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Using Smart Meters for Household Water Consumption Feedback: Knowns and Unknowns

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Abstract

A range of adaptive strategies are needed to mitigate the growing threats to water security. Demand management will play a central role in adaptation. The proliferation of smart metering provides a means for utilities to better quantify end user demand, and to provide consumption feedback to consumers in (near) real-time. Such feedback can help close the gap between perceived and actual water consumption. However, relatively few studies have considered the effectiveness of feedback in promoting water saving behavior. This paper evaluates the evidence for the effectiveness of water consumption feedback technology in promoting water saving behavior.

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Keywords: Demand management; smart technology; water meter; feedback; behavior change.

1. Background

Water scarcity is an increasing global concern, with approximately 500 million people living in countries where the usable water supply is insufficient to support the local population [1]. Global population levels have tripled and water demand for domestic and industrial purposes has increased six-fold, putting intense stress on an already depleted and decreasing global water supply [1]. In addition, the consequences of climate change will continue to impact negatively on global usable water sources [2], with the potential that over four billion people – more than half of the world's population – will be chronically short of water by 2050 [1, 2]. Thus, rather than increasing fresh water

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production (through e.g. desalination or water recycling) to meet the current demand – and in effect further depleting already rapidly diminishing resources – better supply and demand management and conservation efforts must be made to avert water crises in the near future.

Broadly speaking, water consumption can be curbed in two ways: large-scale regulatory and infrastructural action and individual conservation efforts in the home and community. The first method typically involves water use restrictions, increased pricing and tailored water rates, as well as the installation of more efficient irrigation and water recycling technologies, and treatment plant improvements. The second method involves domestic water conservation – the implementation of strategies that result in water savings through changing individual behavior.

The aim of this paper is to review the current evidence base on how to improve domestic water conservation efforts by focusing on various technologies (e.g., smart meters and in-home consumption displays (IHDs) and methods (e.g. consumption feedback) designed to encourage consumers to reduce their water use. Although these methods are somewhat novel in the water consumption domain, such methods have been implemented and tested widely for domestic energy use. Indeed, there is good evidence for the effectiveness of various 'smart' feedback methods in curbing energy use, with reductions in energy consumption demonstrated as due to the provision of real-time energy usage data ranging from 5% to 20% [3-5]. Even in this established field, however, there are gaps in the knowledge base around feedback as a way to reduce consumption – particularly with respect to the most effective feedback format, whether the effect persists over time, as well as assessments of costs and benefits of feedback [5]. The current review draws upon what is known from the energy domain to assess the somewhat limited research on the effectiveness of consumption feedback on domestic water use and to identify avenues for future research.

2. Using smart-meters to provide consumption feedback to consumers

A water smart-meter is an electronic device designed to record water consumption for the utility company and the user. Where traditional water meters are typically read manually in monthly or yearly intervals, smart-meters record consumption in real-time or near real-time, and communicate this information to the utility and consumer [6]. This affords instant up-to-date information on consumption, with the advantages of accurate, site-specific readings, easier and faster identification of leaks and water waste, and greater consumption transparency for the consumer (e.g. bills based on actual rather than estimated use). Governments and water utilities are increasingly focused on the installation of smart meters, largely because smart meters are expected to result in reductions in water consumption. One key way in which smart meters can be used to promote water savings is by using the data recorded and transmitted by smart meters to provide frequent feedback to consumers about their water consumption. However, it is important to examine whether such feedback is effective in changing consumer behavior.

2.1. What do we know about using smart meters and feedback to reduce water consumption?

Given the infancy of smart metering in the water domain, there is not much research on its effectiveness of curbing water consumption. Fielding et al. [7] recruited 221 households in South-East Queensland, Australia and measured the effect of feeding back to consumers tailored information obtained through 5-second, utility-specific smart-meter data. Households were assigned to a control group or one of three experimental groups. The experimental groups comprised an education only group, a social comparison and education group, and a feedback group. The education only group received postcards with information on how to save water (e.g. full dishwasher loads, shorter showers, etc.). The social comparison and education group received postcards that provided information about the percentage of similar households engaging in a range of water saving actions, as well as information on water conservation. Finally, the feedback group received feedback about overall consumption and consumption associated with various activities (shower, laundry, etc.), as well as information postcards on water saving. Analysis revealed significant variations between the control group and the intervention groups: the intervention groups used significantly less water than the control group (11.3 liters, approximately 7.9% reduction). However, there were no differences between the intervention groups and any treatment effects had disappeared after 12 months. Thus, feedback from smart meters may not be more effective than other more established (and lower cost) behavior change strategies (e.g. providing water saving information). However, given that consumers were only provided with feedback from smart meters at a single time point, it is possible that continued access to smart meter data and consistent prompts would prevent decay effects and motivate sustained conservation efforts.

Erickson et al. [8] evaluated the effectiveness of the Dubuque Water Portal (DWP), which involved a near-real time water consumption feedback system for households. Over a 15-week period, smart-meters recorded consumption data in 15-minute intervals, which was then analyzed and fed back to 303 households as well as to the water company via an online portal. The data was updated every two or three hours and presented to the consumer in hourly usage graphs representing not only overall household usage, but also how the given household consumption compared to "neighbors like me". In addition, the online portal involved a team-based weekly game focused on water conservation, as well as a chat room in which participants could communicate anonymously with each other. Results revealed a 6.6% drop in normalized water consumption in the first nine weeks of the study when the intervention group had access to the portal and the rest of the sample did not. However, it should be noted that the majority of households were already engaged in water conservation efforts, such that the impact of the smart meter data portal might have been somewhat muted. Nevertheless, these results suggest that access to more frequent feedback can reduce consumption, at least in the short term.

In a study on the impact of consumption feedback combined with conservation incentives and education, Petersen et al. [9] installed a high resolution automated data monitoring system in two college dormitory buildings and provided users with detailed feedback via an online portal. The portal interface was designed to allow the user to select electricity and water data collected at any time. Consumption was quantified in terms of KW (electricity) and gallons (water), and their impact in terms of environmental and financial costs was also calculated. A comparison group was provided with low-resolution, aggregate data readings once a week. The study was framed as an energy and water saving competition between and within the two study groups (high- and low-resolution feedback) with a prize for the group with the lowest consumption levels. That is, individuals received comparative feedback about the consumption of others, as well as feedback on their own consumption.

Results revealed an average 3% reduction in water use per person (140 liters), with one dormitory recording an 11% decrease. However, electricity savings were substantially higher, with an average 32% reduction in both feedback conditions. Moreover, the high-resolution feedback group recorded greater savings than the low-resolution group (55% vs. 31%). However, it should be noted that there was no high-resolution feedback on water (due to technical errors), such that all dormitories essentially received low-resolution water consumption feedback. Moreover, given that the study was framed primarily in terms of energy conservation, individuals would have been focused on energy rather than water. It should be also noted that any savings occurred in the context of an incentivized competition, meaning that the impact of feedback might be attenuated in contexts without such incentives. Thus, the full impact of real-time feedback on water consumption is yet to be tested fully.

2.2. What do not we know about using smart meters and feedback to reduce water consumption?

To date, there is a dearth of research that examines the effectiveness of using smart meters and high-resolution feedback in reducing water consumption. As a result, there are a number of gaps in the knowledge base, and several avenues for future research. First, it is important to address limitations in the extant literature. For example, in Fielding et al. [7] participants had experienced a severe drought and may have been more sensitive to issues of water conservation and thus more responsive to demand management techniques than usual. Thus, it is important to examine the effects of feedback in locations not prone to drought events or water scarcity. Participation in past research has been on a largely voluntary basis [8, 9], with the result that participants may be more 'water aware' than the general population. As a result, past research might have underestimated the potential water savings produced by a feedback intervention (as participants were already consuming at a low level). Only additional research, with a broader and more representative population of water consumers, can answer this question.

Over and above any limitations associated with sampling, there are more significant unknowns associated with the use of smart meters to reduce water consumption. First, an important question relates to the "half-life" of feedback effects – that is, how long do such effects last? Research has found that water use often returns to baseline levels post-intervention, suggesting that the novelty of smart meters may dissipate, decreasing use of the system [7, 8]. However, it should be noted that Fielding et al. [7] only provided one instance of feedback (at the start of the study), such that households were not able to take advantage of the full benefits of smart meter technology (i.e. near real-time updates on consumption), even though the meters were installed for a 12-month period. In Erickson et al.'s [8] study, individuals were able to access their consumption data more frequently, but the study ran for only 15 weeks, with the result that the long-term impact of the portal could not be assessed fully.

Another unanswered question relates to the most influential type of feedback in changing consumption behavior. Is the provision of more frequent information about one's water consumption (i.e. daily updates versus quarterly updates via the utility bill) sufficient to change water use? Or is there value in the provision of comparative feedback, either in the form of historical comparisons (i.e. is the individual using more or less water now than in some time period in the past) or social comparisons (i.e. is the individual using more or less water than others)? To date, no research has employed a design that would test this question. Fielding et al. [7] found no added value in providing social comparison feedback or high resolution data relative to providing water saving information alone, but households only received such information once. Erickson et al. [8] allowed households to access high resolution data about their water use, and how they compared to others, but did not separate out the effects of the different types of feedback. In order for water utilities to invest in the installation and maintenance of smart metering systems, and the development of consumer portals, it is important to demonstrate that giving consumers more frequent access to information about their water use and how they might compare to others is associated with more significant water savings than standard water awareness campaigns. While research in the energy sector has demonstrated reductions of between 5% and 20%, and highlighted the importance of high frequency, detailed and easily interpretable feedback and consumption advice tailored to the individual user [5], the available literature on using smart meter data to manage consumer demand for water does not allow such conclusions to be made.

3. Using In-Home Displays to provide consumption feedback to consumers

As an alternate to for example web-portals, another feedback method is through in-home consumption displays (IHDs). IHDs are smart-meter connected devices that typically present consumers with real-time (or near real-time) information on water use (e.g. by fixture and/or time of day), cost, and comparisons with others as well as the user's own historical consumption [10]. The rationale for IHDs rests on the fact that most people lack knowledge about their own water use, and how much it costs both financially and in terms of the environment [11]. Greater insight into how one's behavior relates to water consumption – such as that gained through high granular, near real-time smart-meter information presented via IHDs – may motivate behavior change and conservation efforts.

3.1. What do we know about using IHDs to reduce water consumption?

Kenney et al. [12] installed IHD devices in 10 000 households and tracked consumption behavior over an eight year period. The IHDs afforded users access to near real-time consumption data so that users could regulate consumption behavior to fit their monthly water budget. Contrary to expectations, participants recorded significantly *more* water use (16%) following installation of the IHDs. However, this increase probably reflected the fact that consumers modified *when* they used water rather than *how much* water they used to fit with variable price tariffs. Thus, the detailed information provided by the IHD allowed consumers to shift their water use to low peak hours, thus saving money, but not water. Although this might suggest that conservation efforts are driven by financial rather than environmental concerns, Kenney et al.'s evaluation demonstrates that consumers do use IHDs to alter consumption practices. However, it is important to consider how the provision of IHDs fits within other demand management strategies, such as variable price tariffs, to understand – and perhaps shape – consumers' motivations.

In a slight variation of the more 'traditional' IHDs, Willis et al. [13] installed a smart-meter connected *alarming* visual display – *the WaiTEK Shower Monitor* – in bathroom showers of 44 households for three months. The displays were locked at 40 liters. Once usage exceeded this limit, an alarm sounded alerting the user of his or her consumption. The display also provided real-time information about water flow-rate, duration and temperature on an LCD screen. Post-installation, the average reduction in shower water consumption was 15.4 liters (27%) per household. Further, Willis et al. estimated that the payback period would be 1.65 years and that if the devices were installed in all homes in the region the savings would amount to 3% of total city consumption.

Similar alarm-based approaches include ambient light displays, typically installed in showers and at faucets. These devices are connected to simple flow-rate sensors and alert the user to their level of consumption with, for example, traffic light displays [14] and gradually illuminating vertical LED rods representing consumed water volume in real-time [15]. Some success in reducing overall consumption has been achieved using this type of technology with the low installation cost, simplicity and high interpretability of the alarm displays being particularly valued by users [14, 15]. Overall, the *WaiTEK* and similar devices are efficient in encouraging conservation and environmental awareness, but also benefit the user in terms of measurable long-term financial savings.

3.2. What do not we know about using IHDs to reduce water consumption?

There are several limitations to extant research on IHDs. Kenney et al. [12] note that more environmentally conscious and pro-conservation individuals may volunteer for evaluation studies, meaning that the size of the effects in the broader population is unknown. Moreover, as many IHDs present information about cost, as well as volume, of consumption, it is unclear which element is the primary driver of conservation efforts. This is particularly relevant given the fact that IHDs can be used to present a variety of feedback to the consumer and, indeed, this is exactly what consumers want [16]. It is also important to understand potential backfire effects, such that IHDs may actually increase consumption when combined with variable price tariffs [12]. One way to do so might be by changing consumers' perceptions of the purpose of IHDs from being focused on cost savings to environmental savings, or by changing the meaning attached to particular water using practices (e.g. that showers are for cleanliness rather than relaxation). Future research could examine whether the addition of guidelines for consumers on how to translate IHD feedback into efficient water use enhances the water saving potential of IHDs.

4. Mail-Based Consumption Feedback

Technological advances, such as those associated with smart meters, clearly have the potential to be harnessed to change water consumption behaviors by providing higher resolution, more frequent feedback about individuals' water usage. However, other research has tested the effectiveness of low-tech methods, such as mail-based consumption feedback [17-20]. This type of feedback is typically norm-based, socially and/or historically comparative. Given the relative infancy of research on feedback via smart meters, a brief review of the insights obtained from research using other methods may be informative.

4.1. What do we know about using mail-based feedback to reduce water consumption?

Overall, the evidence base for the effectiveness of mail-based feedback on water conservation is mixed. Geller et al. [19] found no effects of weekly or daily social comparison feedback on water consumption in a test of the effects of educational instruction, consumption feedback, and engineering strategies. Similarly, Kurz et al. [20] tested the impact of information leaflets, attunement labels, and biweekly social comparative feedback on water and energy consumption over a 6-month period, and found that feedback had no effect on water consumption. In contrast, Aitken et al. [21] found more promising effects of feedback on residential water consumption in 321 households in Melbourne, Australia: results revealed significant decreases in water consumption for the feedback groups relative to the control group. Finally, Ferraro and Price [18] found that feedback that incorporated social comparisons reduced water consumption. More critically, Ferraro et al [17] found that only the social comparison condition was associated with reduced water consumption two years after the original messages were sent.

4.2. What do not we know about using mail-based consumption feedback to reduce water consumption?

It is perhaps unsurprising that most studies have been conducted in locations that have recently experienced or are currently experiencing water restrictions and drought [7, 12, 13, 17, 20, 21]. As a result, the population may be primed to conserve, making them more responsive to intervention strategies, and diminishing the significance of the drops in consumption. Alternatively, heightened awareness of the importance of conservation could mean that the people were already conserving, making the decrease in water use all the more significant. A preponderance of studies conducted in water-stressed areas could over-estimate *or* under-estimate the true impact of feedback. One clear unknown in this field is the effectiveness of feedback strategies in reducing consumption in areas that do not experience water scarcity, and a priority for future research would be to provide these tests. Another unknown is how feedback strategies interact with other demand management strategies, such as water pricing, given that some research suggests that pricing issues may moderate the effects of feedback on consumption practices [19].

The optimal frequency of feedback and type of feedback is also to be established. It is generally true in the energy domain that feedback is more effective the more frequently it is provided [22]. However, it is unclear whether this is true for water. Kurz et al. [20] found that biweekly feedback was not effective in reducing consumption but Ferraro and Price found that a single shot of comparative feedback did reduce consumption, and continued to do so after a two year period [17, 18]. It is possible that feedback is most effective when consumers are able to set their own level of feedback, by choosing how often to access their own consumption data through web-based portals (e.g. [8]). In relation to the most effective type of feedback, it is important to distinguish between intra-individual comparison feedback (i.e. "how much do I consume now compared to last year?") to inter-individual comparison feedback (i.e. "how much do I consume compared to my neighbors/similar others/efficient others). Many of the studies on consumption feedback involve multiple types of feedback and the effectiveness of each of these needs to be tested separately in order to be able to make firm recommendations.

5. Effective Feedback: Themes and Variations

Although the evidence base on the use of smart meters for household water consumption feedback – or the use of feedback on water consumption more generally – is not extensive, several themes and variations emerge. A direct comparison of the utility of the various feedback methods– or indeed a synthesis of study results – is difficult as past research differs in terms of outcome variables and measurement metrics used, sample sizes, and study methods. At face value, the results are somewhat mixed. In terms of effectiveness in curbing water use, the literature suggests that feedback can reduce water consumption by between 3% [9] and 53.4% [13]. Overall, the majority of the 13 studies reviewed found that feedback was effective in curbing consumption, but two studies [19, 20] found no effect of feedback, and one study reported a 16% increase in consumption [12]. Across all studies that found a positive effect of feedback, the average decrease in consumption was 19.6%, with the greatest decrease recorded by Ferraro and Price [17] as a result of mail-based social and historical comparison feedback.

The nature and delivery of the feedback as well as the characteristics of audience receiving the feedback are important. Social and historical comparisons are perhaps the most valued and effective in curbing consumption, used effectively in mail-based [17, 21], smart-meter [8] and IHD feedback studies [16]. However, more research focusing on consumers' preferred type of feedback is needed. In terms of feedback delivery, there were strong indications that the immediacy of feedback was related to its effectiveness, such as when consumption feedback is delivered at the point of use (i.e. at the fixture; [14, 21]. Responsiveness to feedback appears to depend on the extent of consumption, such that high-users react more positively to consumption feedback than low-users [17, 21]. This indicates the need for feedback information that is more tailored to specific populations or even individuals. Web-portal software may be adapted to vary in response to specific user consumption levels and other pertinent information (e.g. socio-economic status, geographical region, city vs. country, etc.). Other factors that are important to consider in determining the effectiveness of feedback include the framing of the intervention (i.e. saving water versus saving money; see [13]) and the readiness of the consumer population to engage with the demand management strategy (i.e. recent or current experience of drought or water scarcity). Finally, a comparison of the efficacy of IHDs and other smart-meter feedback methods (e.g. web portals) is an important next step. That is, do the advantages of IHDs (e.g. no log-in required, simple medium of information, visual, easily interpretable, etc.) outweigh those of, for example, web-portals (more information, more detailed and precise information, etc.)? And what is the difference in cost in terms of development, installation and potential mass roll-out of these various feedback methods? To date, there is no research investigating these issues.

6. Conclusion and recommendations

Based on the available literature consumption feedback is most efficient in curbing water use when it:

- is delivered at the point of use, such as in the form of attunement labels or ambient light displays.
- includes high-granular time-series data of cost and consumption, social and historical (self) consumption comparisons, as well as appliance-level feedback.
- is tailored to the household, particularly in terms of high- vs. low-users.
- is delivered with water saving advice, detailing how to use feedback to curb consumption.

It should be noted that these recommendations are based on relatively few studies, and there are significant gaps in the knowledge base to be addressed. In light of the reviewed research, these gaps include, but are not limited to:

- Most studies draw upon volunteer samples. It is unclear whether these samples are representative, or comprise people who are particularly environmentally minded, and therefore more inclined to respond to the feedback. In addition, research to date has been concentrated in a few countries (e.g., the USA, Australia, Austria), such that research is needed in other locations (i.e. *for whom* does feedback work?).
- The exact mechanisms and channels through which feedback changes behavior are unclear (i.e. *how* does feedback work?).
- The role of the price of water needs further investigation, as low water prices may moderate the effects of feedback (i.e., *when* does feedback work?).
- Most studies take place over relatively short time-frames, with some evidence of decay effects. Thus, the relative power of feedback effects in the long-term are unknown (i.e. *how long* do feedback effects last?).
- How do the various feedback methods compare in terms of cost and benefit?

This paper has explored and reviewed the current evidence base of the effectiveness of consumption feedback in curbing water use. In particular, the focus has been on recent technologies, including smart-meters and IHDs. There is promise in using such approaches to inform and educate consumers to lower their overall usage. This has been achieved through more detailed, frequent and instant information delivery. The studies included in this review indicate reductions between 3% and 53.4%, with an average of 19.6%. Thus, the overall potential of smart-meter technology in curbing domestic water use is clear, but more research is required to establish the most effective type of feedback in terms of information content and granularity, delivery frequency and medium.

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