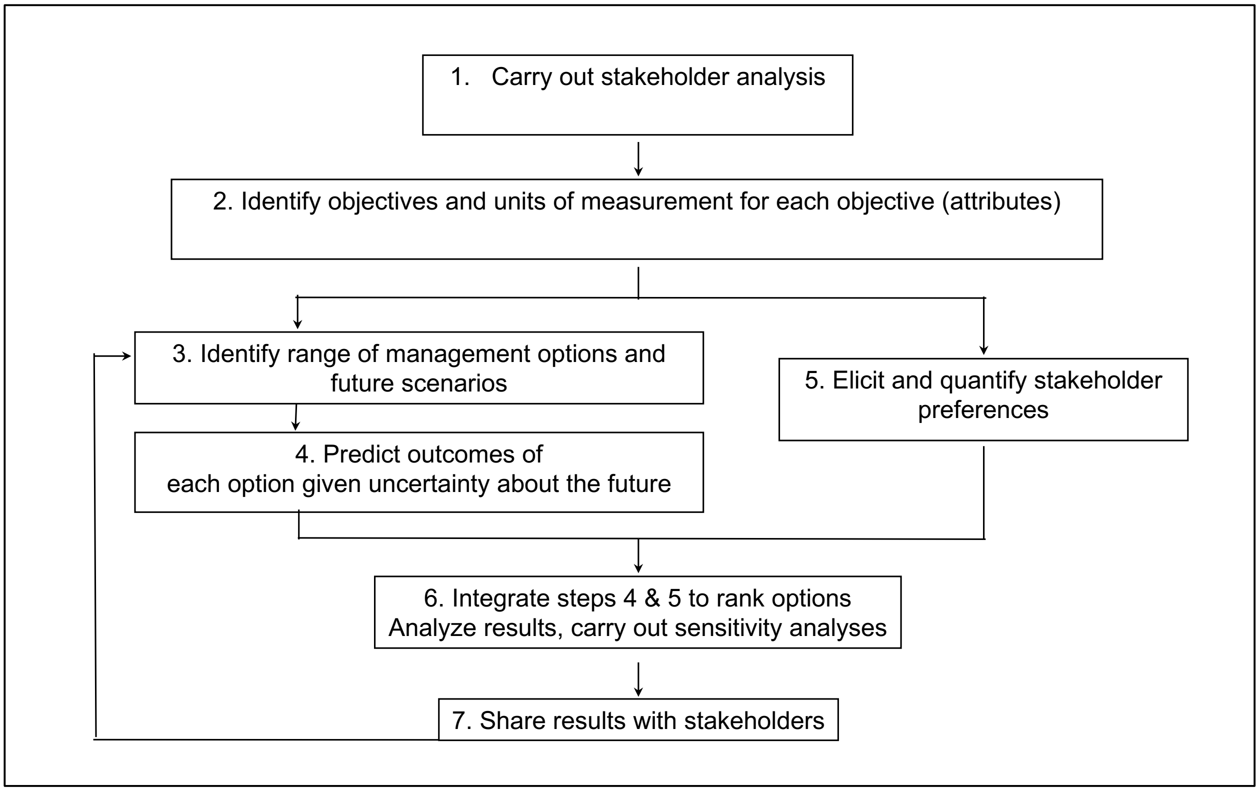


Figure 1. Schematic of the multi-criteria decision analysis process, adapted from (Schuwirth et al., 2012)

An MCDA framework effectively parses out stakeholder preferences from assessment of the technical performance of management options (Marttunen and Hämäläinen, 2008; Matsatsinis and Samaras, 2001). In doing so, it separates the relative importance of stakeholders' preferences from the technical performance of management options during the overall ranking of options (Bojórquez-Tapia et al., 2005). This distinction focuses discussion on objectives of the projects rather than on discrete management options (Greening and Bernow, 2004; Lai et al., 2002), which facilitates consideration of innovative options that would not result from incremental improvements to existing infrastructure.

MCDA also helps identify the tradeoffs between achievement of objectives among different options (Gregory et al., 2001). This allows decision-makers to explicitly weigh trade-offs between social, cultural, environmental, and economic factors which may not be captured in traditional monetary analyses (Kiker et al., 2005).

Previous research suggests transitions towards more sustainable urban water infrastructure are best supported by qualitative analyses of actors, networks, and institutions paired with scientific modeling, because decision-making needs to take into account both social and physical aspects of the available options (Fratini et al., 2012). In particular, combinations of MCDA with other strategic planning methods (i.e., a mixed-methods approach) are considered to be an important area for expanded research in natural resources management (Kangas et al., 2002). To extend this approach to urban water infrastructure planning, we combine stakeholder analysis and analysis of future uncertainties with MCDA to provide decision support and facilitate strategic planning for nutrient management in the San Francisco Bay Area. This study extends previous mixed-methods approaches that have considered a range of uncertain future conditions, like population growth and climate change in multi-criteria decision analysis for water infrastructure planning (Lienert et al., 2014; Zheng et al., 2016).

Case Study: Nitrogen Management in the San Francisco Bay

Nutrient management in the San Francisco Bay Area exhibits many characteristics of complex environmental management decisions that are well-suited for a mixed-methods approach. Decision-makers must balance concerns about human effects on ecosystems, costs, and numerous human interactions and collaborations (Benda et al., 2002). The decision-making process is complicated by scientific uncertainty over the long term, differing stakeholder opinions, and the need for regional solutions (Balint et al., 2011).

Many estuaries and coastal waters are adversely impacted by nitrogen pollution (Howarth, 2008; Howarth et al., 2002, 2000). Excess nutrients can cause oxygen depletion and eutrophication, reduce the productivity of fisheries and decrease recreational value (Dodds et al., 2008). Excessive nutrients discharges to surface waters can also result in growth of algae that exude harmful toxins (Anderson et al., 2002; Heisler et al., 2008; Van Dolah, 2000). Because solutions to nitrogen pollution problems are complex, with no clear answer and context-dependent results to any given solution, it has been referred to as a “wicked” problem (DeFries and Nagendra, 2017; Thornton et al., 2013).

The San Francisco Bay ecosystem has historically been insensitive to nitrogen pollution, likely because algal growth was light-limited due to high levels of suspended particles associated with hydraulic mining the in the nineteenth century and water diversion projects built in the twentieth century (Alpine and Cloern, 1988; Cloern, 1999; Cole and Cloern, 1984). As the turbidity of the Bay declines and nitrogen levels increase with population growth (Cloern and Jassby, 2012), there is evidence that algal growth in the Bay is shifting from being light-limited to nitrogen-limited (Boynton et al., 1982; Cloern, 1999). The extent of the impacts associated with nitrogen pollution are uncertain, especially when the effects of climate change and invasive species are considered (Sutula and Senn, 2015).

Presently, most of the nitrogen entering the San Francisco Bay estuary (“the Bay”) is associated with urban and agricultural runoff and the discharge of municipal wastewater treatment plants (Hager and Schemel, 1992; Novick and Senn, 2014; Wankel et al., 2005). South of the Bay Bridge, more than 90% of the anthropogenic nitrogen load is attributable to the discharge of municipal wastewater effluent (Novick and Senn, 2014) (Figure 2).

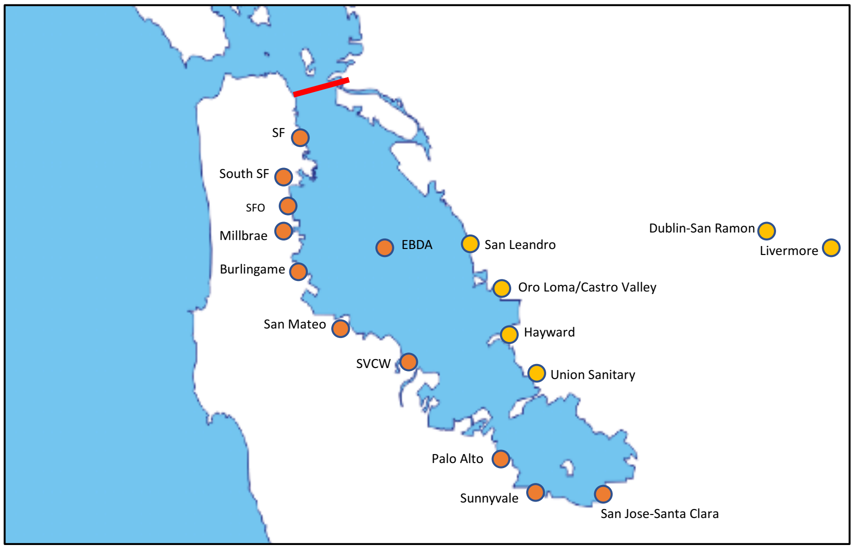


Figure 2. Red dots mark wastewater treatment discharge locations to the southern reach of the San Francisco Bay. SF: San Francisco; SFO: San Francisco Airport; SVCW: Silicon Valley Clean Water; EBDA: East Bay Dischargers Authority. Yellow dots mark facilities that currently discharge effluent via the EBDA outfall pipe. Red line marks the Bay Bridge. (Base image © d-maps.com/Wikimedia Commons/2017)

In response to the potential for future regulatory action to control nitrogen loads (San Francisco Bay Regional Water Quality Control Board, 2014), a varied group of stakeholders in the region have begun to plan strategies to lower nutrient loads (primarily nitrogen) to the Bay. The Nutrient Management Strategy team is advised by a steering committee, a stakeholder advisory group, a technical working group, and a science team (San Francisco Bay Nutrient Management Strategy, 2016).

Although controlling nutrient loads has been viewed traditionally as an issue with mainly two sets of stakeholders – the regulators (in this case, San Francisco Regional Water Quality Control Board and the US Environmental Protection Agency) and the nutrient dischargers (i.e., the municipal wastewater treatment plants), the reality is more complex. There is a strong interest in the region for providing nitrogen control infrastructure that also provides other benefits. These desired co-benefits include increased shoreline habitat, recreational shoreline access, water supply, and resilience to sea level rise (see Chapter 4). Therefore, strategies to manage nitrogen loads in the Bay Area may also affect other stakeholders like water supply managers, baylands land managers, and ecological stewards.

Unlike some other situations in which MCDA has been employed to find a single optimal solution (e.g. choosing a location for an airport; Bojórquez-Tapia et al., 2005), the diverse set of stakeholders in the San Francisco Bay must make a series of separate decisions that will advance collective goals. Wastewater treatment plant managers (dischargers) are obliged by law to preserve water quality in the Bay while respecting the financial limitations of the ratepayers who fund the operation of treatment plants. Regarding nutrient management, each discharger must decide which technologies to employ or actions to take (if any) to control the mass of nutrients released in their effluent. Regulators are charged with enforcing laws and policies designed to protect the Bay ecosystem (e.g., the Clean Water Act), so their decisions entail whether and how to set legal limits on nutrient loading. Other stakeholders, like baylands stewards, coastal planners, or environmental advocates, can decide whether to contest decisions made by regulators and dischargers through litigation.

Within this varied decision-making context, MCDA on its own is not sufficient for providing regional strategic planning support. This issue, like other "wicked" problems of ecosystem management, requires decision support tools to facilitate multi-sector decision-making, enable collaborative decision-making across agencies and administrative boundaries, and balance different stakeholder values (DeFries and Nagendra, 2017). Strategic planning in this decision context endeavors to facilitate greater understanding and teamwork amongst a diverse group of stakeholders without necessarily aiming for consensus or finding a one-size-fits-all solution.

To provide this support, we combined stakeholder analysis and scenario planning with multi-criteria decision analysis. We evaluate the insights derived from this mixed-methods approach and generalize its applicability to strategic water infrastructure planning and management of complex environmental problems. To support decision-making about nutrient management in San Francisco Bay, we addressed the following specific aims:

1. Identify the objectives on which stakeholders agree and disagree, and clarify key areas where consensus should be achieved before decision-making proceeds.
2. Assess how innovative, multi-benefit management options score with respect to stakeholder objectives.
3. Define and bound the uncertainties associated with technical performance and future conditions for each management option, and determine which options, if any, perform most robustly under a range of future scenarios and across stakeholder viewpoints.
4. Determine areas in which further scientific research would be helpful in informing decision-making.

Materials and Methods

Stakeholder selection

Stakeholders were identified based on their professional interest in nutrient loading to San Francisco Bay, specifically whether they were involved with decision-making or would be affected by decisions made (Grimble and Wellard, 1997; Reed et al., 2009). Stakeholder identification proceeded in three iterative stages:

1. We identified organizations and individuals involved with decision-making about nutrient management as evidenced by their presence on relevant advisory committees (e.g., of the Nutrient Management Strategy), by appearances at relevant public meetings (at which records of attendees were kept), or by authorship of relevant documents. When an organization (and no particular person within it) was identified in these searches, the person within the organization with the most responsibility for strategic planning was contacted using publicly-available professional email addresses and asked to participate in the research or to recommend someone within the organization to participate.

2. Once interviews commenced (see Section 2.2), we used snowball sampling (Atkinson and Flint, 2001; Biernacki and Waldorf, 1981) to identify other stakeholders. To further define the set of stakeholders, participants were asked to rate their own influence over decision-making as well the extent to which decisions made about nutrients would affect them, on a scale of 1-7. They also rated the influence and defined the extent to which others would be affected (using the approach described in Lienert et al., 2013). Multiple stakeholders from a single organization were contacted when they had distinct roles in decision-making and when they were specifically identified by other stakeholders.
3. The researchers determined stakeholders who would be affected by proposed management options for nutrient management, which were described in regional planning documents as well as discussed in initial interviews. For example, references to upgrading treatment plants to include biological nutrient removal technologies (e.g., San Francisco Bay Regional Water Quality Control Board, 2014), resulted in inclusion of stakeholders from engineering consulting companies who would conduct the work. References to constructing wetlands for nutrient removal (e.g., Wren, 2017) resulted in the inclusion of coastal land managers whose work would likely be affected such a project.

Initial interviews

Initial interviews were designed to collect data for:

1. Conducting a stakeholder analysis that illuminated the history and current state of decision-making about nutrients.
2. Building an objectives hierarchy for the MCDA.
3. Defining attributes for the decision criteria in the MCDA.
4. Developing ideas for nutrient management options.
5. Determining critical future uncertainties to test in the MCDA.
6. Increasing understanding of how nutrient management fit into other long-term planning objectives for the estuary and into stakeholders' professional mandates (see Chapter 4).

Initial interviews were semi-structured. Open-ended questions were designed to elicit the interest of stakeholders in nutrient management in San Francisco Bay and their role in decision-making. We asked for their objectives for good nutrient management and their ideas for ways to measure fulfillment of these objectives (the 'attributes' for MCDA). We also elicited their ideas for potential nutrient management options and their impressions of future conditions that might affect nutrient management (see interview guidelines in Supplemental Information, Figure S1).

First round interviews lasted 30 to 90 minutes and were conducted primarily by telephone, with the exception of four individuals from one organization who asked to be interviewed in person together. Prior to their interview, these four individuals completed handouts with the same open-ended questions designed to elicit individual preferences and points of view. The entire group engaged in discussion for the remainder of the interview. All interviews were transcribed and coded for themes pertaining to the aims of the interview (listed above) using MaxQDA software.

The interview protocol was reviewed and approved by the Committee for Protection of Human Subjects (the Institutional Review Board) at the University of California, Berkeley.

Development of objectives hierarchy and attributes

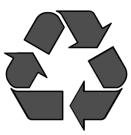
Synthesizing information from the first-round interviews, we developed a hierarchy of fundamental objectives (Eisenführ et al., 2010) for decision-making about nutrient management in San Francisco Bay, along with attributes to measure each of these objectives. A top-level fundamental objective served as an umbrella for a similar number of fundamental sub-objectives (2 or 3). This balanced grouping in hierarchy branches minimized splitting biases (Hämäläinen and Alaja, 2008). Objectives at the highest level were informed by previous research findings from MCDA analysis of water infrastructure planning (Lienert et al., 2014).

To measure fulfillment of each objective, we attempted to choose attributes that directly related to the objectives, that could reasonably be determined for each of the options, that were understandable, comprehensive, and unambiguous (Eisenführ et al., 2010). However, these best practices in MCDA could not always be fulfilled. Specifically, in several cases there was no clear consensus from stakeholders on how to measure fulfillment of an objective, which necessitated a selection of an attribute informed by consultation with specialists engaged in the nutrient management process. One example was "good water quality", a case in which some stakeholders expressed the opinion that this objective should be assessed by probability of impairment, whereas others indicated that the objective would be met only in the absence of impairment, and others indicated that a proxy measure, like abnormally low concentrations of dissolved oxygen or high concentrations of chlorophyll-a would indicate a failure to meet the objective. After consulting with several water quality experts, we chose the attribute of probability of impairment of water quality. In situations where the objective was broad, we chose a proxy that was well-characterized in the literature. For instance, to assess the objective of maximizing removal of contaminants of emerging concern from wastewater effluent, we chose the attribute of mass loading of the antibiotic sulfamethoxazole (Batt et al., 2007; Jasper et al., 2014a; Jasper and Sedlak, 2013; Radjenović et al., 2008)). We expressed attributes in continuous scales only when we deemed no other attribute to be appropriate. One example was the objective of ease of adaptation which scaled from 0% -- impossible to adapt to changing conditions to 100% -- very easy and cheap to adapt to changing conditions.

Development of management options for consideration

Potential options to manage nutrients were derived from stakeholder interviews, technical documents (e.g., permits (San Francisco Bay Regional Water Quality Control Board, 2014)), and options informed by our understanding of management approaches that might be applied. The latter included 'Do nothing' to provide a baseline for comparison, as well as urine source separation and treatment as an approach that was unfamiliar to the local decision-makers but which has been considered a viable option in Europe (Lienert and Larsen, 2007). A brief description of each management option is shown in Table 1 (detailed descriptions see Supplemental Information, Table S1).

Table 1. Nitrogen management options under consideration in the multi-criteria decision analysis. (Photo credits: Wastewater treatment-- By Hasan Zulic/ panoramio/CC BY 3.0/Wikimedia Commons; Wetlands – By US Fish and Wildlife Service/Wikimedia Commons; Recycling – CC-BY-SA3.0/Wikimedia Commons; Roediger NoMix Toilet (urine-separating toilet) – By Sustainable Sanitation Alliance Secretariat/ CC BY 2.0/ Wikimedia Commons)

Management option		**Description**	**Nitrogen loading reduction below 2017 levels**
Do nothing		No additional action.	0
Constructed wetlands 	Horizontal levee wetlands	Vegetated wetland levees are built to the maximum possible extent given spatial constraints.	53%
	Shallow open-water wetlands	Open-water wetlands are built to reduce nitrate loads by 90% at each wastewater treatment plant if possible, given spatial constraints.	65%
Wastewater recycling 	Increase recycling for irrigation	Maximize wastewater recycling for irrigation (without additional treatment for nutrient removal).	28%
	Increase recycling for potable reuse	Maximize recycling of wastewater for potable reuse, with a "brine line" to the ocean, thus diverting nutrients from the Bay.	26%
Urine source-separation and treatment 	Install urine source-separating toilets– early adopters	Deploy urine-separating toilets in all new housing and for some early adopters to divert and treat urine in decentralized facilities.	1%
	Install urine source-separating toilets– with incentives	Deploy urine-separating toilets in new housing to divert and treat urine in decentralized facilities, with financial incentives to encourage 30% adoption in existing housing.	14%
Wastewater treatment plant upgrades (as per HDR report specifications) 	Optimization	Optimize existing wastewater treatment processes for total nitrogen removal.	10%
	Level 2 upgrades	Upgrades to achieve < 15 mg TN/L.	55%
	Level 3 upgrades	Upgrades to achieve < 6 mg TN/L.	82%

We applied each option under consideration to the entire case study region to assess the extent to which the technologies could meet different objectives. However, it is important to note that this approach is not realistic; decisions about technology adoption are much more likely to be made at a local scale to fit specific community needs related to existing infrastructure, local geography and institutional constraints. The MCDA results for each of the management options should be considered instructive and illustrative but not prescriptive.

Three management options were added after follow-up interviews with stakeholders to assess how different permutations of the original options affected final rankings of options:

1. Constructed open-water wetlands were added as a comparison with sub-surface flow "horizontal levee" wetlands, with different assumptions about land availability, wetland sizing, costs, habitat creation, resilience to sea level rise, and nutrient removal.
2. Urine source separation initially focused on "early adopters" of the technology. A second option was added with financial incentives for adoption of urine source-separation technology, which would achieve greater levels of nutrient removal and would increase reliability of this option.
3. Potable water recycling with a line for discharging reverse-osmosis concentrate to the ocean was added to address stakeholders' interest in potable water reuse as a water supply option while still reducing the loading of nutrients to the Bay.

Each option was developed by considering the maximum reasonable extent to which it could be applied in the region, based on high-end estimates obtained in planning documents, scientific literature, and from conversations with stakeholders. As a result, each option represents different levels of nutrient removal as well as different degrees of fulfillment of each of the objectives. All assumptions and detailed parameters of each management option modeled in the MCDA are included in the Supplemental Information, Text S1.

Treatment of future uncertainty

To assess uncertainty in future conditions, we considered several key factors in the year 2050 with which to evaluate technological options for nutrient management. We chose 2050 as the planning target year because most wastewater infrastructure is designed to last at least 30-years (Dominguez and Gujer, 2006).

During interviews, stakeholders were asked to list future conditions in 2050 that would likely affect their choice of nutrient management options ("critical uncertainties"). These critical uncertainties were, by definition, outside of the control of water managers but could have profound impacts on the choices of interviewees (Wilkinson and Kupers, 2014). We distilled this information into factors that were most likely to influence MCDA results (Mahmoud et al., 2009): population growth, effects of climate change, and the Bay's ecological resilience with respect to nutrient loading. Ecological resilience to nutrient loading would affect the attribute measure of "good water quality" for all the treatment options. Changing population size could affect nutrient loading (and hence water quality), loading of contaminants of emerging concern, and sizing of treatment options (which would indirectly affect greenhouse gas emissions and cost). Climate change-related impacts (e.g., magnitude of sea level rise) could affect resilience of treatment options to sea level rise.

Two of these critical uncertainties (i.e., nutrient loading affected by population change and the Bay's ecological resilience to nutrients) were used to develop a matrix of possibilities with which to inform the development of future scenarios (Scott et al., 2012; Wright and Goodwin, 2009) (Figure 3). The effect of climate change on wastewater infrastructure located at or near sea level was used to amplify the Worst- and Best-case scenarios developed in the matrix.

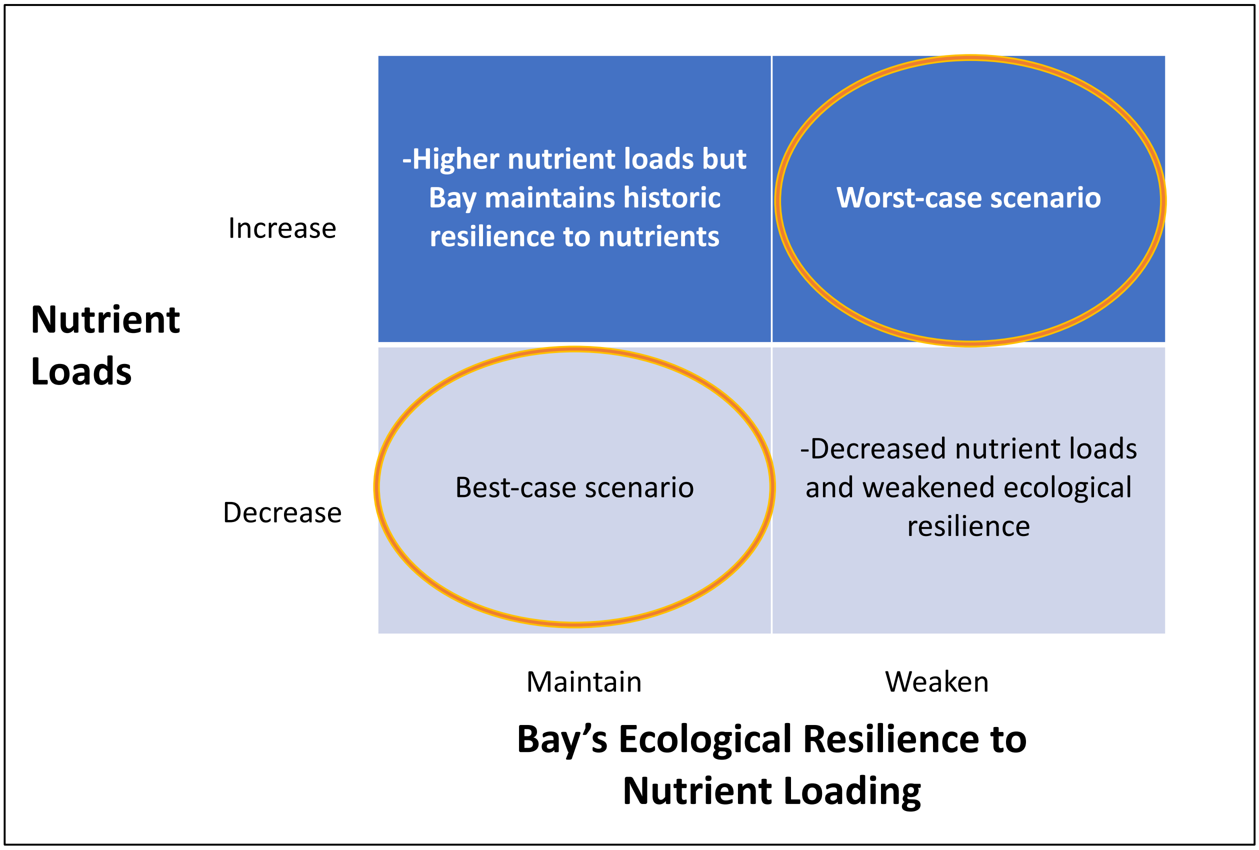


Figure 3. Two key uncertainties, nutrient loads due to population increase and the Bay's ecological resilience to nutrient loading, were used to inform future scenarios for the year 2050.

Our scenarios identify extreme futures by placing positive elements for nutrient control in one scenario and negatives in another (Schoemaker, 1995):

- **Worst-case scenario for nutrient impairment.** In this scenario, the Bay's ecosystem is much more sensitive to nutrient loading due to system attributes like decreased water column turbidity and increased periods of stratification. Nutrient loading to the Bay increases by 60% in this scenario due to rapid population growth between 2017 and 2050. Climate change strongly affects the performance of existing wastewater treatment plants.
- **Best-case scenario: less pressure for nutrient control.** In this scenario, the Bay retains a strong resilience to nutrient pollution. Nutrient loading to the Bay

decreases by 13% due to population decline between 2017 and 2050. Sea level rise does not affect existing wastewater treatment systems.

The "status quo" scenario assumes 33% population growth by 2050 (roughly 1% per year, as per Association of Bay Area Governments and the Metropolitan Transportation Commission, 2017), no effects of climate change on wastewater treatment, and increased ecological sensitivity to nutrient loading. In addition, we designed the model so that attribute values could be calculated for any level of population size change, five levels of climate change effects between these two extremes, and with or without increased ecological sensitivity to nutrient loading (see R code in Supplemental Information, Text S2).

The model was run in the open-source software R (R Core Team, 2013), primarily using the package 'utility' for the MCDA, as well as other packages for analysis and presentation of data (Delignette-Muller and Dutang, 2015; Neuwirth, 2014; Reichert et al., 2013; Trautmann et al., 2014; Wickham, 2011). Open-source software was deliberately chosen to provide a means for stakeholders and other researchers to conduct and evaluate the MCDA under a range of future conditions that were most interesting to them.

The simulations of uncertainty included in the MCDA were based on 1,000 model runs for ease of computing. Although previous MCDA studies which included analyses of uncertainty used 10,000 model runs (Zheng et al., 2016), this larger number of model runs took significantly longer on a laptop computer with a 2.3 GHz processor. Comparison of median overall values with 1,000 compared to 10,000 were similar and did not change the ranking order of any of the alternatives under any future scenario.

Stakeholder analysis and selection for follow-up interviews

We conducted follow-up interviews with a subset of the original group to elicit a range of opinions on the relative importance of the multiple objectives for nutrient control infrastructure. This was done to represent the breadth of opinions amongst the stakeholders because initial interviews suggested that even individual stakeholders with outlier opinions could have an outsize role in affecting the decision-making process through litigation or negative media attention. To sample these differences of opinion, we performed a cluster analysis of the thirty-two stakeholders who participated in the initial interviews (Mardle et al., 2004; Zahir, 1999). We categorized each of the responses based on their stated goals for nutrient management (presence/absence of each objective in their answers to questions about goals for nutrient management).

Our cluster analysis methodology was derived from statistical methods in community ecology (Borcard et al., 2011; McCune and Grace, 2002) and was conducted using the software 'R' with packages 'vegan', 'cluster', 'indicspecies' and 'permute' (Dufrene and Legendre, 1997; Gavin Simpson, 2016; Maechler et al., 2016; Oksanen et al., 2017; R Core Team, 2013). To form the clusters, we excluded mentions of the objective "good water quality", because it was clear from the other interview questions that many stakeholders who had not specifically mentioned "good water quality" as a goal implicitly assumed that it was a high priority in nutrient management. We also removed a stakeholder who did not name any objectives for "good nutrient management".

We used a Bray-Curtis distance measure to form the clusters (which clusters only on shared presence, not shared absences) (Zuur et al., 2007) to group stakeholders by the objectives they considered most important to mention in the limited interview time period. We used a flexible-β linkage, with parameters $\alpha 1 = .625, \alpha 2 = .625,\ \beta = -0.25, \gamma = 0$ to determine the optimal size and shape of each cluster. We then used a Mantel Test to prune the dendrogram formed in the cluster analysis (Borcard et al., 2011). This resulted in seven clusters, ranging from one to eleven stakeholders. We also conducted a statistical analysis to determine the objectives that characterized each cluster of stakeholders and most differentiated them most from the other clusters (called an "indicator species analysis" in ecology) (Dufrene and Legendre, 1997) These results are depicted in Table 2.

From each of these clusters, we contacted those stakeholders that were classified as having the highest relevance to decision-making. This classification was based on the first interview (scale of 1 to 4, with 1 being most engaged with or most affected by decision-making about nutrient loading). Further selection criteria for follow-up interviews included individuals who had the greatest interest in nutrients in the southern reach of the Bay, and those with diverse professional roles in different agencies. We aimed to include at least one stakeholder from each cluster group in follow-up interviews. SH 30 was contacted to participate in a second interview, but this stakeholder had left their job and was not available.

We randomly assigned numbers 1-9 to the stakeholders who participated in the second-round interviews, and numbers 10-32 for stakeholders who participated in the first-round interviews only.

Follow-up interviews for preference elicitation

In follow-up interviews with nine selected stakeholders, we elicited weights using the Swing method, which is common in MCDA (Mustajoki et al., 2005; Schuwirth et al., 2012) and has been used for decision-making about water infrastructure planning (Zheng et al., 2016). Hereby, stakeholders assigned points (from 0-100) for the importance of improving each of the objectives from its worst to best state, assuming that all other objectives would remain on their worst levels. Relative point values were then cross-checked for consistency across the objectives hierarchy with stakeholder feedback and adjustments where necessary (Belton and Stewart, 2002). Assigned points were normalized into weights on a scale of 0-1 for each of the objectives for each stakeholder (Belton and Stewart, 2002). Per definition, the sum of weights for each stakeholder equals 1.

Stakeholders were asked to explain their rationale for assigning points to provide insight into their perspectives on the importance of the objectives and the suitability of the attributes (Marttunen et al., 2015). Attempts to confirm weightings from point allocation results with another common weight elicitation method, the trade-off method (Eisenführ et al., 2010), were almost uniformly rejected by stakeholders (see discussion in Section 4.3.4).

For the objectives that received the highest weights (and others if time allowed), we elicited the shape of the single-attribute value functions (i.e. whether improvement from the worst to best case fulfillment of the objectives was linear, concave, or convex) through the bisection method of elicitation (Eisenführ et al., 2010). In situations where information was missing, we assumed linear value functions. We also identified if there were any thresholds below which everything was equally bad or above which everything was equally good (Scholten et al., 2015). Interview guidelines for follow-up interviews are included in the Supplemental

Information, Figure S1. A more detailed description of methods for preference elicitation is included in Supplemental Information, Text S3.

Second round interviews were conducted in person and took 60 to 120 minutes.

Protocols for follow-up interviews were approved by the Human Subjects Committee (the Institutional Review Board) at the University of California, Berkeley.

Prediction of attribute values for each management option

Predictions of attribute outcomes are uncertain, especially in complex environmental systems (Reichert et al., 2015). To approximate this uncertainty, we used a combination of estimates from the literature, expert assessment, and modeling to determine a range of uncertainty in each of the attribute measures (Scholten et al., 2013).

Given the estimated range and distribution of uncertainty for each attribute value (see Supplemental Information, Table S2), we developed a matrix of 1,000 random potential attribute values for each objective for each option. If less than 3% of modeled values fell outside the worst-best range (as in the case of a normal distribution with a mean of 98 and a standard deviation of 1, with a top limit of 100), the mean value was used to replace those values that exceeded the limits of the range.

After calculation of the attribute values for each option, the option of potable water recycling with a pipeline to the ocean to dispose of reverse-osmosis brine was found to have a value of CO_2 emissions two orders of magnitude higher than the "worst" value used in the elicitation process. (This option was added after the second interviews based on stakeholder interest in potable water recycling as a means of nutrient control.) Although some MCDA practitioners have suggested that the attribute range can be extended with the assumption that stakeholders' preference weights would increase linearly with the change (Eisenführ et al., 2010), this assumption is likely invalid in this case given how far outside the initial range this new option lies. Even with the un-adjusted weightings, the potable water recycling with a pipeline for brine disposal option scored relatively low for most stakeholders (see Supplemental Information, Table S6). Moreover, because the re-adjusted weights within the new range of CO_2 values would dramatically increase the weight of CO_2 emissions (and thus decrease the overall score of the option), we decided not to include this option in the remainder of the analyses. For it to be included, further research would need to re-elicit stakeholder objective weights for such high potential CO_2 emissions or the option would have to be reconfigured with another means of disposing of concentrate, such as zero-liquid discharge systems or an emerging concentrate treatment technology.

Multi-criteria decision analysis

The MCDA was conducted in R using the 'utility' package (Reichert et al., 2013). The attributes for the objectives (termed 'end-nodes' in the MCDA software) were assumed to be single-attribute continuous parametric functions (for each value of 'x' there is only one value of 'y'). Overarching objectives (mid- and top-level aggregation nodes) were assumed to be aggregations of lower-level nodes and were assumed to convert to overall values using a continuous parametric function (rather than one with discrete classes). As a base case, we assumed additive aggregation of the nodes to determine the overall value of each option.

Additive aggregation is not necessarily the most accurate model of stakeholder preferences (Langhans and Lienert, 2016), but it is commonly employed in MCDA and served as a starting point to structure the problem and compare rankings of stakeholder options (Scholten et al., 2015).

Two stakeholders required separate objectives hierarchies. For stakeholder 3 (SH3), an objectives hierarchy was built that did not include water quality because the stakeholder refused to consider a probabilistic measure of impairment. Instead, this stakeholder suggested that impairment should be a "true/false" measure of existing ecological conditions. SH3's objectives hierarchy also did not include habitat because the stakeholder refused to choose between personal sentiments and professional sentiments about the importance of habitat regarding nutrient management, and they indicated that their personal opinions were at odds with their professional mandates. For stakeholder 7 (SH7), the objectives hierarchy did not include recovery of nutrients from wastewater, because the stakeholder refused to accept a measure of nutrient recovery that did not include nutrient recovery from solids removed during conventional wastewater treatment. Though SH3 and SH7 are included in the results, it is important to note that their overall rankings of options, while still instructive, are not comparable to those of other stakeholders.

As an initial base case, all value functions were assumed to be linear and no thresholds (strict limits in attribute values) were included in the analysis. This assumption was made time constraints in interviews prevented us from querying all interviewees about the shape of the marginal value function of attribute fulfillment or thresholds. In addition, most interviewees who discussed value functions gave vague curvatures rather than discrete midpoint values. The base case assumptions and resulting rankings were then tested in a sensitivity analysis (see sections 3.5.1 and 3.5.4) (Scholten et al., 2017; Zheng et al., 2016).

Results

Stakeholder analysis

The selected group of stakeholders included water managers, baylands ecological stewards, scientific researchers and engineers, regulators, urban planners, flood control managers, and advocates for coastal industry or environment at the local, regional, and federal scales (Kunz et al., 2013). The stakeholders represented 76 separate organizations or agencies. Several stakeholders represented more than one organization (e.g., one person served as director of an industrial advocacy group and also served on the board of a public wastewater utility). Of the 88 individuals contacted, 32 stakeholders (representing 29 different organizations) participated in an interview.

Stakeholders with the same professional role (i.e. discharger, regulator) and even within the same organization frequently stated different goals for nutrient management, as evidenced by their failure to cluster together (Table 2). They also weighed the importance of objectives differently. In other words, it would be inaccurate to assume that all dischargers or all regulators have the same objectives. Stakeholder weights for each objective are summarized in the Supplemental Information, Figure S2.

Table 2. Stakeholder clusters based on stated goals for nutrient management. Stakeholders 1-9 (in bold) participated in follow-up interviews. Relevance denotes how strongly a stakeholder was engaged in or affected by decision-making about nutrient loading (1 = directly involved in decision-making; 2 = strongly affected by decision-making, or with strong influence over decision-makers; 3 = slightly affected by decision-making; 4 = interested/concerned with nutrients, but not directly affected by decision-making).

Objective cluster group	Cluster group characteristic	Relevance	Stakeholder	Professional role
1	Wildlife habitat	**1**	**SH6**	**regulator**
		1	SH12	regulator
		2	SH19	discharger
		2	SH16	regulator
		2	SH18	researcher, advocate
		3	SH25	steward, researcher
2	Low costs and water supply	**1**	**SH8**	**advocate**
		1	SH22	discharger
		1	**SH2**	**discharger**
		1	**SH9**	**regulator**
		1	SH10	regulator
		2	SH21	discharger
		2	SH23	engineer
		3	SH26	water supplier
		4	SH17	advocate
		4	SH24	researcher
		4	SH15	water supplier
3	Need science-based understanding of nutrient effects on ecosystem	**1**	**SH1**	**advocate**
		1	SH32	discharger
		1	**SH3**	**discharger**
		1	**SH4**	**regulator**
		1	SH13	regulator
		2	SH27	regulator
4	Technical reliability	2	SH30	discharger
		4	SH11	planner
5	Collaboration across professional fields	1	SH28	discharger
		1	**SH7**	**discharger**
		4	SH31	engineer, planner, regulator
		4	SH20	researcher, steward
6	NA	4	SH14	regulator
7	Balance nutrients with other long-term management goals	**3**	**SH5**	**steward**
		4	SH29	engineer, planner, regulator

Several stakeholders mentioned thresholds in their tolerance for low fulfillment of certain objectives. Stakeholders who stated thresholds tended to have thresholds for several objectives. Three respondents said they would not accept any option for nutrient management that was below a certain level for water quality, measured by probability (%) of deviating from good nutrient-related conditions in the southern reach of the Bay. These levels were worse than 15% (a wastewater dischargers advocate), 20% (a coastal land steward), and 50% (a regulator). One stakeholder (a regulator) would not endorse any nutrient management option that did not protect existing infrastructure from sea level rise. Two stakeholders (a coastal land steward and a wastewater dischargers advocate) would not accept any option with levels of ease of adaptation below 76% and 50%, respectively. Three stakeholders (a regional regulator, a coastal land steward, and a wastewater dischargers advocate) would not accept any option with levels of reliability below 70%, 80%, and 85%, respectively. Effects of these thresholds on the MCDA results are calculated in the sensitivity analysis.

Objectives for good nutrient management

The objectives and attributes for good nutrient management in San Francisco Bay (Table 3) indicate stakeholders have a wide variety of goals, some of which are outside the scope of traditional wastewater infrastructure planning (see Chapter 4). For details and rationale about how each attribute was calculated, see the Supplemental Information, Text S1.

Table 3. Objectives and attributes for good nutrient management in the San Francisco Bay, based on results from stakeholder interviews. (Photo credits: Heron fishing – Chris Harshaw/CC BY-SA 3.0/Wikimedia Commons; Wastewater treatment plant --OpenStax/ CC BY 4.0/Wikimedia Commons; Footprint – from http://www.greencareers.biz/faq/what-does-it-mean-to-offset-your-carbon-footprint/; Thumbs up – Pratheeps/Wikimedia Commons)

Goal	Objective	Attribute	Unit	Description
Healthy estuarine ecosystem 	Good water quality	Probability of deviating from good nutrient-related water conditions	%	Nutrient over-enrichment could result in eutrophication and impairment of beneficial uses (Sutula and Senn, 2015). Expert estimates of the attribute were made based on percent nitrogen load change from current levels.
	Good wildlife habitat	Area of additional wetland habitat created	Square hectares	The modeled area of constructed wetland habitat was based on results from a previous analysis (Wren, 2017).
Maximize treatment and beneficial uses of wastewater 	Increase water supply	Usable water produced	MGD (million gallons /day)	Attribute estimates were derived from utility planning documents (e.g., San Francisco Public Utilities Commission, 2016).
	Increase resource recovery	Recovered nitrogen (N) from effluent that can be used as fertilizer	Kg N/Year	Attribute estimates for nitrogen recovery from urine-source separation were derived from academic literature (e.g., Tarpeh et al., 2017). Recycling for irrigation was assumed to utilize all nutrients (Vazquez-Montiel et al., 1996).
	Maximize removal of unregulated contaminants (CEC)	Total sulfamethoxazole (SMX) loading in the southern reach of the Bay	Kg SMX /year	Sulfamethoxazole was used as a proxy for CECs because its removal in wastewater treatment is relatively well characterized (Batt et al., 2007; Jasper et al., 2014a; Jasper and Sedlak, 2013; Radjenović et al., 2008).
Promote inter-generational equity 	Ease of adaptation as conditions change	Percent ease of adaptation (considers sunk costs, time, physical potential)	%	Wastewater infrastructure that can be quickly and cheaply adapted to deal with changing influent flows and/or concentrations and to achieve more stringent regulatory standards is desirable. Classification: 0-50%: Impossible or hard to adapt; 51-75%: Moderately adaptable**;** 76-100%: Easy to adapt.
	Resilience to sea level rise (SLR)	Extent to which technology is vulnerable to SLR and storm surges	Constructed scale	SLR poses a threat to many of the Bay Area's wastewater treatment plants (Heberger et al., 2009). Scale from -10 to 10; with 10: Protects existing assets from SLR; 0: Unaffected by SLR; -10: Highly vulnerable to SLR.

Goal	Objective	Attribute	Unit	Description
	Low greenhouse gas (GHG) emissions	Lifecycle GHG emissions of wastewater treatment	CO_2 eq. /year	Attribute estimates from literature on emissions of wastewater treatment (Stokes and Horvath, 2009) and nitrogen removal (Corominas et al., 2013).
Good social support	Maximize public's ease of use	Percent ease of use	%	Some technologies could require involvement or behavior change by end users (e.g., urine source-separating toilets requiring men to sit when urinating). Classification: 0-60%: Requires behavior change from users; 61-80%: Mental shift but no behavior change required; 80-100%: Easy to use.
	Increase shoreline access	Additional access points (above 2017 levels)	Number	Access to aesthetically pleasing places along the Bay shore for recreation is desirable.
	Maximize ease of permitting	Percent ease of permitting	%	Classification: 0-60%: Permitting requires much additional staff time and/or legislative change; 61-80%: Permitting requires some additional staff time; 81-100%: Easy to permit.
Minimize costs	Technical reliability	Percent of time technology operates as intended	%	Derived from expert estimates.
	Minimize capital investment and O&M costs	Net present value over 30-year span	$	Cost calculations were based on initial capital investment costs and annual operation and maintenance costs (O&M) over a 30-year technology life span. No depreciation rate was used. If 30-year O&M costs were not available, current annual O&M cost estimates were assumed to remain constant over 30 years.

Prediction of attribute values

Mean attribute values for the Status Quo scenario are shown in Table 4 as an example. Attribute values for the Worst-case scenario, Best-case scenario, and status quo population growth without increased sensitivity to nutrient loading are included in the Supplemental Information, Tables S3-S5.

Table 4. Mean attribute values (rows; see Tab. 2) for each management option (columns; see Tab. 1) in 2050 assuming the Status Quo scenario: 33% population growth, no effects of climate change on wastewater operations, and increased ecological sensitivity to nutrient loading.

Objectives – Attributes [units]	**Management options**									
		Constructed wetlands		**Wastewater recycling**		**Urine separation and treatment**		**Wastewater treatment plant upgrades**		
	Do nothing	**Wetland levee**	**Wetland open water**	**Recycle irrigation**	**Recycle brineline**	**Urine early adopters**	**Urine incentives**	**Optimization**	**Level 2 upgrades**	**Level 3 upgrades**
Good water quality -- Deviation probability from good quality [%]	74	40	32	59	60	68	57	67	35	17
Good wildlife habitat -- Additional wetland habitat [square hectares]	0	4,200	790	0	0	0	0	0	0	0
Increase water supply -- Usable water produced [MGD]	22	22	22	120	100	22	22	22	22	22
Increase resource recovery -- Nitrogen (N) recovery [Mkg N/year]	0	0	0	3,300	0	1,800	4,300	0	0	0
Maximize removal of contaminants of emerging concern -- Total sulfamethoxazole loading [kg SMX /year]	85	56	70	60	64	56	47	86	78	79
Ease of adaptation -- Percent ease of adaptation [%]	100	53	42	45	45	85	55	75	52	10
Resilience to sea level rise -- Scale [-10 (highly vulnerable) to 10 (protects infrastructure)]	-5	8	5	-3	-5	0	0	-5	-5	-5

Objectives – Attributes [units]	Management options									
		Constructed wetlands		Wastewater recycling		Urine separation and treatment		Wastewater treatment plant upgrades		
	Do nothing	Wetland levee	Wetland open water	Recycle irrigation	Recycle brineline	Urine early adopters	Urine incentives	Optimization	Level 2 upgrades	Level 3 upgrades
Low greenhouse gas emissions -- Lifecycle emissions for wastewater treatment [Kkg CO_2 eq. /year]	290	350	310	430	70,000	290	290	290	380	660
Maximize public's ease of use -- Percent public ease of use [%]	100	100	100	100	55	33	35	100	100	100
Increase shoreline access -- Number of access points [#]	0	8.5	8.5	0	0	0	0	0	0	0
Maximize ease of permitting -- Percent ease of permitting [%]	100	33	31	80	45	45	40	90	90	90
Technical reliability -- Percent of time nutrient technology operates as intended [%]	100	77	77	91	98	66	76	98	98	98
Minimize initial capital investment and O&M costs -- Net present value over 30-year span [1,000,000$]	0	2,700	1,200	2,200	370	400	5,300	170	2,500	3,200

Multi-criteria decision analysis

The MCDA produced an overall value for each management option based on the attribute values and the stakeholder weights for each objective (Figure 4). There was no option that scored highest for all stakeholders. However, the options to increase wastewater recycling for irrigation (in dark green) and build horizontal wetland levees (in dark blue) were among the top three options for most stakeholders under all future scenarios. Conversely, both urine source-separation options (in pink and red) and Level 3 upgrades of wastewater treatment plants (in purple) were the lowest ranked options for most stakeholders under all future scenarios.

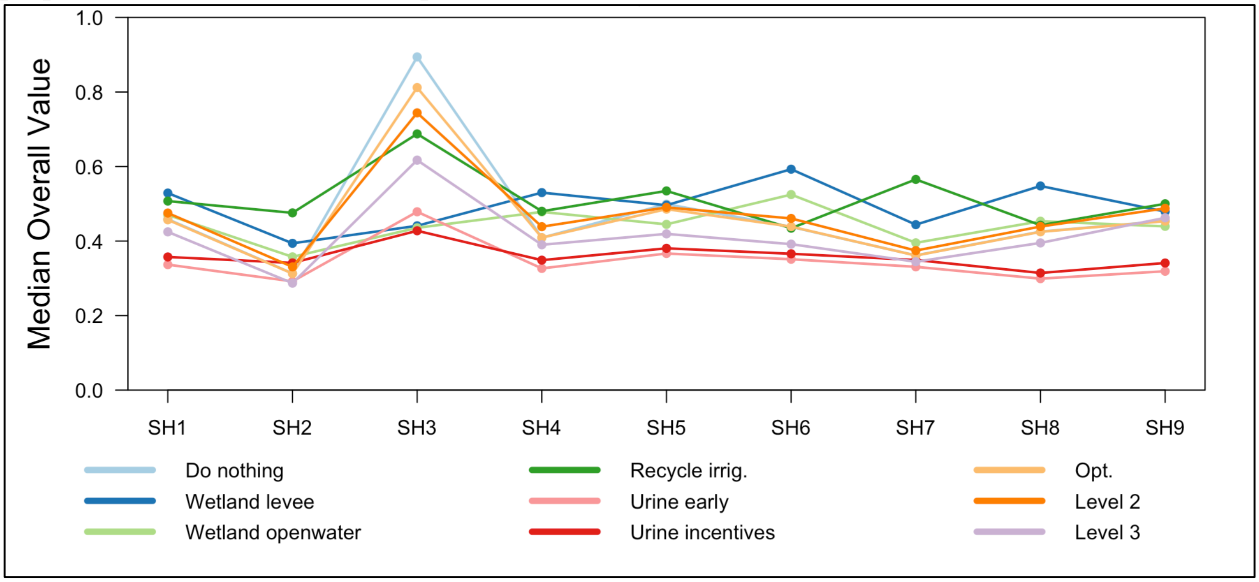


Figure 4. Median overall value as result of the MCDA for each management option (colored lines; see Tab. 1) for each of nine stakeholders (SH; on x-axis) in the Status quo scenario. A value of 1 indicates that all objectives are fully achieved, a value of 0 that none of the objectives are achieved.

In the Best- and Worst-case scenarios, the median overall scores were strikingly similar to those of the Status quo, but the overall values were shifted slighter higher for the Best-case scenario and slightly lower for the Worst-case scenario (see Supplemental Information, Figure S3).

Including uncertainty about attribute predictions into calculations of overall value for each option (Figure 5) indicated that uncertainties in attribute predictions made more difference to overall value than future conditions for the less-established management options like the wetland options (horizontal levee and open water), recycling for irrigation, and the urine source-separation. Future conditions were the main cause of uncertainty in overall value for options in which the management option performance was well established, like optimization, Level 2, and Level 3 upgrades of wastewater treatment plants.

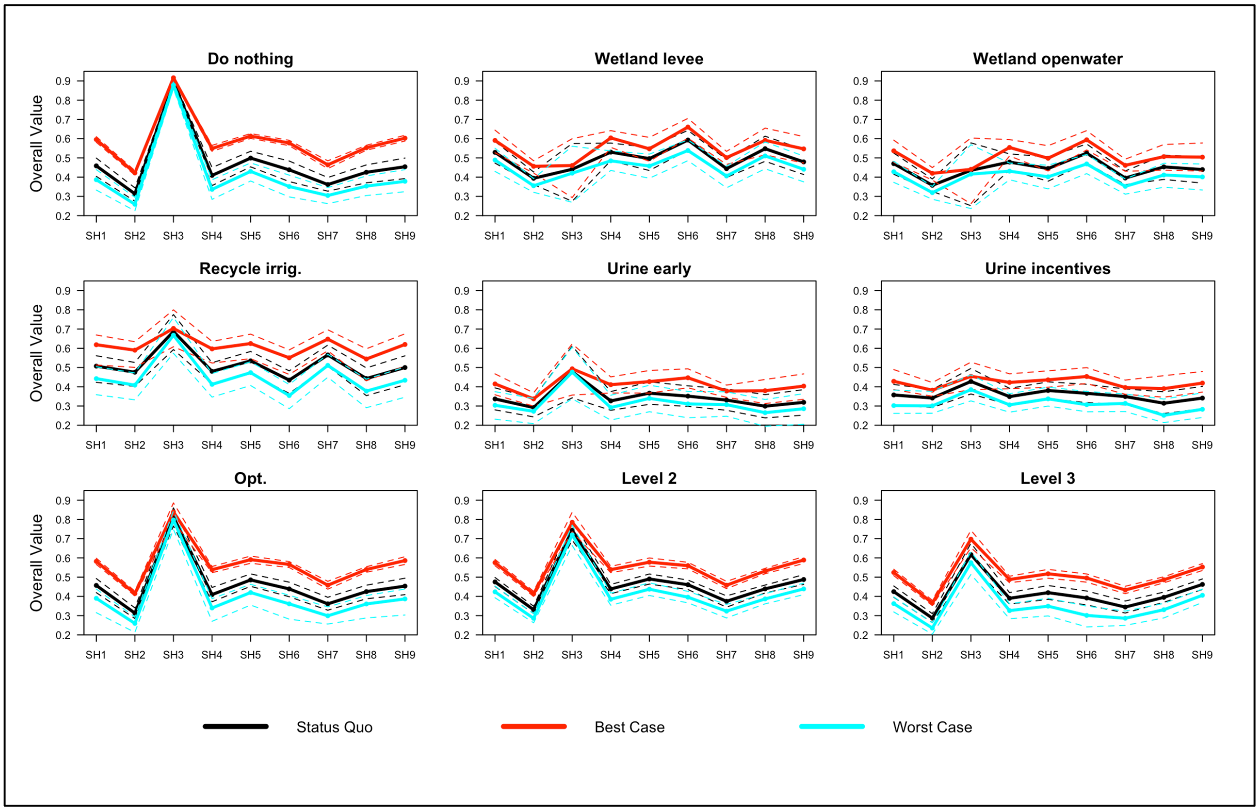


Figure 5. Overall values for each management option (see Tab. 1) for each of nine stakeholders (SH; on x-axis) under three future scenarios (lines: status quo, best, and worst case). Solid lines denote median overall values in each scenario, dashed lines represent 5% and 95% quartile values.

Overall scores for each option for each stakeholder were converted to ranks (from 1-9, with 1 being the top-ranked option compared to the others). In this analysis, less well-established options like constructed wetlands (horizontal levees) and increased recycling for irrigation were likely to be in the top three ranked options for 8 of the 9 stakeholders in the Status quo scenario (Figure 6). In many cases, the rank of each option was affected by uncertainty in attribute prediction, often spanning 4 or more ranks.

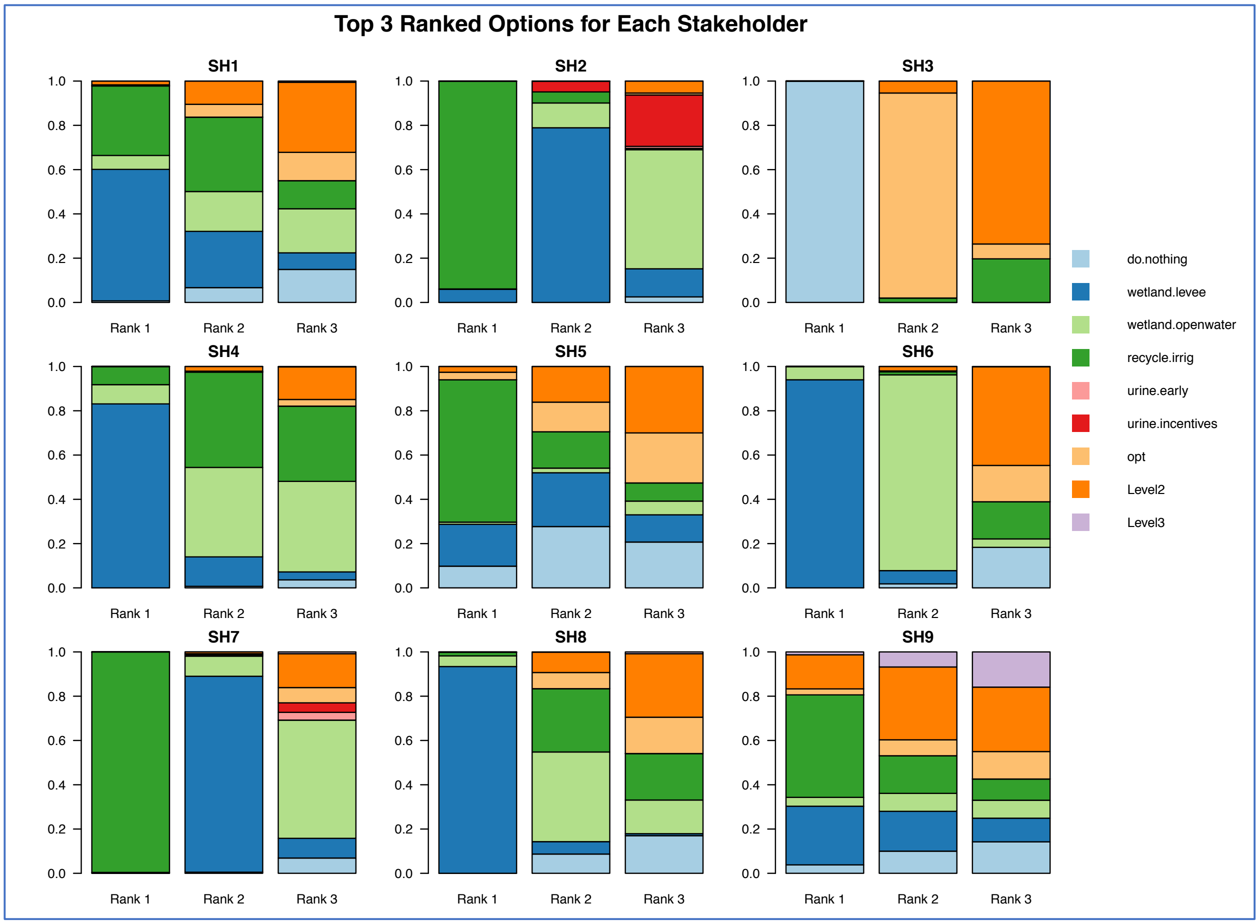


Figure 6. The probability of the top three ranked options for each of nine stakeholders (SH) given uncertainty in attribute predictions, Status quo scenario. Color coding options see legend and Table 1.

The probability of the top three ranked options for each stakeholder was virtually unchanged in the Worst-case scenario (see Supplemental Information, Figure S4) whereas for the Best-case scenario, the 'Do nothing' option moved into the top three or became far more prominent as a preferred option for nearly all stakeholders, and optimization became more favorable for many stakeholders as well (see Supplemental Information, Figure S5). In other words, traditional responses fared better under the best-case scenario. In general, Level 3 upgrades of treatment plants and the urine-source separation options ranked lower than the other options for nearly all stakeholders under a range of future conditions (see Supplemental Information, Figures S6-S8).

A closer look at the contribution of each objective to overall values for individual stakeholders revealed that the benefits other than water quality of some of the less-traditional nutrient management options helped boost their overall value above that of conventional wastewater treatment plant upgrades (Figure 7). For example, for stakeholder 4 (SH4), the three best-performing options (two wetland options, recycling wastewater for irrigation) achieved comparatively high values on nearly all objectives. Notably, the wetland alternatives achieved good values for the added benefits of shoreline access (purple band in Figure 7) and wetland habitat (dark blue), whereas all other options did not contribute to meeting these two objectives at all. The option of recycling wastewater for irrigation was the only one to fulfill the objective of increasing water supply (light green). For Level 3 upgrades of treatment plants, scoring highly in water quality (light blue), permitting (yellow), and reliability (brown) did not compensate for low scores for the CO_2 emissions (orange) and ease of adaptation (red) objectives and a lack of co-benefits like water supply or wetland habitat for SH4.

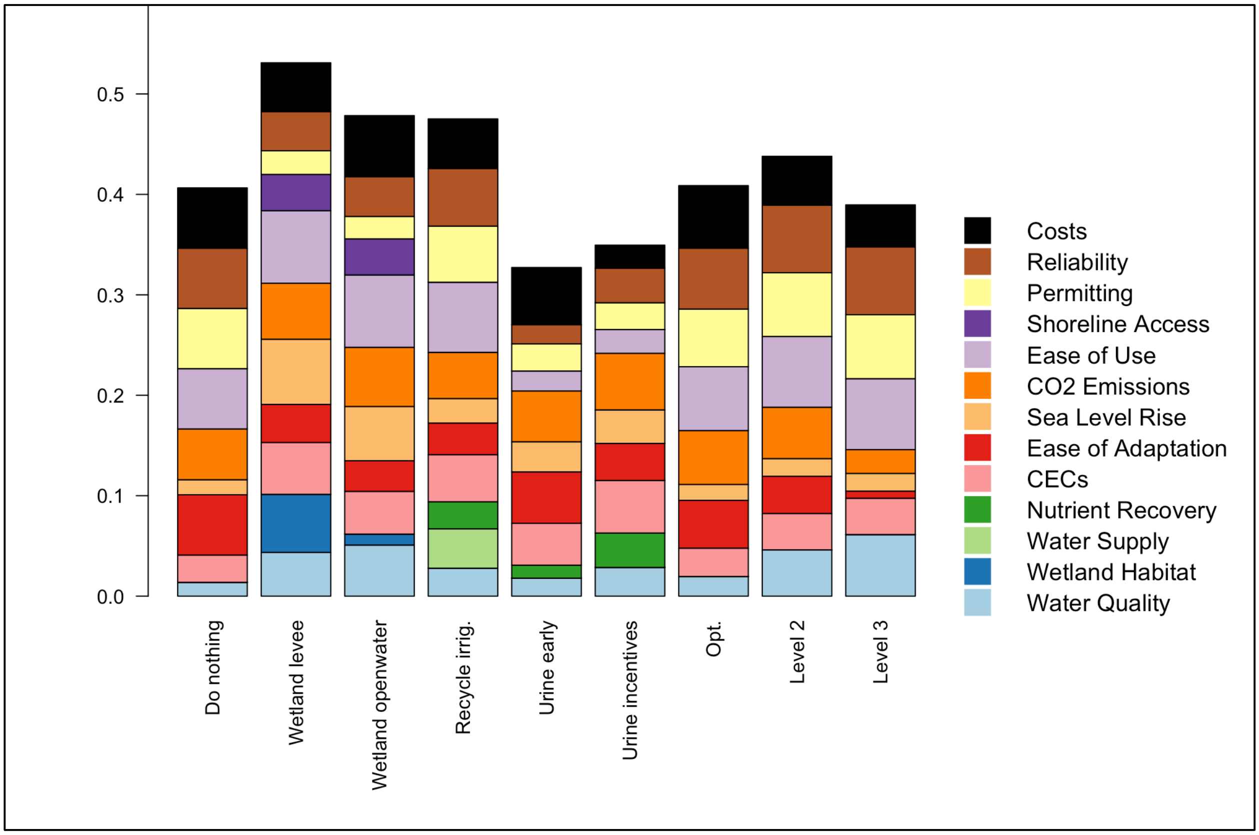


Figure 7. Median overall value of each option (x-axis; see Tab. 1), broken down by objectives (in color; see Tab. 4) for stakeholder SH4 in the Status quo scenario.

Comparison of MCDA with cost efficiency

Several stakeholders expressed that they would normally assess the value of a nutrient management option through a 'cost-efficiency' measure (mass of nutrients removed from wastewater / dollar). The results for each option (Figure 8) assumed the mean cost (total net present value over 30-year technology lifespan) in the uncertainty distributions and the total nitrogen removal (kg of total N removed over a 30-year technology lifespan) in the Status quo scenario.

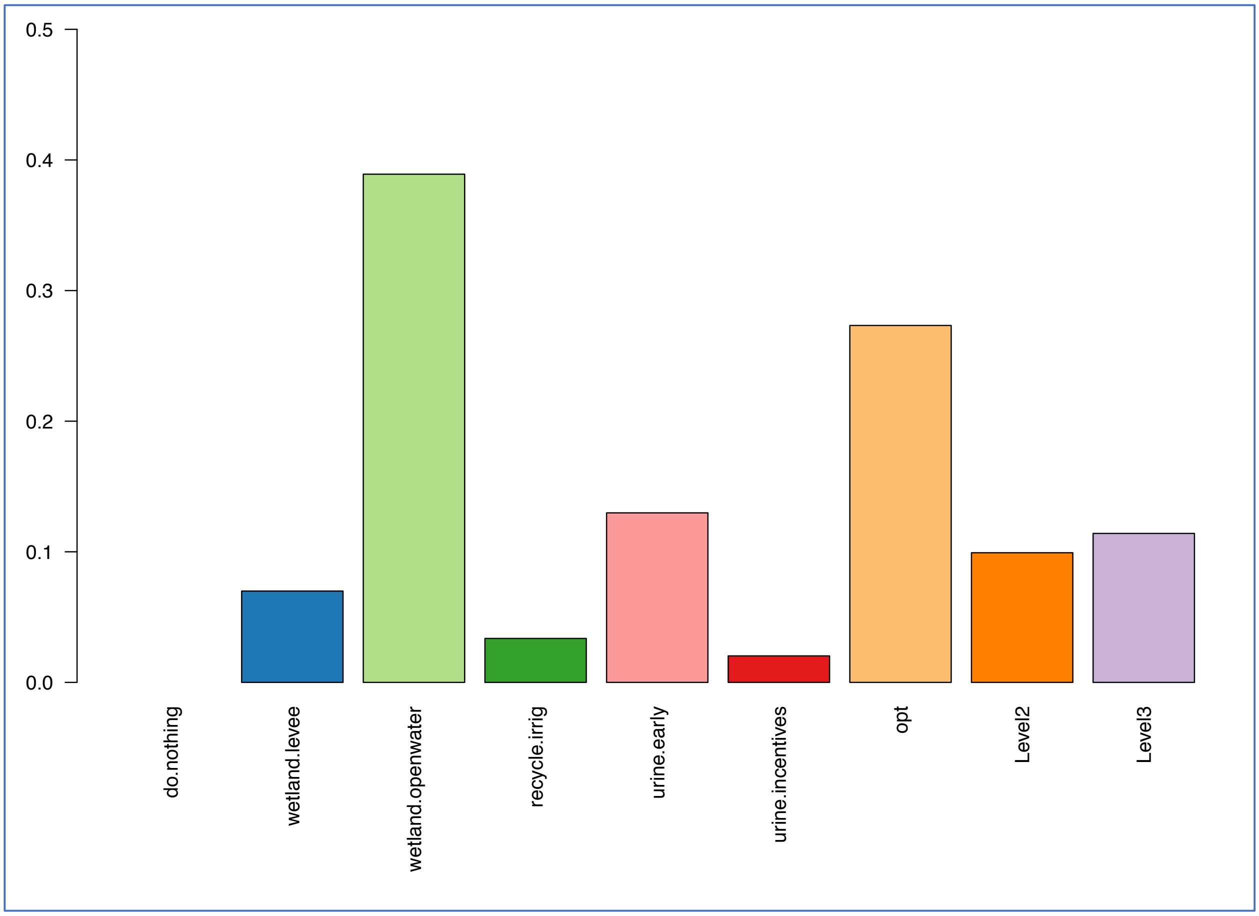


Figure 8. Mean cost-efficiency (kg of nitrogen removal/$) for each option, Status quo scenario.

Open water wetlands (light green) and optimization (light orange) performed well in the cost-efficiency metric. Wetland levees and recycling for irrigation (which ranked highly for many stakeholders in the MCDA), scored relatively low in the cost-efficiency metric.

Although many stakeholders mentioned cost-efficiency as the "standard" method for choosing wastewater management options (i.e., the institutionally-sanctioned method) this was not reflected in the MCDA results for many of the stakeholders. We therefore analyzed the correlation between cost-efficiency and MCDA overall values for each option and stakeholder. Stakeholders exhibited a range in correlations between these two measures (see Supplemental Information, Figure S9). Some stakeholders' preferences for non-traditional goals for nutrient management (which were captured in the MCDA), resulted in a negative correlation between cost-efficiency and MCDA results. Other stakeholders showed a positive correlation between cost-efficiency and MCDA overall value, signifying that they tended to value cost-efficient options in the MCDA.

Sensitivity analysis

Thresholds

Some stakeholders voiced acceptance thresholds (veto conditions) for particular attributes, below which an option would be unacceptable to them. Four stakeholders set thresholds in attribute levels for reliability, water quality, ease of adaptation, and resilience to sea level rise. Inclusion of these thresholds in MCDA calculations would change the overall value of some options for four stakeholders and, in one case, make all options unacceptable. For example, for a stakeholder (SH4) with a reliability threshold at 70% (any option with less than 70% reliability would not be acceptable), recycling for irrigation remained likely to rank highly for this stakeholder, but wetland levees were split between ranking very highly (in the top 4 ranked options 74% of the time) and being unacceptable (26% of the time) due to the uncertainty about reliability of this technology for nutrient removal. Complete results of threshold analysis for all stakeholders with stated thresholds are in the Supplemental Information, Text S6.

Aggregation functions

We used a simpler MCDA model (additive aggregation, no uncertainty in stakeholder weights for each criteria) because the aim of the model is to provide structure for discussion within a broader decision-making effort, not to definitively provide a solution to a problem (Scholten et al., 2017). Additive aggregation implies that high attribute values for one objective completely compensate for low attribute values for another (Eisenführ et al., 2010). However, additive aggregation has been shown to be an inaccurate representation of stakeholder perspectives in some cases, because fulfillment of one objective does not necessarily compensate for lack of fulfillment of another (Langhans et al., 2014). Despite this shortcoming, additive aggregation is considered a valid simplification in some MCDA cases because changes in the aggregation method do not necessarily change the ranking of options in the MCDA output (Scholten et al., 2017).

We tested a range of aggregation variants combining additive aggregation with Cobb-Douglas aggregation (see Supplemental Information, Figure S10) (as in Zheng et al., 2016). Cobb-Douglas aggregation tends to value options more highly that do not have extreme variation in levels of attribute fulfillment between objectives. Although the overall ranking of options remained similar for most stakeholders regardless of the aggregation type, aggregation variants with higher levels of Cobb-Douglas aggregation tended to result in lower overall value for traditional upgrades (which have high fulfillment of some objectives like reliability, ease of permitting and no fulfillment of objectives like shoreline access, increased water supply, or wetland habitat).

Marginal value functions

Linear value functions were initially assumed in the MCDA, which is considered a valid simplifying assumption for MCDAs that are used to guide discussion rather than produce definitive results (Scholten et al., 2017). We tested this assumption with a sensitivity analysis of overall value for each option given different shapes of value functions for the objectives ease of adaptation, permitting, reliability, and water quality. These objectives were chosen because several stakeholders expressed mild-to-moderate concave curvatures for them in interviews. We tested a range of curvatures for these four objectives to assess how they affected the overall value of options for all stakeholders (see Supplemental Information, Figure S11). Convex value functions imply greatest marginal overall value gained with improvement at low levels of attribute value. Concave value functions imply greatest marginal overall value gained with improvement at high levels of attribute value.

Mild-to-moderate concave value functions (what stakeholders expressed in interviews) had little effect on overall ranking of options for any stakeholder. In contrast, convex value functions vaulted the "Do nothing" option to the forefront for many stakeholders.

Weight of the objective category "total cost"

It is possible that stakeholders responded in interviews about the weights of different objectives in ways that did not reflect their true weights in the decision-making process. In particular, many stakeholders seemed to minimize the costs of nutrient management options in comparison to other objectives during interviews. While this may have reflected their feelings, it could also have been a result of trying to answer in a way in which they thought the researcher would appreciate (i.e., social desirability bias) (Nederhof, 1985). MCDA researchers have noted interview participants tend to weigh objectives at approximately 1/n, where 'n' is the number of objectives (Marttunen et al., 2018). This bias holds true for the 'low cost objective', where the median cost weight was 0.073, which is approximately equal to 1/13 (0.077).

Given the strong institutional mandate for minimizing costs for both dischargers and regulators (see Chapter 4), we increased weights for the objective category "total costs" by 25% (and re-scaled other weights accordingly) to see how these changes influenced overall values of different options in the Status quo scenario (see Supplemental Information, Figure S12). Doing so resulted in an increase in the median overall value of the "Do nothing" option for many stakeholders, though the ranking of the top option for most stakeholders did not change.

Discussion

Implications of the MCDA results for nutrient management in the case study

The results of the MCDA provide several interesting insights. First, increasing wastewater recycling for irrigation is an option that is likely to rank among the top three for many stakeholders regardless of future conditions (Figure 6; Supplemental Information, Figures S4-S8), because it increases water supply and utilizes nutrients in the waste stream for fertilizer (Figure 7). This option remained attractive to many stakeholders despite the higher costs per unit of nitrogen removed than many of the other options (Figure 8). Though recycling for irrigation can be expensive – and in some cases has been considered prohibitively so (Bischel et al., 2012) – it may be seen as a viable option if it also prevents nitrogen discharge to sensitive water bodies.

Regarding nutrient management, recycling wastewater for irrigation is far superior to recycling wastewater for potable reuse, because nutrients are not removed from irrigation water prior to reuse. Potable water reuse requires safe disposal of concentrate generated during reverse osmosis treatment. Diverting this concentrate away from sensitive water bodies like the Bay is a significant barrier in terms of costs and greenhouse gas emissions (for pumping brine to the ocean). Treatment technologies to remove nutrients from reverse osmosis concentrate are currently being developed, but most technologies have not been proven in full-scale systems (Pérez-González et al., 2012; Umar et al., 2015). If effective treatment options to remove nutrients from brine were available, potable water reuse could become a more feasible option for nutrient management.

Construction of treatment wetlands (horizontal levees) for nutrient treatment also ranked highly for many stakeholders in various uncertain futures (Figures 6; S4-S8). Additional wetland habitat, increased resilience to sea level rise, shoreline access, and treatment of contaminants of emerging concern favored this option for many stakeholders in the MCDA (Figure 7) despite a very low cost-efficiency ratio of the approach (Figure 8). Because this is a relatively new approach, there is a distinct possibility that the cost will be reduced as designers gain more experience with the construction and operation of the system. Furthermore, additional experience will decrease uncertainty about system performance.

A lack of familiarity with urine source-separation technology is a likely explanation for the low ranking of this option by most stakeholders. In contrast with the situation in the United States, this technology has gained more credibility in Switzerland and Scandinavia (Lienert and Larsen, 2009). If urine source-separation were more popular among members of the public (i.e., if it did not require financial incentives to encourage adoption), it would likely be a very cost-effective way to avoid the discharge of nitrogen to the Bay. Additionally, it provides the added benefits of recovering nutrients from sewage for use as fertilizer and of being more easily adaptable to changing conditions because it is easily adapted to expansion as the need to remove more nitrogen increases (Figure 7). To advance this potentially attractive option, pilot projects to increase public awareness and identify conditions affecting its performance in the United States would be helpful.

It is likely that traditional upgrades would be deployed only in response to regulation about nutrient loading, since the only benefit they provide is nutrient control. In contrast, increased recycling of wastewater for irrigation and construction of horizontal levees provide enough other benefits that they rank more highly than the ‘Do nothing’ option for most stakeholders even under the Best-case scenario, where there is decreased pressure for nutrient loading to cause adverse ecological effects (Figure S5).

The overall value for many of the options is relatively low (scoring under 0.5) for many stakeholders in the Status quo and Worst-case scenarios. This indicates that in the absence of the Best-case scenario, no single option is likely to meet stakeholder goals. It is important to note that these options are not mutually exclusive – for example, optimization and constructed wetlands could both be implemented at the same wastewater treatment plant resulting in much lower concentrations of nutrients being released to the Bay. Combinations could provide effective ways to meet more objectives under less-desirable future scenarios.

Discussion of sensitivity analysis

Acceptability thresholds in criteria mentioned by several stakeholders would greatly influence the ranking of options and would remove many options from consideration in any future scenario (see similar observation and discussion in Scholten et al., 2015). This suggests that further discussion about thresholds is necessary to determine how stakeholders would react to an exceeded threshold (e.g., litigation, disapproval of project, removal of funding). Efforts to limit scientific uncertainty should focus on areas where stakeholders have stated thresholds (e.g., likelihood of deviation from good water quality, resilience to sea level rise, reliability, and ease of adaptation to changing conditions) to provide better estimates of how well different management options perform in each of these categories. In addition, additional options that do not exceed stakeholders' stated thresholds should be developed. Technically, such acceptability thresholds can be modeled by minimum aggregation (e.g., Langhans et al., 2014). However, for the purposes of evaluating options for regional water infrastructure planning, assumed additive aggregation likely provides sufficient insight into management options because rankings of options were largely unchanged for most stakeholders.

The results of a MCDA (the total value and ranking of options) can be highly sensitive to stakeholders' weights, which is why elicitation of this preference parameter is often critical. In this case study, the weights for "total costs" were lower than researchers expected (median of 0.07; see Chapter 4). This is in line with a recent meta-analysis concerning weight elicitation procedures in environmental MCDA cases, where economic objectives usually received lower weights than environmental and social objectives (Marttunen et al., 2018). Because interviewees might not fully express institutional economic constraints or other stakeholders might place a higher value on economic objectives, sensitivity analysis for this parameter is worthy of consideration. Increasing the weight for "total cost" by 25% increased the overall value and rank of the "Do nothing" option for many stakeholders. This finding is significant because it encourages reflection on the part of decision-makers and policy-makers. Specifically, these concerns suggest that stakeholders need to consider the likelihood that they can convince their institutions to overcome a traditional focus on low-cost solutions in order to pursue other goals, which may fall outside of their mandated responsibility (e.g., a wastewater utility funding shoreline access or increased water supply). Further alignment of decision-makers' institutional mandates with their goals for multi-benefit water infrastructure projects would reduce the uncertainty related to the ability of stakeholders to follow through on their stated priorities.

Evaluation of the MCDA process integrated with stakeholder analysis and scenario planning

Choice of stakeholders

When MCDA is applied to a complex problem involving regional water management or other regional environmental planning, it is difficult to choose suitable stakeholders. Because the analysis is affected by stakeholder preferences, this selection process is crucial. This problem is common in decision-making or strategic planning situations in which there is a desire for stakeholder engagement. However, it remains a salient issue, though best practices include efforts to include those affected by decisions as well as decision-makers and expanding beyond the 'usual suspects' (see for example, Achterkamp and Vos, 2007; Bryson, 2004; Colvin et al., 2016; Mitchell et al., 1997; Reed et al., 2009; Vos and Achterkamp, 2006).

It is also noteworthy that stakeholder choice will vary over time; stakeholders who are currently most important to and most affected by decision-making may change (Brugha and Varvasovszky, 2000). This was evident even in this case study. Several people who participated in the first set of interviews changed jobs by the time the follow-up interviews occurred several months later.

Our method of stakeholder selection emphasized diversity of opinion and profession. Despite our efforts to obtain a broad range of opinions, many of our chosen stakeholders were technical experts or represented government/ municipal agencies. This tendency to emphasize the opinions of such experts has been observed in previous MCDA studies (Soltani et al., 2015).

For example, several groups that might have expressed different perspectives were not included in the interviews (e.g., homeowners and renters, subsistence fishers, farmers who might use recycled water for irrigation) because they were less actively engaged in the issue.

In addition, after an organization was positively identified as a "stakeholder", the most appropriate person to interview was not always evident (e.g., managers versus board members). Other researchers have also noted that transparent methods to select and engage stakeholders in a participatory MCDA process are not available (Marttunen et al., 2015). Further research to improve the stakeholder identification process, especially for application to regional environmental MCDA, would be a useful contribution to the field.

Clustering and selecting participants for follow-up interviews based on their goals for nutrient management and their involvement with the issue clarified the differences in objectives amongst people with similar professional roles. Because we deliberately chose stakeholders who reflected a range of opinions, some participants expressed opinions that may be considered as outliers. The importance of this sampling method was validated in interviews, where several participants expressed the opinion that individuals with strong opinions could have an outsize effect on the decision-making process through litigation or soliciting media attention.

Identification of objectives and attributes

Identifying objectives and attributes based on interviews yielded information that was essential to the analysis, but the process was not always orderly. Similarly worded objectives could have different meanings to participants. As a result, we were forced to make subjective decisions to condense the plethora of stated objectives into a manageable set (for more detail see Chapter 4). In addition, we made subjective choices to categorize objectives (e.g., 'ease of permitting' could have fit into the categories of 'low costs' or 'social support'). These choices could have affect weighting of the objectives, based on how many other objectives were in the category and whether they emphasized social or economic values (Marttunen et al., 2018). Providing participants with a list of potential objectives and allowing them to place them into categories (after they came up with their own objectives) might allow researchers to standardize differences in understanding of language among stakeholders.

It was also difficult to identify measureable attributes for each of the criteria. Other researchers recommend the use of workshops with stakeholders to develop such attributes (Belton and Pictet, 1997; Eisenführ et al., 2010; Massey and Wallace, 1996). However, this is a time-consuming process that might not be feasible or agreeable to the participants. As an alternative, we developed our criteria on the basis of ideas expressed by individual stakeholders during the interviews. An advantage is that this allowed individuals with less decision-making influence to have their opinions incorporated into the study design.

Despite these challenges, defining the objectives hierarchy and selecting measurable attributes were some of the most instructive steps of the MCDA process. Vagueness of stated objectives in interviews and discrepancies among opinions about proper attributes to measure fulfillment of each objective are areas where further research and discussion amongst stakeholders may be beneficial to the decision-making process. In this case study, these included a need for developing technologies for nutrient management that are easily adaptable to changing conditions and clearly defining criteria for nutrient-related impairment to the San Francisco Bay ecosystem.

Choice of management options

Generating management options is considered an integral part of the "problem structuring" aspect of MCDA (Belton and Stewart, 2002). Other MCDA analysts suggest choosing options that emphasize fulfillment of different objectives (Pereira et al., 1994). In environmental decision-making, researchers have emphasized the importance of ensuring stakeholder participation and including both standard and innovative options (Lahdelma et al., 2000). However, little guidance exists for determining the scale of the options that need to be considered in regional environmental decisions. In this case study, it was not clear whether the MCDA problem should be considered at the scale of a single wastewater treatment plant (an approach that is much simpler to analyze) or for the whole southern reach of the Bay (a complex problem, but one that is more relevant to actual decision-making). At an early point in the environmental decision-making process about a regional challenge (before any regulations have been set, in this case about nutrient loading), and with so many quasi-independent decision-makers, it is difficult to develop options to model with MCDA that accurately represent actual management options.

To simplify this problem, we applied each option uniformly across wastewater treatment plant service areas. This approach highlights the general benefits, drawbacks, and discussion points of each management option, but does not provide personalized guidance to wastewater treatment plant managers about the specific options that would be optimal for their situation. Further research is needed to assess whether this approach yields results that are substantially different from MCDAs that consider multiple smaller-scale options for different areas within a larger region.

Elicitation of stakeholder preferences

To evaluate the reliability of stakeholders' weights for criteria derived from the Swing elicitation process, they were asked: "How much did you take into account the worst and best values of each goal when you decided on the swings?" (see Chapter 4). Seven stakeholders answered (two did not because of time constraints), but only one chose the response option: "They were essential to my decision." Four responded: "I took them into consideration", and two: "I didn't consider them". Range insensitivity is well-known in the MCDA literature (Clemen and Reilly, 2004). To assure accurate results, weight elicitation methods rely upon respondents' careful deliberation of the worst-best attribute range (Eisenführ et al., 2010). Although this requirement might have been violated to some extent in our case study, the elicitation process may have been useful for decision-makers despite its low reliability in the MCDA process (Marttunen and Hämäläinen, 2008). One reason is that people often form their preferences in the process of assigning weights (Belton and Stewart, 2002), so weight elicitation helps decision-makers clarify what is important to them.

It is good practice to carry out consistency checks of elicited weights with another method; the trade-off method can serve as an alternative to the Swing method (Eisenführ et al., 2010). Despite its strong theoretical foundation (Keeney and Raiffa, 1976) and its usefulness in defining stakeholder preferences in MCDA for environmental management (Reichert et al., 2015), we found the trade-off weight elicitation method to be ineffective in practice. All stakeholders were unwilling to express numerical trade-offs between attributes (e.g., "Paying

$200,000 to reduce the risk of impairing water quality by 5% is better than paying $600,0000 to reduce the risk of impairing water quality by 20%”). These types of value statements are cognitively difficult, as well as highly political. Explicit identification of trade-offs may heighten decisional conflict and lower confidence in decision-making (Kottemann and Davis, 1991). This could explain the reluctance of decision-makers to accept this premise in the interview process. Although some MCDA analysts have successfully employed the trade-off method in similar contexts (Anderson et al., 2001), our experience was consistent with that of researchers who found many stakeholders reluctant to express numeric values for trade-offs (Zheng et al., 2016).

Similarly, we found marginal value functions difficult to elicit in interviews with the bisection method (“Improvement from the worst value to a middle-value point is perceived as equally beneficial as improvement from a middle-value point to the best value”). These questions were almost uniformly met with vague, non-quantitative responses, possibly due to time constraints or an unwillingness or inability to give numeric values for complex decisions such as those considered here. Some of the difficulty may have been due to the relative inexperience of the researcher conducting MCDA interviews (Pöyhönen and Hämäläinen, 2000). The sensitivity analysis indicates that differences in marginal value function curvatures (particularly for convex value functions) could drastically change the overall value of options for many stakeholders. Therefore, avoiding the difficulties by assuming linearity of value functions would be inadequate for this case (e.g. Langhans and Lienert, 2016; Zheng et al., 2016). Thus, other methods of eliciting marginal value functions would have been needed to accomplish these goals.

Our experience suggestions that allocating one hour for follow-up interviews for preference elicitation may be insufficient. This poses a problem for MCDA interviews because many high-level decision-makers have busy schedules; an observation shared by many researchers implementing MCDA. We recommend that future research should focus on developing tools that allow for reliable preference elicitation in a more efficient manner. One idea receiving increasing interest is adaptive elicitation, where specific answers of the decision-maker determine the questions that are asked next. This could considerably reduce the length of the interview (Ciomek et al., 2017; de Almeida et al., 2016).

Our experiences suggest that the main insights gained from the elicitation of stakeholder preferences in this setting are qualitative, and are obtained from conversation about the value of different objectives. For example, attempts to elicit bi-section values for the objective ‘reliability’ led to reflections about reliability for wastewater management in general, compared to nutrient management in particular. Reliability close to 100% is desirable for controlling pathogens, because any lapse can potentially affect public health. In contrast, occasional periods of high nutrients concentrations in effluent due to lapses in reliability are not likely to be ecologically detrimental if their duration is limited.

Another issue raised during the interview process was a tension between personal values, professional roles and institutional mandates. For example, several stakeholders mentioned that they personally valued wetland habitat highly but that this was not within the scope of their professional role. To obtain results that were most reflective of the actual decision-making process, we asked stakeholders to weight criteria based on whatever value (personal or professional) would affect their professional decision-making. However, this was an imperfect approach that made it difficult for several stakeholders to respond to the questions. Future MCDA procedures could include elicitation of value judgements both as a private person and as an official representative, with sensitivity analysis to compare any differences in results. In addition, a greater sociological understanding of how private values influence professional actions in regional environmental decision-making would provide insight into the importance of this potential conflict.

Addressing uncertainty of stakeholder preferences, future scenarios, and attribute predictions

We opted to keep stakeholder weights separate, rather than aggregate them. This allowed the analysis to highlight the diversity of opinions and to assess management options ranked highly by multiple stakeholders (Belton and Pictet, 1997; Gregory et al., 2001; Matsatsinis and Samaras, 2001). However, the disaggregated results do not provide decision-makers with a consensus or a clear path forward. Instead, they raise questions about the importance of opinions held by different stakeholders. Because the MCDA research protocol precludes identification of the stakeholders who express opinions that deviate from the larger group, disaggregated group results only provide information about disagreements that may require attention. In situations where disparate opinions are observed, follow-up stakeholder workshops could be used to promote discussion and build consensus (Ferguson et al., 2013).

Future scenarios were selected to illustrate the robustness of MCDA options in the year 2050 (Marttunen et al., 2017). By designing future scenarios with the "critical uncertainties" for nutrient management stakeholders mentioned, we aimed to capture the range of future possibilities that would likely have the biggest impact on nutrient management. However, this approach considers only the "known-unknowns" – and none of the "unknown-unknowns". "Unknown-unknowns" could originate in another sector entirely (e.g., regulations on greenhouse gas emissions) and could deeply constrain wastewater treatment operations by making a specific technology much less attractive, for example. Characterization of potential "unknown-unknowns" and analysis of the MCDA results under these less-predictable conditions could enhance the reliability of the MCDA.

Including uncertainty in attribute predictions in the MCDA highlighted the ways in which uncertainty about technical performance of the management options could affect outcomes (Durbach and Stewart, 2012; Zheng et al., 2016). This strategy was especially useful in combination with analyzing the MCDA under different future scenarios because it allowed for differentiation between uncertainty that cannot be controlled (future conditions) and uncertainty that can be minimized through the collection of additional data (attribute predictions). In this case study, minimizing uncertainty related to attribute predictions would have a large effect on clarifying rankings of outcomes, because several options for stakeholders spanned very different ranks (from 1st to 6th, for example) depending on attribute predictions (see Supplemental Information, Figures S6-S8). Future scenarios, in contrast, largely changed overall values for options rather than their relative ranking (see Supplemental Information, Figure S3).

A summary of the MCDA steps, the employed methods, and their advantages and disadvantages are in Table 5.

Table 5. Methods integrated into the standard MCDA process to support regional decision-making for multi-benefit infrastructure.

Step	Methods	Advantage	Disadvantage
Initial stakeholder selection	Broad outreach to people and organizations who have authored documents or participated in public meetings related to nutrient management	-Includes perspectives of those who have been publicly working on the issue	-Not necessarily clear whom to include within an organization -Stakeholders with less time or influence, who may still have strong feelings about the issue, are not included
	Snowball sampling	-Personal referrals to targeted individuals -Gain insight on who has been involved in the issue and why	-Can lead to sampling within a 'bubble' of people with similar ideas or professional roles, might neglect important stakeholders from other professional fields or regions
	Inclusion of stakeholders whom researchers deemed would be affected by nutrient management but who were not involved in authoring documents, public meetings, or recommended by other interviewees	-Can include perspectives of marginalized groups who have not traditionally been included in decision-making about water infrastructure	-Researchers may not know or accurately predict who would be affected
Selection of stakeholders for MCDA preference elicitation interviews	Cluster analysis based on stated goals for nutrient management in initial interviews, followed by stratified sampling to choose those stakeholders most relevant to decision-making from each cluster	-Broad representation of stakeholders with different goals -Does not assume stakeholders with same professional role necessarily have the same goals	-May over- or under-represent stakeholders from any particular professional role
Identify objectives and attributes	Solicitation of objectives and attributes from individual stakeholders (rather than focus groups or stakeholder workshops)	-Encourages participation from stakeholders with less influence or political power -Identifies areas of disagreement and agreement among stakeholders	-Differences in language between different stakeholders may result in researcher misinterpretation of objectives and attributes -No consensus reached on objectives and attributes
	Researcher synthesis of objectives and attributes	-Encourages the inclusion of objectives from stakeholders with less influence or political power	-May result in disagreement about the accuracy of attributes for describing objectives -Choices about structuring the objectives hierarchy can bias stakeholder weights

Step	Methods	Advantage	Disadvantage
	Limited objectives to < 15	-Ease of mental processing for stakeholders -Less time required for elicitation	-Possible consolidation of objectives that some stakeholders consider distinct
	Researchers generated objectives that helped differentiate between management options	-Assisted with differentiation between specific management options in the MCDA	-May be less relevant to stakeholders than some of the other objectives
Development of future scenarios	Informed by stakeholder ideas about "critical uncertainties" that would affect nutrient management	-Takes into account the uncertainties stakeholders are considering	-Does not take into account unforeseen situations that could strongly affect future conditions
	Used scenario generation matrix to develop Best- and Worst-case scenarios	-Bounds uncertain futures within the areas specified	-Best- and Worst-case scenarios may be less useful for prescriptive MCDA to choose management options
Development of management options	Illustrative options applied at their maximum extent to the whole region, rather than more realistic combinations of options or site-specific options within the region	-Highlights ways in which different management options can fulfill different stakeholder objectives	-Is not realistic, does not provide a prescriptive 'answer' from the MCDA
Predict outcomes of each option, given uncertainty about the future	Estimated range of values and distribution for attributes from the literature, from expert opinion, and modeled from previous technology implementation	-Approximates uncertainty in attribute values for all objectives -Elucidates magnitude of differences in MCDA results due to uncertainty in technical attribute prediction versus future scenario conditions	-Distribution of uncertainty could be incorrect -Attribute values from the literature and past implementation may be quite different from local values due to local conditions
Elicitation of stakeholder preferences (weights and marginal value functions)	Used notecards of objectives stakeholders could physically move around on the table to represent preference weights for Swing method elicitation	-Allows for kinetic experience of the weightings -Stakeholders can easily re-arrange to 'try' different weights and see what seems most accurate	-Requires in-person interviews -Time intensive

Step	Methods	Advantage	Disadvantage
	Did not include stakeholder uncertainty in preference weights or consideration of differences in weights from a personal vs. professional perspective	-Simplifies MCDA -Less time-intensive	-May inaccurately represent stakeholder preferences
	Used bi-section method to elicit marginal value functions	-Has the potential to provide rough curvature estimates with little elicitation time	-May result in vague, non-quantitative results due to political nature of making some values explicit or time constraints
Integrate preference weights and attribute predictions to rank options	Performed rankings for all stakeholders separately, did not use aggregate by using average weights	-Identifies the range of stakeholder opinions -Identifies areas of conflict and agreement amongst stakeholders	-Complex to analyze and interpret results -No clear 'answer' from the MCDA regarding a consensus solution; this would require further stakeholder workshops

Conclusions

Employing a mixed-methods approach to strategic planning in water infrastructure development and other environmental management provides useful support to the decision-making process. Stakeholder analysis and MCDA paired with analysis of future uncertainties can integrate stakeholders' perspectives into formulating goals for regional water infrastructure planning, and assess the ways in which different management options fulfill these goals. These methods can highlight areas of agreement and disagreement amongst stakeholders, laying the groundwork for discussion, collaboration, and consensus building. They can differentiate between the uncertainties over which decision-makers have little control (future conditions) and the uncertainties which additional data collection, research and development can help minimize (modeled attribute predictions). In addition, these methods can incorporate the perspectives of potentially important stakeholders who may have been excluded from traditional processes for planning water infrastructure.

Although many useful insights to decision-making about water infrastructure and environmental management more broadly can be gained from integrating MCDA with stakeholder analysis and scenario planning, the process has numerous limitations. Policy-makers charged with urban water management tend to be averse to complex assessments like these, rather preferring to act on the precautionary principle to ensure environmental protection or reverting to selection of options that are economically efficient and have low risks (Starkl et al., 2009). Furthermore, time-intensive, in-person interviews with stakeholders may not always be possible (Marttunen and Hämäläinen, 2008). Analysis of qualitative interview data in conjunction with quantitative MCDA requires the help of analysts who are versed in multiple methods of inquiry. Finally, without developing a definite 'answer' to the challenge of nutrient management it may be unclear to stakeholders how to use the results to reach consensus in practice – especially if the research protocol anonymizes the contributions of different stakeholders and thus de-personalizes the MCDA results.

Despite these limitations, integrating stakeholder analysis, MCDA, and scenario planning can support regional environmental decision-making and merits further research. Our method of applying cluster analysis to select stakeholders for in-depth MCDA interviews, rather than selection based solely on their professional role, could be further refined in other research contexts. Explicit consideration of who has been included, and why, in group decision analyses for water infrastructure planning and environmental management could illuminate other methods for selecting stakeholders to participate in different stages of the MCDA and clarify for researchers the most appropriate method(s) to use in their own research. In addition, this type of review could help support efforts to make water infrastructure planning and implementation more equitable. Finally, testing and refining the combination of stakeholder analysis, MCDA, and scenario planning in other contexts, both for water infrastructure planning and for other environmental management options, would be a fruitful area for further inquiry.

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Appendix to Chapter V: Supplemental Information for 'A Mixed-Methods Approach to Strategic Planning for Multi-Benefit Regional Water Infrastructure' by Sasha Harris-Lovett, Judit Lienert and David Sedlak. In review in *Journal of Environmental Management,* 2018.

Supporting Information for

A Mixed-Methods Approach to Strategic Planning for Multi-Benefit Regional Water Infrastructure

By Sasha Harris-Lovett[1,3], Judit Lienert[2], and David Sedlak[3,4]

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Introduction

The following Figures, Text and Tables provide details of methods, results and sensitivity analyses as explained in the main text.

Figure S1. Interview guidelines

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Decision Analysis for Nutrient Management in the San Francisco Bay Area
Interview 1 Guidelines

Interview with: ____________
Conducted by: _____________
Date: ______________
Interview Partner's Organizational affiliation: ___________

Introduction

- Introduction of interviewers and aim of interview
- Permission for audio recording
- Definition of 'nutrients'
- Background on changing environmental conditions of the Bay and status of discussions around regulation
- Information on interviewee: Briefly describe your professional background. Which roles/jobs/positions have you had in your career? How do you see your role in San Francisco Bay's water quality scene?

Interest in nutrient management

- From your perspective, what are the most important functions of the San Francisco Bay?
- Would nutrient regulation affect what your organization does? If so, how?
- Do nutrients fall under your organization's jurisdiction? If so, how?

Classification of objectives for nutrient management and for water management around the Bay? / Indicators (attributes) to measure fulfillment of objectives.

- What are the most important goals for any nutrient management scheme or technology?
- What are the most important goals for broader water management in the San Francisco Bay Area?
- For each objective, classify it into "essential" (without this objective I cannot judge whether the fundamental objective is reached), "important" (without this objective it would be difficult to judge whether the fundamental objective is reached), "nice to have" (attainment of fundamental objective can be judged without this), or "not significant" (not needed to judge fundamental objective). Why did you classify it this way?
- What do you think are good indicators (termed attributes in decision analysis) to assess the fulfillment of each of these goals? What do you think are the appropriate units of measurement (and measurement method) for this indicator?

Stakeholder analysis

- How are decisions about nutrient management made?

- Which organizations and individuals are involved in making the decision?
    - On a scale of 1-7 (seven being highest), please rank each of these organization's and individual's decision-making power about nutrients in the Bay.
- What is your organization's role in decision-making, if any?
    - On a scale of 1-7 (seven being highest), please rank your organization's decision-making power about nutrients in the Bay.
    - If you wanted a certain outcome, who would you talk to?
- Who cares about what happens with nutrients in the San Francisco Bay? Why do they care?
- Who will be most affected by any regulations or management strategies pertaining to nutrients in the San Francisco Bay?
    - On a scale of 1-7 (seven being highest), how much do you think each of those people/organizations would be affected?
- Are there obvious conflicts between some parties? What exactly? Where is it running smoothly, where do people collaborate?
- What have been some of the milestones in the collaborative planning process for nutrients that has been going on?
- What are the main interests of the respective stakeholder or decision makers? What are their most important objectives? (To check important goals in the objectives hierarchy)
- Who else should I talk to about this?
    - On a scale of 1-7 (seven being highest), how important is it that I include this person in my interview campaign?

Elicitation of potential management alternatives

- How are people in the field talking about solving the nutrient problem?
- What do you think should be done, if anything?
- Tell us any other ideas you have about how to decrease the nutrients loads in the Bay, both technical measures as well as organizational measures.
- Can you come up with any non-conventional or even crazy idea to solve the nutrient problem? What would your grandmother recommend? If you were living on Mars in some distant technical future, and looking down onto earth, what would you recommend we do?
- Which alternative seems most suitable for achieving your main goals? Do you have any idea which alternatives other stakeholders might choose? Why?
- Are there any other factors regarding water management more broadly or the Bay ecosystem that should be kept in mind while finding solutions to the nutrient problem?

Snowball sampling

- Who else should I talk to about this?
    o On a scale of 1-7 (seven being highest), how important is it that I include this person in my interview campaign?
- Anything else you'd like to add?

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Decision Analysis for Nutrient Management in the San Francisco Bay Area
Interview 2: Weighting criteria and direct ranking of management alternatives

Interview with: ________________________________
Conducted by: ________________________________
Date: ______________
Interview Partner's Organizational affiliation: _____________________________

Introduction

- *Thank you for being part of this next phase of research*
- *In the first round of interviews, I met with 32 people involved with decision-making about nutrients and people interested in the issue around the Bay Area. From those interviews, I learned about the competing long-term goals that people balance as they think about nutrient management.*
- *In this interview, I'm hoping to get a better sense of how decision-makers prioritize these goals. The information from this interview will be used to perform a quantitative multi-criteria decision analysis for nutrient management option in the southern reach of the Bay.*
- *Permission for audio recording?* Yes No

- *For all these questions, imagine you're taking a 3000 ft. look on the southern reach of the Bay – that you had ultimate decision-making power about nutrients in the southern reach of the Bay. There are no wrong answers! We are interested in your personal perspective. Whenever something is not clear or you might want to make a comment, feel free to interrupt the interview at any point ask. Feel free to think out loud if you are deliberating about any of the questions – it is interesting for our research to understand your considerations about these issues.*

Report back on objectives hierarchy

1. First, let's look at each of the goals for nutrient management I learned were important from the first round of interviews. *(Show objectives hierarchy.)* In the first interview, you mentioned the following goals were important for good nutrient management: ______. This is how they are incorporated into the overall list: __________.

Holistic ranking of alternatives and objectives

2. First, categorize the goals into three piles: most important, somewhat important, and less important. *(Mark piles on sheet.)*
3. Now, how would you arrange these goals from most important to least important? *[Have respondent organize cards] (Mark ranking on sheet.)*
4. What do you think are some good options for managing nutrients in the southern reach of the Bay? *(Write one per notecard)*
5. Please organize these notecards of options in descending order from the best to the worst. *[Have respondent organize cards]*
6. In our analysis, we're also planning to consider several potential nutrient management options: doing nothing, doing optimization at wastewater treatment plants (smaller tweaks to operating systems to maximize nutrient removal without major construction), doing upgrades for nutrient removal at wastewater treatment plants (Level 2 and 3, as per the HDR report), maximizing the construction of wetlands for additional wastewater treatment, maximizing water recycling, and deploying urine source-separating toilets to divert urine from wastewater and recover the nutrients. We'll get into the

details of these options later in the interview. For now, can you give a general "gut feeling" ranking on these options, from best to worst, and integrate them into the stack of notecards you have? *[Have respondent organize cards] (Mark ranking on sheet.)*

7. In our analysis, we'll be looking at these options under several future scenarios for the year 2050, including different population size changes, among others. Are there any particular factors, where if you knew them with certainty now, it would change your opinion about which of these management options would be the best long-term? How would being sure about that aspect of the future change your opinion? Would that change the way you ranked the options?

Shapes of the value functions

8. (*Provide interview partner with a table with objectives, performance measures, worst and best scores based on alternatives, and current level.)* Now let's look more closely at each of the goals, and how we are measuring them in our research model. We've categorized them into clusters of sub-goals. Assuming the worst outcome for sub-goal A, **[xx],** is worth 0 and the best outcome, **[yy],** is worth 1, what measure would you say is exactly in the middle, outcome-wise? That is, an increase from worst to this middle value is equally as good as an increase from the middle value to the best. *(Mark answer on worksheet.)*
9. Are there any thresholds in the potential outcome? That is, is there a level in this range below which everything is worst or above which everything is best? Keep in mind that if there is a lower threshold, that would mean the option is OUT if it is below that level, even it performs really well on all other goals.

   (Do this for each objective.)

Weighting criteria

10. Imagine a hypothetical option for nutrient management that has the worst values across all of the goals in the table. Now suppose that you are able to 'swing' one (and only one) goal from its worst to best value. Which would you choose? Why is this one the most important to 'swing' first?
    a. Give this hypothetical option a rank of 1.
11. Now imagine we've reset that, so we're back to all the worst values across all the goals in the table. Which objective would you swing to its best value, as a second-best option? Assign a rank of 2 to this new hypothetical option where the second most important goal is at its best level, but all others are on their worst. Do that 'swing' and rank with all the rest of the goals.
    b. *(Show the ranking, repeat back.)* You now have ranked the hypothetical options in the following order, where all goals have the worst value, except one: the first choice is where [**objective xx**] is at its best value, second choice is where [**objective yy**] is at its best value, etc. Does that look right to you?
12. Let's assume that the swing ranked option number 1, where [**objective A]** is at its highest level, is worth 100 points. Please assign points to the remaining swing options in accordance with how important they are relative to the top ranked one. Consider that the default option with all the goals on their worst state is worth 0 points.
13. Let's look over your results so far together. Do they reflect your priorities? That is, try to make sure that the points you've assigned reflect the relative importance in the measure swings. For example, if you assign 100 points to swing 1 and 50 points to swing 2, it means that achieving the swing in measure 2 is about half as important to you as achieving the swing in measure 1.
14. *Feedback*. How much did you take into account the worst and best values of each goal when you decided on the swings? Why/why not?
    a. They were essential to my decision.
    b. I took them into consideration
    c. I didn't consider them.

d. Decline to state.

15. *Feedback.* How hard was it to determine the order of the 'swings'? Why?
    e. Hard
    f. Moderate -- neither easy nor hard.
    g. Easy.
    h. Decline to state.
16. *Feedback.* How hard was it to assign the points between 0 and 100? Why?
    c. Hard.
    d. Moderate -- neither easy nor hard.
    e. Easy.
    f. Decline to state.
17. (*Note if ranking of objectives through swing method is different from holistic ranking of objectives at the beginning. If yes, →)* I notice that the order of your 'swings' is different from the order that you ranked the different goals at the beginning of the interview. That's normal, because with the swing ranking you're looking at numbers of how much improvement you might see in any goal. Which one better reflects your real opinion, direct ranking or 'swing' ranking?

Aggregation type

18. Now we want to check how the collected information about the goals can be linked to each other in order to get an overall result. Imagine an option where the goal of **[xx]**, which you indicated was the most important to you, is at its worst value. In order to be able to improve this towards the best value, would you accept a less desirable value of other goals? For example, you'd be willing to pay more money to increase the likelihood from 5 to 95% of having better water quality in the Bay?
    If yes → This would also be true for the reverse case: Imagine an option where the goal achievement with respect to **[yy]** *(any other target)* is on its worst level. In order to be able to improve this goal to the best level, you would allow a worsening of **[the most important goal]**? For example, you'd be willing to have a lower likelihood of good water quality if it meant that it would cost less than $10 billion?
    If yes → Let me confirm what you told me.
    Imagine that in one option, some goals are achieved extremely well, but measures of other goals are extremely low. In a second option, each goal measures approximately halfway through (neither very good nor very bad). The first and second option, overall, rank equally. Does that seem reasonable to you?
    If yes for all → **additive**
19. If yes, but not for all sub-goals →
    Which not? .... *(Check Minimum or Multiplicative aggregation)*

    Minimum → Is there a minimum level that this goal would have to meet in order to make a management option acceptable to you? That is, before this minimum criterion is reached, the state of the other goals is irrelevant. This option would not be acceptable.

If **no** → *(check multiplicative.)*

Multiplicative → For you, is a management option were all the goals are partially achieved preferable to a second option where some goals are achieved as well as possible and other goals are at their lowest level? To say it another way, would you rather have smaller improvements spread over all goals or larger improvements of single goals at the expense of others?

Consistency checks

20. Now let's imagine that the option where [**objective A**] is moved to its highest level, [**xx**], is worth 100 points. How many points would the option where [**objective B]** is moved to its highest level, [**yy**], be worth? What about [**objective C**], [**zz**]?
21. Let's look at this in another way to make sure I understand. In a first option, let's imagine goal A **[highest ranked objective]** is at its highest value, [**xx],** and goal B **[another objective]** is at its lowest value, [**yy**]. Is that better, worse, or equal to a second option where goal A [**highest ranked objective]** is at its lowest level and goal B **[the other objective]** is at its highest level? What if we were to lower the value of goal A down a notch, to [**zz].** Now, would that option be better, worse, or equal to an option where goal A is at its worst level and goal B is at its best level? What value of goal A, with goal B at its lowest level, is approximately equal to an option where goal B is at its highest level and goal A is at its lowest level? *(Do several checks across the objectives hierarchy.)*
22. *(Based on the weight ratios and the value function of the most important attributes elicited earlier, formulate two hypothetical options that have the same value.)* Would you say option 1 and option 2 are approximately equal? *(If no, re-elicit weights and value functions. If impossible to answer, it is an indication that additive aggregation is not appropriate.)*

Holistic rating of alternatives

23. Now we're going to look more closely at some of the management alternatives under consideration in our study. This will help us understand if there are other decision criteria that weren't accurately represented in the list of goals I originally presented to you.

(Provide interview partner with an image and description of all the alternatives under consideration, with the rough predictions of outcomes.)

24. Again, how would you rank these alternatives, in order from best to worst?
25. Intuitively, would you endorse, accept, or oppose this alternative? (Endorse = enthusiastic support, "this is a great solution"; Accept = Support, "Maybe not the best solution in my mind, but one I can support"; Oppose = No support, "I cannot support this solution.") Why?
    - If oppose → are there any modifications you can think of that would make this alternative acceptable to you?

Feedback on interview experience

26. *Feedback.* We're coming to the end of the interview. Did you learn anything during the interview? Yes No
    a. If yes → what did you learn? Was there some point in the interview that triggered your thought?
27. *Feedback.* Did this process of putting numbers to your priorities for nutrient management in the interview change your thinking or provide any insight about the problem?
Yes No
    a. If yes → Please explain how your thinking has changed.
28. *Feedback.* Were you surprised at some point in the interview, because you learned, noticed or discovered something unexpected? Yes No
    a. If yes→ Can you tell me a little more about it? (What was your opinion before that point in the interview? How did that point influence your opinion? Do you think your opinion on this could change again?)
29. *Feedback.* Anything else you would like to add?

That's it! I'll use your responses from this interview to inform a multi-criteria decision analysis, where I'll quantitatively score options for nutrient management based on your priorities for the goals we talked about today.

Thank you very much!

Table S1. Detailed descriptions of the parameters of each of the management options in consideration

Management option	Description
Optimization, as per HDR report	Upgrades for optimization of existing wastewater treatment processes, which are estimated to achieve about 10-15% reduction of 2017 N loading. Specifications for upgrades at each wastewater treatment plant are derived from HDR consulting draft report to Bay Area Clean Water Agencies (HDR Consulting, 2017). Where no specific upgrades are recommended, average attribute values (i.e., for cost) from the HDR draft report are used.
Level 2 upgrades, as per HDR report	Upgrades are designed to achieve < 15 mg TN/L and < 2 mg ammonia/L in effluent. Specifications for upgrades at each wastewater treatment plant are derived from HDR consulting draft report to Bay Area Clean Water Agencies (HDR Consulting, 2017). Where no specific upgrades are recommended, average attribute values (i.e., for cost) from the HDR draft report are used.
Level 3 upgrades, as per HDR report	Upgrades are designed to achieve < 6 mg TN/L and < 2 mg ammonia/L in effluent. Specifications for upgrades at each wastewater treatment plant are derived from HDR consulting draft report to Bay Area Clean Water Agencies (HDR Consulting, 2017). Where no specific upgrades are recommended, average attribute values (i.e., for cost) from the HDR draft report are used.
Construct sub-surface flow, horizontal levee wetlands for nutrient removal	Vegetated, sub-surface flow, wetlands – dubbed "horizontal levees" – are constructed to maximize nutrient removal from wastewater effluent. In addition to polishing wastewater effluent, these wetlands also act as levees to buffer against sea level rise, and are currently being piloted at Oro Loma Sanitary District in the southern reach of the Bay (Oro Loma Sanitary District, n.d.). After nitrification (via existing systems or nitrification ditch with air and circulating water), denitrification occurs by microbes living on woodchips mixed in with underground media in the wetland (Vymazal, 2010). Spatial constraints for horizontal levee construction are based on San Francisco Estuary Institute's analysis of suitable area for treatment wetlands within 3.2 km (2 miles) of effluent discharge locations in the southern reach of the Bay, limited to "high" and "medium" suitability sites (Wren, 2017). In this option, we assume all wastewater effluent passes through treatment wetlands if there is available space in order to achieve maximum nutrient removal. If not, space is the limiting constraint for the size of the wetland.
Construct shallow open-water wetlands for nutrient removal	Shallow open-water wetlands are constructed to reduce nutrient loads by 90% at each wastewater treatment plant, if space is available to do so. Available space is assumed to be 60% of "high", "medium", and "low" ranked area in SFEI's analysis of wetland suitability (Wren, 2017). If space is not available, wetland size is constrained by space in this option. Shallow, open water wetlands foster microbial denitrification by microbes living on a mat of algae in the water (Jasper et al., 2014b); this technology is currently being piloted in Discovery Bay and Orange County, California (Bachand and Horne, 1999; Jasper et al., 2013; Lund et al., 1999).
Increase wastewater recycling for irrigation	Maximize recycling of wastewater from the southern reach of the Bay for irrigation (without additional treatment for nutrient removal), based on the upper range of estimates for planned water reuse capabilities in the region expressed in interviews with water supply managers and from official documentation (City of Palo Alto, 2008; City of Palo Alto Utilities, 2016; City of Sunnyvale, 2013; Livermore-Amador Valley Zone 7 Water Agency, 2016; Rosenblum, 1999; San Francisco Public Utilities Commission, 2016; Santa Clara Valley Water District and City of San Jose, 2014). We assume 1/6 of the wastewater effluent from EBDA (roughly equivalent to Livermore and Dublin-San Ramon recycling all their effluent) is recycled for irrigation because the demand for recycled water greatly surpasses supply in Dublin-San Ramon(Dublin San Ramon Services District, 2016) and because there are strong regulatory and financial incentives to recycle water in Livermore (City of Livermore, 2016). At San Jose-Santa Clara, we assume 2 m^3/sec (45 MGD) are recycled for irrigation. In Sunnyvale, San Mateo, and Palo Alto, we assume 0.4 m^3/sec (10 MGD) each are recycled for irrigation.

Management option	Description
	In South San Francisco/San Bruno, we assume 0.2 m^3/sec (5 MGD) are recycled for irrigation and from San Francisco PUC's Southeast Plant, 0.09 m^3/sec (2 MGD) are recycled for irrigation.
Increase wastewater recycling for potable reuse, with a brine-line to discharge brine to the ocean	Maximize recycling of wastewater for potable reuse (either indirect or direct), based on extremes for planned water reuse (ref?) and interviews with water supply providers in the region. Utilities build a "brine line" for disposal of reverse osmosis concentrate across the peninsula to the ocean, thus diverting nutrients from the Bay. We assume San Francisco recycles 0.9 m^3/sec (20 MGD) for potable reuse from its Southeast plant, and wastewater treatment utilities located within the Bay Area Water Supply and Conservation Agency (BAWSCA) service area on the Peninsula or in the South Bay (Burlingame, Millbrae, Palo Alto, South San Francisco, Sunnyvale, and Silicon Valley Water District each recycle 25% of their effluent for potable water reuse. We assume 0.35 m^3/sec (8 MGD) from San Jose-Santa Clara WF is recycled for potable reuse and 1.5 m^3/sec (35 MGD) is used for groundwater recharge.
Install urine source-separating toilets and decentralized urine treatment – early adopters	Deploy urine-separating toilets to divert urine from wastewater and treat it in decentralized facilities (Larsen et al., 2009). We assume all new housing development in the region installs urine source separating toilets (and that all population growth is housed in new housing), as well as half of employees in the early-adopting fields of technology and education. We assume urine-separating toilets capture 50% of each individual's urine. We will consider a technology that uses ion exchange to convert nitrogen in urine to a pellet that can be used in fertilizer (Tarpeh et al., 2017). Urine would be collected weekly from households and daily from office buildings – residents would set aside urine cartridges for collection. We assume one processing facility would be built in each wastewater service area.
Install urine source-separating toilets and decentralized urine treatment – Incentives for widespread adoption	Deploy urine-separating toilets to divert urine from wastewater and treat it in decentralized facilities, with financial incentives to encourage widespread adoption. We assume utilities fund $5,000 rebates for household installation of a urine-separating toilet (as attempted in a Falmouth, Massachusetts pilot project for urine-source separation (Northwest EcoBuilding Guild, 2014)) , and utilities pay $5/urine cartridge collected (weekly) from each household, as financial incentives have been shown to assist in adoption of new toilet technologies (Tilley and Günther, 2016). In addition, we assume each utility spends an extra $1,000,000 on outreach and education to promote adoption of urine-separating toilets and explain the necessity for nutrient reduction to their customers. We assume these efforts result in 30% adoption of urine-separating toilets in existing households and businesses, in addition to the urine-separating toilets installed in new housing. We assume urine-separating toilets capture 50% of each individual's urine. We will consider the same technology as the option above, which uses ion exchange to convert nitrogen in urine to a pellet that can be used in fertilizer (Tarpeh et al., 2017). Urine would be collected weekly– residents would set aside urine cartridges for collection. We assume several processing facilities would be built in each wastewater service area.
Do nothing	No additional action – all wastewater treatment facilities that discharge to the southern reach of San Francisco Bay continue to treat and discharge wastewater to the extent they do today.

Text S1. Detailed description of assumptions and parameters for each modeled management option

All options

- Current MGD estimates are 4-year dry season (May 1 – Sept 30) averages reported by BACWA member agencies from 2012-2016 (*note* these are significantly lower than reported flows on agencies' websites, likely because of water conservation in the drought).

- We assume MGD and nutrient loading scale with population growth, and with no additional treatment, concentrations of nitrogen and of sulfamethoxazole remain the same. The assumption that MGD scales with population growth is reasonable given the values used were recorded during severe drought conditions, when many conservation and water efficiency measures were in place – so despite the fact that water use doesn't always scale with population growth due to advances in efficiency (Gleick, 2000), it is reasonable to assume that it does in this case.

- Technology lifespan is assumed to be 30 years unless otherwise noted.

- For greenhouse gas emissions calculations, we assume 1 CH_4 = 25 CO_2 equivalents, 1 N_2O = 298 CO_2 equivalents (US EPA, 2015).

- For conversions between reductions in total nitrogen load (from current levels) to percent likelihood of deviation from good water quality such that it would impair beneficial uses under current ecological conditions and under hypothetical ecological conditions in which the Bay is more sensitive to nutrient loading (because of decreased turbidity or increased stratification times), very rough linear relationships were used that were derived from informal conversations about predictions with a nitrogen management expert at San Francisco Estuary Institute (Tables A and B). Where two data points exist for the same percent change in nutrient loading (as in Table B), this reflects two conversations about different reductions in nutrient loading from distinct wastewater treatment plants in different physical locations in the southern reach of the Bay. These relationships should be updated as the effect of nutrient loading on the ecosystem becomes better characterized.

Table A. Expert predictions of percent chance of deviating from good water quality given changes in nutrient loading in the southern reach of the Bay under current ecological conditions.

Percent change in nutrient loading from wastewater treatment plants (X)	0	-100	100
Percent chance of deviating from good water quality (Y)	10	5	95

Rough linear equation: Y = .45 X + 36.66

Any water quality estimates calculated to be less than 5 or above 95 were set to equal 5 and 95%, respectively. It was assumed that even with extremely stringent controls on nutrient loading from wastewater treatment there was a 5% chance of water quality impairment from nutrient loading based on other sources and ecological processes, and even with no controls on nutrient loading from wastewater treatment there was a 5% chance of no impairment due to ecological processes.

Table B. Expert predictions of percent chance of deviating from good water quality given changes in nutrient loading in the southern reach of the Bay with increased sensitivity to nutrient loading.

Percent change in nutrient loading from wastewater treatment plants (X)	-75	-60	-60	-35	-35	-20	-20	-13	33	60
Percent chance of deviating from good water quality (Y)	10	30	30	35	35	40	40	70	75	85

Rough linear equation: Y = .53 X + 56.89

Again, any water quality estimates calculated to be less than 5 or above 95 were set to equal 5 and 95%, respectively, for the reasons outlined above.

Do nothing

In this option, no action is taken to control nutrient loading to the Bay. We also assume no increase in other actions that could incidentally reduce nutrient loading (like increasing water recycling for irrigation).

Parameters	**Unit**	**Estimated value**	**Reference**	**Notes**
Lifecycle greenhouse gas emissions for secondary treatment	Kg CO_2 eq./ m^3	.5	(Hendrickson et al., 2015)	Despite other values available in the literature, the Hendrickson value was chosen since it is also in California and thus includes the same electricity mix as projects in our case study. Other LCA GHG emissions numbers in the literature include: 0.128 kg CO2 e/m^3 treated (without including construction) of secondary treatment plant in Toronto (Racoviceanu et al., 2007); 1.27 kg CO2 e/ m^3 treated (without construction) of secondary treatment in China (Pan et al., 2011); 0.83 kg CO2 e/ m^3 for secondary treatment in Spain (Pasqualino et al., 2011); 0.4 kg CO2 e/ m^3 for modeled secondary treatment (Foley et al., 2010).
Lifecycle greenhouse gas emissions for tertiary treatment (in Lower South Bay treatment plants at San Jose-Santa Clara, Sunnyvale, and Palo Alto)	Kg CO_2 eq./ m^3	.32	(Corominas et al., 2013)	
Concentration of sulfamethoxazole in effluent	ng/L	200	(Batt et al., 2007)	
Wastewater currently recycled for reuse	MGD	22		Calculated from wastewater treatment plant master plans

Maximize water recycling for nutrient removal

This option was developed with information from interviews with regional water supply and wastewater managers, as well as estimations from current and historic long-range planning documents for wastewater and water utilities in the southern reach of the Bay. If the document planning range was sooner than 2050, recycled MGD estimates for 2050 are assumed to be the highest planned values in these documents (City of Palo Alto, 2008; City of Palo Alto Utilities, 2016; City of Sunnyvale, 2013; Livermore-Amador Valley Zone 7 Water Agency, 2016; Rosenblum, 1999; Santa Clara Valley Water District and City of San Jose, 2014).

Parameter	**Unit**	**Estimated value**	**Reference**	**Notes**
Cost of reuse for irrigation	$/ acre foot	930	Calculated median from Bay Area Western Recycled Water Coalition 2017 irrigation reuse projects	Assume scaled beta distribution
Concentration of sulfamethoxazole discharged	Ng/L	0		

in Bay from water reused for irrigation				
Lifecycle greenhouse gas emissions for water reused for irrigation	g CO_2 eq./m^3	1023	Assuming average of 35 km of pipe (Stokes and Horvath, 2009)	
Reliability of water recycling technology	% of time technology operates as intended	98	Interviews with water managers	

Maximize potable water recycling with "brine line" to the ocean

Parameter	Unit	Estimated value	Reference	Notes
Cost of indirect potable reuse	$/acre foot	700 for advanced treatment + mean of (120, 750, 1250) for conveyance	(Tchobanoglous and Raucher, 2014)	
Cost of direct potable reuse	$/acre foot	700+(conveyance + brine management)	(Tchobanoglous and Raucher, 2014)	
Cost of brine line (diameter)	$/acre foot	115	(Tchobanoglous and Raucher, 2014)	
Cost of (brine line) pipe for distance	$/mile	2,000,000	(Bischel et al., 2012)	
Energy required to pump water in brine line per foot of height over the peninsula	Pounds of water x lift in feet (ft-lbs)		(Peacock, 1996)	
Conversion of ft-lbs to kwh	Ft-lbs/kwh	2,655,220	(Peacock, 1996)	
Cost of energy	$/kwh	$0.2	(U.S. Bureau of Labor Statistics, Western Information Office, 2017)	
Height of lift to get brine over peninsula	ft	2000		
Distance of pipeline from southern reach of Bay to ocean	miles	7		
Life cycle GHG emissions from pumping	g CO2 e/Mwh electricity in CA PG&E area/million gallons	320896	("WEST Web," n.d.)	
Life cycle GHG emissions from brineline pipe	g CO2 e/foot of pipe/million gallons	358	("WEST Web," n.d.)	
Volume of brine after NF+RO treatment for potable reuse	% of water treated	20	(Asano et al., 2007)	
Concentration of sulfamethoxazole discharged in Bay from water reused for irrigation	Ng/L	0		
Lifecycle greenhouse gas emissions for water treated with reverse osmosis for indirect potable reuse	kg/466 m^3	438 CO_2 + 0.88 CH_4	(Lyons et al., 2009)	
Reliability of water recycling technology	% of time technology	98	Interviews with water managers	

	operates as intended			

Maximize constructed wetlands for nutrient removal 1: Horizontal levees

Parameter	Unit	Estimated value	Reference	Notes
Cost of treatment wetland	$/acre	650,000 not including land	Calculated from Oro Loma pilot project, assuming total cost is $3,800,000 minus cost of equalization basin ($2,500,000) divided by 2-acre size of ecotone	
Wetland area needed for treatment to 2 mg/L TN in effluent	MGD/acre	.042	Estimate from Oro Loma pilot project	
Reliability of wetland for nutrient removal	Percent of time that wetland removes nutrients as expected	77%	(Jucherski et al., 2017)	
Habitat	Hectares	All treatment wetland area is assumed to be wetland habitat		
Land availability	Hectares available for conversion to treatment wetland	4,754 (though because of the way it is distributed, not all is useful for treatment – a lot is extra in EBDA zone)	Sum of "moderately suitable" and "most suitable" locations for wetland treatment based on Ian Wren's GIS analysis for SFEI (suitable land within 2 miles of treatment plant or discharge point)	
Removal of sulfamethoxazole by wetlands in dry season	%	90	Estimate from Oro Loma pilot project	
Removal of sulfamethoxazole by wetlands in wet season	%	30	Estimate from Oro Loma pilot project	
Concentration of sulfamethoxazole not treated by wetlands	ng/L	200	(Batt et al., 2007)	
Greenhouse gas emissions from treatment wetland operation (direct and indirect)	$mg/m^2/hour$	CO_2 : 137 CH_4 : 4 N_2O : .13	Median estimates from (Mander et al., 2014)	
Greenhouse gas emissions from construction and decommission of treatment wetland	Proportion over 30-year lifespan	7/8 is direct and indirect emissions, 1/8 is construction and decommission	Estimated from (Fuchs et al., 2011)	
Shoreline access points	Number	Assume 1 per treatment plant using treatment wetlands		
Permitting	% ease of permitting	30	Estimated based on interviews with water managers, understanding that it is very difficult now but may get	Vary from 5 to 60.

			easier as there is more precedent.	

Maximize constructed wetlands for nutrient removal 2: Open water wetlands

Parameter	Unit	Estimated value	Reference	Notes
Cost of open-water cell treatment wetland	$/acre	200,000	Based on Prado wetlands costs and 30-year lifetime of maintenance ($175,000 construction costs per acre + $2500/month for vegetation removal (National Science Foundation's Engineering Research Center for Reinventing the Nation's Urban Water Infrastructure, 2015)	
Equation for calculating wetland size based on removal needs		$\frac{Cout}{Cin} = \left(1 + \frac{59.4A}{6.4Q}\right)^{-6.4}$ Cout/Cin = Concentration at outlet/concentration at inlet A = wetland area (m^2) Q = flow rate (m^3/year)	(Jasper et al., 2014b)	59.4 and 6.4 are empirically derived from open-water wetland cells at Discovery Bay, California
Wetland area needed for 75% TN removal	Acres/MGD	12 acres/MGD	(Wren, 2017)	
Reliability of wetland for nutrient removal	Percent of time that wetland removes nutrients as expected	77%	(Jucherski et al., 2017)	
Habitat	Hectares	Half of open-water cell wetland area is assumed to be habitat		Based on expectation that open-water cell wetlands provide less suitable habitat than vegetated wetland areas
Land availability	Hectares available for conversion to treatment wetland		Sum of all locations for wetland treatment based on Ian Wren's GIS analysis for SFEI (suitable land within 2 miles of treatment plant or discharge point)	
Concentration of sulfamethoxazole	ng/L	200	(Batt et al., 2007)	

not treated by wetlands				
Equation for area needed for 90% sulfamethoxazole removal		A90 = .87/(z* kphoto) Z = depth (m) = .3 Kphoto (summer) = .25 Kphoto (winter) = .1		Assume latitude is ~ 40, pH = 8, [DOC] = 7 mg/L; Assume 6 months of summer kphoto and 6 months of winter kphoto; Assume SMX removal scales linearly with area.
Greenhouse gas emissions from treatment wetland operation (direct and indirect)	mg/m^2/hour	CO_2 : 137 CH_4 : 4 N_2O : .13	Median estimates from (Mander et al., 2014)	
Greenhouse gas emissions from construction and decommission of treatment wetland	Proportion over 30 year lifespan	7/8 is direct and indirect emissions, 1/8 is construction and decommission	Estimated from (Fuchs et al., 2011)	
Shoreline access points	Number			Assume 1 per treatment plant using treatment wetlands
Permitting	% ease of permitting	30	Estimated based on interviews with water managers, understanding that it is very difficult now but may get easier as there is more precedent.	Vary from 5 to 60.

Deploy urine source separating toilets 1 – early adopters

Parameter	**Unit**	**Estimated value**	**Reference**
Current population in each service area	people	Burlingame: 30,000 EBDA: 957,000 Millbrae: 22,850 Palo Alto: 217, 330 San Jose-Santa Clara: 1,498,700 San Mateo: 149,800 SFO: 10,000	Burlingame: Phone communication with Burlingame WWTP, 2017. EBDA: Website (2017) and population within service area. Millbrae: (GHD, 2016) Palo Alto: (CH2MHill and RMC, 2014) San Jose-Santa Clara: Projection for 2015 (Carollo, Brown and Caldwell, SOM, 2008) San Mateo: Average of 2010 and 2020 projections(Carollo, 2014) SFO: (San Francisco Bay Regional Water Quality Control Board, 2013) South SF-San Bruno: Email communication with Plant Superintendent, Nov. 2017

		SFPUC Southeast: 670,400 South SF-San Bruno: 110,000 Sunnyvale: 148,000 Silicon Valley Clean Water: 200,600	Sunnyvale: Treatment plant website SVCW: Calculated based on population of cities in service area
Amount of urine excreted	L/day	1.4	(Rose et al., 2015)
Concentration of nitrogen in urine	g/L	7.5	(Rose et al., 2015)
Proportion of nitrogen recovered from urine by ion exchange	Percent	90%	Estimated
Percent of the time that people with source separating toilets use them to urinate	%	50	Estimated
Percent of the population in technology and education industries (proxy for early adopters)	%	3.9	(State of California Employment Development Department, 2015)
Lifecycle greenhouse gas emissions from urine-separating treatment (includes avoided emissions from fertilizer creation via Haber-Bosch)	Kg CO_2 eq./m^3 urine treated	5.5	(Kavvada et al., 2016)
Lifecycle cost for urine separating treatment	\$/m^3	26	(Kavvada et al., 2016)
Percentage of sulfamethoxazole excreted in urine	%	84	(Food and Drug Administration, 2012)
Reliability	% of time nutrient removal operates as expected	66	Extrapolated from a national survey of the percentage of people with curbside glass recycling who recycle their glass items more than 95% of the time (Jenkins et al., 2003)

Maximize urine source-separating toilets 2: Incentives

Parameter	Unit	Estimated value	Reference	Notes
Amount of urine excreted	L/day	1.4	(Rose et al., 2015)	
Concentration of nitrogen in urine	g/L	7.5	(Rose et al., 2015)	
Proportion of nitrogen recovered from urine by ion exchange	Percent	90%	Estimated	
Percent of the time that people with source separating toilets and financial incentives use them to urinate	%	75	Estimated	
Average household size	# of people	2.7	("Bay Area Census -- Bay Area Data," 2010)	
Cost of initial retrofit incentive	#/household	3000	Estimated	In existing housing only

Cost of weekly cartridge pickup incentive	$/week	$2	Estimated	For existing housing and new developments
Cost of outreach and education	$/participating wastewater treatment utility	200,000	Estimated	
Lifecycle greenhouse gas emissions from urine-separating treatment (includes avoided emissions from fertilizer creation via Haber-Bosch)	Kg CO_2 eq./m^3 urine treated	5.5	(Kavvada et al., 2016)	
Lifecycle cost for urine separating treatment	$/$m^3$	26	(Kavvada et al., 2016)	
Percentage of sulfamethoxazole excreted in urine	%	84	(Food and Drug Administration, 2012)	
Reliability	% of time nutrient removal operates as expected	76	Extrapolated from a national survey of the percentage of people with curbside glass recycling who recycle their glass items more than 95% of the time (66%) (Jenkins et al., 2003) + an additional assumed 10% reliability with financial incentives	

Optimization

Optimization entails small changes to existing wastewater treatment operations, as per the HDR Consulting reports. As such, we assume these changes do not affect lifecycle greenhouse gas emissions or removal rates of sulfamethoxazole. Costs are derived from visually estimating wet and dry season costs for each treatment plant from a preliminary, draft HDR report to BACWA, and averaging these two estimates. Where no data is available (HDR hasn't assessed the facilities yet), we assume costs are reflective of the HDR reported average for treatment plants ($124,000,000 for dry season, $130,000,000 for wet season).
Note: HDR assumes 2025 time frame and NO increase in flows, but a 15% increase in loads. These are different from assumptions for the other options.

Parameter	**Unit**	**Estimated value**	**Reference**	**Notes**
Reliability	% of time nutrient removal operates as expected	98	Interviews with water managers	
Cost	$/gpd	0.5	(HDR Consulting, 2017)	HDR report to BACWA says average is $0.4/gpd…but it considers a much shorter time frame (2025), so assume it raises to $0.5/gpd given increased maintenance costs

Level 2 Upgrades

Parameter	Unit	Estimated value	Reference	Notes
Reliability	% of time nutrient removal operates as expected	98	Interviews with water managers	
Concentration of sulfamethoxazole discharged in Bay	ng/L	170	Tertiary treatment removes an additional 15% from initial 200 ng/L in secondary treatment (Batt et al., 2007)	
Lifecycle greenhouse gas emissions	Kg CO_2 eq./m^3	.32	Additional emissions (above secondary treatment level) for tertiary treatment with nutrient removal (Corominas et al., 2013)	
Cost	$/gpd	7.5	Dry season flow-weighted average from HDR Draft report to BACWA (HDR Consulting, 2017)	

Level 3 Upgrades

Parameter	Unit	Estimated value	Reference	Notes
Reliability	% of time nutrient removal operates as expected	98	Interviews with water managers	
Concentration of sulfamethoxazole discharged in Bay	ng/L	170	Tertiary treatment removes 15% from initial 200 ng/L in secondary treatment (Batt et al., 2007)	
Lifecycle greenhouse gas emissions	Kg CO_2 eq./m^3	.8	Additional emissions (above secondary treatment level) for tertiary treatment with most stringent nutrient removal (Corominas et al., 2013)	Another LCA GHG number for Level 3: .6 t CO2 e/ML water treated (= .6 kg/m3) total, with a range of 3.5-8.5 tCO2 e/ML, not additional as Corominas number above, from a model (Foley et al., 2010)
Cost	$/gpd	9.8	Dry season flow-weighted average from HDR Draft report to BACWA (HDR Consulting, 2017)	

Text S2. R code and associated data for calculation of multi-criteria decision analysis for nutrient management in San Francisco Bay.

Note: To work properly, most of the code has to be run in the given order –you cannot skip to the code chunk that is most interesting to you and run it.

Save the following tables as csv files in your working directory:

Attribute tables (These have the basic details and best and worst values of the attributes which are used to measure fulfillment of each objective. SH3 and SH7 had different sets of objectives than the other stakeholders, so they require their own attribute tables.)

- attrs.nutrients.csv

name	main objective	fundamental objective	attribute	unit	worst	best
wq	ecosystem	good nutrient management	Water quality	%	95	5
hab	ecosystem	good nutrient management	Wetland habitat	hectares	0	4800
supply	resource recovery	good nutrient management	Water supply	MGD	0	190
recover y	resource recovery	good nutrient management	Nutrient recovery	kg/year	0	850000 0
CEC	resource recovery	good nutrient management	CECs	kg/year	137	42
adapt	intergen equity	good nutrient management	Ease of adaptation	%	0	100
slr	intergen equity	good nutrient management	Sea level rise	scale_constr	-10	10
CO2	intergen equity	good nutrient management	CO2 emissions	tonnes CO2 eq/year	900000	195000
ease_us e	social support	good nutrient management	Ease of use	%	0	100
access	social support	good nutrient management	Shoreline access	Integer	0	17
permit	social support	good nutrient management	Permitting	%	0	100
reliable	costs	good nutrient management	Reliability	%	50	99
costs	costs	good nutrient management	Costs	$	800000000 0	0

- attrs.nutrients.SH3.csv

name	main objective	fundamental objective	attribute	unit	worst	best
supply	resource recovery	good nutrient management	Water supply	MGD	0	190
recovery	resource recovery	good nutrient management	Nutrient recovery	kg/year	0	8500000

CEC	resource recovery	good nutrient management	CECs	kg/year	137	42
adapt	intergen equity	good nutrient management	Ease of adaptation	%	0	100
slr	intergen equity	good nutrient management	Sea level rise	scale_constr	-10	10
CO2	intergen equity	good nutrient management	CO2 emissions	tonnes CO2 eq/year	900000	200000
access	social support	good nutrient management	Shoreline access	Integer	0	17
permit	social support	good nutrient management	Permitting	%	0	100
reliable	costs	good nutrient management	Reliability	%	50	99
costs	costs	good nutrient management	Costs	$	8000000000	0

- attrs.nutrients.SH7.csv

name	main objective	fundamental objective	attribute	unit	worst	best
wq	ecosystem	good nutrient management	Water quality	%	95	5
hab	ecosystem	good nutrient management	Wetland habitat	hectares	0	5200
supply	resource recovery	good nutrient management	Water supply	MGD	0	190
CEC	resource recovery	good nutrient management	CECs	kg/year	137	22
adapt	intergen equity	good nutrient management	Ease of adaptation	%	0	100
slr	intergen equity	good nutrient management	Sea level rise	scale_constr	-10	10
CO2	intergen equity	good nutrient management	CO2 emissions	tonnes CO2 eq/year	900000	180000
ease_use	social support	good nutrient management	Ease of use	%	0	100
access	social support	good nutrient management	Shoreline access	Integer	0	17
permit	social support	good nutrient management	Permitting	%	0	100
reliable	costs	good nutrient management	Reliability	%	50	100
costs	costs	good nutrient management	Costs	$	8000000000	0

Data for modeling outcomes of management options

- wetland_suitability_area.csv

Rank	Burlingame	EBDA	Millbrae	Palo Alto	San Jose - Santa Clara	San Mateo	SFO Airport	SF (Southeast Plant)	South SF and San Bruno	Sunnyvale	Silicon Valley Clean Water
1 (m2)	158285.05	3772022.22	598712.18	297677.34	4087131.37	28066.77	537308.17	13255.86	489604.22	1471529.65	19262.82
2 (m2)		4666197.41			3494102.46					1818.46	4625.93
3 (m2)	212269.81	30375516.51	154476.9	734748.49	5117377.65	170212	195642.06	954970.01	250842.84	1000000	207574.96

- Dry season discharge summary_BACWA_2012_2016.csv

Unit	Parameter	Burlingame WWTP	EBDA Outfall	Millbrae WWTP	Palo Alto WQCP	San Jose /Santa Clara	San Mateo WWTP	SF Arprt Mel Leong	SF-SE Plant	South San Francisco	Sunnyvale WPCP	SVCW WWTP
mgd	Flow	2.62	53.24	1.33	20.73	78.67	9.40	1.04	54.10	8.11	8.35	11.91
kg/day	Ammonia, Total (as N)	249.49	6526.18	234.32	17.29	182.22	1357.60	196.06	8659.56	809.32	14.32	2006.75
kg/day	TKN	294.21	7207.77	270.36	35.65	458.23	1570.73	172.08	9083.59	973.18	108.12	2066.59
kg/day	Nitrite Plus Nitrate (as N)	69.48	766.65	2.06	2329.68	4331.04	37.27	20.92	752.39	122.35	388.47	68.56
kg/day	Nitrogen, Total (as N)	363.69	7953.08	272.41	2365.42	4789.27	1608.01	193.01	9836.13	1095.53	516.76	2140.87
kg/day	Phosphorus, Total (as P)	56.47	495.82	15.79	390.28	234.58	129.09	13.44	171.79	158.52	185.60	183.25
kg/day	Orthophosphate, Dissolved (as P)	75.17	481.63	15.14	376.68	216.15	152.63	14.34	312.50	167.30	176.95	266.11

Parameters for modeling uncertainty

- uncertainty_distributions.csv

	do.nothing	wetland.levee	wetland.openwater	recycle.irrig	recycle.brine	urine.early	urine.incentive	opt	level2	level3
wq	Minmax	Minmax	Minmax	Minmax	Minmax	Minmax	Minmax	Minmax	Minmax	Minmax
hab	Determined	Minmax	Minmax	Determined	Determined	Determined	Determined	Determined	Determined	Determined
supply	Determined	Determined	Determined	Minmax	Minmax	Determined	Determined	Determined	Determined	Determined
recovery	Determined	Determined	Determined	Minmax	Determined	Minmax	Minmax	Determined	Determined	Determined
CEC	Minmax	Minmax	Minmax	Minmax	Minmax	Minmax	Minmax	Minmax	Minmax	Minmax
adapt	Minmax	Minmax	Minmax	Minmax	Minmax	Minmax	Minmax	Minmax	Minmax	Minmax

	do.nothing	wetland.levee	wetland.openwater	recycle.irrig	recycle.brine	urine.early	urine.incentive	opt	level2	level3
slr	Determined	Determined	Determined	Determined	Determined	Determined	Determined	Determined	Determined	Determined
CO2	Minmax	Minmax	Minmax	Minmax	Minmax	Minmax	Minmax	Determined	Minmax	Minmax
ease_use	Determined	Determined	Determined	Determined	Minmax	Minmax	Minmax	Determined	Determined	Determined
access	Determined	Minmax	Minmax	Determined	Determined	Determined	Determined	Determined	Determined	Determined
permit	Determined	Minmax	Minmax	Minmax	Minmax	Minmax	Minmax	Minmax	Minmax	Minmax
reliable	Determined	Minmax	Minmax	Minmax	Normal	Minmax	Minmax	Normal	Normal	Normal
costs	Determined	Minmax	Minmax	Beta	Minmax	Minmax	Minmax	Normal	Normal	Normal

Stakeholder preferences

- pars.nutrients.sensitivity.csv

name	val.avg	val.SH7	val.SH3	val.SH2	val.SH8	val.SH5	val.SH1	val.SH4	val.SH6	val.SH9
w.ecosystem	0.26	0.2	NA	0.28	0.3	0.19	0.26	0.26	0.29	0.29
w.wq	0.57	0.5	NA	0.67	0.43	0.53	0.56	0.63	0.57	0.67
w.hab	0.43	0.5	NA	0.33	0.57	0.47	0.44	0.38	0.43	0.33
w.r.recovery	0.16	0.2	0.08	0.25	0.12	0.18	0.18	0.21	0.06	0.14
w.supply	0.36	0.5	0	0.5	0.53	0.34	0.23	0.3	0.44	0.36
w.recovery	0.26	NA	0	0.45	0.13	0.28	0.32	0.2	0.33	0.36
w.CEC	0.41	0.5	1	0.05	0.34	0.38	0.45	0.5	0.22	0.27
w.equity	0.24	0.2	0.36	0.25	0.19	0.25	0.19	0.21	0.32	0.14
w.adapt	0.46	0.32	0.95	0.45	0.36	0.39	0.45	0.48	0.29	0.44
w.slr	0.33	0.36	0	0.36	0.45	0.33	0.23	0.29	0.57	0.33
w.CO2	0.2	0.32	0.05	0.17	0.17	0.3	0.3	0.21	0.11	0.21
w.social	0.17	0.2	0.16	0.08	0.13	0.23	0.15	0.16	0.16	0.21
w.ease_use	0.24	0.31	NA	0.5	0.11	0.15	0.36	0.32	0.1	0.07
w.access	0.28	0.31	0.09	0.25	0.37	0.11	0.18	0.45	0.5	0.21
w.permit	0.51	0.38	0.91	0.25	0.53	0.74	0.45	0.23	0.4	0.71
w.tot.costs	0.21	0.2	0.4	0.14	0.25	0.16	0.22	0.16	0.16	0.21
w.reliable	0.59	0.47	0.67	0.5	0.69	0.67	0.63	0.63	0.53	0.57
w.costs	0.41	0.53	0.33	0.5	0.31	0.33	0.38	0.38	0.47	0.43
c.ecosystem	0	0	0	0	0	0	0	0	0	0
c.wq	0	0	0	0	0	0	0	0	0	0
c.hab	0	0	0	0	0	0	0	0	0	0

c.r.recovery	0	0	0	0	0	0	0	0	0	0
c.supply	0	0	0	0	0	0	0	0	0	0
c.recovery	0	0	0	0	0	0	0	0	0	0
c.CEC	0	0	0	0	0	0	0	0	0	0
c.equity	0	0	0	0	0	0	0	0	0	0
c.adapt	0	0	0	0	0	0	0	0	0	0
c.slr	0	0	0	0	0	0	0	0	0	0
c.CO2	0	0	0	0	0	0	0	0	0	0
c.social	0	0	0	0	0	0	0	0	0	0
c.ease_use	0	0	0	0	0	0	0	0	0	0
c.access	0	0	0	0	0	0	0	0	0	0
c.permit	0	0	0	0	0	0	0	0	0	0
c.tot.costs	0	0	0	0	0	0	0	0	0	0
c.reliable	0	0	0	0	0	0	0	0	0	0
c.costs	0	0	0	0	0	0	0	0	0	0
r.nutrients.uncertainty.midnodes	0	0	0	0	0	0	0	0	0	0
add.ecosystem	1	1	1	1	1	1	1	1	1	1
add.wq	1	1	1	1	1	1	1	1	1	1
add.hab	1	1	1	1	1	1	1	1	1	1
add.r.recovery	1	1	1	1	1	1	1	1	1	1
add.supply	1	1	1	1	1	1	1	1	1	1
add.recovery	1	1	1	1	1	1	1	1	1	1
add.CEC	1	1	1	1	1	1	1	1	1	1
add.equity	1	1	1	1	1	1	1	1	1	1
add.adapt	1	1	1	1	1	1	1	1	1	1
add.slr	1	1	1	1	1	1	1	1	1	1
add.CO2	1	1	1	1	1	1	1	1	1	1
add.social	1	1	1	1	1	1	1	1	1	1
add.ease_use	1	1	1	1	1	1	1	1	1	1
add.access	1	1	1	1	1	1	1	1	1	1
add.permit	1	1	1	1	1	1	1	1	1	1
add.tot.costs	1	1	1	1	1	1	1	1	1	1
add.reliable	1	1	1	1	1	1	1	1	1	1
add.costs	1	1	1	1	1	1	1	1	1	1
min.ecosystem	0	0	0	0	0	0	0	0	0	0
min.wq	0	0	0	0	0	0	0	0	0	0
min.hab	0	0	0	0	0	0	0	0	0	0
min.r.recovery	0	0	0	0	0	0	0	0	0	0

min.supply	0	0	0	0	0	0	0	0	0	0
min.recovery	0	0	0	0	0	0	0	0	0	0
min.CEC	0	0	0	0	0	0	0	0	0	0
min.equity	0	0	0	0	0	0	0	0	0	0
min.adapt	0	0	0	0	0	0	0	0	0	0
min.slr	0	0	0	0	0	0	0	0	0	0
min.CO2	0	0	0	0	0	0	0	0	0	0
min.social	0	0	0	0	0	0	0	0	0	0
min.ease_use	0	0	0	0	0	0	0	0	0	0
min.access	0	0	0	0	0	0	0	0	0	0
min.permit	0	0	0	0	0	0	0	0	0	0
min.tot.costs	0	0	0	0	0	0	0	0	0	0
min.reliable	0	0	0	0	0	0	0	0	0	0
min.costs	0	0	0	0	0	0	0	0	0	0
cd.ecosystem	0	0	0	0	0	0	0	0	0	0
cd.wq	0	0	0	0	0	0	0	0	0	0
cd.hab	0	0	0	0	0	0	0	0	0	0
cd.r.recovery	0	0	0	0	0	0	0	0	0	0
cd.supply	0	0	0	0	0	0	0	0	0	0
cd.recovery	0	0	0	0	0	0	0	0	0	0
cd.CEC	0	0	0	0	0	0	0	0	0	0
cd.equity	0	0	0	0	0	0	0	0	0	0
cd.adapt	0	0	0	0	0	0	0	0	0	0
cd.slr	0	0	0	0	0	0	0	0	0	0
cd.CO2	0	0	0	0	0	0	0	0	0	0
cd.social	0	0	0	0	0	0	0	0	0	0
cd.ease_use	0	0	0	0	0	0	0	0	0	0
cd.access	0	0	0	0	0	0	0	0	0	0
cd.permit	0	0	0	0	0	0	0	0	0	0
cd.tot.costs	0	0	0	0	0	0	0	0	0	0
cd.reliable	0	0	0	0	0	0	0	0	0	0
cd.costs	0	0	0	0	0	0	0	0	0	0

- Inputs/Stakeholder points.csv

Name_ID	Name_R	Role	Water quality	Wetland habitat	Water supply	Nutrient recovery	CECs	Ease of adaptation	Sea level rise	CO2 emissions	Ease of use	Shoreline access	Permitting	Reliability	Costs	Ecosystem	Improve.wastewater	Intergen.equity	Social.support	Low.costs
xx	SH7	WW	75	75	75	NA	75	75	85	75	75	75	90	90	100	75	75	78.33	80	95
xx	SH3	WW	NA	NA	0	0	20	90	0	4.5	NA	4	40	100	50	NA	6.66	31.5	22	75
xx	SH2	WW	100	50	90	81	9	90	72	36	30	15	15	50	50	75	60	66	20	50
xx	SH8	Eco	75	100	40	10	26	52	65	26	9	31.5	45	85	38.25	87.5	25.33	47.66	28.5	61.625
xx	SH5	Eco	75	67.5	63	52.5	70	100	85	70	18	13.5	90	65	32.5	71.25	61.83	85	40.5	48.75
xx	SH1	WW	100	80	35	49	70	75	37.5	52.5	48	24	60	85	51	90	51.33	55	44	68
xx	SH4	Reg	100	60	48	32	80	80	48	40	42	60	30	60	36	80	53.33	56	44	48
xx	SH6	Reg	90	67.5	25	18.75	12.5	50	100	25	10	50	40	50	45	78.75	18.75	58.33	33.33	47.5
xx	SH9	Reg	100	50	50	50	37.5	50	37.5	25	7.5	22.5	75	75	56.25	75	45.83	37.5	35	65.625

Install the following packages (this only has to be done once).

```
install.packages("utility")
install.packages("fitdistrplus")
install.packages("truncnorm")
install.packages("RColorBrewer")
install.packages("plyr")
```

Load the following libraries (this has to be done every time you run the code).

```
library(utility)
library(fitdistrplus)
library(truncnorm)
library(RColorBrewer)
library(plyr)
```

Set the scenario parameters. Population can vary between .87 and 1.6, climate impacts between 0 (no impact of sea level rise on existing wastewater treatment plant operations) and 5 (large impact), and ecological threshold is 0 (current ecological resilience to nutrient loading) or 1 (increased ecological sensitivity to nutrient loading). For the 'Status quo' scenario, there is 33% population growth (1.33 multiplier), 0 impact of climate change, and ecological threshold is 1.

```
scenario<-c(population= 1.33,
            climate.impact = 0,
            eco.threshold = 1)
```

Load attribute tables.

```
attrs.nutrients <- read.table(paste("attrs.nutrients.csv", sep = ""), header
= TRUE, sep=",")
head(attrs.nutrients)
class(attrs.nutrients$worst)
attrs.nutrients$name <- as.character(attrs.nutrients$name)

attrs.nutrients.SH3 <- read.table(paste("attrs.nutrients.SH3.csv", sep = ""),
header = TRUE, sep=",")
attrs.nutrients.SH3$name <- as.character(attrs.nutrients.SH3$name)

attrs.nutrients.SH7 <- read.table(paste("attrs.nutrients.SH7.csv", sep = ""),
header = TRUE, sep=",")
attrs.nutrients.SH7$name <- as.character(attrs.nutrients.SH7$name)
```

Set aggregation parameters for the objectives hierarchy.

```
aggregation.parameters<-function(add,min,cd){
  pref.nutrients.sensitivity <-
read.table(paste("pars.nutrients.sensitivity.csv", sep = ""), header = TRUE,
sep=",")
  pref.nutrients.sensitivity[38:55,2:11]<-add ##additive
  pref.nutrients.sensitivity[56:73,2:11]<-min ##minimum
  pref.nutrients.sensitivity[74:91,2:11]<-cd ##cob douglass
  assign("pref.nutrients.sensitivity", pref.nutrients.sensitivity,envir =
globalenv())
  assign("aggregation.all",c(add,min,cd),envir = globalenv())
}

aggregation.parameters(add=1,min=0,cd=0)
pref.nutrients.sensitivity
aggregation.all
```

Specify aggregation type for objectives hierarchy. Add = additive aggregation; Min = minimum aggregation; cd = Cobb-Douglas aggregation.

```
aggregation.parameters(add=1,min=0,cd=0)
```

Make the objectives hierarchy for all the stakeholders (except SH3 and SH7– we'll make their objectives hierarchies next).

```
# create lowest level nodes (marginal value functions)
#################################################################

for (i in 1:nrow(attrs.nutrients)) {
  print(paste("No. ", i, sep = ""))
  assign(print(attrs.nutrients$name[i], sep=""),
         utility.endnode.parfun1d.create(name.node = attrs.nutrients$name[i],
                                         name.attrib =
as.character(attrs.nutrients$name[i]) ,
                                         range =
c(min(attrs.nutrients[i,6:7]),max(attrs.nutrients[i,6:7])),
                                         name.fun = "utility.fun.exp",
```

```
                                          par =
c(0,attrs.nutrients$worst[i],attrs.nutrients$best[i]),
                                          names.par =
c(paste("c.",attrs.nutrients$name[i], sep=""),"worst.v","best.v"),
                                          utility = FALSE,
                                          required = FALSE,
                                          col = "black",
                                          shift.levels = 0))
}

# create mid-level aggregation nodes
#################################################################

ecosystem <- utility.aggregation.create(name.node = "ecosystem",
                                         nodes = list(wq, hab),
                                         name.fun = "utility.aggregate.mix",
                                         par= c(1,1,1,0,0),
                                         names.par = c("w.wq","w.hab",

"add.ecosystem","min.ecosystem", "CD.ecosystem"),
                                         required= FALSE)

r.recovery <- utility.aggregation.create(name.node = "r.recovery",
                                          nodes = list(supply, recovery, CEC),
                                          name.fun = "utility.aggregate.mix",
                                          par= c(1,1,1,aggregation.all),
                                          names.par =
c("w.suppy","w.recovery","w.CEC",

"add.r.recovery","min.r.recovery", "CD.r.recovery"),
                                          required= FALSE)

equity <- utility.aggregation.create(name.node = "equity",
                                      nodes = list(adapt, slr, CO2),
                                      name.fun = "utility.aggregate.mix",
                                      par= c(1,1,1,aggregation.all),
                                      names.par = c("w.adapt","w.slr","w.C02",
                                                    "add.equity","min.equity",
"CD.equity"),
                                      required= FALSE)

social <- utility.aggregation.create(name.node = "social",
                                      nodes = list(ease_use, access, permit),
                                      name.fun = "utility.aggregate.mix",
                                      par= c(1,1,1,aggregation.all),
                                      names.par =
c("w.ease_use","w.access","w.permit",
                                                    "add.social","min.social",
"CD.social"),
                                      required= FALSE)

tot.costs <- utility.aggregation.create(name.node = "tot.costs",
                                         nodes = list(reliable, costs),
                                         name.fun = "utility.aggregate.mix",
                                         par= c(1,1,aggregation.all),
                                         names.par =
c("w.reliable","w.costs","w.CEC",
```

```
"add.tot.costs","min.tot.costs", "CD.tot.costs"),
                                          required= FALSE)

#####

## create top-level aggregation node
#################################################################

nutrients.uncertainty.midnodes <- utility.aggregation.create(name.node =
"nutrients.uncertainty.midnodes",
                                                              nodes =
list(ecosystem, r.recovery, equity, social, tot.costs),
                                                              name.fun =
"utility.aggregate.mix",
                                                              par=
c(1,1,1,1,1,aggregation.all),
                                                              names.par = c(
"w.ecosystem", "w.r.recovery", "w.equity", "w.social", "w.tot.costs",

"add.nutrients.uncertainty","min.nutrients.uncertainty",
"CD.nutrients.uncertainty"),
                                                              required= FALSE)
# Convert to utility
nutrients.uncertainty.midnodes.u <-
utility.conversion.parfun.create(name.node =
"nutrients.uncertainty.midnodes.u",
                                                                      node =
nutrients.uncertainty.midnodes,
                                                                      name.fun
= "utility.fun.exp",
                                                                      par =
c(0,0,1),

names.par = c("r.nutrients.uncertainty","worst.u","best.u"),

required= FALSE)
```

Load general objects.

```
criteria <- c("wq", "hab",  "supply",   "recovery", "CEC",  "adapt",
"slr",  "CO2",  "ease_use", "access",   "permit",   "reliable", "costs")
options <- c("Do nothing", "Wetland levee", "Wetland openwater", "Recycle
irrig.", "Recycle brineline", "Urine early", "Urine incentives", "Opt.",
"Level 2", "Level 3")
options.no.brine <- options[c(1:4, 6:10)]
SHs<- c("SH1", "SH2", "SH3", "SH4", "SH5", "SH6", "SH7", "SH8", "SH9")
Criteria.names<- c("Water Quality", "Wetland Habitat", "Water Supply",
"Nutrient Recovery", "CECs",
                   "Ease of Adaptation", "Sea Level Rise", "CO2 Emissions",
"Ease of Use",
                   "Shoreline Access", "Permitting", "Reliability" ,"Costs")
Criteria.names.main.obj <- c("Ecosystem", "Improve wastewater", "Intergen.
Equity", "Social support", "Low costs")
```

Make objectives hierarchy for SH3.

```
# create lowest level nodes (marginal value functions)
#################################################################
for (i in 1:nrow(attrs.nutrients.SH3)) {
  print(paste("No. ", i, sep = ""))
  assign(print(attrs.nutrients.SH3$name[i], sep=""),
         utility.endnode.parfun1d.create(name.node =
attrs.nutrients.SH3$name[i],
                                         name.attrib =
as.character(attrs.nutrients.SH3$name[i]) ,
                                         range =
c(min(attrs.nutrients.SH3[i,6:7]),max(attrs.nutrients.SH3[i,6:7])),
                                         name.fun = "utility.fun.exp",
                                         par =
c(0,attrs.nutrients.SH3$worst[i],attrs.nutrients.SH3$best[i]),
                                         names.par =
c(paste("c.",attrs.nutrients.SH3$name[i], sep=""),"worst.v","best.v"),
                                         utility = FALSE,
                                         required = FALSE,
                                         col = "black",
                                         shift.levels = 0))
}


# create mid-level aggregation nodes
#################################################################

r.recovery <- utility.aggregation.create(name.node = "r.recovery",
                                         nodes = list(supply, recovery, CEC),
                                         name.fun = "utility.aggregate.mix",
                                         par= c(1,1,1,1,0,0),
                                         names.par =
c("w.suppy","w.recovery","w.CEC",

"add.r.recovery","min.r.recovery", "CD.r.recovery"),
                                         required= FALSE)

equity <- utility.aggregation.create(name.node = "equity",
                                     nodes = list(adapt, slr, CO2),
                                     name.fun = "utility.aggregate.mix",
                                     par= c(1,1,1,1,0,0),
                                     names.par = c("w.adapt","w.slr","w.C02",
                                                   "add.equity","min.equity",
"CD.equity"),
                                     required= FALSE)

social.SH3 <- utility.aggregation.create(name.node = "social.SH3",
                                     nodes = list(access, permit),
                                     name.fun = "utility.aggregate.mix",
                                     par= c(1,1,1,0,0),
                                     names.par = c("w.access","w.permit",

"add.social.SH3","min.social.SH3", "CD.social.SH3"),
                                     required= FALSE)

tot.costs <- utility.aggregation.create(name.node = "tot.costs",
                                        nodes = list(reliable, costs),
                                        name.fun = "utility.aggregate.mix",
```

```
                                        par= c(1,1,1,0,0),
                                        names.par =
c("w.reliable","w.costs","w.CEC",

"add.tot.costs","min.tot.costs", "CD.tot.costs"),
                                        required= FALSE)

#####

## create top-level aggregation node
#################################################################

nutrients.sowatt.midnodes.SH3 <- utility.aggregation.create(name.node =
"nutrients.sowatt.midnodes.SH3",
                                                            nodes =
list(r.recovery, equity, social.SH3, tot.costs),
                                                            name.fun =
"utility.aggregate.mix",
                                                            par=
c(1,1,1,1,1,0,1),
                                                            names.par =
c("w.r.recovery", "w.equity", "w.social.SH3", "w.tot.costs",

"add.nutrients.sowatt.midnodes.SH3","min.nutrients.sowatt.midnodes.SH3",
"CD.nutrients.sowatt.midnodes.SH3"),
                                                            required= FALSE)

# Convert to utility
nutrients.sowatt.midnodes.SH3.u <- utility.conversion.parfun.create(name.node
= "nutrients.sowatt.midnodes.SH3.u",
                                                                    node =
nutrients.sowatt.midnodes.SH3,
                                                                    name.fun
= "utility.fun.exp",
                                                                    par =
c(0,0,1),
                                                                    names.par
= c("r.nutrients.sowatt.midnodes.SH3","worst.u","best.u"),
                                                                    required=
FALSE)
```

Make objectives hierarchy for SH7.

```
# create lowest level nodes (marginal value functions)
#################################################################
for (i in 1:nrow(attrs.nutrients.SH7)) {
  print(paste("No. ", i, sep = ""))
  assign(print(attrs.nutrients.SH7$name[i], sep=""),
         utility.endnode.parfun1d.create(name.node =
attrs.nutrients.SH7$name[i],
                                         name.attrib =
as.character(attrs.nutrients.SH7$name[i]) ,
                                         range =
c(min(attrs.nutrients.SH7[i,6:7]),max(attrs.nutrients.SH7[i,6:7])),
                                         name.fun = "utility.fun.exp",
```

```
                                          par =
c(0,attrs.nutrients.SH7$worst[i],attrs.nutrients.SH7$best[i]),
                                          names.par =
c(paste("c.",attrs.nutrients.SH7$name[i], sep=""),"worst.v","best.v"),
                                          utility = FALSE,
                                          required = FALSE,
                                          col = "black",
                                          shift.levels = 0))
}


# create mid-level aggregation nodes
#################################################################

ecosystem <- utility.aggregation.create(name.node = "ecosystem",
                                        nodes = list(wq, hab),
                                        name.fun = "utility.aggregate.mix",
                                        par= c(1,1,1,0,0),
                                        names.par = c("w.wq","w.hab",

"add.ecosystem","min.ecosystem", "CD.ecosystem"),
                                        required= FALSE)

r.recovery.SH7 <- utility.aggregation.create(name.node = "r.recovery.SH7",
                                          nodes = list(supply, CEC),
                                          name.fun = "utility.aggregate.mix",
                                          par= c(1,1,1,0,0),
                                          names.par = c("w.suppy","w.CEC",

"add.r.recovery.SH7","min.r.recovery.SH7", "CD.r.recovery.SH7"),
                                          required= FALSE)

equity <- utility.aggregation.create(name.node = "equity",
                                     nodes = list(adapt, slr, CO2),
                                     name.fun = "utility.aggregate.mix",
                                     par= c(1,1,1,1,0,0),
                                     names.par = c("w.adapt","w.slr","w.C02",
                                                   "add.equity","min.equity",
"CD.equity"),
                                     required= FALSE)

social <- utility.aggregation.create(name.node = "social",
                                     nodes = list(ease_use, access, permit),
                                     name.fun = "utility.aggregate.mix",
                                     par= c(1,1,1,1,0,0),
                                     names.par =
c("w.ease_use","w.access","w.permit",
                                                   "add.social","min.social",
"CD.social"),
                                     required= FALSE)

tot.costs <- utility.aggregation.create(name.node = "tot.costs",
                                        nodes = list(reliable, costs),
                                        name.fun = "utility.aggregate.mix",
                                        par= c(1,1,1,0,0),
                                        names.par =
c("w.reliable","w.costs","w.CEC",
```

```
"add.tot.costs","min.tot.costs", "CD.tot.costs"),
                                        required= FALSE)

#####

## create top-level aggregation node
#################################################################

nutrients.sowatt.midnodes.SH7 <- utility.aggregation.create(name.node =
"nutrients.sowatt.midnodes.SH7",
                                                            nodes =
list(ecosystem, r.recovery.SH7, equity, social, tot.costs),
                                                            name.fun =
"utility.aggregate.mix",
                                                            par=
c(1,1,1,1,1,1,0,1),
                                                            names.par = c(
"w.ecosystem", "w.r.recovery.SH7", "w.equity", "w.social", "w.tot.costs",

"add.nutrients.sowatt.midnodes.SH7","min.nutrients.sowatt.midnodes.SH7",
"CD.nutrients.sowatt.midnodes.SH7"),
                                                            required= FALSE)

# Convert to utility
nutrients.sowatt.midnodes.SH7.u <- utility.conversion.parfun.create(name.node
= "nutrients.sowatt.midnodes.SH7.u",
                                                               node =
nutrients.sowatt.midnodes.SH7,
                                                               name.fun =
"utility.fun.exp",
                                                               par =
c(0,0,1),
                                                               names.par =
c("r.nutrients.sowatt.midnodes.SH7","worst.u","best.u"),
                                                               required=
FALSE)
```

Load data for calculating attributes for all management options.

```
#WETLAND AREA SUITABILITY DATA
##############################
# Load csv of Ian Wren's/SFEI's GIS assessment of wetland area
wetland.area.data <- read.csv ("wetland_suitability_area.csv")
wetland.area.data [is.na(wetland.area.data)] <- 0
wetland.area.data

# Convert to hectares
wetland.ha <- wetland.area.data [,2:12]/10000
wetland.ha

# Convert to acres
wetland.acre <- wetland.area.data [,2:12]/4046.86
wetland.acre

# DISCHARGE DATA
```

```
################

# Load csv of all nutrient loading and flows (2012-2016)#
# units is average in the dry season (BACWA definition of May  1- Sept. 30)

Discharge.data.current <- read.csv("Dry season discharge
summary_BACWA_2012_2016.csv")
Discharge.data.current

# for future scenarios, assume loads and flows scale with population growth,
but concentrations stay the same
Discharge.scenario <-
cbind(Discharge.data.current[,1:2],Discharge.data.current
[,3:13]*scenario[1])
Discharge.scenario

# Calculate dry season average TN concentrations for each plant (mg/L)

Discharge.TN.conc.scenario <- Discharge.scenario
[5,3:13]/Discharge.scenario[1,3:13]*10^6/3785412
Discharge.TN.conc.scenario
```

Calculate the parameters for each management option.

```
#do nothing
###########
do.nothing.load <- sum (Discharge.scenario [5, 3:13]) # in kg/day
SMX <- 200 # ng/L SMX in secondary treated effluent
# here do.nothing.CEC is how much SMX is produced
do.nothing.CEC <- sum((data.frame(Discharge.scenario [1, c(3:5, 8:11, 13)] *
SMX,
                                  Discharge.scenario [1, c(6,7,12)] * .85 *
SMX)*
                         365 * 10^6 /.26417 / 10^9 / 10^3)) # final unit is
kg/year SMX, days/year, gal/day, L/gal, g/ng, kg/g
do.nothing.CEC.WWTPs <- (data.frame(Discharge.scenario [1, c(3:5, 8:11, 13)]
* SMX,
                                    Discharge.scenario [1, c(6,7,12)] * .85 *
SMX)*
                           365 * 10^6 /.26417 / 10^9 / 10^3)
do.nothing.reliable <- 100 # realiably nothing.
do.nothing.cost <- 0
do.nothing.CO2 <- ((.5 # in kg CO2e/m3, for secondary treatment, model as
minmax distribution +/- 30%
                    * sum(data.frame(Discharge.scenario [1, c(3:5, 8:11,
13)]))
                    + (0.5 + 0.32) * sum( data.frame(Discharge.scenario [1,
c(6,7,12)]))) # these already have tertiary treatment
                   * 365 * 3785.41 / 1000) # final units is tonnes CO2e/year,
days/year, m3/million gallons, tonnes/kg
do.nothing.habitat <- 0
do.nothing.supply <- 22
do.nothing.n.recovery <- 0
do.nothing.adapt <- 100
do.nothing.slr <- -5 - 1 * scenario[2]
```

```
do.nothing.ease.of.use <- 100
do.nothing.access <- 0
do.nothing.permit <- 100

#wetland.levee
#############

wetland.levee.potential <- colSums (wetland.acre [2:3,])  #area -- sum of
ranking 2 and 3, in acres
MGD.acre <- .042 # MGD/acre for wetland levee
wetland.levee.area <-  apply(cbind (t(Discharge.scenario [1, 3:13]),
wetland.levee.potential * MGD.acre), 1, min)/MGD.acre # units are mgd. Uses
two columns, left column is total flow, right column is flow treatable within
area, 'apply' takes the minimum of these two to find treated flow given area
constraints

#wetland.levee.load = mass removed by treatment, kg/day by levee wetlands
treated.flow.levee <- apply(cbind (t(Discharge.scenario [1, 3:13]),
wetland.levee.potential * MGD.acre), 1, min) # units are mgd. Uses two
columns, left column is total flow, right column is flow treatable within
area, 'apply' takes the minimum of these two to find treated flow given area
constraints, assuming all TN goes through wetland
wetland.levee.load <- sum (treated.flow.levee # per treatment plant
                          * (Discharge.TN.conc.scenario - 2) # mg TN /L
after treatment
                          * 3785411.78 / 1000000) # final unit is kg/day,
L/MG, kg/mg

# wetland.levee.cec = mass SMX removed by treatment

wetland.levee.CEC <- do.nothing.CEC - (sum(treated.flow.levee * (0.9 * SMX) *
153 # assume 90% removal, dry season removal only (5 months), assume
significantly less in wet season
                                          + treated.flow.levee * (0.3 * SMX)
* (365-153)) # assume 30% removal in wet season
                                      * 3785411.78 / 10^12) # final unit is
kg/year, L/MG, ng/kg
wetland.levee.CEC.removal <- (sum(treated.flow.levee * (0.9 * SMX) * 153 #
assume 90% removal, dry season removal only (5 months), assume significantly
less in wet season
                                  + treated.flow.levee * (0.3 * SMX) * (365-
153)) # assume 30% removal in wet season
                              * 3785411.78 / 10^12)
wetland.levee.CEC/do.nothing.CEC

wetland.levee.reliable <- 77 - 0.1 * scenario[2] # assuming wetland
reliability would be very slightly affected (1% decrease) per unit of
reliability.climate.impact
wetland.levee.cost <- sum (wetland.levee.area * 650000) # $/acre
wetland.levee.CO2 <- do.nothing.CO2 + sum (wetland.levee.area *
                                            (((137 + 25 * 4 + 298 * .13) #
in mg/m2/hour, operations
                                              + (1/8 * (137 + 25 * 4 + 298 *
.13))) # mg/m2/hour, construction
                                             * 4046.86 * 24 * 365 / 10 ^ 9))
# final unit is tonnes CO2e/year, m2/acre, hours/day, days/year, tonnes/mg
wetland.levee.habitat <- sum(wetland.levee.area)
```

```
wetland.levee.supply <- do.nothing.supply + 0
wetland.levee.n.recovery <- 0
wetland.levee.adapt <- 52 ### vary from 40-65
wetland.levee.slr <- 8 - 1 * scenario[2]
wetland.levee.ease.of.use <- 100
wetland.levee.access <- 11
wetland.levee.permit <- 30 # vary from 5-60

#wetland.openwater
#################
wetland.openwater.area <- 0.6 * colSums(wetland.area.data [,2:12]) # square
meters, area -- input parameter, assume 60% of ranking 1, 2 and 3 available
#wetland.openwater.load = mass removed by openwater wetland treatment kg TN
/day
openwater.flow <- (Discharge.scenario [1,3:13]
                   * 3785.41178 * 365) # final unit is m3/year, m3/MG,
days/year
# Cout/Cin = (1 + ((59.4 * area/(6.4*flow)))^(-6.4) # per treatment plant,
area is in m2, C in is influent/effluent nitrate concentration - assume all
TN is converted to nitrate (mass/m3), flow is m3/year, assume all flow goes
through wetlands
# this below maximizes removal for open water wetlands (using all area for
each). It also seeks to optimize flow to maximize removal through wetlands of
the largest area. The model shows you should put all the flow through for all
areas to get maximum removal
test.seq<-NULL
discharge.seq<-NULL
Cout.Cin<-NULL
wetland.openwater.load<-NULL # kg/day
wetland.openwater.flow<-NULL
wetland.openwater.flow.proportion<-NULL
Cout.Cin.all<-NULL
for( i in 1:11 ){
  test.seq<- seq(0,as.numeric(openwater.flow[i]),
by=as.numeric(openwater.flow[i]/100))
  discharge.seq <- seq(0,as.numeric(Discharge.scenario[5,i+2]),
by=as.numeric(Discharge.scenario[5,i+2]/100))
  Cout.Cin = (1 + ((59.4 * wetland.openwater.area[i])/(6.4*test.seq)))^(-6.4)
  wetland.openwater.load[i]<-((1-
Cout.Cin)*Discharge.scenario[5,i+2]*(0.01*0:100))[which.max((1-
Cout.Cin)*Discharge.scenario[5,i+2]*(0.01*0:100))]
  wetland.openwater.flow[i]<-(which.max((1-
Cout.Cin)*Discharge.scenario[5,i+2]*(0.01*0:100))-
1)/100*Discharge.scenario[1,i+2]
  wetland.openwater.flow.proportion[i]<-(which.max((1-
Cout.Cin)*Discharge.scenario[5,i+2]*(0.01*0:100))-1)/100
  Cout.Cin.all[i]<-Cout.Cin[101]
}
names(wetland.openwater.load)<-colnames(Discharge.scenario[3:13]) # units is
kg/day removed
names(wetland.openwater.flow)<-colnames(Discharge.scenario[3:13])
names(wetland.openwater.flow.proportion)<-colnames(Discharge.scenario[3:13])
# the result of this crazy for loop is that it treats most N to put all the
flow through at all the sites
# now try solving for A -- basically set Cout/Cin to .1 (90% removal) unless
there is not enough area to do so, in which case maximize area
```

```
# this gives amount TN removed (in kg/day, wetland.openwater.load), as well
as Cout/Cin,  given 90% removal or max wetland area if not enough space for
90% removal
# wetland.openwater.area.TN gives area for 90% nitrogen removal or max space
(if 90% N removal requires more space than availabe), in m2
wetland.openwater.load=NULL
Cout.Cin.all<-NULL
wetland.openwater.area.TN<- NULL

for(i in 1:11){
  Area.90 = (((exp(log(0.1)/-6.4))-1)*6.4*Discharge.scenario[1,i +2]*
3785.41178 * 365)/59.4 # unit is meters2
  openwater.area.actual <- ifelse(Area.90 >
wetland.openwater.area[i],wetland.openwater.area[i], Area.90)
  Cout.Cin = (1 + ((59.4 * openwater.area.actual)/(6.4*Discharge.scenario[1,i
+2]* 3785.41178 * 365)))^(-6.4)
  wetland.openwater.load[i]<-((1-Cout.Cin)*Discharge.scenario[5,i+2]) # units
is kg/day, assume TN is treated (and all ammonia is converted to nitrate
prior to wetland)
  Cout.Cin.all[i]<-Cout.Cin
  wetland.openwater.area.TN [i] <- openwater.area.actual
}
names(wetland.openwater.area.TN)<-colnames(Discharge.scenario[3:13]) # units
are m2
names(wetland.openwater.load)<-colnames(Discharge.scenario[3:13]) # units is
kg/day removed
names(Cout.Cin.all)<-colnames(Discharge.scenario[3:13])
wetland.openwater.load
Cout.Cin.all
wetland.openwater.area.TN

#wetland.openwater.cec = kg of SMX removed by treatment
# A90 = .87/(z * kphoto), hectares/MGD for 90% removal of SMX, z = depth (m)
= .3, kphoto = transformation rate/day, assume .25
z <- .3 # meters
kphoto.summer <- .25 #/day (assume pH is 8, [DOC] = 7 mg/L, latitude is ~40)
kphoto.winter <- .1 #.day (assume pH is 8, [DOC] = 7 mg/L, latitude is ~40)
A90.SMX.summer = .87/(z * kphoto.summer) * 10000 # units is m2/MGD, area
needed to remove 90% of SMX, given summer conditions
A90.SMX.winter = .87/(z * kphoto.winter) * 10000 # units is m2/MGD, area
needed to remove 90% of SMX, given winter conditions
# assume SMX removal scales linearly with area, assume 6 months of summer and
6 months of winter conditions
A90.SMX = mean(c(A90.SMX.summer,A90.SMX.winter)) # units is m2/MGD
# wetland.openwater.cec = total amount of SMX removed by treatment, final
unit is kg/year
wetland.openwater.cec.all <- data.frame(NULL)

for (i in 1:11){
  wetland.openwater.cec.all [1,i]<- (wetland.openwater.area.TN[i]/(A90.SMX *
Discharge.scenario [1, i +2] ))*.9*do.nothing.CEC.WWTPs[i]
}
wetland.openwater.CEC <- do.nothing.CEC - sum(wetland.openwater.cec.all)

wetland.openwater.CEC/do.nothing.CEC # this is interesting...basically you
need about twice as much space to treat SMX to 90% removal than nitrogen...
```

```
# assume SMX removal scales linearly with area
wetland.openwater.reliable <- 77 - 0.3 * scenario[2] # assuming wetland
reliability would be slightly affected (3% decrease) per unit of
climate.impact
wetland.openwater.cost <- 200000 * sum(wetland.openwater.area.TN) / 4046.86 #
final unit is $, m2/acre
wetland.openwater.CO2 <- do.nothing.CO2 + ((sum(wetland.openwater.area.TN) *
                                             137 + (25 * 4) + (298 * .13) #
in mg/m2/hour
                                            + (1/8)  * (137 + (25 * 4) + (298
* .13))) # in mg/m2/hour
                                           /(10^9) * 24 * 365) # final unit
is tonnes CO2e/year, mg/tonne, hr/day, days/year
wetland.openwater.habitat <- sum(wetland.openwater.area.TN/10000) /2 # assume
this is half as good as sub-surface flow for habitat
wetland.openwater.supply <- 0 + do.nothing.supply
wetland.openwater.n.recovery <- 0
wetland.openwater.adapt <- 42 ### vary from 30-55
wetland.openwater.slr <- 5 - 1 * scenario[2]
wetland.openwater.ease.of.use <- 100
wetland.openwater.access <- 11  ## ask Felix, should by number of treatment
plants
wetland.openwater.permit <- 30 # vary from 1-60

#recycle.irrig
##############

recycle.irrig.amount<-  c(0, (1/6) * Discharge.scenario [1,4], 0, 10, 45, 10,
0, 2, 5, 10, 0) #amount of water recycled for irrigation, MGD per treatment
plant
names (recycle.irrig.amount) <- colnames(Discharge.scenario [3:13])
recycle.irrig.load <- recycle.irrig.amount * Discharge.TN.conc.scenario /
(10^6) * 3785411.78  # final unit is kg/day, mg/kg, L/million gallons
recycle.irrig.CEC <- do.nothing.CEC - (sum(recycle.irrig.amount) * SMX # ng/L
                                       * 3785411.78 * 365 / (10^12)) # final
unit is kg/year, liters/ million gallons, days/year, ng/kg. Assume all gets
recycled in the wet season also
recycle.irrig.CEC.removal <- (sum(recycle.irrig.amount) * SMX # ng/L
                             * 3785411.78 * 365 / (10^12))
recycle.irrig.reliable <- 96 - .5 * scenario [2]
recycle.irrig.cost <- ((sum(recycle.irrig.amount)
                        * 930) # $/AF/year
                       * 3.06888785 * 365 * 30) # final unit is $ over 30
years
recycle.irrig.CO2 <- do.nothing.CO2 + (sum(recycle.irrig.amount) * 1023 # g
CO2e/m3
                                       * 3785.41178 * 365 / (10^6)) # final
unit is final unit is tonnes CO2e/year, m3/million gallons, days/year,
g/tonne

recycle.irrig.habitat <- 0
recycle.irrig.supply <- sum(recycle.irrig.amount) + do.nothing.supply
recycle.irrig.n.recovery <- sum(recycle.irrig.load) * 365
recycle.irrig.adapt <- 45 ### vary from 30-60
recycle.irrig.slr <- -3 - 1 * scenario[2]
recycle.irrig.ease.of.use <- 100
recycle.irrig.access <- 0
```

```
recycle.irrig.permit <- 70 # vary from 55-85

# recycle.brineline
#################
names (Discharge.scenario)
recycle.ipr <- c(.25  * Discharge.scenario [1,3], 0, .25 * Discharge.scenario
[1,5], .25 * Discharge.scenario [1,6], 35, 0, 0, 20, .25 * Discharge.scenario
[1,11], .25 * Discharge.scenario [1,12], .25 * Discharge.scenario [1,13]) #
in MGD, vector of amounts from wwtps with IPR
recycle.dpr <- c(0,0,0,0,8,0,0,0,0,0,0) # MGD
recycle.brineline.amount  <- recycle.ipr + recycle.dpr #amount of water
recycled for potable reuse, MGD
recycle.brine <- .2 * sum (recycle.brineline.amount) # amount of brine, MGD,
assume 80% efficiency of RO
recycle.brineline.load <- (sum(recycle.brineline.amount *
Discharge.TN.conc.scenario)
                           * 3785411.78 / (10^6)) # final unit is kg/day,
L/million gallons, mg/kg
recycle.brineline.CEC <- do.nothing.CEC - (sum(recycle.brineline.amount) *
SMX #ng/L
                                           * 3785411.78 * 365 / (10^12)) #
final unit is kg/year
recycle.brineline.reliable <- 98 - .5 * scenario [2] # mean of normal
distribution with SD .01
pumping.energy <- ((1/2655220) # kwh/ft-lbs of lift assume weight of brine =
weight of water
                   * recycle.brine #units is MGD
                   * 2000 # ft, height over the peninsula
                   * (8.34 * 10^6) *365 / 1000) # final unit is Mwh/year
pumping.energy.CO2 <- (pumping.energy * 320896  # unit here after
multiplication is g CO2 e/ million gallons (conversion from
west.berkeley.edu)
                       * recycle.brine / (10^6) * 365) # final unit is tonnes
CO2 e/year, g/tonne, days/year
# run through WEST (west.berkeley.edu), get 11866708406 g CO23/million
gallons
pipe.length <- 36960 # ft across peninsula (roughly Millbrae to Pacifica)
pipe.CO2 <- (pipe.length * 358  # unit here after multiplication is g CO2 e/
million gallons (conversion from west.berkeley.edu)
             * recycle.brine / (10^6) * 365) #final unit is tonnes CO2
e/year, g/tonne, days/year
pumping.CO2 <- pumping.energy.CO2 + pipe.CO2 # unit is tonnes CO2e/year
# unit is CO2e/year (need CO2 e/kwh in CA)
recycle.brineline.CO2 <- do.nothing.CO2 + ((sum(recycle.brineline.amount) *
(438 + 25 * (.88)) # kg CO2e/466 m3
                                            * 3785.41178 * 365 / 466 / (10^3)
# m3/million gallons, days/year, m3/kg, kg/ tonne
                                            + pumping.CO2)) # final unit is
tonnes CO2 e/year
pumping.cost <- ((1/2655220) # kwh/ft-lbs of lift assume weight of brine =
weight of water
                 * 0.2 # $/kwh for energy
                 * recycle.brine #units is MGD
                 * 2000 # ft, height over the peninsula
                 * (8.34 * 10^6) *365*30) # final unit is $ for 30 years,
pounds/million gallons, days/year, years
```

```
recycle.brineline.cost <- ((sum(recycle.ipr) * 3.06888785 * 365 * 30  #
AF/million gallons, days/year, years
                            * (700 + mean(c( 120, 750, 1250)))) # $/AF,
advanced treatment plus conveyance to drinking water
                           + (sum(recycle.dpr) * 3.06888785 * 365 * 30 #
AF/million gallons, days/year, years
                             * (700 + 120)) # $/AF, advanced treatment plus
conveyance to drinking water
                           + (recycle.brine * 115 * 3.06888785 * 365 * 30 ) #
final unit is $/AF, cost of pipe for amount of water, AF/million gallons,
days/year, year
                           + 2000000 * (pipe.length/5280) # cost of brineline
pipe per distance, ft/mile
                           +  pumping.cost) # final unit is $ for 30 years of
operation
recycle.brineline.habitat <- 0
recycle.brineline.supply <- sum(recycle.brineline.amount) + do.nothing.supply
recycle.brineline.n.recovery <- 0
recycle.brineline.adapt <- 50 ### vary from 40-60
recycle.brineline.slr <- -5 - 1 * scenario[2]
recycle.brineline.ease.of.use <- 65
recycle.brineline.access <- 0
recycle.brineline.permit <- 40 # vary from 30-50

#urine.early
##########

# proportion of population that is early adopters (tech and ed industries)
Early.adopt <- .039
# grams of N excreted in urine
N.excreted <- 10.5 # g N/person/day
# Proportion of a person's urine recovered by urine source separation
U.recovery.toilet <- .5
# Proportion of N recovered by ion exchange resin
N.recovery.resin <- .9
toilet.use <- .5 # percent of the time that people with urine-separating
toilets use them
population <-  scenario [1] * c(30000, 957000, 22850, 217330, 1498700, 0.5 *
(143100 + 156500), 10000, 670400, 110000, 148000, 200600) # shown in order of
WWTPs in Discharge.scenario.
names(population)<- colnames(Discharge.scenario[3:13])
urine.early <- Early.adopt * sum(population) + ifelse((scenario
[1])>1,(scenario [1]-1)*(sum(population)/scenario[1]),0) # if population
grows, it's early adopters + whatever population growth. If population
declines, it's just early adopters
urine.early.load <- (urine.early *  N.excreted *  N.recovery.resin *
U.recovery.toilet * toilet.use
                     / 1000 ) # final unit is kg/day, g/kg

total.CEC <- sum(data.frame(Discharge.scenario [1, c(3:5, 8:11, 13)] * SMX,
                            Discharge.scenario [1, c(6,7,12)] * .85 * SMX)*
                   365 * 10^6 /.26417 / 10^9 / 10^3) # final unit is kg/year
SMX, days/year, gal/day, L/gal, g/ng, kg/g
urine.early.CEC.removal <- urine.early/sum(population) * total.CEC * .84
urine.early.CEC <- do.nothing.CEC - urine.early.CEC.removal # proportion of
SMX excreted in urine vs. feces, final unit is kg/year of SMX removed
urine.early.reliable <- 66 # +/- 20%
```

```
urine.early.cost <- (26 # $/m3 of urine
                     * urine.early * 1.4 # L urine excreted/person/day
                     * toilet.use
                     * 365 * 30 / 1000) # final units is $ over 30 years,
days/year, yrs, L/m3
urine.early.CO2 <- do.nothing.CO2 + (urine.early * 1.4 # L urine
excreted/person/day
                                     * toilet.use
                                     * 5.5 # kg CO2 e/m3 urine treated
                                     / 1000 / 1000) # final units is tonnes
CO2e/year, kg/tonne, L/m3
urine.early.habitat <- 0
urine.early.supply <- 0 + do.nothing.supply
urine.early.n.recovery <- urine.early.load * 365
urine.early.adapt <- 85 ### vary from 75-95
urine.early.slr <- 0
urine.early.ease.of.use <- 35 ## vary from 25-45
urine.early.access <- 0
urine.early.permit <- 40 # vary from 30-50


#urine.incentives
###############

urine.incentives <- (0.3 * sum(population)) + ifelse((scenario
[1])>1,(scenario [1]-1)*(sum(population)/scenario[1]),0) # 30% of current
population + all population growth
#urine.incentives.load = kg TN/day removed by urine source separation
toilet.use.incentives <- .75 # percent of the time that people with urine-
separating toilets use them
urine.incentives.load <- (urine.incentives *  N.excreted *  N.recovery.resin
* U.recovery.toilet * toilet.use.incentives
                          / 1000 ) # final unit is kg/day, g/kg
urine.incentives.CEC.removal <- (urine.incentives/sum(population) * total.CEC
* .84)
urine.incentives.CEC <- do.nothing.CEC - urine.incentives.CEC.removal #
proportion of SMX excreted in urine vs. feces, final unit is kg/year of SMX
removed
urine.incentives.reliable <- 76 # +/- 20%
incentive1 <- 3000 # initial retrofit incentive
incentive2 <- (2 * 52 * 30) #  weekly reward for turning in cartridge for 30
year lifecycle, $ reward, weeks/year, years
household <- 2.7
outreach <- 200000 * 11 # ask Felix about this... 11 is number of
participating utilities
urine.incentives.cost <- (((26 # $/m3 of urine
                            * urine.incentives * 1.4 # L urine
excreted/person/day
                            * toilet.use.incentives
                            * 365 * 30 / 1000) # final units is $ over 30
years, days/year, yrs, L/m3
                           + (incentive1 * (0.3 *
(sum(population)/scenario[1]) / household )) # $/household to install toilet
for all existing population
                           + (incentive2 * urine.incentives/household) #
people per household, initial incentive only for retrofits, not new housing
stock
```

```
                          + outreach)) # final unit is $
urine.incentives.CO2 <- do.nothing.CO2 + (urine.incentives * 1.4 # L urine
excreted/person/day
                                          * toilet.use.incentives
                                          * 5.5 # kg CO2 e/m3 urine treated
                                          / 1000 / 1000) # final units is
tonnes CO2e/year, kg/tonne, L/m3)
urine.incentives.habitat <- 0
urine.incentives.supply <- 0 + do.nothing.supply
urine.incentives.n.recovery <- urine.incentives.load * 365
urine.incentives.adapt <- 55 ### vary from 45-65
urine.incentives.slr <- 0
urine.incentives.ease.of.use <- 35 ## vary from 25-45
urine.incentives.access <- 0
urine.incentives.permit <- 40 # vary from 30-50

# opt
####
opt <- # binary yes or no
  opt.load <- sum(Discharge.scenario [5,3:13]) * .1 # assuming optimization
removes 10%, final unit is kg/day
opt.CEC <- do.nothing.CEC # CECs removed by optimization is 0
opt.cost <- sum(Discharge.scenario[1, 3:13]) * 1000000 * 0.5 #assume $0.5/gpd
(estimated from HDR draft report).
opt.reliable<- 98 # normal with sd .1
opt.CO2 <- do.nothing.CO2 + 0
opt.habitat <- 0
opt.supply <- 0 + do.nothing.supply
opt.n.recovery <- 0
opt.adapt <- 75 ### vary from 60-90
opt.slr <- -5 -1 * scenario [2]
opt.ease.of.use <- 100
opt.access <- 0
opt.permit <- 90 # vary from 80-100


# Level2
Level2 <- # binary yes or no
  #Level2.load = amount TN (kg/day) removed by Level 2 treatment
  Level2.load <- (sum(Discharge.scenario [5,3:13]) - (sum(Discharge.scenario
[1,3:13]) * 15 # mg/L
                                                    * 3785411.78 / (10^6)))
# final units is kg/day, L/million gallons, mg/kg
#Level2.CEC = additonal amount SMX (kg/year) removed by Level 2 treatment,
assumes no additional removal from plants that already have tertiary
treatment
Level2.CEC <- do.nothing.CEC - (sum(data.frame(Discharge.scenario [1, c(3:5,
8:11, 13)])) * .15 * SMX
                                * 3785411.78 / (10^12) * 365) # final unit is
kg SMX/year, L/million gallons, ng/kg, days/year
Level2.cost <- sum(Discharge.scenario[1, 3:13]) * 1000000 * 7.5 # $7.5/gpd
dry season flow-weighted average from HDR draft report to BACWA
Level2.reliable <- 98 # normal with SD .1
Level2.CO2 <- do.nothing.CO2 + (sum(data.frame(Discharge.scenario [1, c(3:5,
8:11, 13)])) * 0.32 # kg CO2 e/m3, for all the plants that don't already have
tertiary treatment
```

```
                                * 3785.41178 * 365 / 1000) # final unit is
tonnes CO2 e/year, m3/million gallons, days/year, kg/tonne
Level2.habitat <- 0
Level2.supply <- 0 + do.nothing.supply
Level2.n.recovery <- 0
Level2.adapt <- 55 ### vary from 30-75
Level2.slr <- -5 -1 * scenario [2]
Level2.ease.of.use <- 100
Level2.access <- 0
Level2.permit <- 90 # vary from 80-100

# Level3
Level3 <- # binary yes or no
  #Level3.load = amount TN (kg/day) removed by Level 3 treatment
  Level3.load <- (sum(Discharge.scenario [5,3:13]) - (sum(Discharge.scenario
[1,3:13]) * 6 # mg/L
                                                      * 3785411.78 / (10^6)))
# final units is kg/day, L/million gallons, mg/kg
Level3.CEC <- do.nothing.CEC - (sum(data.frame(Discharge.scenario [1, c(3:5,
8:11, 13)])) * .15 * SMX
                                * 3785411.78 / (10^12) * 365) # final unit is
kg SMX/year, L/million gallons, ng/kg, days/year
Level3.cost <- sum(Discharge.scenario[1, 3:13]) * 1000000 * 9.8 # $9.8/gpd
dry season flow-weighted average from HDR draft report to BACWA
Level3.reliable <- 98 # normal with SD .01
Level3.CO2 <- do.nothing.CO2 + (sum(data.frame(Discharge.scenario [1, 3:13]))
* 0.8 # kg CO2 e/m3, for all the plants that don't already have tertiary
treatment
                                * 3785.41178 * 365 / 1000) # final unit is
tonnes CO2 e/year, m3/million gallons, days/year, kg/tonne
Level3.habitat <- 0
Level3.supply <- 0 + do.nothing.supply
Level3.n.recovery <- 0
Level3.adapt <- 10 ### vary from 5-15
Level3.slr <- -5 -1 * scenario [2]
Level3.ease.of.use <- 100
Level3.access <- 0
Level3.permit <- 90 # vary from 80-100
```

Calculate percent change in nutrient loading from current conditions per option.

```
# do nothing
do.nothing.load.change <- (do.nothing.load - sum((Discharge.data.current
[5,3:13])))/sum(Discharge.data.current [5,3:13]) * 100
# wetland levee
wetland.levee.load.change <- ((do.nothing.load - wetland.levee.load) -
sum(Discharge.data.current [5,3:13])) / sum(Discharge.data.current [5,3:13])
* 100
#wetland openwater
wetland.openwater.load.change <- ((do.nothing.load -
sum(wetland.openwater.load)) - sum(Discharge.data.current [5,3:13])) /
sum(Discharge.data.current [5,3:13]) * 100
#recycle irrigation
recycle.irrig.load.change <- ((do.nothing.load - sum(recycle.irrig.load)) -
sum(Discharge.data.current [5,3:13])) / sum(Discharge.data.current [5,3:13])
* 100
```

```
# recycle brineline
recycle.brineline.load.change <- ((do.nothing.load - recycle.brineline.load)
- sum(Discharge.data.current [5,3:13])) / sum(Discharge.data.current
[5,3:13]) * 100
# urine early
urine.early.load.change <- ((do.nothing.load - urine.early.load) -
sum(Discharge.data.current [5,3:13])) / sum(Discharge.data.current [5,3:13])
* 100
# urine incentives ### hmm, something looks wrong here...should be much more
reduction because is supposed to be all new growth + 30% of existing...
urine.incentives.load.change <- ((do.nothing.load - urine.incentives.load) -
sum(Discharge.data.current [5,3:13])) / sum(Discharge.data.current [5,3:13])
* 100
# opt
opt.load.change <- ((do.nothing.load - sum(opt.load)) -
sum(Discharge.data.current [5,3:13])) / sum(Discharge.data.current [5,3:13])
* 100
# level 2
Level2.load.change <- ((do.nothing.load - Level2.load) -
sum(Discharge.data.current [5,3:13])) / sum(Discharge.data.current [5,3:13])
* 100
# level 3
Level3.load.change <- ((do.nothing.load - Level3.load) -
sum(Discharge.data.current [5,3:13])) / sum(Discharge.data.current [5,3:13])
* 100
```

Create objects for the different parameter vectors.

```
load.change.par <-
c(do.nothing.load.change,wetland.levee.load.change,wetland.openwater.load.cha
nge,
recycle.irrig.load.change,recycle.brineline.load.change,urine.early.load.chan
ge, urine.incentives.load.change, opt.load.change,Level2.load.change,
Level3.load.change)
names (load.change.par) <- options

#translating from load.change to wq
###################################

## very basic, assuming linear fit from data points
#data points if no threshold
percent.change <- c(0, -100, 100)
wq.graph <- c(10, 5, 95)

plot(percent.change, wq.graph)
abline(lm(wq.graph ~ percent.change))
regmodel=lm(wq.graph ~percent.change) #fit a regression model
summary(regmodel) #get results from fitting the regression model

wq.par<-NULL
if (scenario [3] == 0) wq.par <- regmodel$coefficients[2]* load.change.par +
regmodel$coefficients[1]

#wq.par
# data points if threshold
# very basic, assuming linear fit based on elicitation from SFEI
```

```
percent.change.thresh <- c(33, 60, -13, -35, -35, -20, -20, -60, -60, -75)
wq.graph.thresh <- c(75, 85, 70, 35, 35, 40, 40, 30, 30, 10)
plot (percent.change.thresh, wq.graph.thresh)
abline(lm(wq.graph.thresh~percent.change.thresh))
regmodel.thresh=lm(wq.graph.thresh~percent.change.thresh) #fit a regression
model
summary(regmodel.thresh) #get results from fitting the regression model

if (scenario [3] == 1) wq.par <- regmodel.thresh$coefficients[2]*
load.change.par + regmodel.thresh$coefficients[1] #simply linear with y =
mx+b
wq.par
for (i in 1:10){
  if (wq.par [i] <= 5) wq.par[i] <- 5
  if (wq.par [i] >=95) wq.par[i] <- 95

}
wq.par

#habitat
habitat.par <- c(do.nothing.habitat, wetland.levee.habitat,
wetland.openwater.habitat, recycle.irrig.habitat, recycle.brineline.habitat,
urine.early.habitat, urine.incentives.habitat, opt.habitat, Level2.habitat,
Level3.habitat)
names (habitat.par) <- options
# water supply
supply.par <- c(do.nothing.supply, wetland.levee.supply,
wetland.openwater.supply, recycle.irrig.supply, recycle.brineline.supply,
urine.early.supply, urine.incentives.supply, opt.supply, Level2.supply,
Level3.supply)
names (supply.par) <- options
# nutrient recovery
n.recovery.par <- c(do.nothing.n.recovery, wetland.levee.n.recovery,
wetland.openwater.n.recovery, recycle.irrig.n.recovery,
recycle.brineline.n.recovery, urine.early.n.recovery,
urine.incentives.n.recovery, opt.n.recovery, Level2.n.recovery,
Level3.n.recovery)
names (n.recovery.par) <- options
# CECs - this is amount that gets through after treatment
CEC.par <- c(do.nothing.CEC, wetland.levee.CEC, wetland.openwater.CEC,
recycle.irrig.CEC, recycle.brineline.CEC, urine.early.CEC,
urine.incentives.CEC, opt.CEC, Level2.CEC, Level3.CEC)
names (CEC.par) <- options
# ease of adaptation
adapt.par <- c(do.nothing.adapt, wetland.levee.adapt,
wetland.openwater.adapt, recycle.irrig.adapt, recycle.brineline.adapt,
urine.early.adapt, urine.incentives.adapt, opt.adapt, Level2.adapt,
Level3.adapt)
names (adapt.par) <- options
# resilience to sea level rise
slr.par <- c(do.nothing.slr, wetland.levee.slr, wetland.openwater.slr,
recycle.irrig.slr, recycle.brineline.slr, urine.early.slr,
urine.incentives.slr, opt.slr, Level2.slr, Level3.slr)
names (slr.par) <- options
# GHG emissions
```

```
CO2.par <- c(do.nothing.CO2, wetland.levee.CO2, wetland.openwater.CO2,
recycle.irrig.CO2, recycle.brineline.CO2, urine.early.CO2,
urine.incentives.CO2, opt.CO2, Level2.CO2, Level3.CO2)
names (CO2.par) <- options
# ease of use
ease.of.use.par <- c(do.nothing.ease.of.use, wetland.levee.ease.of.use,
wetland.openwater.ease.of.use, recycle.irrig.ease.of.use,
recycle.brineline.ease.of.use, urine.early.ease.of.use,
urine.incentives.ease.of.use, opt.ease.of.use, Level2.ease.of.use,
Level3.ease.of.use)
names (ease.of.use.par) <- options
# shoreline access
access.par <- c(do.nothing.access, wetland.levee.access,
wetland.openwater.access, recycle.irrig.access, recycle.brineline.access,
urine.early.access, urine.incentives.access, opt.access, Level2.access,
Level3.access)
names (access.par) <- options
# permitting
permit.par <- c(do.nothing.permit, wetland.levee.permit,
wetland.openwater.permit, recycle.irrig.permit, recycle.brineline.permit,
urine.early.permit, urine.incentives.permit, opt.permit, Level2.permit,
Level3.permit)
names (permit.par) <- options
#reliability
reliable.par <- c(do.nothing.reliable, wetland.levee.reliable,
wetland.openwater.reliable, recycle.irrig.reliable,
recycle.brineline.reliable, urine.early.reliable, urine.incentives.reliable,
opt.reliable, Level2.reliable, Level3.reliable)
names (reliable.par) <- options
#costs
cost.par <- c(do.nothing.cost, wetland.levee.cost, wetland.openwater.cost,
recycle.irrig.cost, recycle.brineline.cost, urine.early.cost,
urine.incentives.cost, opt.cost, Level2.cost, Level3.cost)
names (cost.par) <- options
# cost per capita
cost.per.cap <- cost.par/sum(population)
names(cost.per.cap) <- options

criteria.calcs<- data.frame(cbind(wq.par, habitat.par, supply.par,
n.recovery.par, CEC.par, adapt.par, slr.par, CO2.par, ease.of.use.par,
access.par, permit.par, reliable.par, cost.par))
```

Calculate and plot cost-efficiency of each option.

```
# cost efficiency (cost.par/nitrogen removal)
n.removal <- 365*30* c(0, wetland.levee.load, sum(wetland.openwater.load),
sum(recycle.irrig.load), recycle.brineline.load, urine.early.load,
urine.incentives.load, opt.load, Level2.load, Level3.load)

cost.efficiency <- cost.par / n.removal
cost.efficiency2 <- n.removal/cost.par
cost.efficiency3 <- n.removal[c(1:4, 6:10)]/cost.par[c(1:4, 6:10)] # no
brineline
cost.efficiency4 <- cost.par[c(1:4, 6:10)]/n.removal[c(1:4, 6:10)] #no
brineline
names(cost.efficiency2) <- options
```

```
names(cost.efficiency3) <- options.no.brine
names(cost.efficiency4) <- options.no.brine

par(mfrow = c(1,1))
par(mar=c(10,4.1,5,2),
    oma = c(0,0,0,0),
    xpd = T)
barplot(cost.efficiency, main = "Cost efficiency ($/kg TN removal)", las = 2)
barplot(cost.efficiency2, main = "Cost efficiency (kg TN removal/$)", las =
2, col = brewer.pal(10, "Paired"))
barplot(cost.efficiency3, main = "Cost efficiency (kg TN removal/$)", las =
2, col = brewer.pal(9, "Paired"), ylim = c(0,.5))
barplot(cost.efficiency4, main = "Cost efficiency ($/kg TN removal)", las =
2, col = brewer.pal(9, "Paired"), ylim = c(0,70))
```

Set parameters for modeling uncertainty for each option.

```
uncertainty.distributions<- read.csv("uncertainty_distributions.csv",
row.names = 1)

#do nothing
###########

#do.nothing.load
do.nothing.load.change.par1<- .8  * do.nothing.load.change
do.nothing.load.change.par2<-1.2 * do.nothing.load.change

#do.nothing.wq
do.nothing.wq.par1<- .8 * wq.par[1]
do.nothing.wq.par2<- 1.2 * wq.par[1]

# here do.nothing.CEC is actually how much SMX is produced
#do.nothing.CEC
do.nothing.CEC.par1<- .8 * sum(do.nothing.CEC)
do.nothing.CEC.par2<-  1.2 * sum(do.nothing.CEC)

#do.nothing.reliable
do.nothing.reliable.par1<- do.nothing.reliable
do.nothing.reliable.par2<- do.nothing.reliable

#do.nothing.cost
do.nothing.cost.par1<- do.nothing.cost
do.nothing.cost.par2<- do.nothing.cost

#do.nothing.CO2
do.nothing.CO2.par1<- .7 * do.nothing.CO2
do.nothing.CO2.par2<- 1.3 * do.nothing.CO2

#do.nothing.habitat
do.nothing.habitat.par1<- do.nothing.habitat
do.nothing.habitat.par2<- do.nothing.habitat

#do.nothing.supply
do.nothing.supply.par1<- do.nothing.supply
do.nothing.supply.par2<- do.nothing.supply
```

```
#do.nothing.n.recovery
do.nothing.n.recovery.par1<- do.nothing.n.recovery
do.nothing.n.recovery.par2<- do.nothing.n.recovery

#do.nothing.adapt
do.nothing.adapt.par1<- do.nothing.adapt
do.nothing.adapt.par2<- do.nothing.adapt

#do.nothing.slr
do.nothing.slr.par1<- do.nothing.slr
do.nothing.slr.par2<- do.nothing.slr

#do.nothing.ease.of.use
do.nothing.ease.of.use.par1<- do.nothing.ease.of.use
do.nothing.ease.of.use.par2<- do.nothing.ease.of.use

#do.nothing.access
do.nothing.access.par1<- do.nothing.access
do.nothing.access.par2<- do.nothing.access

#do.nothing.permit
do.nothing.permit.par1<-do.nothing.permit
do.nothing.permit.par2<- do.nothing.permit

# WETLAND LEVEE
###############
wetland.levee.dist<- c("Minmax", "Minmax", "Determined", "Determined", "")
MGD.acre <- (.042) # MGD/acre for wetland levee
treated.flow.levee <- apply(cbind (t(Discharge.scenario [1, 3:13]),
wetland.levee.potential * MGD.acre), 1, min) # units are mgd. Uses two
columns, left column is total flow, right column is flow treatable within
area, 'apply' takes the minimum of these two to find treated flow given area
constraints, assuming all TN goes through wetland
wetland.levee.load <- sum (treated.flow.levee # per treatment plant
                           * (Discharge.TN.conc.scenario - 2) # mg TN /L
after treatment
                           * 3785411.78 / 1000000) # final unit is kg/day,
L/MG, kg/mg

MGD.acre.8 <- .8 * (.042) # MGD/acre for wetland levee
treated.flow.levee.8 <- apply(cbind (t(Discharge.scenario [1, 3:13]),
wetland.levee.potential * MGD.acre.8), 1, min) # units are mgd. Uses two
columns, left column is total flow, right column is flow treatable within
area, 'apply' takes the minimum of these two to find treated flow given area
constraints, assuming all TN goes through wetland
wetland.levee.load.8 <- sum (treated.flow.levee.8 # per treatment plant
                             * (Discharge.TN.conc.scenario - 2) # mg TN /L
after treatment
                             * 3785411.78 / 1000000) # final unit is kg/day,
L/MG, kg/mg
MGD.acre1.2 <- 1.2 * (.042) # MGD/acre for wetland levee
treated.flow.levee1.2 <- apply(cbind (t(Discharge.scenario [1, 3:13]),
wetland.levee.potential * MGD.acre1.2), 1, min) # units are mgd. Uses two
columns, left column is total flow, right column is flow treatable within
area, 'apply' takes the minimum of these two to find treated flow given area
constraints, assuming all TN goes through wetland
```

```
wetland.levee.load1.2 <- sum (treated.flow.levee1.2 # per treatment plant
                              * (Discharge.TN.conc.scenario - 2) # mg TN /L
after treatment
                              * 3785411.78 / 1000000) # final unit is kg/day,
L/MG, kg/mg

wetland.levee.load.change <- ((do.nothing.load - wetland.levee.load) -
sum(Discharge.data.current [5,3:13])) / sum(Discharge.data.current [5,3:13])
* 100
wetland.levee.load.change.8 <- ((do.nothing.load - wetland.levee.load.8) -
sum(Discharge.data.current [5,3:13])) / sum(Discharge.data.current [5,3:13])
* 100
wetland.levee.load.change1.2 <- ((do.nothing.load - wetland.levee.load1.2) -
sum(Discharge.data.current [5,3:13])) / sum(Discharge.data.current [5,3:13])
* 100
levee.load.change.variation <-
c(wetland.levee.load.change,wetland.levee.load.change.8,wetland.levee.load.ch
ange1.2)
names(levee.load.change.variation)<- c("0.042 MGD/acre", "0.0336 MGD/acre",
"0.0504 MGD/acre")
wetland.levee.load.change.8/wetland.levee.load.change
wetland.levee.load.change1.2/wetland.levee.load.change

# vary from - 20% to + 17 % based on +/- 20% change to area needed for
treatment
#wetland.levee.load.change: +/- 20%, uniform distribution
wetland.levee.load.change.par1 <- .8 * wetland.levee.load.change
wetland.levee.load.change.par2 <- 1.17* wetland.levee.load.change

#wetland levee.wq
wetland.levee.wq.par1 <- .8 * wq.par[2]
wetland.levee.wq.par2 <- 1.2 * wq.par[2]

# wetland.levee.cec
wetland.levee.CEC.par1 <- do.nothing.CEC.par1 - (1.2 *
wetland.levee.CEC.removal)
wetland.levee.CEC.par2 <- do.nothing.CEC.par2 - (.8 *
wetland.levee.CEC.removal)

#wetland.levee.reliable
wetland.levee.reliable.par1 <- .8 * wetland.levee.reliable
wetland.levee.reliable1.par2 <- 1.2 * wetland.levee.reliable

#wetland.levee.cost
wetland.levee.cost.par1 <- sum (wetland.levee.area * 100000) # $/acre
wetland.levee.cost.par2 <- sum (wetland.levee.area * 1000000) # $/acre

#wetland.levee.CO2
wetland.levee.CO2.par1 <- .8 * wetland.levee.CO2
wetland.levee.CO2.par2 <- 1.2 * wetland.levee.CO2

#wetland.levee.habitat
wetland.levee.habitat.par1 <- .75 * wetland.levee.habitat
wetland.levee.habitat.par2 <- wetland.levee.habitat

#wetland.levee.supply
wetland.levee.supply.par1<- wetland.levee.supply
```

```
wetland.levee.supply.par2<- wetland.levee.supply

#wetland.levee.n.recovery
wetland.levee.n.recovery.par1<- wetland.levee.n.recovery
wetland.levee.n.recovery.par2<- wetland.levee.n.recovery

#wetland.levee.adapt
wetland.levee.adapt.par1 <- 40
wetland.levee.adapt.par2 <- 65

#wetland.levee.slr
wetland.levee.slr.par1<- wetland.levee.slr
wetland.levee.slr.par2<- wetland.levee.slr

#wetland.levee.ease.of.use
wetland.levee.ease.of.use.par1<- wetland.levee.ease.of.use
wetland.levee.ease.of.use.par2<- wetland.levee.ease.of.use

#wetland.levee.access
wetland.levee.access.par1 <- 6
wetland.levee.access.par2 <- 11

#wetland.levee.permit
wetland.levee.permit.par1 <- 5
wetland.levee.permit.par2 <- 60

# WETLAND OPENWATER
###################

#wetland.openwater.load.change
wetland.openwater.load.change.par1 <- 0.8 * wetland.openwater.load.change
wetland.openwater.load.change.par2 <- 1.2 * wetland.openwater.load.change

#wetland.openwater.wq
wetland.openwater.wq.par1 <- .8 * wq.par [3]
wetland.openwater.wq.par2 <- 1.2 * wq.par [3]

#wetland.openwater.CEC
wetland.openwater.CEC.par1 <- .8 * wetland.openwater.CEC
wetland.openwater.CEC.par2 <- 1.2 * wetland.openwater.CEC

#wetland.openwater.reliable
wetland.openwater.reliable.par1 <- .8 * wetland.openwater.reliable
wetland.openwater.reliable.par2 <- 1.2 * wetland.openwater.reliable

#wetland.openwater.cost
wetland.openwater.cost.par1 <- .8 * wetland.openwater.cost
wetland.openwater.cost.par2 <- 1.2 * wetland.openwater.cost + 300000 *
sum(wetland.openwater.area.TN/4046.86) # conversion for m2 to acres, extra
$300,000/acre for land costs on top end

#wetland.openwater.CO2: model with +/- 20%
wetland.openwater.CO2.par1 <- .8 * wetland.openwater.CO2
wetland.openwater.CO2.par2 <- 1.2 * wetland.openwater.CO2

#wetland.openwater.habitat
wetland.openwater.habitat.par1 <- .4 * sum(wetland.openwater.area.TN/10000)
```

```
wetland.openwater.habitat.par2 <- .7 * sum(wetland.openwater.area.TN/10000)

#wetland.openwater.supply
wetland.openwater.supply.par1<- wetland.openwater.supply
wetland.openwater.supply.par2<- wetland.openwater.supply

#wetland.openwater.n.recovery
wetland.openwater.n.recovery.par1<- wetland.openwater.n.recovery
wetland.openwater.n.recovery.par2<- wetland.openwater.n.recovery

#wetland.openwater.adapt
wetland.openwater.adapt.par1 <- 30
wetland.openwater.adapt.par2 <- 55

#wetland.openwater.slr
wetland.openwater.slr.par1<- wetland.openwater.slr
wetland.openwater.slr.par2<- wetland.openwater.slr

#wetland.openwater.ease.of.use
wetland.openwater.ease.of.use.par1<- wetland.openwater.ease.of.use
wetland.openwater.ease.of.use.par2<- wetland.openwater.ease.of.use

#wetland.openwater.access
wetland.openwater.access.par1 <- 6
wetland.openwater.access.par2 <- 11

#wetland.openwater.permit
wetland.openwater.permit.par1 <- 1
wetland.openwater.permit.par2 <- 60

#RECYCLE IRRIGATION
###################

#recycle.irrig.load.change
recycle.irrig.load.change.par1 <- .8 * recycle.irrig.load.change
recycle.irrig.load.change.par2 <- 1.2 * recycle.irrig.load.change

#recycle.irrig.wq
recycle.irrig.wq.par1<- .8 * wq.par[4]
recycle.irrig.wq.par2<- 1.2 * wq.par[4]

# recycle.irrig.CEC
recycle.irrig.CEC.par1 <- do.nothing.CEC.par1 - ( .8 *
recycle.irrig.CEC.removal)
recycle.irrig.CEC.par2 <- do.nothing.CEC.par2 - (1.2 *
recycle.irrig.CEC.removal)

# recycle.irrig.reliable
recycle.irrig.reliable.par1 <- .8* recycle.irrig.reliable
recycle.irrig.reliable.par2 <- 1.2 * recycle.irrig.reliable

irrig.cost.Bay.Area <- c(522.88, 493.12, 1379.31, 242.42, 1200.87, 387.0,
1972.39, 1041.67, 258.75, 601.31, 130.03, 963.39, 665.00, 797.78, 645.99,
133.33, 4385.96) # $/ AF
irrig.scaled <- (irrig.cost.Bay.Area-
min(irrig.cost.Bay.Area))/(max(irrig.cost.Bay.Area)-
min(irrig.cost.Bay.Area))
```

```
irrig.scaled2 <- (irrig.cost.Bay.Area-min(irrig.cost.Bay.Area)+
.00001)/(max(irrig.cost.Bay.Area)) # this one worked, because it couldn't be
at 0

sort (irrig.scaled2)

irrig.beta.fit<- fitdistr (irrig.scaled2, "beta", start = list(shape1=2,
shape2=5), control=list(trace=1, REPORT=1))
str(irrig.beta.fit)
irrig.beta.fit$estimate [1]
irrig.beta <- rbeta(10000, irrig.beta.fit$estimate [1],
irrig.beta.fit$estimate [2])

irrig.descaled<- irrig.beta* max(irrig.cost.Bay.Area)+
min(irrig.cost.Bay.Area)

recycle.irrig.cost.par1<- irrig.beta.fit$estimate [1] # these are the beta
parameters, but scaled 0-1
recycle.irrig.cost.par2<- irrig.beta.fit$estimate [2]

irrig.quant <- qbeta(c(.1, .9), 0.31317989, 1.16505723)
irrig.quant.descaled<- irrig.quant* max(irrig.cost.Bay.Area)+
min(irrig.cost.Bay.Area)
irrig.quant.descaled[1]

recycle.irrig.cost.quant10 <- ((sum(recycle.irrig.amount)
                                 * irrig.quant.descaled[1]) # $/AF/year
                               * 3.06888785 * 365 * 30) # final unit is $

recycle.irrig.cost.quant90 <- ((sum(recycle.irrig.amount)
                                 * irrig.quant.descaled[2]) # $/AF/year
                               * 3.06888785 * 365 * 30) # final unit is $

# recycle.irrig.CO2
recycle.irrig.CO2.par1 <- .8 * recycle.irrig.CO2
recycle.irrig.CO2.par2 <- 1.2 * recycle.irrig.CO2

# recycle.irrig.habitat
recycle.irrig.habitat.par1<- recycle.irrig.habitat
recycle.irrig.habitat.par2<- recycle.irrig.habitat

#recycle.irrig.supply
recycle.irrig.supply.par1<- .8 * recycle.irrig.supply
recycle.irrig.supply.par2<- 1.2 * recycle.irrig.supply

#recycle.irrig.n.recovery
recycle.irrig.n.recovery.par1<- .8 * recycle.irrig.n.recovery
recycle.irrig.n.recovery.par2<- 1.2 * recycle.irrig.n.recovery

#recycle.irrig.adapt
recycle.irrig.adapt.par1<- 30
recycle.irrig.adapt.par2 <- 60

#recycle.irrig.slr
recycle.irrig.slr.par1<- recycle.irrig.slr
recycle.irrig.slr.par2<- recycle.irrig.slr
```

```
#recycle.irrig.ease.of.use
recycle.irrig.ease.of.use.par1<- recycle.irrig.ease.of.use
recycle.irrig.ease.of.use.par2<- recycle.irrig.ease.of.use

#recycle.irrig.access
recycle.irrig.access.par1<- recycle.irrig.access
recycle.irrig.access.par2<- recycle.irrig.access

#recycle.irrig.permit
recycle.irrig.permit.par1 <- 65
recycle.irrig.permit.par2 <- 95

# recycle.brineline
#################

#recycle.brineline.load.change
recycle.brineline.load.change.par1 <- .8 * recycle.brineline.load.change
recycle.brineline.load.change.par2 <- 1.2 * recycle.brineline.load.change

#recycle.brineline.wq
recycle.brineline.wq.par1<- .8 * wq.par[5]
recycle.brineline.wq.par2<- 1.2 * wq.par[5]

#recycle.brineline.CEC
recycle.brineline.CEC.par1<- .8 * recycle.brineline.CEC
recycle.brineline.CEC.par2<- 1.2 * recycle.brineline.CEC

#recycle.brineline.reliable
recycle.brineline.reliable.par1 <- recycle.brineline.reliable
recycle.brineline.reliable.par2 <- .01 * recycle.brineline.reliable

pumping.energy <- ((1/2655220) # kwh/ft-lbs of lift assume weight of brine =
weight of water
                   * recycle.brine #units is MGD
                   * 2000 # ft, height over the peninsula
                   * (8.34 * 10^6) *365 / 1000) # final unit is Mwh/year
pumping.energy.CO2 <- (pumping.energy * 320896  # unit here after
multiplication is g CO2 e/ million gallons (conversion from
west.berkeley.edu)
                       * recycle.brine / (10^6) * 365) # final unit is tonnes
CO2 e/year, g/tonne, days/year

pumping.energy.low <- ((1/2655220) # kwh/ft-lbs of lift assume weight of
brine = weight of water
                       * recycle.brine #units is MGD
                       * 1500 # ft, height over the peninsula
                       * (8.34 * 10^6) *365 / 1000) # final unit is Mwh/year
pumping.energy.CO2.low <- (pumping.energy.low * 320896  # unit here after
multiplication is g CO2 e/ million gallons (conversion from
west.berkeley.edu)
                           * recycle.brine / (10^6) * 365) # final unit is
tonnes CO2 e/year, g/tonne, days/year

pumping.energy.high <- ((1/2655220) # kwh/ft-lbs of lift assume weight of
brine = weight of water
                        * recycle.brine #units is MGD
                        * 2500 # ft, height over the peninsula
```

```
                         * (8.34 * 10^6) *365 / 1000) # final unit is Mwh/year
pumping.energy.CO2.high <- (pumping.energy.high * 320896    # unit here after
multiplication is g CO2 e/ million gallons (conversion from
west.berkeley.edu)
                             * recycle.brine / (10^6) * 365) # final unit is
tonnes CO2 e/year, g/tonne, days/year
pumping.energy.CO2.high/pumping.energy.CO2
pumping.energy.CO2.low/pumping.energy.CO2
#...so +/- 25 %

# pipe length isn't a huge CO2 contributer here...mostly pumping energy
pipe.length <- 36960 # ft across peninsula (roughly Millbrae to Pacifica)
pipe.CO2 <- (pipe.length * 358  # unit here after multiplication is g CO2 e/
million gallons (conversion from west.berkeley.edu)
             * recycle.brine / (10^6) * 365) #final unit is tonnes CO2
e/year, g/tonne, days/year
pumping.CO2 <- pumping.energy.CO2 + pipe.CO2 # unit is tonnes CO2e/year

pipe.length.low <- 5* 5280 # ft across peninsula (roughly Millbrae to
Pacifica)
pipe.CO2.low <- (pipe.length.low * 358  # unit here after multiplication is g
CO2 e/ million gallons (conversion from west.berkeley.edu)
                 * recycle.brine / (10^6) * 365) #final unit is tonnes CO2
e/year, g/tonne, days/year
pumping.CO2.low <- pumping.energy.CO2 + pipe.CO2.low # unit is tonnes
CO2e/year

pipe.length.high <- 18* 5280 # ft across peninsula (roughly Millbrae to
Pacifica)
pipe.CO2.high <- (pipe.length.high * 358    # unit here after multiplication
is g CO2 e/ million gallons (conversion from west.berkeley.edu)
                  * recycle.brine / (10^6) * 365) #final unit is tonnes CO2
e/year, g/tonne, days/year
pumping.CO2.high <- pumping.energy.CO2 + pipe.CO2.high # unit is tonnes
CO2e/year

#recycle.brineline.CO2: model with +/- 25%
recycle.brineline.CO2.par1 <- .75 * recycle.brineline.CO2
recycle.brineline.CO2.par2 <- 1.25 * recycle.brineline.CO2

pumping.cost <- ((1/2655220) # kwh/ft-lbs of lift assume weight of brine =
weight of water
                 * 0.2 # $/kwh for energy
                 * recycle.brine #units is MGD
                 * 2000 # ft, height over the peninsula
                 * (8.34 * 10^6) *365*30) # final unit is $ for 30 years,
pounds/million gallons, days/year, years
pumping.cost.low <- ((1/2655220) # kwh/ft-lbs of lift assume weight of brine
= weight of water
                     * 0.05 # $/kwh for energy
                     * recycle.brine #units is MGD
                     * 1500 # ft, height over the peninsula
                     * (8.34 * 10^6) *365*30) # final unit is $ for 30 years,
pounds/million gallons, days/year, years
pumping.cost.high <- ((1/2655220) # kwh/ft-lbs of lift assume weight of brine
= weight of water
                      * 0.3 # $/kwh for energy
```

```
                      * recycle.brine #units is MGD
                      * 2500 # ft, height over the peninsula
                      * (8.34 * 10^6) *365*30) # final unit is $ for 30
years, pounds/million gallons, days/year, years
pumping.cost.low/pumping.cost
pumping.cost.high/pumping.cost
#...more than 85% differences based on height and price of energy
recycle.brineline.cost <- ((sum(recycle.ipr) * 3.06888785 * 365 # AF/million
gallons, days/year
                            * (700 + mean(c( 120, 750, 1250)))) # $/AF,
advanced treatment plus conveyance to drinking water
                           + (sum(recycle.dpr) * 3.06888785 * 365 #
AF/million gallons, days/year
                              * (700 + 120)) # $/AF, advanced treatment plus
conveyance to drinking water
                           + (recycle.brine * 115 * 3.06888785 * 365 ) #
final unit is $/AF, cost of pipe for amount of water, AF/million gallons,
days/year
                           + 2000000 * (pipe.length/5280) # cost of brineline
pipe per distance, ft/mile
                           +  pumping.cost) # final unit is $
recycle.brineline.cost.low <- ((sum(recycle.ipr) * 3.06888785 * 365 #
AF/million gallons, days/year
                                * (700 + 120)) # $/AF, advanced treatment
plus conveyance to drinking water
                               + (sum(recycle.dpr) * 3.06888785 * 365 #
AF/million gallons, days/year
                                  * (700 + 120)) # $/AF, advanced treatment
plus conveyance to drinking water
                               + (recycle.brine * 115 * 3.06888785 * 365 ) #
final unit is $/AF, cost of pipe for amount of water, AF/million gallons,
days/year
                               + 2000000 * (pipe.length.low/5280) # cost of
brineline pipe per distance, ft/mile
                               +  pumping.cost.low) # final unit is $
recycle.brineline.cost.high <- ((sum(recycle.ipr) * 3.06888785 * 365 #
AF/million gallons, days/year
                                 * (700 + 1250)) # $/AF, advanced treatment
plus conveyance to drinking water
                                + (sum(recycle.dpr) * 3.06888785 * 365 #
AF/million gallons, days/year
                                   * (700 + 120)) # $/AF, advanced treatment
plus conveyance to drinking water
                                + (recycle.brine * 115 * 3.06888785 * 365 ) #
final unit is $/AF, cost of pipe for amount of water, AF/million gallons,
days/year
                                + 2000000 * (pipe.length.high/5280) # cost of
brineline pipe per distance, ft/mile
                                +  pumping.cost.high) # final unit is $
recycle.brineline.cost.low/recycle.brineline.cost
recycle.brineline.cost.high/recycle.brineline.cost

#recycle.brineline.cost
recycle.brineline.cost.par1 <- .35 * recycle.brineline.cost
recycle.brineline.cost.par2 <- 1.7 * recycle.brineline.cost

#recycle.brineline.habitat
```

```
recycle.brineline.habitat.par1<- recycle.brineline.habitat
recycle.brineline.habitat.par2<- recycle.brineline.habitat

#recycle.brineline.supply
recycle.brineline.supply.par1 <- .8 * recycle.brineline.supply
recycle.brineline.supply.par2 <- 1.2 * recycle.brineline.supply

#recycle.brineline.n.recovery
recycle.brineline.n.recovery.par1<- recycle.brineline.n.recovery
recycle.brineline.n.recovery.par2<- recycle.brineline.n.recovery

#recycle.brineline.adapt
recycle.brineline.adapt.par1 <- 30
recycle.brineline.adapt.par2 <- 60

#recycle.brineline.slr
recycle.brineline.slr.par1<- recycle.brineline.slr
recycle.brineline.slr.par2<- recycle.brineline.slr

#recycle.brineline.ease.of.use
recycle.brineline.ease.of.use.par1 <- 30
recycle.brineline.ease.of.use.par2 <- 80

#recycle.brineline.access
recycle.brineline.access.par1<- recycle.brineline.access
recycle.brineline.access.par2<- recycle.brineline.access

#recycle.brineline.permit
recycle.brineline.permit.par1 <- 20
recycle.brineline.permit.par2 <- 70

#urine.early
##########

# proportion of population that is early adopters (tech and ed industries)
Early.adopt <- .039
# grams of N excreted in urine
N.excreted <- 10.5 # g N/person/day
# Proportion of a person's urine recovered by urine source separation
U.recovery.toilet <- .5
# Proportion of N recovered by ion exchange resin
N.recovery.resin <- .9
toilet.use <- .5 # percent of the time that people with urine-separating
toilets use them
population <-  scenario [1] * c(30000, 957000, 22850, 217330, 1498700, 0.5 *
(143100 + 156500), 10000, 670400, 110000, 148000, 200600) # shown in order of
WWTPs in Discharge.scenario.
names(population)<- colnames(Discharge.scenario[3:13])
urine.early <- Early.adopt * sum(population) + ifelse((scenario
[1])>1,(scenario [1]-1)*(sum(population)/scenario[1]),0) # if population
grows, it's early adopters + whatever population growth. If population
declines, it's just early adopters
urine.early.load <- (urine.early *  N.excreted *  N.recovery.resin *
U.recovery.toilet * toilet.use
                     / 1000 ) # final unit is kg/day, g/kg

# proportion of population that is early adopters (tech and ed industries)
```

```
Early.adopt.low <- .01
# grams of N excreted in urine
N.excreted <- 10.5 # g N/person/day
# Proportion of a person's urine recovered by urine source separation
U.recovery.toilet <- .5
# Proportion of N recovered by ion exchange resin
N.recovery.resin.low <- .8
toilet.use.low <- .4 # percent of the time that people with urine-separating
toilets use them
population <-  scenario [1] * c(30000, 957000, 22850, 217330, 1498700, 0.5 *
(143100 + 156500), 10000, 670400, 110000, 148000, 200600) # shown in order of
WWTPs in Discharge.scenario.
names(population)<- colnames(Discharge.scenario[3:13])
urine.early.low <- Early.adopt.low * sum(population) + ifelse((scenario
[1])>1,(scenario [1]-1)*(sum(population)/scenario[1]),0) # if population
grows, it's early adopters + whatever population growth. If population
declines, it's just early adopters
urine.early.load.low <- (urine.early.low *  N.excreted *
N.recovery.resin.low * U.recovery.toilet * toilet.use.low
                         / 1000 ) # final unit is kg/day, g/kg

# proportion of population that is early adopters (tech and ed industries)
Early.adopt.high <- .10
# grams of N excreted in urine
N.excreted <- 10.5 # g N/person/day
# Proportion of a person's urine recovered by urine source separation
U.recovery.toilet <- .5
# Proportion of N recovered by ion exchange resin
N.recovery.resin.high <- .99
toilet.use.high <- .8 # percent of the time that people with urine-separating
toilets use them
population <-  scenario [1] * c(30000, 957000, 22850, 217330, 1498700, 0.5 *
(143100 + 156500), 10000, 670400, 110000, 148000, 200600) # shown in order of
WWTPs in Discharge.scenario.
names(population)<- colnames(Discharge.scenario[3:13])
urine.early.high <- Early.adopt.high * sum(population) + ifelse((scenario
[1])>1,(scenario [1]-1)*(sum(population)/scenario[1]),0) # if population
grows, it's early adopters + whatever population growth. If population
declines, it's just early adopters
urine.early.load.high <- (urine.early.high *  N.excreted *
N.recovery.resin.high * U.recovery.toilet * toilet.use.high
                          / 1000 ) # final unit is kg/day, g/kg
urine.early.load.low/urine.early.load
urine.early.load.high/urine.early.load
# vary by - 35% to + 200%, depending on number of early adopters

#urine.early.load.change
urine.early.load.change.par1 <- .65 * urine.early.load.change
urine.early.load.change.par2 <- 2.1 * urine.early.load.change

#urine.early.wq
urine.early.wq.par1<- .8 * wq.par [6]
urine.early.wq.par2<- 1.2 * wq.par [6]

#urine.early.CEC
urine.early.CEC.par1<- do.nothing.CEC.par1 - (2.1 * urine.early.CEC.removal)
urine.early.CEC.par2<- do.nothing.CEC.par2 - (.65 * urine.early.CEC.removal)
```

```
urine.early.cost <- (26 # $/m3 of urine
                     * urine.early * 1.4 # L urine excreted/person/day
                     * toilet.use
                     * 365 * 30 / 1000) # final units is $ over 30 years,
days/year, yrs, L/m3
urine.early.cost.low <- (16 # $/m3 of urine
                         * urine.early.low * 1.4 # L urine
excreted/person/day
                         * toilet.use.low
                         * 365 * 30 / 1000) # final units is $ over 30 years,
days/year, yrs, L/m3
urine.early.cost.high <- (30 # $/m3 of urine
                          * urine.early.high * 1.4 # L urine
excreted/person/day
                          * toilet.use.high
                          * 365 * 30 / 1000) # final units is $ over 30
years, days/year, yrs, L/m3
urine.early.cost.low/urine.early.cost
urine.early.cost.high/urine.early.cost
#big variation (-55% - + %220) depending on adoption rates and cost of
treatment (depends most on number of facilities built)
#urine.early.cost
urine.early.cost.par1 <- .45 * urine.early.cost
urine.early.cost.par2 <- 2.2 * urine.early.cost

#urine.early.CO2
# note: the CO2 number is mostly influenced by do.nothing.CO2, only about 1%
by urine
urine.early.CO2.par1 <- .8 * urine.early.CO2
urine.early.CO2.par2 <- 1.2 * urine.early.CO2

#urine.early.habitat
urine.early.habitat.par1<- urine.early.habitat
urine.early.habitat.par2<- urine.early.habitat

#urine.early.supply
urine.early.supply.par1<- urine.early.supply
urine.early.supply.par2<- urine.early.supply

#urine.early.n.recovery
urine.early.n.recovery.par1<- .65* urine.early.n.recovery
urine.early.n.recovery.par2<- 2.1 *urine.early.n.recovery

#urine.early.adapt
urine.early.adapt.par1 <- 75
urine.early.adapt.par2 <- 95

#urine.early.slr
urine.early.slr.par1<- urine.early.slr
urine.early.slr.par2<- urine.early.slr

#urine.early.ease.of.use
urine.early.ease.of.use.par1 <- 15
urine.early.ease.of.use.par2 <- 50

#urine.early.reliable
```

```
urine.early.reliable.par1<- .8 * urine.early.reliable
urine.early.reliable.par2<- 1.2 * urine.early.reliable

#urine.early.access
urine.early.access.par1<- urine.early.access
urine.early.access.par2<- urine.early.access

#urine.early.permit
urine.early.permit.par1 <- 20
urine.early.permit.par2 <- 70

#urine.incentives
###############

urine.incentives <- (0.3 * sum(population)) + ifelse((scenario
[1])>1,(scenario [1]-1)*(sum(population)/scenario[1]),0) # 30% of current
population + all population growth
urine.incentives.low <- .8 * urine.incentives
urine.incentives.high <- 1.4 * urine.incentives
#urine.incentives.load = kg TN/day removed by urine source separation
toilet.use.incentives <- .75 # percent of the time that people with urine-
separating toilets use them
urine.incentives.load <- (urine.incentives *  N.excreted *  N.recovery.resin
* U.recovery.toilet * toilet.use.incentives
                         / 1000 ) # final unit is kg/day, g/kg

#urine.incentives.load.change
urine.incentives.load.change.par1 <- .8 * urine.incentives.load.change
urine.incentives.load.change.par2 <- 1.4 * urine.incentives.load.change

#urine.incentives.wq
urine.incentives.wq.par1 <- .8 * wq.par [7]
urine.incentives.wq.par2 <- 1.2 * wq.par [7]

#urine.incentives.CEC
urine.incentives.CEC.par1<- do.nothing.CEC.par1 - (1.4 *
urine.incentives.CEC.removal)
urine.incentives.CEC.par2<- do.nothing.CEC.par2 - (.8 *
urine.incentives.CEC.removal)

#urine.incentives.reliable
urine.incentives.reliable.par1<- .8 * urine.incentives.reliable
urine.incentives.reliable.par2<- 1.2 * urine.incentives.reliable

incentive1.low <- 500 # initial retrofit incentive
incentive2.low <- (1 * 52 * 30) #  weekly reward for turning in cartridge for
30 year lifecycle, $ reward, weeks/year, years
#household <- 2.7
outreach.low <- 100000 * 11 # 11 is number of participating utilities
urine.incentives.cost.low <- (((16 # $/m3 of urine
                                * urine.incentives.low * 1.4 # L urine
excreted/person/day
                                * toilet.use.incentives
                                * 365 * 30 / 1000) # final units is $ over 30
years, days/year, yrs, L/m3
```

```
                              + (incentive1.low * (0.3 *
(sum(population)/scenario[1]) / household )) # $/household to install toilet
for all existing population
                              + (incentive2.low *
urine.incentives.low/household) # people per household, initial incentive
only for retrofits, not new housing stock
                              + outreach.low)) # final unit is $

incentive1.high <- 4000 # initial retrofit incentive
incentive2.high <- (4 * 52 * 30) #  weekly reward for turning in cartridge
for 30 year lifecycle, $ reward, weeks/year, years
#household <- 2.7
outreach.high <- 400000 * 11 # 11 is number of participating utilities
urine.incentives.cost.high <- (((30 # $/m3 of urine
                                * urine.incentives.high * 1.4 # L urine
excreted/person/day
                                * toilet.use.incentives
                                * 365 * 30 / 1000) # final units is $ over
30 years, days/year, yrs, L/m3
                               + (incentive1.high * (0.3 *
(sum(population)/scenario[1]) / household )) # $/household to install toilet
for all existing population
                               + (incentive2.high *
urine.incentives.high/household) # people per household, initial incentive
only for retrofits, not new housing stock
                               + outreach.high)) # final unit is $
urine.incentives.cost.low/urine.incentives.cost
urine.incentives.cost.high/urine.incentives.cost

#cost
urine.incentives.cost.par1<- .35 * urine.incentives.cost
urine.incentives.cost.par2<-2.4 * urine.incentives.cost

#urine.incentives.CO2
#again, these variables have very small affect on the outcomes
urine.incentives.CO2.par1<- .8 * urine.incentives.CO2
urine.incentives.CO2.par2<- 1.2 * urine.incentives.CO2

#urine.incentives.habitat
urine.incentives.habitat.par1<- urine.incentives.habitat
urine.incentives.habitat.par2<- urine.incentives.habitat

#urine.incentives.supply
urine.incentives.supply.par1<- urine.incentives.supply
urine.incentives.supply.par2<-urine.incentives.supply

#urine.incentives.n.recovery
urine.incentives.n.recovery.par1<- .8 * urine.incentives.n.recovery
urine.incentives.n.recovery.par2<- 1.5 * urine.incentives.n.recovery

#urine.incentives.adapt
urine.incentives.adapt.par1<- 45
urine.incentives.adapt.par2<-65

#urine.incentives.slr
urine.incentives.slr.par1<- urine.incentives.slr
urine.incentives.slr.par2 <- urine.incentives.slr
```

```
#urine.incentives.ease.of.use
urine.incentives.ease.of.use.par1<- 25
urine.incentives.ease.of.use.par2<- 45

#urine.incentives.access
urine.incentives.access.par1<- urine.incentives.access
urine.incentives.access.par2<- urine.incentives.access

#urine.incentives.permit
urine.incentives.permit.par1<- 30
urine.incentives.permit.par2<- 50

# opt
####

#opt.load
# assuming optimization removes 10%, final unit is kg/day
opt.load.change.par1<- opt.load.change
opt.load.change.par2<- abs(.1 * opt.load.change)

#opt.wq
opt.wq.par1<- .8 * wq.par[8]
opt.wq.par2<- 1.2 * wq.par[8]

#opt.CEC
opt.CEC.par1<- .8 * opt.CEC
opt.CEC.par2<- 1.2 * opt.CEC

#opt.cost
opt.cost.par1<- opt.cost
opt.cost.par2<- .1 * opt.cost

#opt.CO2
opt.CO2.par1<- opt.CO2
opt.CO2.par2<- opt.CO2

#opt.habitat
opt.habitat.par1<- opt.habitat
opt.habitat.par2<- opt.habitat

#opt.supply
opt.supply.par1<- opt.supply
opt.supply.par2<- opt.supply

#opt.n.recovery
opt.n.recovery.par1<- opt.n.recovery
opt.n.recovery.par2<- opt.n.recovery

#opt.adapt
opt.adapt.par1<- 60
opt.adapt.par2<- 90

#opt.slr
opt.slr.par1<- opt.slr
opt.slr.par2<- opt.slr
```

```
#opt.ease.of.use
opt.ease.of.use.par1<- opt.ease.of.use
opt.ease.of.use.par2<- opt.ease.of.use

#opt.access
opt.access.par1<- opt.access
opt.access.par2<- opt.access

#opt.permit
opt.permit.par1<- 80
opt.permit.par2<- 100

#opt.reliable
opt.reliable.par1<- opt.reliable
opt.reliable.par2<- .01 * opt.reliable

# Level2
########

#Level2.load
Level2.load.change.par1<- Level2.load.change
Level2.load.change.par2<- abs(.1 * Level2.load.change)

#Level2.wq
Level2.wq.par1<- .8 * wq.par[9]
Level2.wq.par2<- 1.2 * wq.par[9]

#Level2.CEC
# assumes no additional removal from plants that already have tertiary
treatment
Level2.CEC.par1<- .8 * Level2.CEC
Level2.CEC.par2<- 1.2 * Level2.CEC

#Level2.cost
Level2.cost.par1<- Level2.cost
Level2.cost.par2<- .1 * Level2.cost

#Level2.reliable
Level2.reliable.par1<- Level2.reliable
Level2.reliable.par2<- .01 * Level2.reliable

#Level2.CO2
Level2.CO2.par1<- .8 * Level2.CO2
Level2.CO2.par2<- 1.2 * Level2.CO2

#Level2.habitat
Level2.habitat.par1<- Level2.habitat
Level2.habitat.par2<- Level2.habitat

#Level2.supply
Level2.supply.par1<- Level2.supply
Level2.supply.par2<- Level2.supply

#Level2.n.recovery
Level2.n.recovery.par1<- Level2.n.recovery
Level2.n.recovery.par2<- Level2.n.recovery
```

```
#Level2.adapt
Level2.adapt.par1<- 30
Level2.adapt.par2<- 75

#Level2.slr
Level2.slr.par1<- Level2.slr
Level2.slr.par2<- Level2.slr

#Level2.ease.of.use
Level2.ease.of.use.par1<- Level2.ease.of.use
Level2.ease.of.use.par2<- Level2.ease.of.use

#Level2.access
Level2.access.par1<- Level2.access
Level2.access.par2<- Level2.access

#Level2.permit
Level2.permit.par1<- 80
Level2.permit.par2<- 100

# Level3
########


#Level3.load
Level3.load.change.par1<- Level3.load.change
Level3.load.change.par2<- abs(.1 * Level3.load.change)

#Level3.wq
Level3.wq.par1<- .8 * wq.par[10]
Level3.wq.par2<- 1.2 * wq.par[10]

#Level3.CEC
Level3.CEC.par1<- .8 * Level3.CEC
Level3.CEC.par2<- 1.2 * Level3.CEC

#Level3.cost
Level3.cost.par1<- Level3.cost
Level3.cost.par2<- .1 * Level3.cost

#Level3.reliable
Level3.reliable.par1<- Level3.reliable
Level3.reliable.par2<- .01 * Level3.reliable

#Level3.CO2
Level3.CO2.par1<- .8 * Level3.CO2
Level3.CO2.par2<- 1.2 * Level3.CO2

#Level3.habitat
Level3.habitat.par1<- Level3.habitat
Level3.habitat.par2<- Level3.habitat

#Level3.supply
Level3.supply.par1<- Level3.supply
Level3.supply.par2<- Level3.supply

#Level3.n.recovery
```

```
Level3.n.recovery.par1<- Level3.n.recovery
Level3.n.recovery.par2<- Level3.n.recovery

#Level3.adapt
Level3.adapt.par1<- 5
Level3.adapt.par2<- 15

#Level3.slr
Level3.slr.par1<- Level3.slr
Level3.slr.par2<- Level3.slr

#Level3.ease.of.use
Level3.ease.of.use.par1<- Level3.ease.of.use
Level3.ease.of.use.par2<- Level3.ease.of.use

#Level3.access
Level3.access.par1<- Level3.access
Level3.access.par2<- Level3.access

#Level3.permit
Level3.permit.par1<- 80
Level3.permit.par2<- 100

######Parameter 1--create master dataframe with all par.1 values
par.1.test<-ls(globalenv())[grepl(".par1",ls(globalenv()))]

par.1.master<-cbind(
  mget(par.1.test[grepl("wq", par.1.test)]),
  mget(par.1.test[grepl("habitat", par.1.test)]),
  mget(par.1.test[grepl("supply", par.1.test)]),
  mget(par.1.test[grepl("recovery", par.1.test)]),
  mget(par.1.test[grepl("CEC.par", par.1.test)]),
  mget(par.1.test[grepl("adapt", par.1.test)]),
  mget(par.1.test[grepl("slr", par.1.test)]),
  mget(par.1.test[grepl("CO2", par.1.test)]),
  mget(par.1.test[grepl("ease.of", par.1.test)]),
  mget(par.1.test[grepl("access", par.1.test)]),
  mget(par.1.test[grepl("permit", par.1.test)]),
  mget(par.1.test[grepl("reliable", par.1.test)]),
  mget(par.1.test[grepl("cost.par", par.1.test)]))
par.1.master<-par.1.master[c(1,9,10,6,5,7,8,4,2,3),]
colnames(par.1.master)<-criteria
rownames(par.1.master)<-options
par.1.master[1,1]

######Parameter 2--create master dataframe with all par.2 values
par.2.test<-ls(globalenv())[grepl(".par2",ls(globalenv()))]
par.2.master<-cbind(
  mget(par.2.test[grepl("wq", par.2.test)]),
  mget(par.2.test[grepl("habitat", par.2.test)]),
  mget(par.2.test[grepl("supply", par.2.test)]),
  mget(par.2.test[grepl("recovery", par.2.test)]),
  mget(par.2.test[grepl("CEC.par", par.2.test)]),
  mget(par.2.test[grepl("adapt", par.2.test)]),
  mget(par.2.test[grepl("slr", par.2.test)]),
  mget(par.2.test[grepl("CO2", par.2.test)]),
  mget(par.2.test[grepl("ease.of", par.2.test)]),
```

```
  mget(par.2.test[grepl("access", par.2.test)]),
  mget(par.2.test[grepl("permit", par.2.test)]),
  mget(par.2.test[grepl("reliable", par.2.test)]),
  mget(par.2.test[grepl("cost.par", par.2.test)]))
par.2.master<-par.2.master[c(1,9,10,6,5,7,8,4,2,3),]
colnames(par.2.master)<-criteria
rownames(par.2.master)<-options
par.2.master

# for beta distribution, scalars
################################

Max_scalar_beta<- data.frame(matrix(nrow = 10, ncol = 13))
rownames(Max_scalar_beta)<- options
colnames(Max_scalar_beta)<- criteria

Min_scalar_beta<- data.frame(matrix(nrow = 10, ncol = 13))
rownames(Min_scalar_beta)<- options
colnames(Min_scalar_beta)<- criteria

Max_scalar_beta[4,13]<- ((sum(recycle.irrig.amount)
                          * max(irrig.cost.Bay.Area)) # $/AF/year
                         * 3.06888785 * 365 * 30)

Min_scalar_beta[4,13]<- ((sum(recycle.irrig.amount)
                          * min(irrig.cost.Bay.Area)) # $/AF/year
                         * 3.06888785 * 365 * 30)

#making data sheet from parameters
csv.columns <-c("Scenario", "Criteria", "Code_name",    "Unit",
"Distribution", "Parameter1",   "Parameter2",   "Max_scalar_beta",
"Min_scalar_beta",  "Alt_sample",   "Best", "Worst",    "Description")
master.csv <- data.frame (matrix(ncol=13, nrow=13))
colnames (master.csv) <- csv.columns

best <- c(5,    5200,   190.1,  8500000,    22, 100,    10, 180000, 100,
17, 100,    99, 0)
worst <- c(95,  0,  22, 0,  137,    0,  -10,    900000, 0,  0,  0,  50,
8000000000)

master.csv[,2]<- criteria
master.csv[,3]<- criteria
master.csv[,4]<- c( "%",    "hectares", "MGD",  "kg/year",  "kg/year",  "%",
"scale_constr", "tonnes CO2 eq/year",   "%",    "Integer",  "%",    "%",
"$")
master.csv [, 11] <- best
master.csv[,12]<- worst

master.csv

csv.list<-list(NULL)
for(i in 1:10){
  csv.list[[i]]<-master.csv
}
names(csv.list)<-options
csv.list
```

```
for (j in 1:10){

  for(i in 1:13){
    csv.list[[j]][i,1] <- paste("pop=", scenario[1], ",", "SeaLev=",
scenario[2], "Threshold=", scenario[3])
    csv.list[[j]][i,10]<- criteria.calcs[j,i] # this fills in Alt_sample
    csv.list[[j]][i,6]<- par.1.master[j,i]
    csv.list[[j]][i,7]<- par.2.master[j,i]
    csv.list[[j]][i,5]<- as.character(uncertainty.distributions[i,j])
    csv.list[[j]][i,8]<- Max_scalar_beta[j,i]
    csv.list[[j]][i,9]<- Min_scalar_beta[j,i]
  }
}
csv.list
```

Do a Monte-Carlo style simulation of uncertainty of all the parameters.

```
n <- 1000 #number of runs
column.x<-NULL
option.sample <- data.frame(matrix(NA, nrow = n, ncol = 14))
option.list <-  NULL
boundary.min <- 0
boundary.max <- 0
out.of.bounds.min<-data.frame(matrix(ncol=3))
out.of.bounds.max<-data.frame(matrix(ncol=3))

a.matrix.names <- c("a", criteria)
colnames(option.sample) <- a.matrix.names

for(j in 1:10){# 10 is number of options in the list

  for (i in 1:13){# 13 is number of criteria
    # column.x is to keep everything within the range of best and worst
    # This loop runs an 'n' numbered sample from truncated normal
distribution if "Normal", otherwise a sample from a uniform distribution
    #Parameters are mean and SD for normal distribution, min and max for
uniform distribution. If 'Determined', min = max in uniform

    column.x<-{
      if(csv.list [[j]]$Distribution[i] == "Normal") rtruncnorm(n, a =
min(c(csv.list[[j]]$Best[i],csv.list[[j]]$Worst[i])), b =
max(c(csv.list[[j]]$Best[i],csv.list[[j]]$Worst[i])), mean =
as.numeric(csv.list[[j]]$Parameter1[i]), sd = as.numeric(csv.list
[[j]]$Parameter2[i]))
    else if (csv.list [[j]]$Distribution[i] == "Minmax") runif(n, min =
min(c(as.numeric(csv.list[[j]]$Parameter1[i]),
as.numeric(csv.list[[j]]$Parameter2[i]))), max =
max(c(as.numeric(csv.list[[j]]$Parameter1[i]),
as.numeric(csv.list[[j]]$Parameter2[i]))))
    else if (csv.list [[j]]$Distribution[i] == "Determined") csv.list
[[j]]$Alt_sample [i]
    else if (csv.list [[j]]$Distribution[i] == "Beta") rbeta(n,csv.list
[[j]]$Parameter1[i], csv.list [[j]]$Parameter2[i])*csv.list
[[j]]$Max_scalar_beta[i] + csv.list [[j]]$Min_scalar_beta[i]
    }
```

```
      min.x<-min(c(csv.list [[j]]$Best[i],csv.list [[j]]$Worst[i]))
    max.x<-max(c(csv.list [[j]]$Best[i],csv.list [[j]]$Worst[i]))

    column.x[column.x<min.x]<-csv.list[[j]]$Alt_sample[i]
    column.x[column.x>max.x]<-csv.list[[j]]$Alt_sample[i]

   boundary.min <- boundary.min + sum(column.x<min.x)
   boundary.max <- boundary.max + sum(column.x > max.x)
   out.of.bounds.min[(j-1)*13+i,] <- c(sum(column.x<min.x), options[j],
criteria[i])
   out.of.bounds.max[(j-1)*13+i,] <- c(sum(column.x>max.x), options[j],
criteria[i])


    option.sample[,i+1]<-column.x
    option.sample[,1]<-rep(options[j],n)

  }

  option.list[[j]] <- option.sample
}

table(round(option.list[[2]]$access))
names(option.list) <- options

str(option.list)

out.of.bounds.max[out.of.bounds.max[,1]>0,]
out.of.bounds.min[out.of.bounds.min[,1]>0,]

boundary.max
boundary.min

#option list without recycle.brineline
option.list.no.brine<- option.list[c(1:4,6:10)]
str(option.list.no.brine)
```

Make tables of all the attribute values.

```
attr.table<- rbind(apply(data.frame(lapply(option.list.no.brine, `[`, 2)), 2,
mean),
apply(data.frame(lapply(option.list.no.brine, `[`, 3)), 2, mean),
apply(data.frame(lapply(option.list.no.brine, `[`, 4)), 2, mean),
apply(data.frame(lapply(option.list.no.brine, `[`, 5)), 2, mean),
apply(data.frame(lapply(option.list.no.brine, `[`, 6)), 2, mean),
apply(data.frame(lapply(option.list.no.brine, `[`, 7)), 2, mean),
apply(data.frame(lapply(option.list.no.brine, `[`, 8)), 2, mean),
apply(data.frame(lapply(option.list.no.brine, `[`, 9)), 2, mean),
apply(data.frame(lapply(option.list.no.brine, `[`, 10)), 2, mean),
apply(data.frame(lapply(option.list.no.brine, `[`, 11)), 2, mean),
apply(data.frame(lapply(option.list.no.brine, `[`, 12)), 2, mean),
apply(data.frame(lapply(option.list.no.brine, `[`, 13)), 2, mean),
apply(data.frame(lapply(option.list.no.brine, `[`, 14)), 2, mean))
rownames(attr.table)<-criteria
colnames(attr.table) <- options.no.brine
```

```
head(attr.table)

#table of mean attribute values with units and brine option
###########################################################
attr.table.complete<- rbind(apply(data.frame(lapply(option.list, `[`, 2)), 2,
mean),
                   apply(data.frame(lapply(option.list, `[`, 3)), 2, mean),
                   apply(data.frame(lapply(option.list, `[`, 4)), 2, mean),
                   apply(data.frame(lapply(option.list, `[`, 5)), 2, mean),
                   apply(data.frame(lapply(option.list, `[`, 6)), 2, mean),
                   apply(data.frame(lapply(option.list, `[`, 7)), 2, mean),
                   apply(data.frame(lapply(option.list, `[`, 8)), 2, mean),
                   apply(data.frame(lapply(option.list, `[`, 9)), 2, mean),
                   apply(data.frame(lapply(option.list, `[`, 10)), 2, mean),
                   apply(data.frame(lapply(option.list, `[`, 11)), 2, mean),
                   apply(data.frame(lapply(option.list, `[`, 12)), 2, mean),
                   apply(data.frame(lapply(option.list, `[`, 13)), 2, mean),
                   apply(data.frame(lapply(option.list, `[`, 14)), 2, mean))
rownames(attr.table.complete)<-criteria
colnames(attr.table.complete) <- options
units.df <- c("% likelihood deviation", "square hectares", "MGD", "Kg
N/year", "Kg SMX/year", "% ease of adaptation", "scale -10 to 10", "CO2
eq/year", "% ease of use", "Number of access points", "% ease of permitting",
"% of time reliable", "Total present value (30 year life span)")
attr.table.complete.w.units<-data.frame(cbind(units = units.df,
attr.table.complete))
rownames(attr.table.complete.w.units)<-NULL
colnames(attr.table.complete.w.units)<-NULL


attr.table.final<-data.frame(matrix(ncol = 11))
for(i in 2:11){
  attr.table.final[1:13,i]<-
signif(as.numeric(as.character(attr.table.complete.w.units[,i])), digits = 3)

}

attr.table.final[,1]<-units.df
rownames(attr.table.final)  <- criteria
colnames(attr.table.final) <- c("units", options)


head(attr.table.final)
```

Plot the uncertainty distributions of attribute values for each of the objectives.

```
#plot attribute values for each criteria

par(mfrow=c(1,1),
    mar = c(2,2,2,2),
    oma = c(4,2,2,2),
    cex.lab = .8)

#wq
boxplot(data.frame(lapply(option.list.no.brine, `[`, 2)), names =
options.no.brine,
```

```
        main = "% likelihood of deviating from good water quality",
        ylim = c(100,0))
mtext(paste("Population change =", "", scenario [1]), side = 1, line = 2, cex
= 0.6)
mtext(paste("Climate effect =", "", scenario [2]), side = 1, line = 3, cex =
0.6)
mtext(paste("Ecological threshold =", "", scenario [3]), side = 1, line = 4,
cex = 0.6)

#hab
boxplot(data.frame(lapply(option.list.no.brine, `[`, 3)), names =
options.no.brine,
        main = "Hectares of wetland area created")
mtext(paste("Population change =", "", scenario [1]), side = 1, line = 2, cex
= 0.6)
mtext(paste("Climate effect =", "", scenario [2]), side = 1, line = 3, cex =
0.6)
mtext(paste("Ecological threshold =", "", scenario [3]), side = 1, line = 4,
cex = 0.6)

#supply
boxplot(data.frame(lapply(option.list.no.brine, `[`, 4)), names =
options.no.brine,
        main = "MGD of useable water supplied")
mtext(paste("Population change =", "", scenario [1]), side = 1, line = 2, cex
= 0.6)
mtext(paste("Climate effect =", "", scenario [2]), side = 1, line = 3, cex =
0.6)
mtext(paste("Ecological threshold =", "", scenario [3]), side = 1, line = 4,
cex = 0.6)

#recovery
boxplot(data.frame(lapply(option.list.no.brine, `[`, 5)), names =
options.no.brine,
        main = "Kg/year of nitrogen recovered for fertilizer")
mtext(paste("Population change =", "", scenario [1]), side = 1, line = 2, cex
= 0.6)
mtext(paste("Climate effect =", "", scenario [2]), side = 1, line = 3, cex =
0.6)
mtext(paste("Ecological threshold =", "", scenario [3]), side = 1, line = 4,
cex = 0.6)

#CEC
boxplot(data.frame(lapply(option.list.no.brine, `[`, 6)), names =
options.no.brine,
        main = "Kg/year total sulfamethoxazole loading to southern reach of
Bay")
mtext(paste("Population change =", "", scenario [1]), side = 1, line = 2, cex
= 0.6)
mtext(paste("Climate effect =", "", scenario [2]), side = 1, line = 3, cex =
0.6)
mtext(paste("Ecological threshold =", "", scenario [3]), side = 1, line = 4,
cex = 0.6)

#ADAPT
boxplot(data.frame(lapply(option.list.no.brine, `[`, 7)), names =
options.no.brine,
```

```
        main = "% Ease of adaptation")
mtext(paste("Population change =", "", scenario [1]), side = 1, line = 2, cex
= 0.6)
mtext(paste("Climate effect =", "", scenario [2]), side = 1, line = 3, cex =
0.6)
mtext(paste("Ecological threshold =", "", scenario [3]), side = 1, line = 4,
cex = 0.6)

#SLR
boxplot(data.frame(lapply(option.list.no.brine, `[`, 8)), names =
options.no.brine,
        main = "Resilience to Sea Level Rise (-10 = highly vulnerable, 0  =
unaffected, 10 = protects other infrastructure)", ylim = c(-10, 10))
mtext(paste("Population change =", "", scenario [1]), side = 1, line = 2, cex
= 0.6)
mtext(paste("Climate effect =", "", scenario [2]), side = 1, line = 3, cex =
0.6)
mtext(paste("Ecological threshold =", "", scenario [3]), side = 1, line = 4,
cex = 0.6)

#CO2
boxplot(data.frame(lapply(option.list.no.brine, `[`, 9)), names =
options.no.brine,
        main = "Tonnes CO2 e/year from wastewater treatment")
mtext(paste("Population change =", "", scenario [1]), side = 1, line = 2, cex
= 0.6)
mtext(paste("Climate effect =", "", scenario [2]), side = 1, line = 3, cex =
0.6)
mtext(paste("Ecological threshold =", "", scenario [3]), side = 1, line = 4,
cex = 0.6)

#EASE of USE
boxplot(data.frame(lapply(option.list.no.brine, `[`, 10)), names =
options.no.brine,
        main = "% Ease of use")
mtext(paste("Population change =", "", scenario [1]), side = 1, line = 2, cex
= 0.6)
mtext(paste("Climate effect =", "", scenario [2]), side = 1, line = 3, cex =
0.6)
mtext(paste("Ecological threshold =", "", scenario [3]), side = 1, line = 4,
cex = 0.6)

#ACCESS
boxplot(data.frame(lapply(option.list.no.brine, `[`, 11)), names =
options.no.brine,
        main = "Additional shoreline access points")
mtext(paste("Population change =", "", scenario [1]), side = 1, line = 2, cex
= 0.6)
mtext(paste("Climate effect =", "", scenario [2]), side = 1, line = 3, cex =
0.6)
mtext(paste("Ecological threshold =", "", scenario [3]), side = 1, line = 4,
cex = 0.6)

#PERMIT
boxplot(data.frame(lapply(option.list.no.brine, `[`, 12)), names =
options.no.brine,
        main = "% Ease of permitting")
```

```
mtext(paste("Population change =", "", scenario [1]), side = 1, line = 2, cex
= 0.6)
mtext(paste("Climate effect =", "", scenario [2]), side = 1, line = 3, cex =
0.6)
mtext(paste("Ecological threshold =", "", scenario [3]), side = 1, line = 4,
cex = 0.6)

#RELIABLE
boxplot(data.frame(lapply(option.list.no.brine, `[`, 13)), names =
options.no.brine,
        main = "% of time nutrient control operates as expected")
mtext(paste("Population change =", "", scenario [1]), side = 1, line = 2, cex
= 0.6)
mtext(paste("Climate effect =", "", scenario [2]), side = 1, line = 3, cex =
0.6)
mtext(paste("Ecological threshold =", "", scenario [3]), side = 1, line = 4,
cex = 0.6)

#COSTS
boxplot(data.frame(lapply(option.list.no.brine, `[`, 14)), names =
options.no.brine,
        main = "Costs (30 year net present value)")
mtext(paste("Population change =", "", scenario [1]), side = 1, line = 2, cex
= 0.6)
mtext(paste("Climate effect =", "", scenario [2]), side = 1, line = 3, cex =
0.6)
mtext(paste("Ecological threshold =", "", scenario [3]), side = 1, line = 4,
cex = 0.6)
```

Read stakeholder preferences into R.

```
pref.nutrients <- pref.nutrients.sensitivity
head(pref.nutrients)
class(pref.nutrients$val.SH7)
#SH7
pars.nutrients.SH7 <- pref.nutrients$val.SH7
names(pars.nutrients.SH7) <- pref.nutrients$name
pars.nutrients.SH7
sum(pref.nutrients[1:18,3], na.rm = TRUE)
#SH3
pars.nutrients.SH3 <- pref.nutrients$val.SH3
names(pars.nutrients.SH3) <- pref.nutrients$name
pars.nutrients.SH3
sum(pref.nutrients[1:18,4], na.rm = TRUE)
#SH2
pars.nutrients.SH2 <- pref.nutrients$val.SH2
names(pars.nutrients.SH2) <- pref.nutrients$name
pars.nutrients.SH2
sum(pref.nutrients[1:18,5])
#SH8
pars.nutrients.SH8 <- pref.nutrients$val.SH8
names(pars.nutrients.SH8) <- pref.nutrients$name
pars.nutrients.SH8
sum(pref.nutrients[1:18,6])
#SH5
pars.nutrients.SH5 <- pref.nutrients$val.SH5
```

```
names(pars.nutrients.SH5) <- pref.nutrients$name
pars.nutrients.SH5
sum(pref.nutrients[1:18,7])
#SH1
pars.nutrients.SH1 <- pref.nutrients$val.SH1
names(pars.nutrients.SH1) <- pref.nutrients$name
pars.nutrients.SH1
sum(pref.nutrients[1:18,8])
#SH4
pars.nutrients.SH4 <- pref.nutrients$val.SH4
names(pars.nutrients.SH4) <- pref.nutrients$name
pars.nutrients.SH4
sum(pref.nutrients[1:18,9])
#SH6
pars.nutrients.SH6 <- pref.nutrients$val.SH6
names(pars.nutrients.SH6) <- pref.nutrients$name
pars.nutrients.SH6
sum(pref.nutrients[1:18,10])
#SH9
pars.nutrients.SH9 <- pref.nutrients$val.SH9
names(pars.nutrients.SH9) <- pref.nutrients$name
pars.nutrients.SH9
sum(pref.nutrients[1:18,11])

#vector of stakeholder preferences
SH.pars.nutrients.all<- data.frame(cbind(pars.nutrients.SH1,
pars.nutrients.SH2, pars.nutrients.SH3, pars.nutrients.SH4,
pars.nutrients.SH5, pars.nutrients.SH6, pars.nutrients.SH7,
pars.nutrients.SH8, pars.nutrients.SH9))
SH.pars.nutrients.all[2]

#vector of stakeholder preferences with regular objectives hierarchy
(excluding special cases)
SH.pars.nutrients.normal <- SH.pars.nutrients.all[c(1,2,4:6,8,9)]
```

Plot stakeholder points for each criteria.

```
SH.points <- read.csv("Inputs/Stakeholder points.csv")
SH.points
Criteria.names<- c("Water Quality", "Wetland Habitat", "Water Supply",
"Nutrient Recovery", "CECs",
         "Ease of Adaptation", "Sea Level Rise", "CO2 Emissions", "Ease of
Use",
         "Shoreline Access", "Permitting", "Reliability" ,"Costs")
Criteria.names.main.obj <- c("Ecosystem", "Improve wastewater", "Intergen.
Equity", "Social support", "Low costs")
SH.weights.added.full<- read.csv("Inputs/Stakeholder weights.csv")
SH.weights.added<- SH.weights.added.full [1:9, 17:21]

#plot stakeholder points for each criteria (criteria on x axis, points on y
axis)
par(las=2)
par(mar=c(9,4.1,4.1,2.1))
boxplot(SH.points[,4:16],
```

```
        names= c("Water Quality", "Wetland Habitat", "Water Supply",
"Nutrient Recovery", "CECs",
                 "Ease of Adaptation", "Sea Level Rise", "CO2 Emissions",
"Ease of Use",
                 "Shoreline Access", "Permitting", "Reliability" ,"Costs"))

title("Stakeholder points for improvement of each criteria from worst to best
state", cex.main = 1.5,
      ylab = "Stakeholder Preferences (Points)", cex.lab = 1.5)

boxplot(SH.points[,17:21],
        names = c("Ecosystem", "Improve wastewater", "Intergen. Equity",
"Social support", "Low costs"))
title(" Stakeholder average points of objectives within each category",
cex.main = 1.5,
      ylab = "Stakeholder Preferences (Points)", cex.lab = 1.5)

# show in order from highest to lowest median
SH.medians <- apply(SH.points [, 4:16], 2, median, na.rm = T)
point.orders<-order(SH.medians, decreasing = T)

SH.medians.main.obj <- apply(SH.points [, 17:21], 2, median, na.rm = T)
point.orders.main.obj<-order(SH.medians.main.obj, decreasing = T)

par(las=2)
par(mar=c(9,4.1,4.1,2.1))
boxplot(SH.points[,point.orders+3],
        names= Criteria.names[point.orders])

title("Stakeholder points for improvement of each criteria from worst to best
state", cex.main = 1.5,
      ylab = "Stakeholder Preferences (Points)", cex.lab = 1.5)

#Medians of overarching objective categories

par(las=2)
par(mar=c(9,4.1,4.1,2.1))
boxplot(SH.points[,point.orders.main.obj+16],
        names= Criteria.names.main.obj[point.orders.main.obj])

title("Average stakeholder points for criteria within each category",
cex.main = 1.5,
      ylab = "Stakeholder Preferences (Points)", cex.lab = 1.5)

#create weights from the points
point.sums <- apply(SH.points [,4:16], 1, sum, na.rm = T)
SH.weights <- SH.points [,4:16]/ point.sums
apply(SH.weights, 1, sum, na.rm = T) # check that all rows add to 1

  #and for main objectives
point.sums.main.obj <- apply(SH.points [,17:21], 1, sum, na.rm = T)
SH.weights.main.obj <- SH.points [,17:21]/ point.sums.main.obj
apply(SH.weights.main.obj, 1, sum, na.rm = T)

#plot the weights

par(las=2)
```

```
par(mar=c(9,4.1,4.1,2.1))
boxplot(SH.weights, range = 0,
        names= c("Water Quality", "Wetland Habitat", "Water Supply",
"Nutrient Recovery", "CECs",
                 "Ease of Adaptation", "Sea Level Rise", "CO2 Emissions",
"Ease of Use",
                 "Shoreline Access", "Permitting", "Reliability" ,"Costs"),
cex.lab = 1.5)

title("Average stakeholder weights for improvement of each criteria from
worst to best state", cex.main = 1.5,
      ylab = "Stakeholder Preferences (weights)", cex.lab = 1.5)

  #and for main objectives
par(las=2)
par(mar=c(9,4.1,4.1,2.1))
boxplot(SH.weights.main.obj, range = 0,
        names= Criteria.names.main.obj, cex.lab = 1.5)

title("Average stakeholder weights for criteria within each category",
cex.main = 1.5,
      ylab = "Stakeholder Preferences (weights)", cex.lab = 1.5)

# for added main objectives
boxplot(SH.weights.added, range = 0,
        names= Criteria.names.main.obj, cex.lab = 1.5)
title("Sum of stakeholder weights for criteria in each category", cex.main =
1.5,
      ylab = "Stakeholder Preferences (weights)", cex.lab = 1.5)

#plot boxplots from the weights, ordered from highest to lowest median
SH.medians.weights <- apply(SH.weights, 2, median, na.rm = T)
weight.orders<-order(SH.medians.weights, decreasing = T)
par(las=2)
par(mar=c(12,6,4.1,2.1), mgp=c(4,1,0))
boxplot(SH.weights[,weight.orders],
        names= Criteria.names[weight.orders], cex.axis = 1.5)

title("Stakeholder weights for each criteria", cex.main = 1.5,
      ylab = "Stakeholder Preferences (weights)", cex.lab = 1.5)

  #and for main objectives
SH.medians.weights.main.obj <- apply(SH.weights.main.obj, 2, median, na.rm =
T)
weight.orders.main.obj<-order(SH.medians.weights.main.obj, decreasing = T)
par(las=2)
par(mar=c(13,6,4.1,2.1), mgp=c(4,1,0))
boxplot(SH.weights.main.obj[,weight.orders.main.obj],
        names= Criteria.names.main.obj[weight.orders.main.obj], cex.axis =
1.5)

title("Average stakeholder weights for criteria within each category",
cex.main = 1.5,
      ylab = "Stakeholder Preferences (weights)", cex.lab = 1.5)

#and for added main objectives
SH.medians.weights.added <- apply(SH.weights.added, 2, median, na.rm = T)
```

```
weight.orders.added<-order(SH.medians.weights.added, decreasing = T)
par(las=2)
par(mar=c(13,6,4.1,2.1), mgp=c(4,1,0))
boxplot(SH.weights.added[,weight.orders.added],
        names= Criteria.names.main.obj[weight.orders.added], cex.axis = 1.5)

title("Sum of stakeholder weights for criteria within each category",
cex.main = 1.5,
      ylab = "Stakeholder Preferences (weights)", cex.lab = 1.5)
```

Calculate results of MCDA for each stakeholder without brineline option.

```
#SH1
#this one has the code to be able to see sub-node scores for each option
option.scores.unc.no.brine.1 <- matrix(ncol = 9, nrow = n) #n is specified in
the chunk on Monte Carlo simulations of uncertainty
colnames(option.scores.unc.no.brine.1) <- options.no.brine
v.eval.unc.1<-list(NULL)

for (i in 1:9){# 9 is number of options
  v.eval.unc.1[[i]] <- evaluate(nutrients.uncertainty.midnodes, attrib =
data.frame(option.list.no.brine[[i]]), par = unlist(pars.nutrients.SH1))
  option.scores.unc.no.brine.1[,i]<- v.eval.unc.1[[i]][,1]
}
option.scores.unc.no.brine.1
v.eval.unc.1[[6]]
apply(v.eval.unc.1[[5]],2, mean)

##loop with just final scores
for (i in 1:9){# 9 is number of options
  v.eval.unc.1 <- evaluate(nutrients.uncertainty.midnodes, attrib =
data.frame(option.list.no.brine[[i]]), par = unlist(pars.nutrients.SH1))
  v.eval.unc.1
  option.scores.unc.no.brine.1[,i]<- v.eval.unc.1 [,1]
}


option.scores.unc.no.brine.1

#find ranking for each option in each row
library(plyr)

Ranking.options.unc.no.brine.1 <- option.scores.unc.no.brine.1
rank(1-option.scores.unc.no.brine.1 [1,])

for (i in 1:n){
  Ranking.options.unc.no.brine.1 [i,]<-rank(1-option.scores.unc.no.brine.1
[i,])
}

Ranking.options.unc.no.brine.1
head(Ranking.options.unc.no.brine.1)

#Plot rankings
```

```
rank.counts.no.brine.1 <- matrix(rep(0,81), ncol = 9) # 9 is number of
options, 81 is ncol squared
count.test.no.brine.1<-NULL
for(i in 1:9){# the 9 is number of options
  count.test.no.brine.1<-count(Ranking.options.unc.no.brine.1, i)

rank.counts.no.brine.1[as.numeric(as.matrix(count.test.no.brine.1[,1])),i]<-
count.test.no.brine.1[,2]
}
rownames(rank.counts.no.brine.1)<- c("Rank 1", "Rank 2", "Rank 3", "Rank 4",
"Rank 5", "Rank 6", "Rank 7", "Rank 8", "Rank 9")
colnames(rank.counts.no.brine.1)<-options.no.brine
rank.counts.no.brine.1

#to set as probabilities, divide each value by n
rank.counts.prob.no.brine.1 <- rank.counts.no.brine.1/n

par(mfrow = c(1,1))
par(mar=c(5.1,4.1,4.1,12),
    oma = c(0,0,0,0),
    xpd = T)
barplot(t(rank.counts.prob.no.brine.1), col = brewer.pal(10, "Paired"), main
= "Probability of ranks for each option, SH1", ylab = "Probability of each
rank", cex.lab = .7, density = 60 , angle=c(120,45,90,11,270, 200, 80, 140,
20) )
legend("topright", inset = c(-.7,0), legend = options.no.brine, col =
brewer.pal(10, "Paired"), pch = 15, bty = "n", density = 60 ,
angle=c(120,45,90,11,270, 200, 80, 140, 20))
mtext(paste("Population change", sep = "=", scenario[1]), cex = .5)
mtext(paste("Climate effect", sep = "=", scenario [2]), cex = .5, side = 1,
line = 3)
mtext(paste("Ecological threshold", sep = "=", scenario [3]), cex = .5, side
= 1, line = 2)


#SH2
option.scores.unc.no.brine.2 <- matrix(ncol = 9, nrow = n)
colnames(option.scores.unc.no.brine.2) <- options.no.brine
for (i in 1:9){
  v.eval.unc.2 <- evaluate(nutrients.uncertainty.midnodes, attrib =
data.frame(option.list.no.brine[[i]]), par = unlist(pars.nutrients.SH2))
  v.eval.unc.2
  option.scores.unc.no.brine.2[,i]<- v.eval.unc.2 [,1]
}

option.scores.unc.no.brine.2
head(option.scores.unc.no.brine.2)

## do summary stats

apply(option.scores.unc.no.brine.2, 2, mean)
boxplot(option.scores.unc.no.brine.2)

#find ranking for each option in each row

Ranking.options.unc.no.brine.2 <- option.scores.unc.no.brine.2
rank(1-option.scores.unc.no.brine.2 [1,])
```

```
for (i in 1:n){
  Ranking.options.unc.no.brine.2 [i,]<-rank(1-option.scores.unc.no.brine.2
[i,])
}

Ranking.options.unc.no.brine.2
head(Ranking.options.unc.no.brine.2)

## Plot rankings

rank.counts.no.brine.2 <- matrix(rep(0,81), ncol = 9)
count.test.no.brine.2<-NULL
for(i in 1:9){
  count.test.no.brine.2<-count(Ranking.options.unc.no.brine.2, i)

rank.counts.no.brine.2[as.numeric(as.matrix(count.test.no.brine.2[,1])),i]<-
count.test.no.brine.2[,2]
}
rownames(rank.counts.no.brine.2)<- c("Rank 1", "Rank 2", "Rank 3", "Rank 4",
"Rank 5", "Rank 6", "Rank 7", "Rank 8", "Rank 9")
colnames(rank.counts.no.brine.2)<-options.no.brine
rank.counts.no.brine.2

#to set as probabilities, divide each value by n
rank.counts.prob.no.brine.2 <- rank.counts.no.brine.2/n

par(mfrow = c(1,1))
par(mar=c(5.1,4.1,4.1,12), xpd = T)
barplot(t(rank.counts.prob.no.brine.2), col = brewer.pal(10, "Paired"), main
= "Probability of ranks for each option, SH2", ylab = "Probability of each
rank" )
legend("topright", inset = c(-.6,0), legend = options.no.brine, col =
brewer.pal(10, "Paired"), pch = 15, bty = "n")
mtext(paste("Population change", sep = "=", scenario[1]), cex = .5)
mtext(paste("Climate effect", sep = "=", scenario [2]), cex = .5, side = 1,
line = 3)
mtext(paste("Ecological threshold", sep = "=", scenario [3]), cex = .5, side
= 1, line = 2)



#SH3
option.scores.unc.no.brine.3 <- matrix(ncol = 9, nrow = n)
colnames(option.scores.unc.no.brine.3) <- options.no.brine
for (i in 1:9){
  v.eval.unc.3 <- evaluate(nutrients.sowatt.midnodes.SH3.u, attrib =
data.frame(option.list.no.brine[[i]]), par = unlist(pars.nutrients.SH3))
  v.eval.unc.3
  option.scores.unc.no.brine.3[,i]<- v.eval.unc.3 [,1]
}

option.scores.unc.no.brine.3
head(option.scores.unc.no.brine.3)

## do summary stats
```

```
apply(option.scores.unc.no.brine.3, 2, mean)
boxplot(option.scores.unc.no.brine.3)

#find ranking for each option in each row

Ranking.options.unc.no.brine.3 <- option.scores.unc.no.brine.3
rank(1-option.scores.unc.no.brine.3 [1,])

for (i in 1:n){
  Ranking.options.unc.no.brine.3 [i,]<-rank(1-option.scores.unc.no.brine.3
[i,])
}

Ranking.options.unc.no.brine.3
head(Ranking.options.unc.no.brine.3)

## Plot rankings

rank.counts.no.brine.3 <- matrix(rep(0,81), ncol = 9)
count.test.no.brine.3<-NULL
for(i in 1:9){
  count.test.no.brine.3<-count(Ranking.options.unc.no.brine.3, i)

rank.counts.no.brine.3[as.numeric(as.matrix(count.test.no.brine.3[,1])),i]<-
count.test.no.brine.3[,2]
}
rownames(rank.counts.no.brine.3)<- c("Rank 1", "Rank 2", "Rank 3", "Rank 4",
"Rank 5", "Rank 6", "Rank 3", "Rank 3", "Rank 9")
colnames(rank.counts.no.brine.3)<-options.no.brine
rank.counts.no.brine.3

#to set as probabilities, divide each value by n
rank.counts.prob.no.brine.3 <- rank.counts.no.brine.3/n

par(mfrow = c(1,1))
par(mar=c(5.1,4.1,4.1,12), oma = c(0,0,0,0), xpd = T)
barplot(t(rank.counts.prob.no.brine.3), col = brewer.pal(10, "Paired"), main
= "Probability of ranks for each option, SH3", ylab = "Probability of each
rank" )
legend("topright", inset = c(-.6,0), legend = options.no.brine, col =
brewer.pal(10, "Paired"), pch = 15, bty = "n")
mtext(paste("Population change", sep = "=", scenario[1]), cex = .5)
mtext(paste("Climate effect", sep = "=", scenario [2]), cex = .5, side = 1,
line = 3)
mtext(paste("Ecological threshold", sep = "=", scenario [3]), cex = .5, side
= 1, line = 2)

#SH4
option.scores.unc.no.brine.4 <- matrix(ncol = 9, nrow = n)
colnames(option.scores.unc.no.brine.4) <- options.no.brine
for (i in 1:9){
  v.eval.unc.4 <- evaluate(nutrients.uncertainty.midnodes, attrib =
data.frame(option.list.no.brine[[i]]), par = unlist(pars.nutrients.SH4))
  v.eval.unc.4
  option.scores.unc.no.brine.4[,i]<- v.eval.unc.4 [,1]
}
```

```
option.scores.unc.no.brine.4
head(option.scores.unc.no.brine.4)

## do  summary stats

apply(option.scores.unc.no.brine.4, 2, mean)
boxplot(option.scores.unc.no.brine.4)

#find ranking for each option in each row

Ranking.options.unc.no.brine.4 <- option.scores.unc.no.brine.4
rank(1-option.scores.unc.no.brine.4 [1,])

for (i in 1:n){
  Ranking.options.unc.no.brine.4 [i,]<-rank(1-option.scores.unc.no.brine.4
[i,])
}

Ranking.options.unc.no.brine.4
head(Ranking.options.unc.no.brine.4)

## Plot rankings


rank.counts.no.brine.4 <- matrix(rep(0,81), ncol = 9)
count.test.no.brine.4<-NULL
for(i in 1:9){
  count.test.no.brine.4<-count(Ranking.options.unc.no.brine.4, i)

rank.counts.no.brine.4[as.numeric(as.matrix(count.test.no.brine.4[,1])),i]<-
count.test.no.brine.4[,2]
}
rownames(rank.counts.no.brine.4)<- c("Rank 1", "Rank 2", "Rank 3", "Rank 4",
"Rank 5", "Rank 6", "Rank 7", "Rank 8", "Rank 9")
colnames(rank.counts.no.brine.4)<-options.no.brine
rank.counts.no.brine.4

#to set as probabilities, divide each value by n
rank.counts.prob.no.brine.4 <- rank.counts.no.brine.4/n

par(mfrow = c(1,1))
par(mar=c(5.1,4.1,4.1,12), xpd = T)
barplot(t(rank.counts.prob.no.brine.4), col = brewer.pal(10, "Paired"), main
= "Probability of ranks for each option, SH4", ylab = "Probability of each
rank" )
legend("topright", inset = c(-.6,0), legend = options.no.brine, col =
brewer.pal(10, "Paired"), pch = 15, bty = "n")
mtext(paste("Population change", sep = "=", scenario[1]), cex = .5)
mtext(paste("Climate effect", sep = "=", scenario [2]), cex = .5, side = 1,
line = 3)
mtext(paste("Ecological threshold", sep = "=", scenario [3]), cex = .5, side
= 1, line = 2)

#SH5

option.scores.unc.no.brine.5 <- matrix(ncol = 9, nrow = n)
colnames(option.scores.unc.no.brine.5) <- options.no.brine
```

```
for (i in 1:9){
  v.eval.unc.5 <- evaluate(nutrients.uncertainty.midnodes, attrib =
data.frame(option.list.no.brine[[i]]), par = unlist(pars.nutrients.SH5))
  v.eval.unc.5
  option.scores.unc.no.brine.5[,i]<- v.eval.unc.5 [,1]
}

option.scores.unc.no.brine.5
head(option.scores.unc.no.brine.5)

## do summary stats
apply(option.scores.unc.no.brine.5, 2, mean)
boxplot(option.scores.unc.no.brine.5)

#find ranking for each option in each row

Ranking.options.unc.no.brine.5 <- option.scores.unc.no.brine.5
rank(1-option.scores.unc.no.brine.5 [1,])

for (i in 1:n){
  Ranking.options.unc.no.brine.5 [i,]<-rank(1-option.scores.unc.no.brine.5
[i,])
}

Ranking.options.unc.no.brine.5
head(Ranking.options.unc.no.brine.5)

## Plot rankings

rank.counts.no.brine.5 <- matrix(rep(0,81), ncol = 9)
count.test.no.brine.5<-NULL
for(i in 1:9){
  count.test.no.brine.5<-count(Ranking.options.unc.no.brine.5, i)

rank.counts.no.brine.5[as.numeric(as.matrix(count.test.no.brine.5[,1])),i]<-
count.test.no.brine.5[,2]
}
rownames(rank.counts.no.brine.5)<- c("Rank 1", "Rank 2", "Rank 3", "Rank 4",
"Rank 5", "Rank 6", "Rank 7", "Rank 8", "Rank 9")
colnames(rank.counts.no.brine.5)<-options.no.brine
rank.counts.no.brine.5

#to set as probabilities, divide each value by n
rank.counts.prob.no.brine.5 <- rank.counts.no.brine.5/n

par(mfrow = c(1,1))
par(mar=c(5.1,4.1,4.1,12), xpd = T)
barplot(t(rank.counts.prob.no.brine.5), col = brewer.pal(10, "Paired"), main
= "Probability of ranks for each option, SH5", ylab = "Probability of each
rank" )
legend("topright", inset = c(-.6,0), legend = options.no.brine, col =
brewer.pal(10, "Paired"), pch = 15, bty = "n")
mtext(paste("Population change", sep = "=", scenario[1]), cex = .5)
mtext(paste("Climate effect", sep = "=", scenario [2]), cex = .5, side = 1,
line = 3)
mtext(paste("Ecological threshold", sep = "=", scenario [3]), cex = .5, side
= 1, line = 2)
```

```
#SH6

option.scores.unc.no.brine.6 <- matrix(ncol = 9, nrow = n)
colnames(option.scores.unc.no.brine.6) <- options.no.brine
for (i in 1:9){
  v.eval.unc.6 <- evaluate(nutrients.uncertainty.midnodes, attrib =
data.frame(option.list.no.brine[[i]]), par = unlist(pars.nutrients.SH6))
  v.eval.unc.6
  option.scores.unc.no.brine.6[,i]<- v.eval.unc.6 [,1]
}

option.scores.unc.no.brine.6
head(option.scores.unc.no.brine.6)

## do summary stats
apply(option.scores.unc.no.brine.6, 2, mean)
boxplot(option.scores.unc.no.brine.6)

#find ranking for each option in each row
Ranking.options.unc.no.brine.6 <- option.scores.unc.no.brine.6
rank(1-option.scores.unc.no.brine.6 [1,])

for (i in 1:n){
  Ranking.options.unc.no.brine.6 [i,]<-rank(1-option.scores.unc.no.brine.6
[i,])
}

Ranking.options.unc.no.brine.6
head(Ranking.options.unc.no.brine.6)

## Plot rankings
rank.counts.no.brine.6 <- matrix(rep(0,81), ncol = 9)
count.test.no.brine.6<-NULL
for(i in 1:9){
  count.test.no.brine.6<-count(Ranking.options.unc.no.brine.6, i)

rank.counts.no.brine.6[as.numeric(as.matrix(count.test.no.brine.6[,1])),i]<-
count.test.no.brine.6[,2]
}
rownames(rank.counts.no.brine.6)<- c("Rank 1", "Rank 2", "Rank 3", "Rank 4",
"Rank 5", "Rank 6", "Rank 7", "Rank 8", "Rank 9")
colnames(rank.counts.no.brine.6)<-options.no.brine
rank.counts.no.brine.6

#to set as probabilities, divide each value by n
rank.counts.prob.no.brine.6 <- rank.counts.no.brine.6/n

par(mfrow = c(1,1))
par(mar=c(5.1,4.1,4.1,12), xpd = T)
barplot(t(rank.counts.prob.no.brine.6), col = brewer.pal(10, "Paired"), main
= "Probability of ranks for each option, SH6", ylab = "Probability of each
rank" )
legend("topright", inset = c(-.6,0), legend = options.no.brine, col =
brewer.pal(10, "Paired"), pch = 15, bty = "n")
mtext(paste("Population change", sep = "=", scenario[1]), cex = .5)
```

```
mtext(paste("Climate effect", sep = "=", scenario [2]), cex = .5, side = 1,
line = 3)
mtext(paste("Ecological threshold", sep = "=", scenario [3]), cex = .5, side
= 1, line = 2)

#SH7
option.scores.unc.no.brine.7 <- matrix(ncol = 9, nrow = n)
colnames(option.scores.unc.no.brine.7) <- options.no.brine
for (i in 1:9){
  v.eval.unc.7 <- evaluate(nutrients.sowatt.midnodes.SH7.u, attrib =
data.frame(option.list.no.brine[[i]]), par = unlist(pars.nutrients.SH7))
  v.eval.unc.7
  option.scores.unc.no.brine.7[,i]<- v.eval.unc.7 [,1]
}

option.scores.unc.no.brine.7
head(option.scores.unc.no.brine.7)

## do summary stats
apply(option.scores.unc.no.brine.7, 2, mean)
boxplot(option.scores.unc.no.brine.7)

#find ranking for each option in each row
Ranking.options.unc.no.brine.7 <- option.scores.unc.no.brine.7
rank(1-option.scores.unc.no.brine.7 [1,])

for (i in 1:n){
  Ranking.options.unc.no.brine.7 [i,]<-rank(1-option.scores.unc.no.brine.7
[i,])
}

Ranking.options.unc.no.brine.7
head(Ranking.options.unc.no.brine.7)

## Plot rankings
rank.counts.no.brine.7 <- matrix(rep(0,81), ncol = 9)
count.test.no.brine.7<-NULL
for(i in 1:9){
  count.test.no.brine.7<-count(Ranking.options.unc.no.brine.7, i)

rank.counts.no.brine.7[as.numeric(as.matrix(count.test.no.brine.7[,1])),i]<-
count.test.no.brine.7[,2]
}
rownames(rank.counts.no.brine.7)<- c("Rank 1", "Rank 2", "Rank 3", "Rank 4",
"Rank 5", "Rank 6", "Rank 7", "Rank 8", "Rank 9")
colnames(rank.counts.no.brine.7)<-options.no.brine
rank.counts.no.brine.7

#to set as probabilities, divide each value by n
rank.counts.prob.no.brine.7 <- rank.counts.no.brine.7/n

par(mfrow = c(1,1))
par(mar=c(5.1,4.1,4.1,12), xpd = T)
barplot(t(rank.counts.prob.no.brine.7), col = brewer.pal(10, "Paired"), main
= "Probability of ranks for each option, SH7", ylab = "Probability of each
rank" )
```

```
legend("topright", inset = c(-.6,0), legend = options.no.brine, col =
brewer.pal(10, "Paired"), pch = 15, bty = "n")
mtext(paste("Population change", sep = "=", scenario[1]), cex = .5)
mtext(paste("Climate effect", sep = "=", scenario [2]), cex = .5, side = 1,
line = 3)
mtext(paste("Ecological threshold", sep = "=", scenario [3]), cex = .5, side
= 1, line = 2)

#SH8
option.scores.unc.no.brine.8 <- matrix(ncol = 9, nrow = n)
colnames(option.scores.unc.no.brine.8) <- options.no.brine
for (i in 1:9){
  v.eval.unc.8 <- evaluate(nutrients.uncertainty.midnodes, attrib =
data.frame(option.list.no.brine[[i]]), par = unlist(pars.nutrients.SH8))
  v.eval.unc.8
  option.scores.unc.no.brine.8[,i]<- v.eval.unc.8 [,1]
}

option.scores.unc.no.brine.8
head(option.scores.unc.no.brine.8)

## do summary stats
apply(option.scores.unc.no.brine.8, 2, mean)
boxplot(option.scores.unc.no.brine.8)

#find ranking for each option in each row
Ranking.options.unc.no.brine.8 <- option.scores.unc.no.brine.8
rank(1-option.scores.unc.no.brine.8 [1,])

for (i in 1:n){
  Ranking.options.unc.no.brine.8 [i,]<-rank(1-option.scores.unc.no.brine.8
[i,])
}

Ranking.options.unc.no.brine.8
head(Ranking.options.unc.no.brine.8)

## Plot rankings
rank.counts.no.brine.8 <- matrix(rep(0,81), ncol = 9)
count.test.no.brine.8<-NULL
for(i in 1:9){
  count.test.no.brine.8<-count(Ranking.options.unc.no.brine.8, i)

rank.counts.no.brine.8[as.numeric(as.matrix(count.test.no.brine.8[,1])),i]<-
count.test.no.brine.8[,2]
}
rownames(rank.counts.no.brine.8)<- c("Rank 1", "Rank 2", "Rank 3", "Rank 4",
"Rank 5", "Rank 6", "Rank 7", "Rank 8", "Rank 9")
colnames(rank.counts.no.brine.8)<-options.no.brine
rank.counts.no.brine.8

#to set as probabilities, divide each value by n
rank.counts.prob.no.brine.8 <- rank.counts.no.brine.8/n

par(mfrow = c(1,1))
par(mar=c(5.1,4.1,4.1,12), xpd = T)
```

```
barplot(t(rank.counts.prob.no.brine.8), col = brewer.pal(10, "Paired"), main
= "Probability of ranks for each option, SH8", ylab = "Probability of each
rank" )
legend("topright", inset = c(-.6,0), legend = options.no.brine, col =
brewer.pal(10, "Paired"), pch = 15, bty = "n")
mtext(paste("Population change", sep = "=", scenario[1]), cex = .5)
mtext(paste("Climate effect", sep = "=", scenario [2]), cex = .5, side = 1,
line = 3)
mtext(paste("Ecological threshold", sep = "=", scenario [3]), cex = .5, side
= 1, line = 2)

#SH9
option.scores.unc.no.brine.9 <- matrix(ncol = 9, nrow = n)
colnames(option.scores.unc.no.brine.9) <- options.no.brine
for (i in 1:9){
  v.eval.unc.9 <- evaluate(nutrients.uncertainty.midnodes, attrib =
data.frame(option.list.no.brine[[i]]), par = unlist(pars.nutrients.SH9))
  v.eval.unc.9
  option.scores.unc.no.brine.9[,i]<- v.eval.unc.9 [,1]
}

option.scores.unc.no.brine.9
head(option.scores.unc.no.brine.9)

## do summary stats
apply(option.scores.unc.no.brine.9, 2, mean)
boxplot(option.scores.unc.no.brine.9)

#find ranking for each option in each row
Ranking.options.unc.no.brine.9 <- option.scores.unc.no.brine.9
rank(1-option.scores.unc.no.brine.9 [1,])

for (i in 1:n){
  Ranking.options.unc.no.brine.9 [i,]<-rank(1-option.scores.unc.no.brine.9
[i,])
}

Ranking.options.unc.no.brine.9
head(Ranking.options.unc.no.brine.9)

## Plot rankings
rank.counts.no.brine.9 <- matrix(rep(0,81), ncol = 9)
count.test.no.brine.9<-NULL
for(i in 1:9){
  count.test.no.brine.9<-count(Ranking.options.unc.no.brine.9, i)

rank.counts.no.brine.9[as.numeric(as.matrix(count.test.no.brine.9[,1])),i]<-
count.test.no.brine.9[,2]
}
rownames(rank.counts.no.brine.9)<- c("Rank 1", "Rank 2", "Rank 3", "Rank 4",
"Rank 5", "Rank 6", "Rank 7", "Rank 8", "Rank 9")
colnames(rank.counts.no.brine.9)<-options.no.brine
rank.counts.no.brine.9

#to set as probabilities, divide each value by n
rank.counts.prob.no.brine.9 <- rank.counts.no.brine.9/n
```

```
par(mfrow = c(1,1))
par(mar=c(5.1,4.1,4.1,12), xpd = T)
barplot(t(rank.counts.prob.no.brine.9), col = brewer.pal(10, "Paired"), main
= "Probability of ranks for each option, SH9", ylab = "Probability of each
rank" )
legend("topright", inset = c(-.6,0), legend = options.no.brine, col =
brewer.pal(10, "Paired"), pch = 15, bty = "n")
mtext(paste("Population change", sep = "=", scenario[1]), cex = .5)
mtext(paste("Climate effect", sep = "=", scenario [2]), cex = .5, side = 1,
line = 3)

mtext(paste("Ecological threshold", sep = "=", scenario [3]), cex = .5, side
= 1, line = 2)
colors()

#vector of resulting scores with uncertainty for each SH
SH.eval.unc.all <- data.frame(cbind (v.eval.unc.1, v.eval.unc.2,
v.eval.unc.3, v.eval.unc.4, v.eval.unc.5, v.eval.unc.6, v.eval.unc.7,
v.eval.unc.8, v.eval.unc.9))
SH.eval.unc.normal <- SH.eval.unc.all[c(1,2,4:6,8,9),]
```

Plot the top three ranked options for each stakeholder.

```
par(mfrow = c(3,3))
par(oma = c(5,4,4,12),
    mar = c(2,2,2,2),
    xpd = NA,
    las = 1)

barplot(t(rank.counts.prob.no.brine.1)[,1:3], col = brewer.pal(10, "Paired"),
main = "SH1", ylab = "Probability of each rank")
barplot(t(rank.counts.prob.no.brine.2)[,1:3], col = brewer.pal(10, "Paired"),
main = "SH2", ylab = "Probability of each rank" )
barplot(t(rank.counts.prob.no.brine.3)[,1:3], col = brewer.pal(10, "Paired"),
main = "SH3", ylab = "Probability of each rank" )
barplot(t(rank.counts.prob.no.brine.4)[,1:3], col = brewer.pal(10, "Paired"),
main = "SH4", ylab = "Probability of each rank" )
barplot(t(rank.counts.prob.no.brine.5)[,1:3], col = brewer.pal(10, "Paired"),
main = "SH5", ylab = "Probability of each rank" )
barplot(t(rank.counts.prob.no.brine.6)[,1:3], col = brewer.pal(10, "Paired"),
main = "SH6", ylab = "Probability of each rank" )
barplot(t(rank.counts.prob.no.brine.7)[,1:3], col = brewer.pal(10, "Paired"),
main = "SH7", ylab = "Probability of each rank" )
barplot(t(rank.counts.prob.no.brine.8)[,1:3], col = brewer.pal(10, "Paired"),
main = "SH8", ylab = "Probability of each rank" )
barplot(t(rank.counts.prob.no.brine.9)[,1:3], col = brewer.pal(10, "Paired"),
main = "SH9", ylab = "Probability of each rank" )

legend(x=3.4,y=3, inset = c(-1, -.2), y.intersp = .5, legend =
options.no.brine, col = brewer.pal(9, "Paired"), pch = 15, bty = "n", pt.cex
= 3)
mtext(paste("Population change", sep = "=", scenario[1]), side = 1, outer =
TRUE, line = 1, cex = .8)
mtext(paste("Climate effect", sep = "=", scenario [2]), cex = .8, side = 1,
outer = TRUE, line = 2)
```

```
mtext(paste("Ecological threshold", sep = "=", scenario [3]), cex = .8, side
= 1, outer = TRUE, line = 3)
mtext("Top 3 Ranked Options for Each Stakeholder", cex = 1.2, side = 3, outer
= TRUE, line = 1, font=2)
```

Plot overall value of options for stakeholders.

```
#plots of median overall value for all options for each stakeholder (Status
quo scenario)

  ##make dataframes of the median overall values
option.scores.unc.no.brine.medians.sq <-
data.frame(lapply(option.scores.unc.no.brine.list.sq, apply,2,median))
colnames(option.scores.unc.no.brine.medians.sq) <- SHs

##status quo scenario
par(mfrow = c(2,1))
par(oma = c(1,2,1,1),
    mar = c(2,3,2,1),
    xpd = NA)
plot(100,100, xlim=c(1,9), xaxt = 'n', xlab = '', ylab = "Median Overall
Value", ylim = c(0,1), cex.lab = 1.5, main = "Status Quo Scenario", cex.main
= 1.5)
axis(1, at=1:9, labels = SHs)
for(i in 1:length(option.scores.unc.no.brine.medians.sq[,1])){
points(1:length(option.scores.unc.no.brine.medians.sq[,1]),
option.scores.unc.no.brine.medians.sq[i,], col = brewer.pal(9, "Paired")[i],
pch = 16, lwd = 2)
lines(1:length(option.scores.unc.no.brine.medians.sq[,1]),
option.scores.unc.no.brine.medians.sq[i,], col = brewer.pal(9, "Paired")[i],
pch = 16, lwd = 2)
}
par(mar=c(0,0,0,0))
plot(1, type = "n", axes=FALSE, xlab="", ylab="")

legend(x = "topleft",inset = 0,
       legend = options.no.brine,
       col = brewer.pal(9, "Paired"), lwd=5, cex=1, horiz = F, ncol = 3, bty
= "n")
```

Text S3. Detailed description of elicitation methods for preference elicitation.

In follow-up interviews, nine selected stakeholders assigned points (from 0-100) for the importance of improving each of the sub-objectives from its worst to best value using the Swing method for elicitation, which is commonly used in multi-criteria decision analysis (Mustajoki et al., 2005; Schuwirth et al., 2012) and has been used for decision-making about water infrastructure planning (Zheng et al., 2016). First, stakeholders read a description of each goal printed on a notecard (see Supplemental Information, Text S4). They were then asked to discuss the importance of the objective to good nutrient management with the interviewer. These notecards were identically formatted and the objectives were described in roughly the same number of words to minimize bias (Hämäläinen and Alaja, 2008).

Next, stakeholders were given notecards with a printed description of each objective, the measurement attribute, and the attribute values for the best case, worse case and current value on it (see Supplemental Information, Text S5). Within each group of goals (healthy estuarine ecosystem, improve wastewater treatment and resource recovery, promote intergenerational equity, good social support, minimize costs), stakeholders were asked to systematically determine the most important objective to improve from the worst to the best value and slide it upwards in position on the table; this objective was assigned 100 points. Stakeholders then chose the second-most and third-most important objective to improve from worst to best values within that goal group and assigned points to each. Finally, stakeholders were asked to compare each of the objectives that received 100 points (the top pick from each group) and evaluate the most important of these to improve from worst to best case values; this choice was given 100 points. Stakeholders then assigned points to the second-most, third-most, fourth-most, and fifth-most important objective to improve from worst to best values within the top five.

The rest of the objectives' point values were scaled accordingly in comparison to the top-ranking value in its group (Belton and Stewart, 2002). Relative point values were then cross-checked for consistency across the objectives hierarchy with stakeholder feedback and adjustments where necessary (Belton and Stewart, 2002). This cross-check also served to illuminate instances in which additive aggregation models for synthesizing preferences of the different objectives were insufficient (Zheng et al., 2016).

Stakeholders were then asked to explain why they assigned points as they did in order to better understand their thought processes about the importance of the objectives and the suitability of the attributes (Marttunen et al., 2015). These point values were confirmed by comparison to an initial qualitative description of the importance of each of the objectives. Attempts to confirm weightings from point allocation results with the trade-off method of elicitation (Eisenführ et al., 2010) were almost uniformly rejected by stakeholders (see Discussion). We then normalized the assigned points into quantitative weights on a scale of 0-1 for each of the objectives for each of the stakeholders (Belton and Stewart, 2002).

For the objectives that received the highest weights (and others if time allowed), we elicited whether improvement from the worst to best case fulfillment of the objectives was linear, concave, convex through the bisection method of elicitation (Eisenführ et al., 2010). We also checked if there were any thresholds below which everything was equally bad or above which everything was equally good (Scholten et al., 2015).

Text S4. ***Descriptions of objectives (printed on notecards) for follow-up interviews***

Healthy estuarine ecosystem
This goal refers to promotion of good water quality and robust aquatic food webs in the Bay, and protection of wetlands and the terrestrial wildlife they support.

A healthy estuarine ecosystem protects beneficial uses in the Bay (as designated by the State Water Resources Control Board), like estuarine habitat, commercial and sport fishing, habitat for rare and endangered species, wetland wildlife habitat, fish migrations, and fish spawning.

Improve wastewater treatment and resource recovery
This goal refers to upgrade of wastewater treatment facilities to produce higher-quality effluent, as well as recovery of resources from sewage like nutrients and fresh water.

Improving wastewater treatment and resource recovery entails ensuring that water treatment removes contaminants of emerging concern like pharmaceuticals and other chemicals from effluent while also extracting resources like fresh water and fertilizer from sewage.

Promote intergenerational equity
This goal refers to design of infrastructure to not only meet existing needs, but also to meet the needs of people in the future.

Promoting intergenerational equity means accounting for the fact that our water infrastructure is designed to last multiple decades, and providing fairly for future generations by making infrastructure easy to adapt as conditions change. It also is resilient to sea level rise and minimizes carbon dioxide emissions.

Good social support
This goal refers to promotion of positive feelings about the option for nutrient management, both within the community of decision-makers and within Bay Area residents.

Good social support arises from the public being able to see improvements in Bay water quality, and a good nutrient management option shouldn't require undue effort for residents to use effectively. Professionals in the field should be able to easily get permits to create a good nutrient management option.

Minimize costs
This goal refers to minimization of expenses over a thirty-year period, including the initial capital investment and yearly operations and maintenance costs. It also entails system reliability, which avoids costs of unexpected regulatory violations.

Minimizing costs arises from a respect that water infrastructure for nutrient management will likely be largely publicly funded, via fees for water and sewage use. As such, minimizing project costs – and associated fee hikes – is fiscally responsible and most fair to residents.

Text S5. Descriptions of sub-objectives (printed on notecards) for Swing method of weight elicitation

<table>
<tr>
<td>Good Bay water quality
[HEALTHY ESTUARINE ECOSYSTEM]

Measured by: Probability (%) of deviating from good ambient nutrient-related conditions in the southern reach of the Bay such that it would impair beneficial uses.

<table><tr><td>Best case</td><td>Worst case</td><td>Current value</td></tr></table></td>
<td>Good wildlife habitat
[HEALTHY ESTUARINE ECOSYSTEM]

Measured by: Area (hectares) of additional wetland habitat in the southern reach of the Bay provided by the nutrient management option.

<table><tr><td>Best case</td><td>Worst case</td><td>Current value</td></tr></table></td>
<td>Good Bay water quality
[HEALTHY ESTUARINE ECOSYSTEM]

Measured by: Probability (%) of deviating from good ambient nutrient-related conditions in the southern reach of the Bay such that it would impair beneficial uses.

<table><tr><td>Best case</td><td>Worst case</td><td>Current value</td></tr></table></td>
</tr>
</table>

5%	95%	<10%

5,200	0	7,200

5%	95%	<10%

Good wildlife habitat
[HEALTHY ESTUARINE ECOSYSTEM]

Measured by: Area (hectares) of additional wetland habitat in the southern reach of the Bay provided by the nutrient management option.

Best case	Worst case	Current value
4,800	0	7,200

Increase water supply
[IMPROVE WASTEWATER TREATMENT AND RESOURCE RECOVERY]

Measured by: Amount of useable water produced (MGD) from wastewater effluent in the southern reach of the Bay.

Best case	Worst case	Current value
154	22	22

Increase resource recovery
[IMPROVE WASTEWATER TREATMENT AND RESOURCE RECOVERY]

Measured by: Amount of nitrogen (kg/year) recovered from sewage for use in fertilizer.

Best case	Worst case	Current value
8.5 million*	0	0

*enough to fertilize 125,000 acres of corn

Remove contaminants of emerging concern
[IMPROVE WASTEWATER TREATMENT AND RESOURCE RECOVERY]

Measured by: Total sulfamethoxazole (an antibiotic) loading (kg/year) to the southern reach of the Bay.

Best case	Worst case	Current value
31	137	86

Resilience to sea level rise
[INTERGENERATIONAL EQUITY]

Measured by: A scale from -10 to 10. (10 – is unaffected and fully protects existing assets from predicted sea level rise and storm surges; 0 – sea level rise would not affect the technology; -10 – is highly vulnerable to predicted sea level rise and storm surges)

Best case	Worst case	Current value
7	-10	-10

Ease of adaptation to changing conditions
[INTERGENERATIONAL EQUITY]

Measured by: Percent ease of adaptation, including sunk costs, time needed to adapt, physical potential for change. (0-50%: Impossible or hard to adapt; 51-75% Moderately adaptable**;** 76-100% Easy to adapt.)

Best case	Worst case	Current value
100%	0%	60%

Public ease of use of nutrient technology
[GOOD SOCIAL SUPPORT]

Measured by: Percent ease of use. (0-60%: Hard for public to use— unfamiliar technology, requires adapting to source-separating toilets and weekly time to replace urine cartridge; 61-80%: Public less familiar with technology (as in potable reuse), but no time or lifestyle changes are required; 80-100% Standard— fully legitimate

Increase shoreline access
[GOOD SOCIAL SUPPORT]

Measured by: Number of access points to shoreline recreation areas (above current levels) in the southern reach of the Bay.

Best case	Worst case	Current value
17	0	25

Ease of permitting for nutrient technology
[GOOD SOCIAL SUPPORT]

Measured by: Percent ease of permitting. (0-60% Huge permitting headache— unconventional technology requires large negotiations, much additional staff time, and possibly legislative change to permit; 61-80%: difficult to permit— does not fit easily into current permitting structure, would require additional staff time and

<table>
<tr>
<td>to public, no time or lifestyle changes need to use

<table><tr><td>Best case</td><td>Worst case</td><td>Current value</td></tr><tr><td>100%</td><td>0%</td><td>100%</td></tr><tr><td></td><td></td><td></td></tr></table></td>
<td></td>
<td>appeals; 81-100% Easy to permit – no problem obtaining permits.)

<table><tr><td>Best case</td><td>Worst case</td><td>Current value</td></tr><tr><td>100%</td><td>0%</td><td>varies</td></tr></table></td>
</tr>
<tr>
<td>Low initial capital investment and O&M costs
[MINIMIZE COSTS]

Measured by: Total present value to build and maintain new nutrient removal technology, assuming 30 year horizon ($ and $/person in southern Bay Area).

<table><tr><td>Best case</td><td>Worst case</td><td>Current value</td></tr><tr><td>$0</td><td>$8 billion</td><td>$0</td></tr><tr><td>$0</td><td>$2400</td><td>$0</td></tr></table></td>
<td></td>
<td></td>
</tr>
</table>

Text S6. Detailed results of threshold analysis.

For SH5, who set thresholds in water quality at 20% (would not tolerate an option with more than 20% chance of resulting in impairment of water quality), in ease of adaptation at 76% (would not accept an option that was difficult to adapt to changing conditions), and in reliability at 80% (would not accept an option that was reliable less than 80% of the time), no option was acceptable. SH6 set thresholds in probability of impairment of water quality at 50%, and would not accept any option for nutrient management that did not protect existing infrastructure from sea level rise (note that this second threshold would make many current systems for nutrient control in the Bay Area unacceptable). This limited SH6's acceptable options to only the two wetland options (horizontal levees and open water wetlands). SH8 had thresholds for likelihood of impairing water quality (15%), ease of adaptation (50%), and reliability (85%). This resulted in Level 2 upgrades having a 46% probability of ranking in the top three, but being unacceptable 44% of the time. Wetland levees ranked first 14% of the time, but were unacceptable 86% of the time. Open-water wetland were ranked in the top two 5% of the time, but were unacceptable 95% of the time. All other options would not be tolerated with the stated thresholds.

Table S2. Range and distribution of each attribute value, Status quo scenario

Option	Decision criteria	Unit	Uncertainty distribution	Parameter 1	Parameter 2	Max scalar (for beta dist.)	Min scalar (for beta dist)	Sample value	Best value	Worst value
Do nothing	**wq**	%	Minmax	59.5	89.2	NA	NA	74.3	5	95
	hab	hectares	Determined	0	0	NA	NA	0	5200	0
	supply	MGD	Determined	22	22	NA	NA	22	190	22
	recovery	kg/year	Determined	0	0	NA	NA	0	8,500,000	0
	CEC	kg/year	Minmax	68.6	102.9	NA	NA	85.8	22	137
	adapt	%	Minmax	100	100	NA	NA	100	100	0
	slr	scale_constr	Determined	-5	-5	NA	NA	-5	10	-10
	CO2	tonnes CO2 eq / year	Minmax	205,000	380,000	NA	NA	293,000	180,000	9.00E+05
	ease_use	%	Determined	100	100	NA	NA	100	100	0
	access	Integer	Determined	0	0	NA	NA	0	17	0
	permit	%	Determined	100	100	NA	NA	100	100	0
	reliable	%	Normal	98	9.8	NA	NA	98	99	50
	costs	$	Determined	0	0	NA	NA	0	0	8.00E+09
Wetland- levee	**wq**	%	Minmax	32.6	48.9	NA	NA	40.8	5	95
	hab	hectares	Minmax	3,570	4,760	NA	NA	4,760	5,200	0
	supply	MGD	Determined	22	22	NA	NA	22	190.1	22
	recovery	kg/year	Determined	0	0	NA	NA	0	8,500,000	0
	CEC	kg/year	Minmax	32.1	78.5	NA	NA	55.3	22	137
	adapt	%	Minmax	40	65	NA	NA	52	100	0
	slr	scale_constr	Determined	8	8	NA	NA	8	10	-10
	CO2	tonnes CO2 eq/year	Minmax	276,000	414,000	NA	NA	345,000	180,000	900,000
	ease_use	%	Determined	100	100	NA	NA	100	100	0

	access	Integer	Minmax	6	11	NA	NA	11	17	0
	permit	%	Minmax	5	60	NA	NA	30	100	0
	reliable	%	Minmax	61.6	92.4	NA	NA	77	99	50
	costs	$	Minmax	476,000	4,760,000,000	NA	NA	3,090,000,000	0	8,000,000,000
Wetland- openwater	**wq**	%	Minmax	25.2	37.8	NA	NA	31.5	5	95
	hab	hectares	Minmax	574	1000	NA	NA	718	5200	0
	supply	MGD	Determined	22	22	NA	NA	22	190	22
	recovery	kg/year	Determined	0	0	NA	NA	0	8,500,000	0
	CEC	kg/year	Minmax	55.3	83.0	NA	NA	69.1	22	137
	adapt	%	Minmax	30	55	NA	NA	42	100	0
	slr	scale_constr	Determined	5	5	NA	NA	5	10	-10
	CO2	tonnes CO2 eq/year	Minmax	248,000	372,000	NA	NA	310,000	180,000	900,000
	ease_use	%	Determined	100	100	NA	NA	100	100	0
	access	Integer	Minmax	6	11	NA	NA	11	17	0
	permit	%	Minmax	1	60	NA	NA	30	100	0
	reliable	%	Minmax	61.6	92.4	NA	NA	77	99	50
	costs	$	Minmax	567,000,000	1,920,000,000	NA	NA	709,000	0	8,000,000,000
Recycle -- irrigation	**wq**	%	Minmax	47.2	70.8	NA	NA	59.0	5	95
	hab	hectares	Determined	0	0	NA	NA	0	5200	0
	supply	MGD	Minmax	92.6	139	NA	NA	116	190	22
	recovery	kg/year	Minmax	2,630,000	3,950,000	NA	NA	3,290,000	8,500,000	0
	CEC	kg/year	Minmax	47.9	71.8	NA	NA	59.8	22	137
	adapt	%	Minmax	30	60	NA	NA	45	100	0
	slr	scale_constr	Determined	-3	-3	NA	NA	-3	10	-10
	CO2	tonnes CO2 eq/year	Minmax	340,000	510,000	NA	NA	425,000	180,000	900,000
	ease_use	%	Determined	100	100	NA	NA	100	100	0

	access	Integer	Determined	0	0	NA	NA	0	17	0
	permit	%	Minmax	65	95	NA	NA	70	100	0
	reliable	%	Minmax	76.8	115.2	NA	NA	96	99	50
	costs	$	Beta	0.313	1.17	4385.96	130.03	97,700,000	0	8,000,000,000
Recycle -- brineline	**wq**	%	Minmax	47.9	71.9	NA	NA	59.9	5	95
	hab	hectares	Determined	0	0	NA	NA	0	5200	0
	supply	MGD	Minmax	82.1	123	NA	NA	103	190	22
	recovery	kg/year	Determined	0	0	NA	NA	0	8,500,000	0
	CEC	kg/year	Minmax	50.8	76.2	NA	NA	63.5	22	137
	adapt	%	Minmax	30	60	NA	NA	50	100	0
	slr	scale_constr	Determined	-5	-5	NA	NA	-5	10	-10
	CO2	tonnes CO2 eq/year	Minmax	5,280,000	87,900,000	NA	NA	70,300,000	180,000	900,000
	ease_use	%	Minmax	30	80	NA	NA	65	100	0
	access	Integer	Determined	0	0	NA	NA	0	17	0
	permit	%	Minmax	20	70	NA	NA	40	100	0
	reliable	%	Normal	98	0.98	NA	NA	98	99	50
	costs	$	Minmax	126,000,000	612,000,000	NA	NA	360,000,000	0	8,000,000,000
Urine separation -- early adopters	**wq**	%	Minmax	54.6	81.8	NA	NA	68.2	5	95
	hab	hectares	Determined	0	0	NA	NA	0	5200	0
	supply	MGD	Determined	22	22	NA	NA	22	190	22
	recovery	kg/year	Minmax	860,000	2,780,000	NA	NA	1,320,000	8,500,000	0
	CEC	kg/year	Minmax	25.2	89.5	NA	NA	65.1	22	137
	adapt	%	Minmax	75	95	NA	NA	85	100	0
	slr	scale_constr	Determined	0	0	NA	NA	0	10	-10
	CO2	tonnes CO2 eq/year	Minmax	234,000	351,000	NA	NA	263,000	180,000	900,000
	ease_use	%	Minmax	15	50	NA	NA	35	100	0

	access	Integer	Determined	0	0	NA	NA	0	17	0
	permit	%	Minmax	20	70	NA	NA	40	100	0
	reliable	%	Minmax	52.8	79.2	NA	NA	66	99	50
	costs	$	Minmax	137,000,000	672,000,000	NA	NA	305,000,000	0	8,000,000,000
Urine separation -- incentives	**wq**	%	Minmax	45.4	68.1	NA	NA	56.7	5	95
	hab	hectares	Determined	0	0	NA	NA	0	5200	0
	supply	MGD	Determined	22	22	NA	NA	22	190.1	22
	recovery	kg/year	Minmax	3,030,000	5,680,000	NA	NA	3,790,000	8,500,000	0
	CEC	kg/year	Minmax	13.3	71.3	NA	NA	46.3	22	137
	adapt	%	Minmax	45	65	NA	NA	55	100	0
	slr	scale_constr	Determined	0	0	NA	NA	0	10	-10
	CO2	tonnes CO2 eq/year	Minmax	234,000	351,000	NA	NA	293,000	180,000	900,000
	ease_use	%	Minmax	25	45	NA	NA	35	100	0
	access	Integer	Determined	0	0	NA	NA	0	17	0
	permit	%	Minmax	30	50	NA	NA	40	100	0
	reliable	%	Minmax	60.8	91.2	NA	NA	76	99	50
	costs	$	Minmax	1,960,000,000	13,400,000,000	NA	NA	5,600,000,000	0	8,000,000,000
Optimization	**wq**	%	Minmax	53.8	80.8	NA	NA	67.3	5	95
	hab	hectares	Determined	0	0	NA	NA	0	5200	0
	supply	MGD	Determined	22	22	NA	NA	22	190	22
	recovery	kg/year	Determined	0	0	NA	NA	0	8500000	0
	CEC	kg/year	Minmax	68.6	102.9	NA	NA	85.8	22	137
	adapt	%	Minmax	60	90	NA	NA	75	100	0
	slr	scale_constr	Determined	-5	-5	NA	NA	-5	10	-10
	CO2	tonnes CO2 eq/year	Determined	293,000	293,000	NA	NA	293,000	180,000	900,000
	ease_use	%	Determined	100	100	NA	NA	100	100	0

	access	Integer	Determined	0	0	NA	NA	0	17	0
	permit	%	Minmax	80	100	NA	NA	90	100	0
	reliable	%	Normal	98	0.98	NA	NA	98	99	50
	costs	$	Normal	166,000,000	16,600,000	NA	NA	166,000,000	0	8,000,000,000
Level 2	**wq**	%	Minmax	28.8	43.2	NA	NA	36.0	5	95
	hab	hectares	Determined	0	0	NA	NA	0	5200	0
	supply	MGD	Determined	22	22	NA	NA	22	190	22
	recovery	kg/year	Determined	0	0	NA	NA	0	8500000	0
	CEC	kg/year	Minmax	62.4	93.5	NA	NA	77.9	22	137
	adapt	%	Minmax	30	75	NA	NA	55	100	0
	slr	scale_constr	Determined	-5	-5	NA	NA	-5	10	-10
	CO2	tonnes CO2 eq/year	Minmax	301,000	451,000	NA	NA	376,000	180,000	900,000
	ease_use	%	Determined	100	100	NA	NA	100	100	0
	access	Integer	Determined	0	0	NA	NA	0	17	0
	permit	%	Minmax	80	100	NA	NA	90	100	0
	reliable	%	Normal	98	0.98	NA	NA	98	99	50
	costs	$	Normal	2,490,000,000	249,000,000.8	NA	NA	2,490,000,000	0	8,000,000,000
Level 3	**wq**	%	Minmax	13.5	20.2	NA	NA	16.8	5	95
	hab	hectares	Determined	0	0	NA	NA	0	5200	0
	supply	MGD	Determined	22	22	NA	NA	22	190	22
	recovery	kg/year	Determined	0	0	NA	NA	0	8,500,000	0
	CEC	kg/year	Minmax	62.4	93.5	NA	NA	77.9	22	137
	adapt	%	Minmax	5	15	NA	NA	10	100	0
	slr	scale_constr	Determined	-5	-5	NA	NA	-5	10	-10
	CO2	tonnes CO2 eq/year	Minmax	528,000	791,000	NA	NA	659,000	180,000	900,000
	ease_use	%	Determined	100	100	NA	NA	100	100	0

	access	Integer	Determined	0	0	NA	NA	0	17	0
	permit	%	Minmax	80	100	NA	NA	90	100	0
	reliable	%	Normal	98	0.98	NA	NA	98	99	50
	costs	$	Normal	3,250,000,000	325,000,000	NA	NA	3,250,000,000	0	8,000,000,000

Abbreviations:
Criteria:
wq = water quality (% likelihood of deviating from good ambient water quality based on nutrient loading such that it impairs beneficial uses)
Hab = provision of wetland habitat (hectares of wetland habitat)
Supply = provision of useable water (MGD of recycled water supplied)
Recovery = resource recovery from wastewater (kg/year of nitrogen recovered from urine)
CEC = treatment of contaminants of emerging concern (kg/year sulfamethoxazole loading)
Adapt = ease of adaptation of technology to changing conditions (% ease of adaptation)
Slr = resilience to sea level rise (constructed scale in which -10 is highly vulnerable, 0 is unaffected, and 10 protects other infrastructure)
CO_2 = lifecycle CO_2 emissions associated with wastewater treatment (including the nutrient control option) (tonnes CO_2 equivalents/year)
Ease_use = ease of public to use the technology (% ease of use)
Access = increased shoreline access to aesthetically nice places (number of access points)
Permit = ease of acquiring permits for technology (% ease of permitting)
Reliable = reliability of technology (% of time the technology operates as intended)
Costs = net present value of capital investment and 30-year operations and maintenance costs
Uncertainty distributions:
Minmax = uniform distribution (parameter 1 is minimum value, parameter 2 is maximum value
Determined = no uncertainty
Normal = normally distributed (parameter 1 is mean, parameter 2 is standard deviation)
Beta = beta distribution (parameter 1 is alpha, parameter 2 is beta; max scalar and min scalar columns scale the beta distribution to the values of the data based on 10 and 90 quantiles)

Table S3. Mean attribute values for Worst-case scenario (uncertainty distributions for each parameter remain the same as in Table S2)

objective	units	Do nothing	Wetland levee	Wetland openwater	Recycle irrig.	Recycle brineline	Urine early	Urine incentives	Opt.	Level 2	Level 3
wq	% likelihood deviation	84.7	51.6	39.7	73.3	74	77.8	63.2	79.7	42.4	19.6
hab	square hectares	0	4,470	901	0	0	0	0	0	0	0
supply	MGD	22	22	22	119	106	22	22	22	22	22
recovery	Kg N/year	0	0	0	3,420,000	0	3,150,000	6,480,000	0	0	0
CEC	Kg SMX/year	103	70.9	83.6	76.9	80.5	61.2	47.7	103	93.4	93.9
adapt	% ease of adaptation	100	52.2	42.8	45.4	45	85.1	54.8	75.4	52.9	9.97
slr	scale -10 to 10	-10	3	0	-8	-10	0	0	-10	-10	-10
CO2	CO2 eq/year	351,000	407,000	374,000	486,000	767,00000	354,000	351,000	352,000	451,000	772,000
ease_use	% ease of use	100	100	100	100	55.7	32.7	35.1	100	100	100
acces	Number of access points	0	8.56	8.56	0	0	0	0	0	0	0
permit	% ease of permitting	100	33.2	30.3	80	45.3	44.5	40.1	89.9	90.3	90
reliable	% of time reliable	100	76.9	75.2	89.5	95.5	66	75.4	97.7	97.7	97.7
costs	Total present value (30 year life span)	0	2.83E+09	1.44E+09	2.34E+09	3.83E+08	7.09E+08	6.89E+09	2.01E+08	2.99E+09	3.93E+09

Table S4. Mean attribute values for Best-case scenario (uncertainty distributions for each parameter remain the same as in Table S2)

objective	units	Do nothing	Wetland levee	Wetland openwater	Recycle irrig.	Recycle brineline	Urine early	Urine incentives	Opt.	Level 2	Level 3
wq	% likelihood deviation	30.9	9.34	5.25	18.8	19.5	30.3	25.5	26.9	9.47	5.26
hab	square hectares	0	3130	558	0	0	0	0	0	0	0
supply	MGD	22	22	22	112	96.3	22	22	22	22	22
recovery	Kg N/year	0	0	0	3,070,000	0	160,000	1,570,000	0	0	0
CEC	Kg SMX/year	55.9	35	44.5	31.2	35.6	53.6	40.1	56.1	50.9	51.1
adapt	% ease of adaptation	100	52.4	42.7	45.4	44.5	84.9	55.4	75.1	52.7	9.97
slr	scale -10 to 10	-5	8	5	-3	-5	0	0	-5	-5	-5
CO2	CO2 eq/year	204,000	230,000	211,000	316,000	60,100,000	2.00E+05	2.00E+05	191,000	248,000	431,000
ease_use	% ease of use	100	100	100	100	54.5	32.7	35.3	100	100	100
access	Number of access points	0	8.55	8.46	0	0	0	0	0	0	0
permit	% ease of permitting	100	32.8	31.7	80	45.9	44.8	40	90.2	89.8	89.8
reliable	% of time reliable	100	76.8	76.9	91.5	97.7	65.6	75.8	97.7	97.8	97.7
costs	Total present value (30 year life span)	0	1.99E+09	8.73E+08	2.25E+09	3.46E+08	35600000	3.93E+09	1.08E+08	1.64E+09	2.12E+09

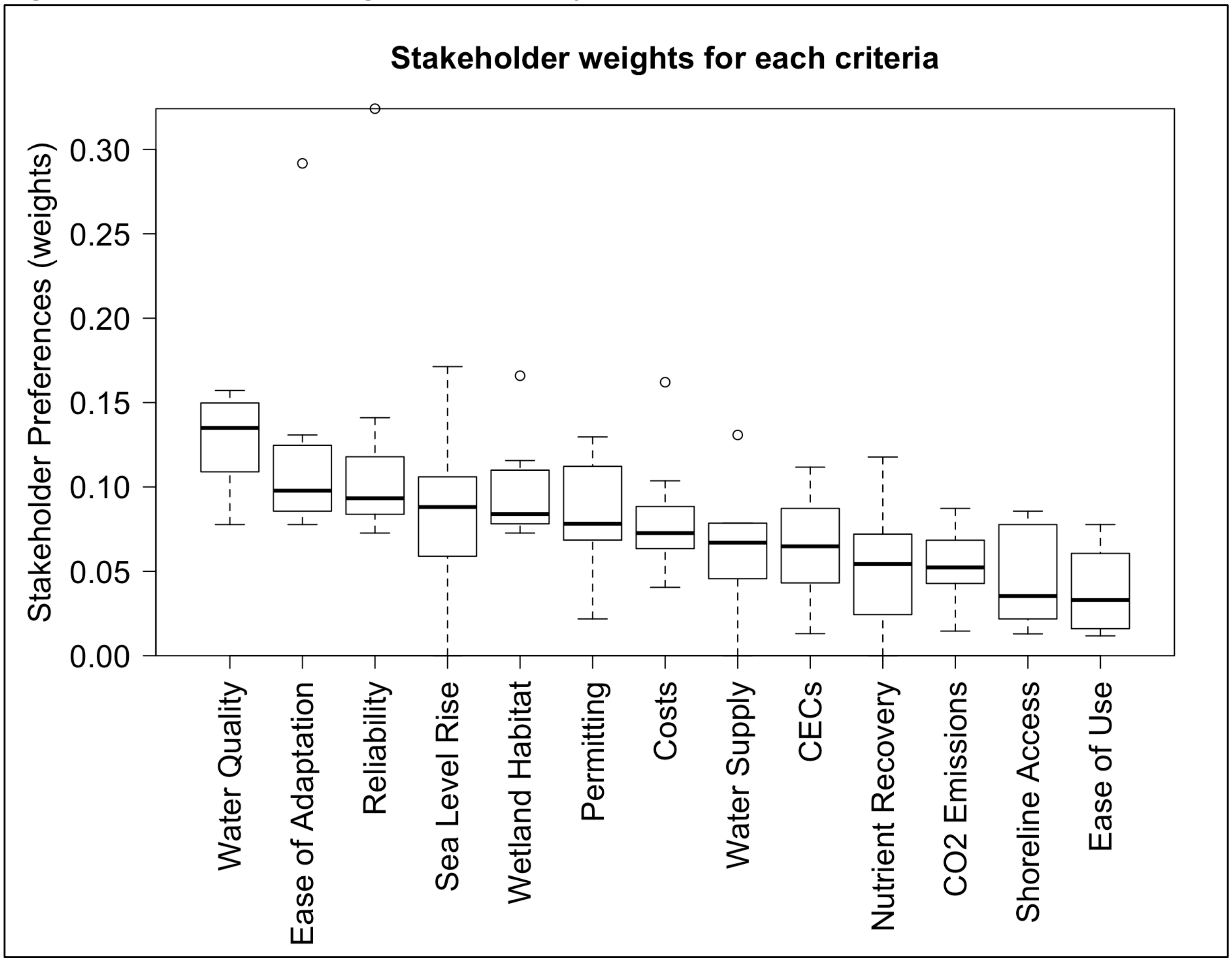
Table S5. Mean attribute values for status quo population growth with current ecological response to nutrient loading (uncertainty distributions for each parameter remain the same as in Table S2)

objective	units	Do nothing	Wetland levee	Wetland openwater	Recycle irrig.	Recycle brineline	Urine early	Urine incentives	Opt.	Level 2	Level 3
wq	% likelihood deviation	51.3	23.1	15.1	38.6	39.4	46.5	36.5	45.8	19	5.24
hab	square hectares	0	4,160	792	0	0	0	0	0	0	0
supply	MGD	22	22	22	116	103	22	22	22	22	22
recovery	Kg N/year	0	0	0	3,310,000	0	1,830,000	4,330,000	0	0	0
CEC	Kg SMX/year	86.1	55.2	69.1	59.6	63.5	57	46.4	85.8	78.7	78
adapt	% ease of adaptation	100	52.6	42.7	45.2	44.5	85	54.8	74.7	52.8	9.9
slr	scale -10 to 10	-5	8	5	-3	-5	0	0	-5	-5	-5
CO2	CO2 eq/year	292,000	345,000	309,000	424,000	70,300,000	292,000	293,000	293,000	375,000	657,000
ease_use	% ease of use	100	100	100	100	54.8	31.6	35.1	100	100	100
access	Number of access points	0	8.5	8.5	0	0	0	0	0	0	0
permit	% ease of permitting	100	32.2	30.7	80	45	45.2	40.2	90.1	90.3	90
reliable	% of time reliable	100	76.7	77.5	91.5	97.7	66.1	75.9	97.7	97.7	97.8
costs	Total present value (30 year life span)	0	2.59E+09	1.24E+09	2.22E+09	3.71E+08	4.05E+08	5.28E+09	1.66E+08	2.49E+09	3.24E+09

Table S6. Median overall scores for each option including recycle-brineline, Status quo scenario

	Do nothing	Wetland levee	Wetland openwater	Recycle irrig.	Recycle brineline	Urine early	Urine incentives	Opt.	Level 2	Level 3
SH1	0.536	0.591	0.529	0.545	0.432	0.424	0.400	0.515	0.508	0.492
SH2	0.536	0.591	0.529	0.545	0.432	0.424	0.400	0.515	0.508	0.492
SH3	0.536	0.591	0.529	0.545	0.432	0.424	0.400	0.515	0.508	0.492
SH4	0.536	0.591	0.529	0.545	0.432	0.424	0.400	0.515	0.508	0.492
SH5	0.536	0.591	0.529	0.545	0.432	0.424	0.400	0.515	0.508	0.492
SH6	0.536	0.591	0.529	0.545	0.432	0.424	0.400	0.515	0.508	0.492
SH7	0.536	0.591	0.529	0.545	0.432	0.424	0.400	0.515	0.508	0.492
SH8	0.536	0.591	0.529	0.545	0.432	0.424	0.400	0.515	0.508	0.492
SH9	0.536	0.591	0.529	0.545	0.432	0.424	0.400	0.515	0.508	0.492

Figure S2. Stakeholder weights for each objective



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

Figure S3. Median overall values of options for each stakeholder in Best- and Worst-case scenarios

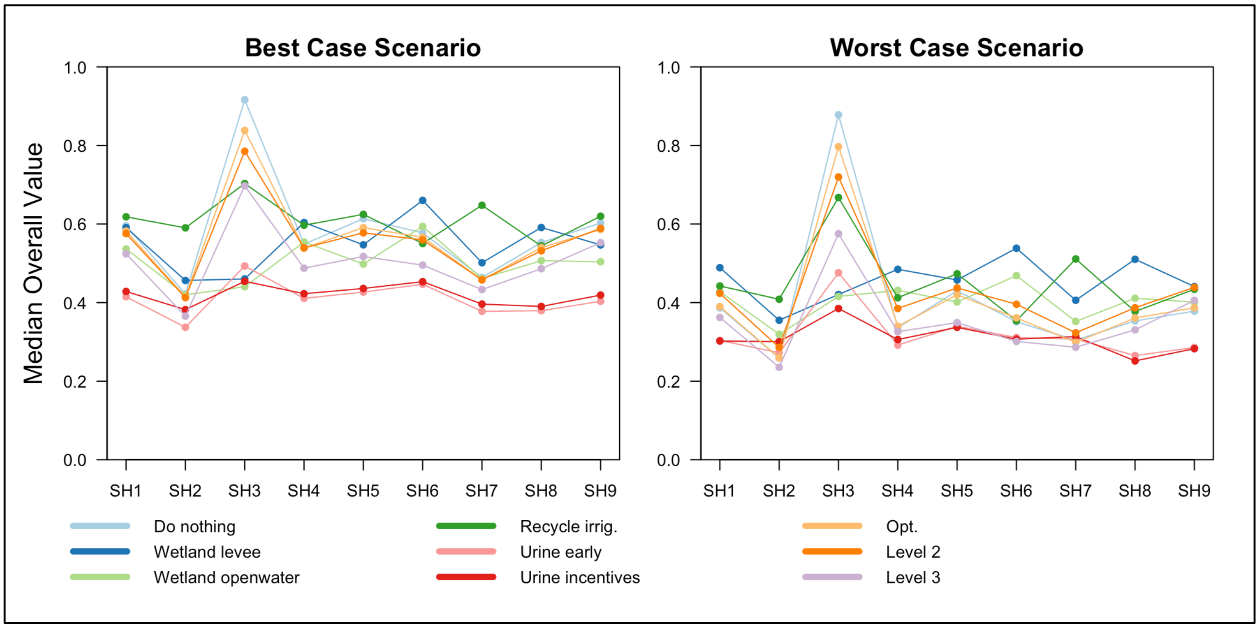
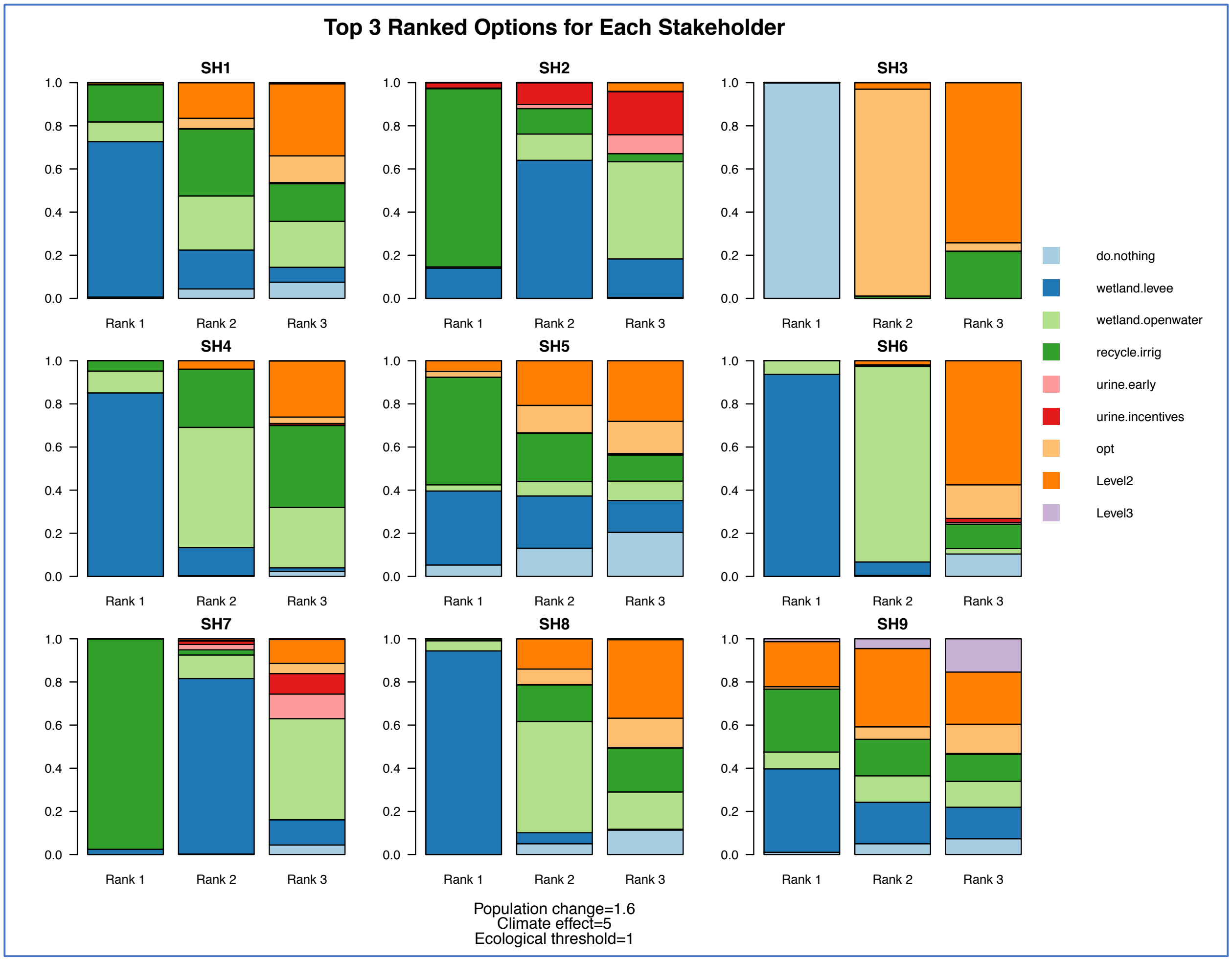
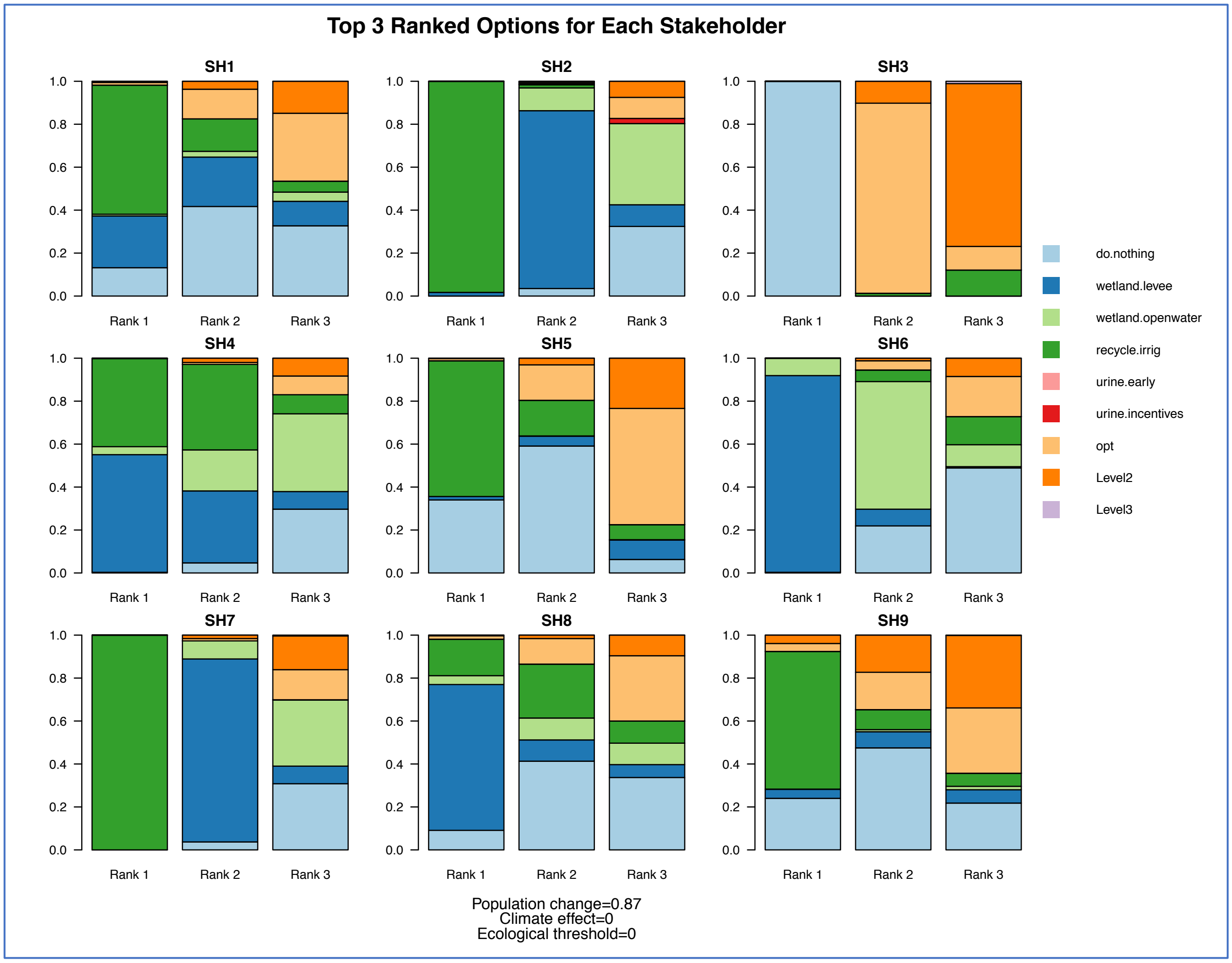


Figure S4. Probability of top 3 ranked options for each stakeholder, Worst-case scenario



The probability of the top three ranked options for each stakeholder given uncertainty in attribute predictions, assuming 60% population growth, large effects of climate change on wastewater treatment, and increased ecological sensitivity to nutrient loading in the Bay.

Figure S5. Probability of top 3 ranked options for each stakeholder, Best-case scenario



The probability of the top three ranked options for each stakeholder given uncertainty in attribute predictions, assuming 13% population decline, no effects of climate change on wastewater treatment, and current resilience to nutrient loading in the Bay.

Figure S6. Probability of ranks of options for each stakeholder, Status quo scenario

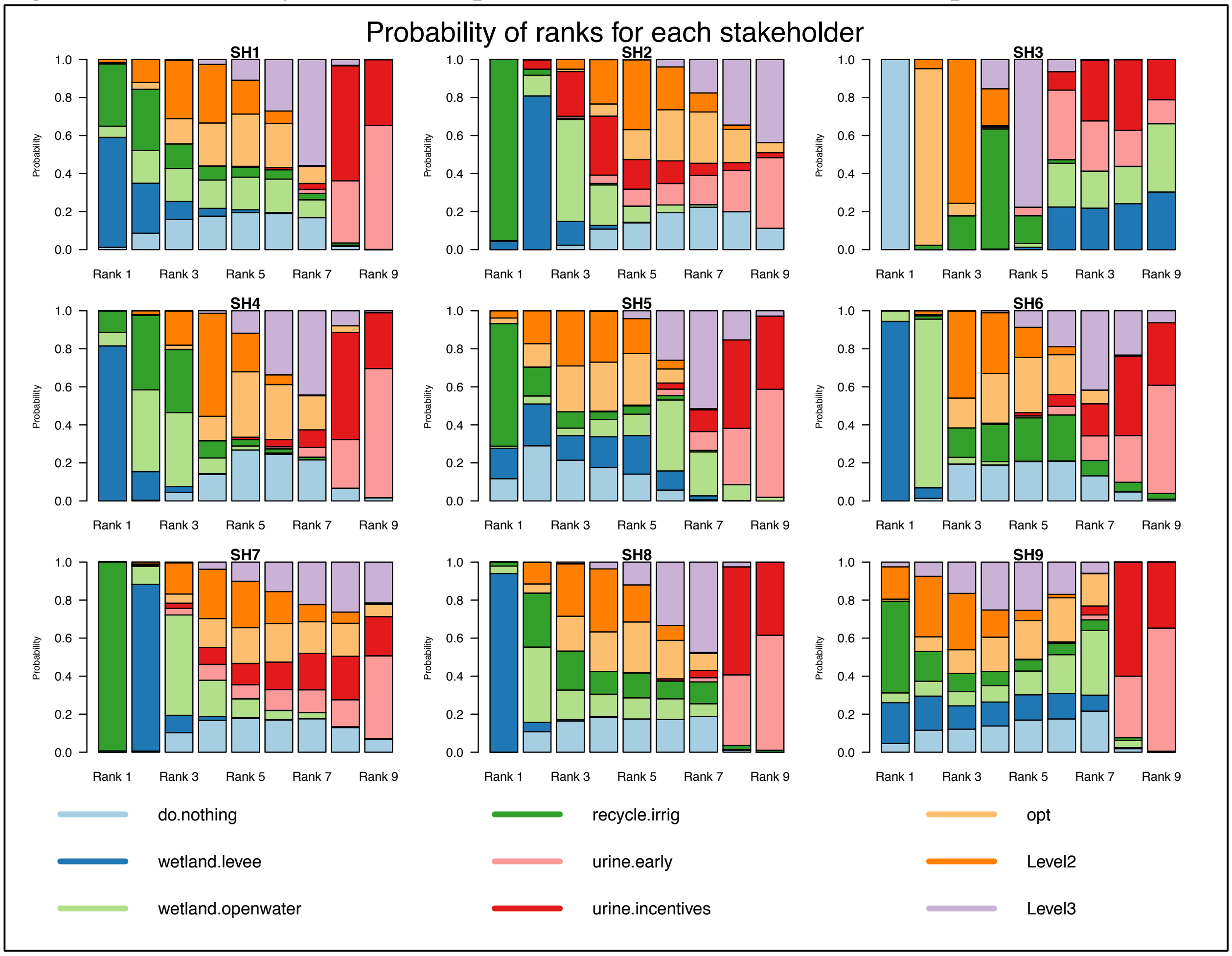


Figure S7. Probability of ranks of options for each stakeholder, Best-case scenario

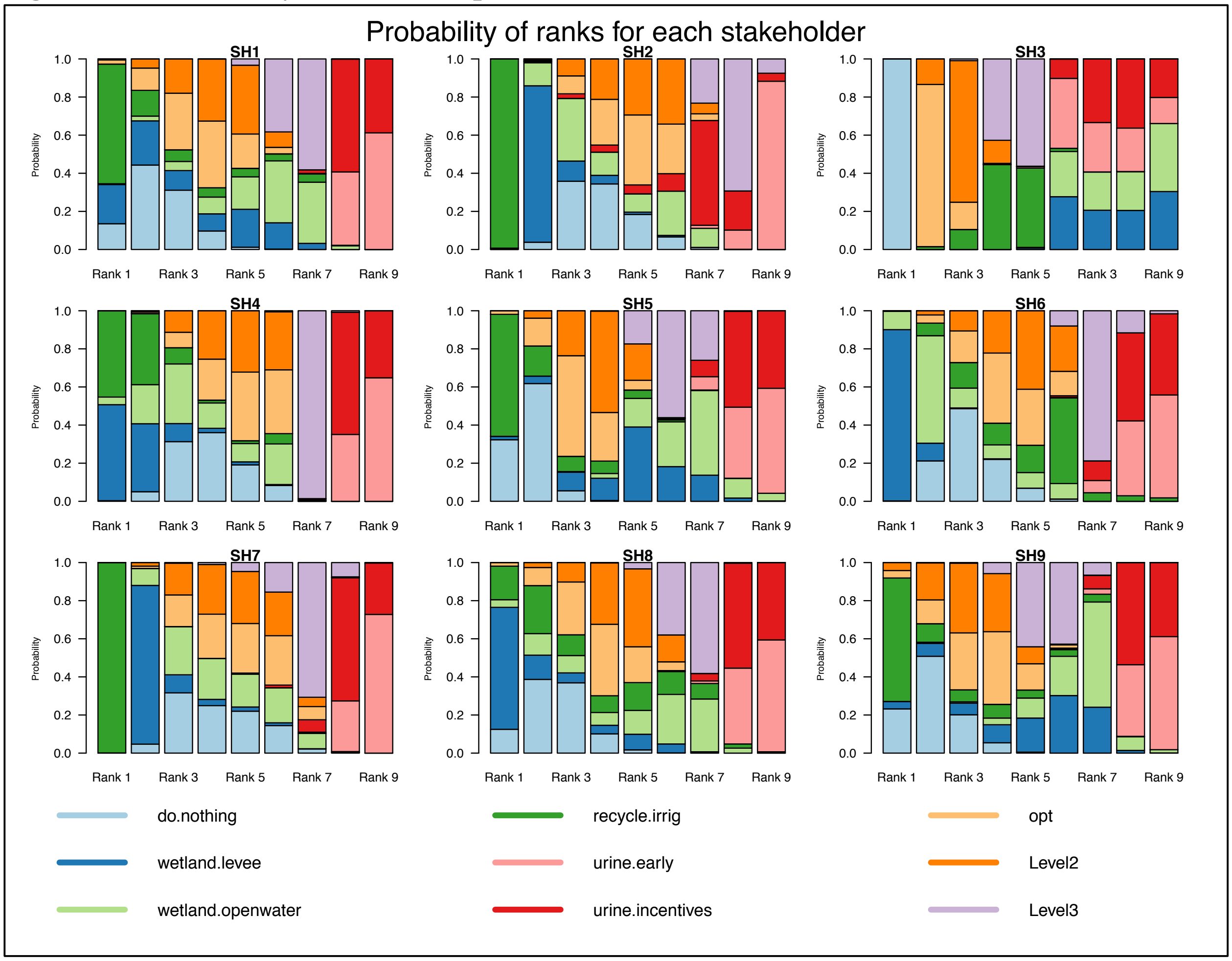


Figure S8. Probability of ranks of options for each stakeholder, Worst-case scenario

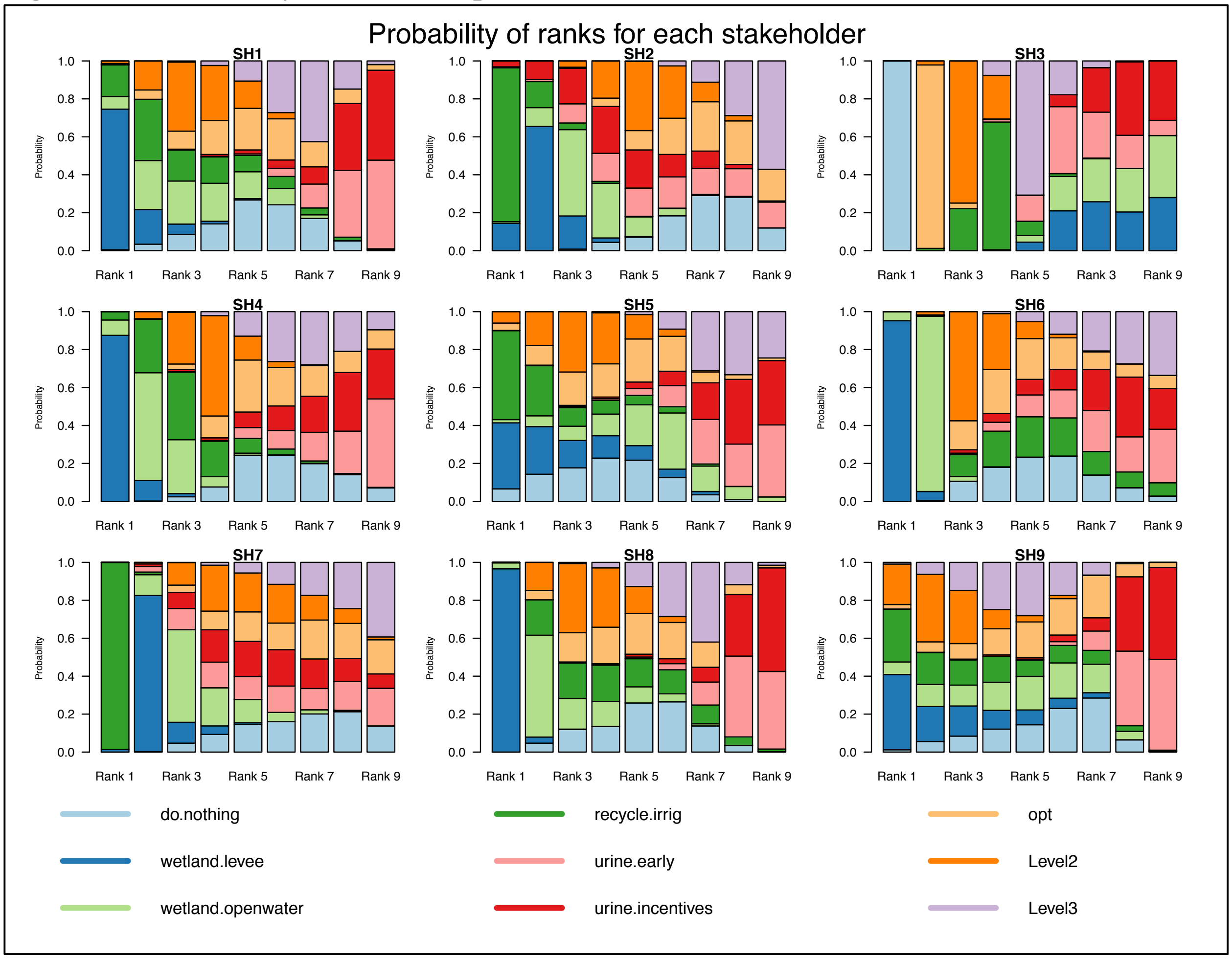


Figure S9. Cost-efficiency compared to median MCDA overall value for three stakeholders.

These three stakeholders exemplify the range in regression slopes amongst all interviewed stakeholders. Stakeholder SH2 (a discharger) had a slight negative correlation between cost-efficiency and MCDA overall value. This person's preferences depended more on other goals for nutrient management (which were captured in the MCDA) than on traditional cost and nutrient removal metrics. Less cost-efficient options tended to appeal more to SH2 because of the option's other benefits. SH5 (a Baylands steward) had roughly 0 correlation between cost-efficiency and MCDA overall value, signifying that cost-efficiency had no bearing on the overall value of an option for this person. SH6 (a regulator) had a positive correlation between cost-efficiency and MCDA overall value, signifying that this person tended to value options more highly in the MCDA that were more cost-efficient.

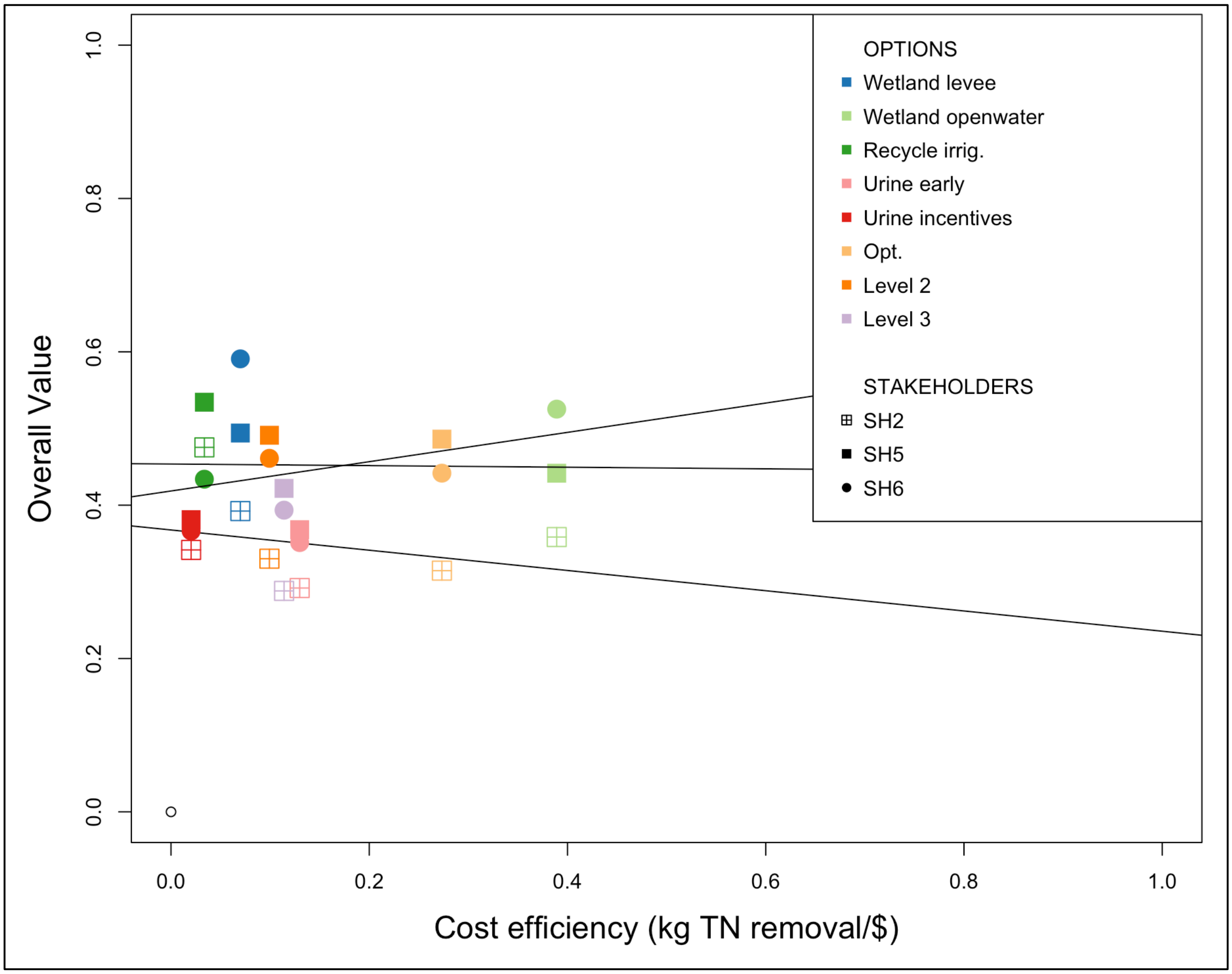


Figure S9. Cost efficiency compared to MCDA median overall value for each option for stakeholders SH2, SH5, and SH6. Ordinary least squares regression lines show SH2 has a negative correlation between cost efficiency and overall value (slope of -0.13), SH5 has roughly 0 correlation (slope of -0.01), and SH6 has a positive correlation (slope of 0.19). The higher the cost efficiency score and the overall value, respectively, the better is the performance of an alternative.

Figure S10. Sensitivity analysis of overall value for each option with different combinations of additive and Cobb-Douglas aggregation functions, assuming Status quo scenario.

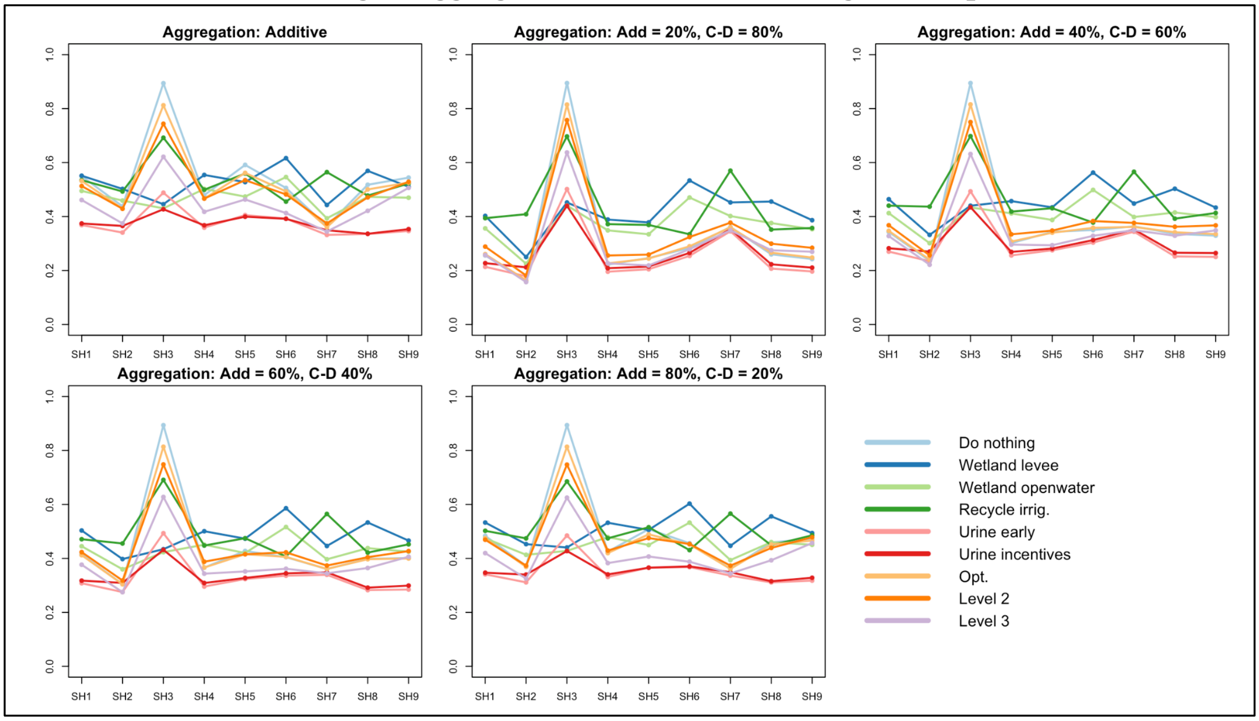
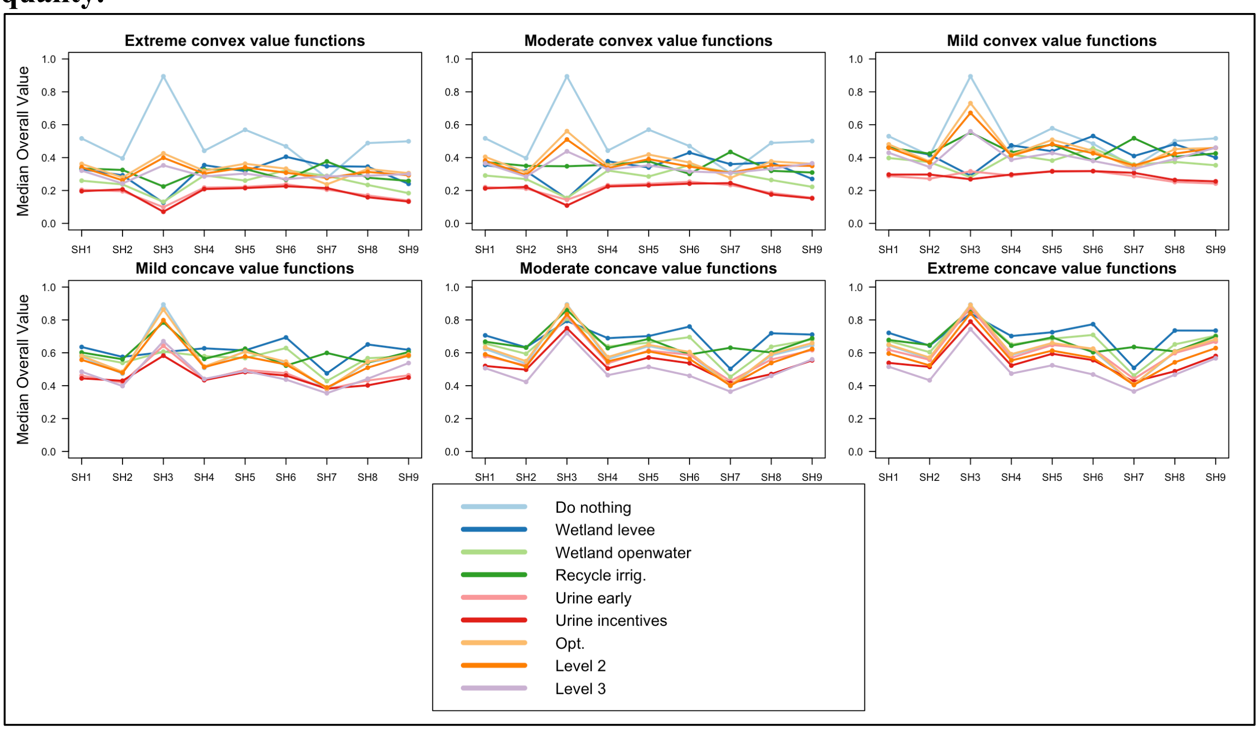
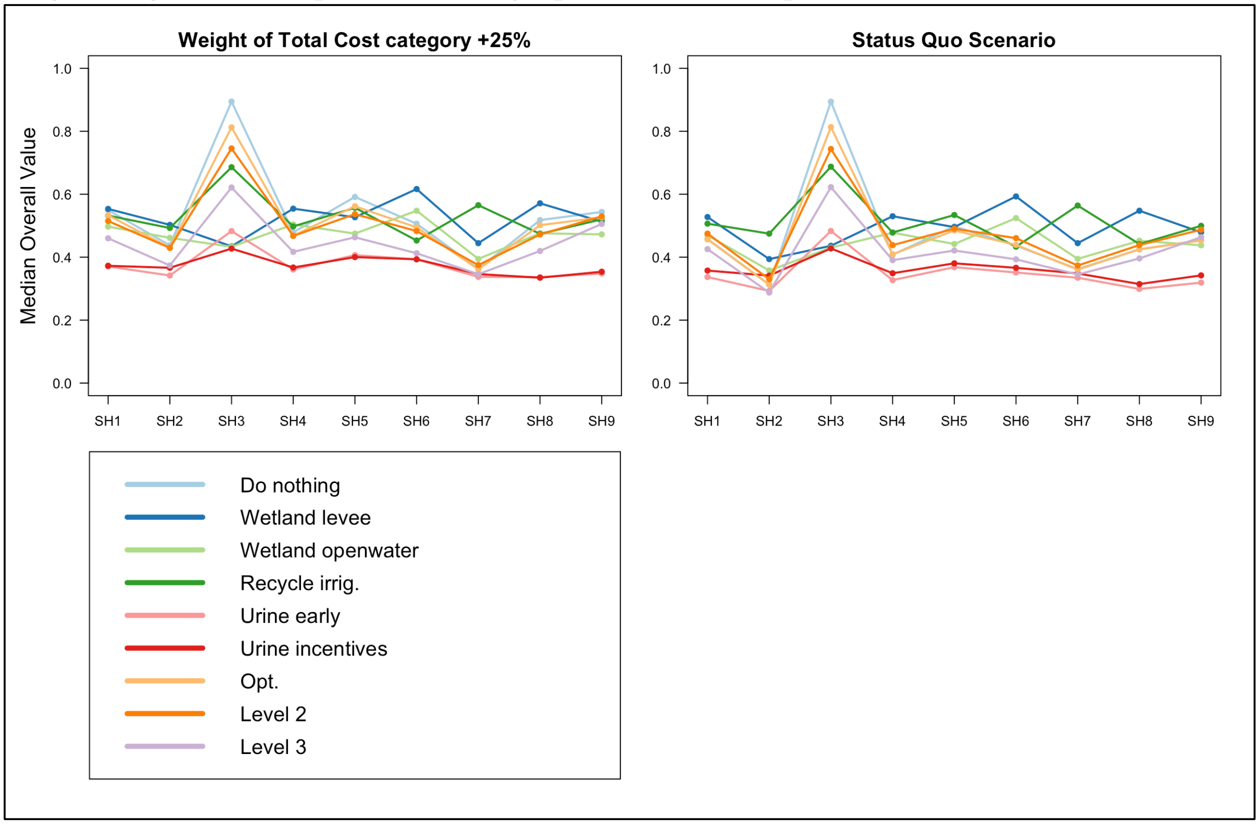


Figure S11. Sensitivity analysis of overall value for each option given different curvatures of value functions for the objectives ease of adaptation, permitting, reliability, and water quality.



Convex value functions imply greatest marginal overall value gained with improvement at low *levels of attribute value. Concave value functions imply greatest marginal overall value gained with improvement at high levels of attribute value. Several stakeholders mentioned concave value functions for the objectives stated above; convex value functions are shown here as well for comparison.*

Figure S12. Sensitivity analysis of median overall value for each option if stakeholders undervalued weight of total cost in interviews by 25% (left). Shown with voiced cost weights (right) for comparison. Both graphs show status quo scenario.



Conclusion

There is broad interest in transitioning urban water systems from a linear model that consists of unit processes for purifying water in treatment plants, to integrated systems that recover resources and provide other benefits such as wildlife habitat and aesthetic values. Such water systems are designed to protect public and environmental health while also integrating other community values, like intergenerational equity, holistic ecosystem health, and participation in a circular economy. This new paradigm of water system builds towards a community-driven definition of livable, sustainable communities rather than being constructed with the sole goals of responding to regulations for protection of public and environmental health as traditional water systems are.

The multi-benefit technologies emphasized in this new paradigm of water infrastructure systems are well-suited to simultaneously preventing environmental degradation in multiple arenas like water, air, and habitat, while also providing services like water supply or habitat creation. These multiple benefits help hedge against risks posed by future uncertainties, because even if the primary design impetus (i.e., nutrient control) ends up being less problematic than expected, a multi-benefit solutions that provides wildlife habitat, freshwater supply, or resource recovery would still be seen as a net benefit overall. In addition, water systems designed with multiple benefits can appeal to the needs of different stakeholders by incorporating diverse objectives into design criteria. For these reasons, multi-benefit water infrastructure provides promise in today's context of climate change, complex environmental problems that span the mandates of different agencies in different jurisdictional areas, and expectations of increasing participation by previously marginalized stakeholders in environmental planning.

In California, integrated water management, a process in which water managers and planners jointly consider steps to improve water quality, create effective flood management, restore ecosystems, and increase water supply reliability, is becoming increasingly important in the planning process. This importance is codified in planning documents that highlight a trending interest toward integrated water management. For example, the 2013 Update to the California Water Plan stated that new water systems should be sustainable and resilient, meaning they should have social benefits in terms of enhanced public safety, environmental benefits, and foster economic stability (California Department of Water Resources, 2014). The California Water Plan also highlights the importance of multi-benefit projects. It asserts a need for "inter-agency alignment" and collaboration among agencies, technical experts, and other stakeholders. The San Francisco Bay's Integrated Regional Water Management Plan (IRWMP), another long-term planning document, also focuses on the importance of stakeholder engagement, multi-objective water infrastructure solutions, and water planning that integrates management of drinking water, stormwater and wastewater (*San Francisco Bay Area Integrated Regional Water Management Plan*, 2013).

Yet these documents do not provide managers with guidance about how to transition from current modes of planning and decision making about water infrastructure to the new practices that are essential to integrated water management. Decision-makers are often cautious about new approaches for water management because they are concerned about the risks associated with adoption of unproven technologies (Kiparsky et al., 2013), and they lack the tools needed to balance the many factors associated with IRWMP and other multi-benefit water infrastructure (Ferguson et al., 2013a).

Realizing this new paradigm for multi-benefit water systems will require institutions to overcome many practical constraints. Moving towards implementation of multi-benefit urban water infrastructure requires radical shifts in planning processes, legitimization of innovative technologies in their socio-cultural contexts, and institutional collaboration across agencies. Furthermore, it may require re-thinking and re-defining the roles of environmental institutions like regulatory agencies, who currently have constrained institutional mandates limited to setting and enforcing environmental regulations. Public water utilities may also need to broaden their scope to include collaboration with other agencies, with city planners, or with ecologists.

It is important to note that ignoring the environmental and social drivers towards multi-benefit water infrastructure entails several risks. For example, water projects conceived without participatory planning and associated community input of goals and desired outcomes has doomed several costly projects to failure because of public opposition (Hartley, 2006). In addition, designing water systems for the sole purpose of responding to environmental degradation under shifting ecological conditions and with many stakeholders can sometimes be extremely expensive without being wholly effective, as in the case of nutrient management in the Chesapeake Bay (Butt and Brown, 2000).

New tools will be required to support decision-making for this new paradigm of water infrastructure. Qualitative research approaches that take a sociological lens to water infrastructure planning can be helpful in this regard, as can a historical focus to contextualize the issues, as demonstrated in previous chapters. In addition, quantitative multi-criteria decision analysis can help define the problem and facilitate the elicitation of multiple goals from stakeholders, while providing analysis and encouraging discussion of a range of potential solutions. Scenario planning can facilitate development of innovative options as well as determine the effects of future uncertainties on management options. Stakeholder analysis provides a means of understanding and defining who is involved with the problem, its scope, and the social and institutional challenges to finding mutually acceptable solutions. These methods can contribute to a growing body of academic literature which addresses socio-technical transitions towards sustainability in water infrastructure and environmental resources management (Farrelly and Brown, 2011; Ferguson et al., 2013b; Pahl-Wostl, 2007; Truffer et al., 2010).

My dissertation research provides an example of several potential approaches that can help address these needs. Sociological analysis of legitimacy of an innovative technology (i.e., potable water reuse) can improve understanding of how a new technology can diffuse into practice if it fits into societal norms and cultural contexts. Multi-criteria decision analysis paired with stakeholder analysis and scenario planning (i.e., in the case study on nutrient management strategies in the San Francisco Bay) facilitates regional planning and network formation associated with multi-benefit infrastructure investments. These case studies aimed to consider water reuse and nutrient management in their social, technological, and environmental contexts in order to illustrate the ways in which tools not currently in wide use by utilities and water managers can support decision-making around these complex issues in the future. Both of these approaches could aid planning and implementation around different types of water challenges and new technologies, for example, decentralized wastewater treatment or stormwater capture and reuse.

Application of the sociological lens of legitimacy to an innovative water technology like potable reuse provided a means for engineers, managers, and public health experts to better understand the socio-cultural conditions which facilitate adoption of a new technology in a particular locale. By employing concepts developed by sociologists to socio-technical transitions in water infrastructure planning, this research provided insight into the social and institutional arrangements that enabled potable water reuse to be adopted in some places and caused it to be rejected in others. Building greater understanding of how ideas of legitimacy play into adoption of potable reuse projects in different cultural contexts and with institutional arrangements, for example in Texas or in the European Union, would be an interesting extension of the research.

Since its publication in 2015, the concept of legitimacy for explaining adoption of innovative urban water infrastructure has gained traction: the U.S. Environmental Protection Agency has consulted with the authors and referred to the legitimacy framework address other innovative water technologies and management strategies, including innovative stormwater management technologies. This positive response from this key group indicates the approach can be useful in a range of water infrastructure planning contexts. For example, research to apply a sociological lens of legitimacy to understand adoption and barriers to implementation of decentralized wastewater treatment and reuse could also be a useful addition.

Public perceptions towards innovative water technologies are only part of the enabling conditions towards a new paradigm of water infrastructure. Rules and regulations may constrain the development and implementation of these options even if there is strong public support for them. More understanding of regulatory legitimacy for innovative water technologies – that is, the context in which regulations are formed and interpreted to support these systems and practices, would also be a valuable extension to this work.

The mixed-methods approach to gaining insight into alternative nutrient management strategies in the San Francisco Bay employed both quantitative and qualitative methodologies to develop and analyze options for comprehensive water infrastructure planning. These methods provided a means of highlighting and realizing stakeholder preferences and objectives the development of potential management options. In contrast to many existing approaches to water infrastructure planning, it incorporated a diverse set of stakeholders into setting objectives for water infrastructure, examined innovative as well as traditional management options, and clarified areas of agreement and disagreement among stakeholders that could lead to difficulties in regional collaboration if not addressed. In addition, this methodological approach resulted in an improved understanding of the role of multi-criteria decision analysis can play in regional environmental planning,

One specific outcome of the mixed-methods approach to understanding nutrient management options was that it highlighted the need to establish shared regional goals and a vision of success that is common to key stakeholders. Multi-benefit water infrastructure faces the nebulous (and sometimes Herculean) task of providing many different services to users and the environment. Clear shared definitions of what these benefits should be, and how to measure their fulfillment, are essential to planning and implementing successful multi-benefit water infrastructure projects. By articulating these goals at the outset of project planning, stakeholders are more able to accurately assess the ways in which innovative and multi-benefit technologies meet their needs (or not) compared to traditional infrastructure options.

In the Bay Area nutrients management case, further iterations of stakeholder-informed multi-criteria decision analysis could refine management options as regulation progresses, to improve outcome predictions as scientific advances about nitrogen effects on the Bay ecosystem are made, and to provide insight at the wastewater utility scale (rather than solely at the regional scale). Each wastewater utility in the region will need to engage with local stakeholders to develop nutrient management options that meet local goals and constraints within the context of regional goals. Further refinement of the analytical code to quantitatively assess the multi-criteria decision analysis (developed in the open-source software program R) to be more 'user-friendly' for regional planners and utility-scale water managers would be highly beneficial for making the research methods more broadly useable and applicable going forward. In addition, application of multi-criteria decision analysis combined with stakeholder analysis and scenario planning to other environmental problems, such as water supply provision, transportation planning, or energy planning could provide useful insight to these cases.

One limitation of our mixed-methods approach to planning for nutrient management was that it did not result in an actionable solution. Furthermore, since stakeholders' identities are anonymized in the research protocol, it may be difficult in practice for stakeholders to have productive discussions about areas of disagreement made evident in the research. Further application and modification of these methods to clearly analyze and support options for practical action for water management would be helpful.

The core studies in this dissertation highlight the need for increased stakeholder participation in planning processes for water infrastructure. Part of this need stems from the fact that the collaborative planning process itself appears to make communities and agencies more able to tackle forthcoming complex environmental problems because of strengthened social networks and enhanced communication (Duane, 1997; Hester, Randolph, 2010; Innes and Booher, 2005; Stern et al., 2008) Stakeholder participation in water infrastructure planning is stark change from historical norms for urban and environmental planning processes, in which natural resource (and much other landscape level) planning was conducted by "neutral" experts who were called on to compile and analyze data to make rational decisions (Innes and Booher, 2010).

However, stakeholder participation for collaborative planning is not easy to achieve in practice. If it does not live up to its claims, it can be an expensive, frustrating process that does not result in clear, easily-implemented outcomes (Reed, 2008). Ideally, participatory processes enable the voices of marginalized or ignored groups to be heard and expressed (Sanoff, 2000), but this is not always the case in practice, because stakeholders with more time, money, or political capital may have an outsized voice in the process (Irvin and Stansbury, 2004; Reed et al., 2009). Facilitation of collaborative planning processes can be expensive, with more initial capital required than the traditional "decide, announce, defend" approach to expert planning (Charnley and Engelbert, 2005; Innes and Booher, 2005). Further research on the types and modes of stakeholder participation that are most beneficial for urban water infrastructure planning would be useful. For example, guidelines for how to choose stakeholders for regional MCDA processes, and analysis of ways in which different types of participation in planning result in different outcomes, would be valuable additions to the literature.

Though the research used to develop and exemplify the decision-support tools for water infrastructure planning in this dissertation focused on California case studies, the strategies themselves are likely applicable in many other cases such as transportation, energy planning, and urban planning. Future applications and modifications of these strategies in new contexts and to different local environmental challenges would be useful. In addition, though the cases studied focused on centralized water systems, similar methods could be used to assist with the planning and implementation of decentralized options for water and wastewater treatment and reuse.

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