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REVIEW

A review of residential water conservation policies and attempts to measure their effectiveness

Alexander Maas[1]*, Roshan Puri[2], Christopher Goemans[3]

1 Dept. of Agricultural Economics and Rural Sociology, University of Idaho, Moscow, Idaho, United States of America, **2** Center for Watershed Sciences, UC Davis, Davis, California, United States of America, **3** Dept. of Agricultural and Resource Economics, Colorado State University, Fort Collins, Colorado, United States of America

* alexmaas@uidaho.edu

Abstract

With escalating global water scarcity and increasing pressures on freshwater resources, demand-side management has emerged as a crucial tool for sustainable water resource management. This paper reviews residential, demand-side water management strategies, focusing primarily on price mechanisms. We trace the evolution of price structures and attempts to estimate consumer responses under these structures, highlighting the methodological and practical difficulties with estimating elasticity under non-linear billing structures. We also include a tertiary review of previous research into non-pecuniary strategies, such as restrictions, and information/education campaigns. This review serves as a primer for policymakers, water managers, and researchers seeking to design and evaluate demand-side management in residential water use.

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Introduction

Water scarcity is an escalating global challenge and of particular concern in arid regions with growing populations and changing climate regimes. Arid lands are currently home to more than 38% of the total global population, and this proportion is expected to grow over the next century [1]. In the United States (US), seven of the ten fastest growing states—measured by percent change from 2010 to 2020 [2]—are also ranked in the top ten most arid states, as measured by average precipitation. In the context of this increased pressure, utilities, municipalities, and regional decision-makers are tasked with balancing water supply and demand, with the ultimate goal of creating resilient drinking water systems with sufficient supplies to promote economic prosperity and healthy communities.

Traditional supply-side approaches have become increasingly unpopular for several reasons. First, most high-quality dam sites have already been developed. Where options do exist, rapidly increasing environmental, monetary, and regulatory costs make supply expansion projects difficult to pursue [3]. Questions about the effectiveness of new storage projects in the face of climate change have also been raised [4]. Transporting water long distances (from wet to dry areas) is often prohibitively expensive and usually faces public scrutiny. Other supply-side management programs, including water reallocation via water markets, have also been called into question given concerns surrounding their economic and social impacts [5]. For these and other reasons, water regulators and policymakers have focused largely on demand-side management (DSM) strategies in recent decades.

DSM includes a wide range of policies aimed at balancing municipal water demand with available short- and long-term supplies by reducing water consumption (either temporarily or permanently). For the purposes of this article, we classify DSM into three categories: (1) pricing policies, in which the price of water is used directly to incentivize reductions in water use; (2) non-price policies, which include restrictions on water use and rebates offered to incentivize the adoption of water saving practices and technologies; and (3) information and education policies, in which additional information or "nudges" are used to change customer behavior regarding their water use.

Here we provide a broad overview of residential and municipal water use in the US, along with a detailed overview of DSM strategies, and academic literature that estimates their effectiveness. For context, we begin by presenting consumption trends and the laws governing water treatment and delivery to utility customers. We then discuss the current state of the literature relating to each of the DSM categories presented above, highlighting important areas for future research.

Water use trends and the provision of water to residential, commercial, and industrial users

Despite growing concerns regarding future water shortages, total freshwater water withdrawals in the US have plateaued—or even declined—since the 1980's [6–8]. This is true for all major categories (e.g., agriculture, industrial, etc.), including withdrawals for domestic use and public supply. This decline reflects the impacts of DSMs as well as physical scarcity, since withdrawal cannot occur when water in not available. Nationally, agriculture represents roughly 80% of total consumptive use [9]. (Understanding the distinction between withdrawals and consumptive use is critical to understanding water demand and planning. The majority of water used inside a home is collected and treated by a wastewater system before it is returned to the natural environment. In most cases, these return flows then become available for natural and human downstream in the watershed. As such, replacing an old toilet may reduce the water use of a household, but is unlikely to provide additional water to the watershed. By comparison, water diverted for irrigation—residential or agricultural—consumptively uses most of that application through evapotranspiration, such that water does not return to the river or infiltrate to an aquifer to be used by others in the watershed.) Municipal, commercial, and industrial uses—excluding power generation—account for a small portion of total water withdrawals and an even smaller portion of consumptive use. However, despite representing a small portion of total use, municipal water demand has been the focus of many policymakers and researchers.

Today over 90% of the US population receives treated water from public water providers [10]. The term public, as used by the Environmental Protection Agency (EPA), refers to any system that delivers water for human use to a minimum of 15 service connections and 25 people for at least 60 days per year [10]. Importantly, under this definition, water utilities can be publicly or privately owned. In practice, water utilities' management and financial structures have many permutations. For example, drinking water utilities may be part of municipal governance or combined with public works; in other cases, they may be run as separate enterprises or concessionaires. Recent estimates suggest that while publicly owned and operated utilities are currently more common than private utilities, public-private partnerships have gained traction over the last decades as municipal and regional governments have struggled to fund legacy infrastructure and manage costs [11]. (One reason government and quasi-government utilities have struggled to cover costs is the inherently political nature of providing a private good, water, through a public service. Local politicians may be hesitant to raise rates to sufficiently cover long-run costs because they will face backlash in the polls. A somewhat infamous example of this retribution occurred in Tucson's 1977 recall of three city council members after they voted to drastically increase water rates [12].) These distinctions have considerable financial implications, which are beyond the scope of this review.

In the US, public water providers are governed by a complex web of federal and state laws that significantly impact how they operate and the costs incurred. Generally, the laws governing water treatment and delivery can be split into three categories: (1) water quantity laws that determine how water is allocated across competing uses within a state, (2) water quality laws regulating the quality of water provided by public water providers, and (3) operational regulations that govern the operation of water providers as public utilities.

Water allocation laws

Throughout the U.S., institutions and laws governing water allocation differ by state, but are generally rooted in one of two systems: *Riparian Law* or the *Doctrine of Prior Appropriation (DPA)*. Riparian law is a legal doctrine that governs water access based on the ownership of land adjacent to a waterway. In this legal system, the right to withdraw water from its natural system is tied to land ownership, such that water can be diverted or pumped with few restrictions, so long as the water is used for reasonable and beneficial purposes. Riparian law generally exists in the eastern US, where water scarcity has been less pronounced. Alternatively, DPA, commonly referred to as the "first in time, first in right" principle, allocates water rights based on a system of priority. Individuals and entities who diverted water first historically, are given priority over those who began diverting and using water more recently. The seniority of a water right determines who will be forced to curtail water use when supplies are insufficient to meet full demand. Under this system, the right to divert water is separate and distinct from land ownership.

While water utilities promote conservation under both types of legal systems, much of the initial conservation efforts were in states with DPA, where the risk of curtailment exists. As such utilities in the western US must own a sufficient water rights portfolio to meet demand even in times of extreme drought. Reducing per capita water use through conservation is one strategy to accomplish that goal. Indeed, through most of the twentieth century, water utilities generally used decreasing block rates (DBR), such that the marginal cost of water decreased with use—inducing additional consumption. As water scarcity increased, utilities across the US and other OECD countries largely replaced DBRs with increasing block rates (IBR), which are more effective in promoting conservation [13].

Water quality laws

Unlike water allocation laws, which are determined at the state level, the Safe Drinking Water Act (SDWA), enacted in the 1974 and administered by the EPA, provides minimum drinking water standards for public water providers. Although the SDWA establishes national standards for public water systems, individual states retain the ability to set and enforce their own standard, so long as they are at least as rigorous as those recommended by the EPA. As such, water providers charge customers the price necessary to cover the costs necessary to achieve these targets.

Operational laws

Most states have public utility commissions (PUCs) or public service commissions that regulate how privately or publicly owned public water providers operate. PUCs typically oversee rates, service quality, infrastructure investments, and financial performance. In many instances, water providers are also subject to local ordinances governing water use, conservation, infrastructure maintenance, and rates. Because the goal of PUCs is to assure utilities provide efficient service to customers at reasonable prices, water utilities may be somewhat constrained in making substantive changes to their billing structures.

Demand-side management strategies

Demand-side management strategies are broadly defined as price-based, non-price-based, and informational/educational policy instruments. In practice, utilities often apply a suite of policies simultaneously, and such distinctions may not be brightline. While many utilities promote water conservation, it is worth noting that such efforts must be balanced with sufficient revenue generation to cover costs.

Pricing policies

The costs for residential water service usually include an up-front fee associated with connecting to the utility and reoccurring—usually monthly—charges associated with water use and maintenance of the system. The former is referred to generically as a "connection charge" and generally includes the cost to secure water supplies (e.g., water rights), material expenses associated with connecting the customer to the system, and plant investment fees, which are designed to pass along a share of the system capacity/infrastructure fixed costs to the new customer. The size of these fees varies by location and across customer type (e.g., single family versus multi-family versus commercial); in theory, they are designed to recover the costs associated with adding that customer onto the system. The second category of billing, referred to here as "rates," are designed to recover costs associated with treating, delivering, and maintaining water across the service area. Connection fees have major implications for land-use and development, but they do not directly influence customer water use decisions. To date, most residential water demand studies have focused on customer response to changing water rates (i.e., the monthly bill). In fact, the authors are unaware of any peer-reviewed studies that have explored the impact of connection charges on long-term water use, beyond general examination of development impact fees [14]. As a result, we focus on water rates as the policy instrument for generating short- and long-term reductions in water use.

While regulations vary by state, most have either an explicit or implicit requirement that water rates should reflect cost recovery—akin to functioning as a non-profit. The typical utility customer's bill splits these costs between a monthly fixed fee, charged independent of the quantity delivered, and a volumetric charge based on the quantity of water consumed by the customer. Consumers have traditionally faced one of four pricing structures: flat fee, uniform rate (UR), IBR, or DBR.

The major benefit of a flat fee structure is the ability to bill without the installation of household meters, which can be costly. We largely omit discussion of this structure, since it is exceedingly rare today, though there are some cities where it is still in use (e.g., Idaho Falls, Idaho). Moreover, the flat fee structure does not create a marginal cost, to which consumers can respond and is antithetical to DSM, since additional water is essentially free once the fixed cost is paid.

Uniform rate pricing entails a constant volumetric marginal price, where the cost per additional unit does not change across levels of consumption—though it may differ by customer class. This type of rate structure is simple for utilities to implement and for consumers to understand. From the utility's perspective, uniform pricing also offers a relatively stable revenue stream, since revenues vary linearly with consumption at every level.

In contrast, both IBR and DBR are consumption-based, tiered structures, with a per unit charge that varies over specified ranges of use—the price increases with use for IBR and decreases for DBR. Historically, DBRs existed when water supplies were abundant to encourage use and reflect the economies of scale of water systems that had high fixed costs, but relatively low variable costs [15]. DBRs were adopted as water utilities felt pressure to keep prices low, given their perceived natural monopoly status, and to contribute to economic growth by providing affordable water for industrial users. However, with increasing population and water scarcity, starting in the 1990s IBR began to replace other billing structures to encourage conservation [15, 16].

While incremental price increases and block sizes differ by utility, IBRs are designed to promote conservation—since per unit water cost increases as customers use more water—while ensuring affordability for low-income households. The first block of IBR remains cheap, such that conscientious households can generally meet their water needs at a lower price, while high-use households—properties with large lawns for example—pay higher per unit costs, since they consume in later tiers. In practice, this imbalance may mean that high-use households are indirectly subsidizing low-use households [16–18]. Indeed, it was this incongruity with the cost-recovery mandate that brought IBRs to the California Court of Appeals in 2015. (Although not frequently discussed, cost-recovery rate setting principles provide an additional complication to using price to incentivize reductions in water use. Some have argued that drought surcharges, IBR structures, etc. are at odds with cost recovery principles. Indeed, it was this incongruity with the cost-recovery mandate that brought IBRs to the California Court of Appeals (See Capistrano Taxpayers Association v. City of San Juan Capistrano).)

IBR structures are ubiquitous across the western US, but their financial and economic implications are nuanced. For example, conventional IBR's create substantial uncertainty in revenue, since outdoor demand (often in a higher price-tier) depends on weather. Given the need for water utilities to cover costs, these fluctuations in revenue can be problematic. Some utilities, such as those in California, have previously attempted to achieve this balance by restructuring their pricing models, often relying on high fixed rates. While such rates stabilize revenue, if the fixed charges constitute a substantial portion of the monthly bill, they may reduce affordability and impede consumers' ability to save money through water conservation efforts, reducing the effectiveness of IBRs [19]. Regardless of the specific structure, costumer responses to IBRs can be difficult to estimate (discussed in the next section).

Despite the difficulty in estimation, it is critical to understand consumer responses to billing structures and pricing, since this relationship determines the effectiveness of conservation efforts and revenue stability. Accordingly, the next section reviews numerous studies and methodological considerations regarding water demand and own-price elasticity estimation.

Estimating demand: Methodological approaches and considerations

While there is considerable variation in the methods used to predict and explain water demand, we largely focus on previous efforts that have used econometric analysis, and thus price elasticity. Price elasticity is a measure of price responsiveness, defined as the percentage change in the quantity demanded divided by the percentage change in the price. The accuracy of elasticity estimates depends on the correct specification of a demand function, though the literature is somewhat inconsistent in these choices. Arbués [17] and Puri and Maas [20] discuss the complexities in selecting an appropriate model, highlighting two key challenges in demand estimation: 1) how to address the problem of simultaneity and 2) uncertainty in the appropriate price signal.

The first practical issue with demand estimation in the presence of tiered block rates is the simultaneous determination of price and quantity. Without proper correction, consumption under IBR appears to break the law of demand such that higher consumption occurs with higher prices. This positive correlation between price and quantity is a result of the structural relationship in the billing structure itself. Those households that consume more are charged a higher marginal (and average) price, but this fact does not imply that those same households would use more water if marginal prices increased. Additionally, economic theory suggests a rational consumer intends to maximize their utility, and hence consumes at the point where marginal benefit equals marginal cost. In the case of tiered block rates, it is possible to have numerous tangencies, or none at all [21]. These are not trivial issues and have been the subject of considerable work since the 1970s [22–24].

Several methods have been proposed to break the simultaneity problem; perhaps the most common econometric solution is to instrument for price [20, 25–27]. The specific choice of instruments varies by context, but generally they include a single block price, multiple block prices, and/or the difference between block prices, as well as any other explanatory variables that are correlated to price but not individual consumption [20, 21]. In theory, instrumental variables can address endogeneity concerns, so long as they are sufficiently correlated with the explanatory variable of interest (price in the case of water demand) and uncorrelated with the unobserved error related to that variable [28].

A related, but separate pricing issue that arises under IBR is the choice of an appropriate price signal. In a normal market, we expect consumers to perceive and respond to marginal prices. However, under non-linear pricing structures, such as IBR, consumers may not respond to the marginal price for two reasons. First, the high information cost associated with understanding the pricing structure makes it difficult for consumers to track cumulative consumption throughout billing periods, which is a necessary condition for consumers to know the (marginal) price for an additional unit of water. Second, the bill for consumption may be lagged, such that the consumer will not receive the signal until the next billing period. This issue is confounded in the absence of smart meters, since consumers may be billed on average consumption over several months. Due to these fuzzy price signals, researchers have often elected to use lagged price when modeling demand [18, 20, 29–31]. The high information cost associated with understanding complex pricing structures means that consumers might perceive the average price rather than the marginal price, even though it is less consistent with economic theory [31, 32]. Recent work has highlighted additional complications with price perception and cognitive bias if we assume water users are less than rational, in the neoclassical sense. Specifically, a complicated billing structure and delayed price signal may lead consumers to act with "limited-rationality," in which consumers form reference prices to which actual price is then compared in a way that affects consumption [33]. Given the myriad potential issues, there remains a longstanding debate among economists and researchers regarding the appropriate choice of price signal in the demand specification process, especially under non-linear pricing.

Investigations into this modelling choice are prolific [23, 24, 34, 35]; in recent years a new approach to determining the appropriate price signal has gained traction, leveraging discontinuity and event study paradigms for a cleaner causal identification strategy [18, 36]. To date, there is still no consensus among researchers on the appropriate price signal, with some studies using average price [32, 37–39], others using marginal price [40–44], and still others using average-marginal price [30]. Because the choice of price signal is not trivial in demand estimation, it remains a current topic that requires attention beyond this brief presentation [20, 45, 46].

Regardless of price signal and specification, there is an additional concern over price responsiveness, since water expenses often constitute a small portion of household budgets and consumers generally have a poor understanding of both bill structure, the amount of water consumed for given household uses, and their relative use compared to others [45, 47–49].

The relatively small share of consumers' total expenditures and the complication of billing structures has led some researchers to suggest water consumers may be "rational inattentive" which has clear implications for water policies based on price signals [50]. Indeed, given the ubiquitous use of autopay, it is unclear if many customers even see their bill. To our knowledge, no study to-date has comprehensively examined the relationship of price responsiveness and autopay enrollment in residential water demand, though several studies mention it as a complication [51].

Price elasticities: Results and implications

Own-price elasticity may depend not only on price, but also on the bill structure itself. For example, Nieswiadomy and Molina [52] find that IBR structures produce a higher estimate of price elasticity when compared to DBR. This result is subsequently supported by three meta-studies [26, 53, 54]. Olmstead et al. [55] arrive at a similar conclusion when comparing IBR to UR. (Following Kenney et al. (2008), Boyer et al. (2012) argue that while switching from UR to IBR would increase the estimates of elasticity, the differences may not be significantly high if a given utility area already faces higher water prices.) To the authors' knowledge, Sebri [56] is the only study that finds higher estimates of price elasticity when DBR is used, although Stevens et al. [15] find no significant difference in elasticity across all pricing structures. While conclusions conflict across studies, it is reasonable to assume that consumers' behavioral responses may lead to different responses across billing structures even when average or marginal prices are equivalent [55].

The choice of the price signal (discussed above) also has implications for the magnitude of price elasticity estimate. In general, studies indicate a tendency for higher elasticity estimates when average price is employed [20, 26]. Taylor et al. argue that the presence of a fixed fee in the average price is responsible for such elevated (upward-biased) estimates.

Despite the many nuances in estimating water demand, a substantial body of literature has provided defensible own-price, point elasticity estimates [15, 26, 32, 38, 55]. Previous meta-studies present a wide spectrum of these estimates, covering both highly elastic (-7.54) and inelastic ranges (nearly 0). For instance, Arbués et al. [17] report elasticity from -3.33 to -0.002, Sebri [56] from -3.054 to -0.002, Worthington & Hoffman [57] from -1.63 to -0.02, and Marzano et al. [26] from -7.54 to 0.

Restrictions and other demand-side management tools

Confronted with affordability concerns and general opposition to raising rates, utilities have increasingly sought non-price alternatives to incentivize reductions in water use. This includes a suite of pecuniary and non-pecuniary policies ranging from subsidizing the adoption of water saving practices, to information campaigns designed to alter household water use.

Water use restrictions. Restrictions on outdoor water use represent one of the more commonly used non-price policies aimed at reducing water use [58, 59]. Typically utilized to generate temporary reductions in outdoor water use during drought, restrictions limit either the number of days per week or time of day that residential users can irrigate their lawns/gardens. Outdoor water restrictions have been well-studied; while their implementation varies across utilities/cities, their effectiveness is clear with estimated reduction in summer water use ranging from 10–30% [60, 61]. Despite robust evidence of their effect on average water use, there is considerable heterogeneity in their effectiveness across households [62]. Not surprisingly, and consistent with their intended effect, outdoor water restrictions tend to generate water reductions from high-use households, specifically those with large outdoor water demands. While their overall effectiveness of temporarily reducing water use is well-documented, less information exists regarding how they impact household behavior in the long term, including water use patterns after the restrictions have been lifted. For example, it is possible that landscaping changes are made in response to the imposition of restrictions leading to longer term reductions in water use.

Water restrictions have become common in the western US, but they can be politically unpopular, particularly when they are not effectively communicated within the service area [63]. In a choice experiment conducted by Awad et al. [64], investigating preferences to balance supply with withdrawals, respondents ranked watering and turf grass area restrictions as their least preferred option. Water users who intentionally or unintentionally flout restrictions may be subject to hefty fines, which complicates enforcement and degrades public support [65–67].

Rebates and subsidies. Non-price DSM programs often incorporate the installation of water-efficient household technologies and appliances that induce conservation without relying on behavioral change. Comprehensive studies examining the effectiveness of these campaigns have been conducted in the United States, Australia, and Europe, where household retrofit and rebate programs have been extensively implemented [68, 69]. In practice, these programs generally include a rebate or subsidy to reduce the cost of installing the new technology or appliance; in some cases (e.g., faucet aerators), they may even be provided gratis from the utility. When policies offer incentives for voluntary activities that occur even without the incentive, it becomes crucial to determine the additionality of the policy. Additionality refers to the extent to which the policy leads to actions that would not have taken place otherwise, which can be difficult to determine without a strong identification strategy. Estimates range, but they suggest rebate and retrofit programs can lead to a reduction in indoor water consumption ranging from 7 to 50% of indoor use [70]. Bennear et al. [71] find that a high efficiency toilet rebate program led to a 7% reduction in water use and only accounted for 37% of the total water reduction that occurred across the time of the study. They suggest the remaining reduction would have occurred even without the program.

While rebate programs can effectively induce conservation—in part because they do not require behavioral change—there are several drawbacks to implementing such programs. First, they can be costly to implement. Second, many appliance and toilet efficiency programs cover only a small portion of the total cost (e.g., $50 of a $600 purchase). As such, they may be regressive in nature, since only those households with sufficient disposable income purchase the efficient product—though little research exists examining this phenomenon in municipal water demand. Lastly, some policies may have unintended consequences. For example, cash-for-grass programs that are not implemented carefully may increase land surface temperatures [72–74].

Information and education campaigns. Information campaigns are designed to promote conservation while providing consumers with information to make better decisions regarding their water use. Informational campaigns include billboards, mailers, classes, and social media; although the effects of such efforts have been difficult to broadly estimate due to their idiosyncratic implementation [75]. In an attempt to measure the efficiency of informational campaigns, several studies have randomly assigned households to receive specific material. To our knowledge, Geller et al. [76] was the first such study to randomly distribute mailers to specific households to be observed as the treatment group. Curiously, they found the treatment led to a small *increase* in use, compared to households who did not receive the message.

While traditional education campaigns provide general information to consumers (e.g., lawn water tips), many recent efforts provide normative nudges. While the specifics of these programs vary, they generally involve presenting a household with a comparison of their historic use and/or showing how their use compares to similar neighbors. These normative nudges to induce water conservation have received significant academic attention in the last decade [77–79]. Interestingly, Ferraro and Price [78] find that social comparison messaging is most effective among households identified as the least price sensitive. In general, household comparison messaging may be most effective for (pre-treatment) high-use households [80, 81]. Unlike price elasticity, social comparison strategies have been relatively consistent in the estimated response, between 2 to 8 percent reductions in average use [82, 83].

Residential reuse and reclamation

Although it is not the primary focus of this review, water reuse and reclamation have been identified as potential conservation strategies to meet increased residential demand. Reuse is common is many industrial applications, particularly when such water is primarily used for cooling. To date, formal reuse policies and technologies are less common for residential users. Residential adoption of reuse has been slow for several reasons. First, retrofitting existing housing is costly [84]. Second, recycled water often has an "ick" factor, defined as a psychological barrier linked to perceptions of cleanliness or safety, which impedes its adoption [85]. Third, there are idiosyncratic ways in which households may already reuse water without additional technologies that are largely unobserved (e.g. collecting the initial cold water of a shower in a watering can). Despite these limitations, reuse technologies are becoming increasingly more common in new developments [86], and are likely to continue to gain popularity in the face of limited freshwater supplies.

Concluding remarks

This review is meant to provide a primer for policymakers and researchers interested in residential water conservation efforts, and reference seminal concepts and papers necessary to estimate their effectiveness. DSM has been a successful strategy to balance human water needs with increasingly scarce supplies, though magnitude of conservation induced by such policies is highly variable. While IBRs, restrictions, and information campaigns clearly promote conservation, estimating the effectiveness of any specific policy is often impeded by the lack of experimental controls and econometric identification issues. Water utilities rarely introduce a single program at a time, such that every strategy may exist simultaneously. Thus, the researcher must attempt to control for each ex-post through statistical analysis. Even in such cases where a single program exists (e.g., active drought restrictions), the weather and other confounding factors may limit the external validity of a given estimate. Only a few studies have examined the relative and combined effectiveness of multiple programs when introduced simultaneously [87]. Similarly, Strong and Goemans [44] find that households, when provided real-time information about their water use, were significantly more responsive to temporary increases in price. Future research aimed at developing a better understanding of how utilities should develop a portfolio of programs, where interaction (both positive and negative) between policies is possible, is needed.

By promoting water conservation, DSM not only helps alleviate immediate pressure on water supplies, but also contributes to long-term resilience in the face of growing water scarcity and variability. Embracing these strategies represents a crucial step towards creating sustainable communities, where the needs of both present and future populations are met. However, proper evaluation of these programs is equally important, since consumer responses are context specific. This review covers the long history of research in this area and highlights future research areas.

Author Contributions

Conceptualization: Alexander Maas, Christopher Goemans.

Data curation: Alexander Maas, Roshan Puri, Christopher Goemans.

Investigation: Alexander Maas, Roshan Puri, Christopher Goemans.

Methodology: Alexander Maas, Christopher Goemans.

Project administration: Alexander Maas.

Validation: Alexander Maas, Roshan Puri, Christopher Goemans.

Writing – original draft: Alexander Maas, Roshan Puri, Christopher Goemans.

Writing – review & editing: Alexander Maas, Roshan Puri, Christopher Goemans.

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