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Reducing Waste Outflow to Motivate Water Conservation

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A novel intervention to increase water-conserving behavior was developed and tested. Behavior-change interventions range from information-based, where individuals have full control over whether they act on the provided information, to forcing/automation, where individuals have no control over the desired behavior. This study's intervention was devised to be more forceful than providing information alone, but unlike forcing/automation, still allows individuals to control whether they perform the desired behavior. While resource-conservation strategies tend to target resource intake, the studied intervention examines whether limiting resource waste outflow can also limit resource intake. Specific to water, this study explored whether reducing wastewater outflow, causing accumulation, can reduce water inflow. Data were collected online using simulations of handwashing at a sink, which had different sink-outflow rates. Amazon Mechanical Turk workers completed three randomly ordered handwashing simulations. Study participants ($n = 72$) significantly reduced simulated consumption of water when it accumulated quickly in the sink ($p < 0.001$). Participants reduced simulated water consumption, on average by 14% at lower outflow rates, as they decreased inflow rates to prevent sink overflow. In contrast to informational interventions that rely on user motivation, reducing outflow significantly decreased simulated water usage, independent of participant-reported performance of other pro-environmental behaviors. Thus, reducing outflow may be effective regardless of individuals' motivation to act sustainably. Also discussed is the value of online simulations to test pro-environmental behavior interventions. Finally, limitations and next steps, including in-person testing, are outlined as future work. [DOI: 10.1115/1.4064042]

Keywords: pro-environmental behavior, water conservation, simulation design, design for the environment, sustainable design, user-centered design

1 Motivation and Introduction

Of the United Nations' 17 Sustainable Development Goals (SDGs) to be achieved by 2030, one is to promote sustainable consumption and production [1]. Interventions are urgently required to aid individuals, communities, and industries to consume fewer resources. In fact, the SDGs provide engineers with "targets to steer societies towards sustainable production and consumption" [2]. This requires stronger action from all segments of society: Citizens need to modify their habits and ways of living, and engineers must address sustainability as a central, rather than peripheral, challenge [2].

In addition to the product purchase and end-of-life phases, Thurston and Behdad also noted the complex role of consumer behavior during product use itself [3]. She and Macdonald found that exposing consumers to visible product features that trigger pro-environmental behavior, increased consideration of sustainability-related criteria [4]. Goucher-Lambert et al. noted that decisions about sustainable options that are less desirable or cost more can be moral-choice scenarios, where benefit to society is weighed against personal gain [5]. An important aspect of eco-design is first understanding how users interact with products, to identify opportunities for more sustainable use.

The current work aims to better understand how products could be designed to increase pro-environmental behavior. While much work has focused on providing information, or automatically performing the desired behavior, the current work aims to guide or steer users towards the desired behavior. One such intervention was studied to better understand its utility and limitations, toward generalizable implications for the class of guiding/steering interventions.

1.1 Sustainable Consumer Use of Products. Thurston and Behdad highlighted the importance of considering how consumers interact with products during the use phase [3]. Specifically, designers can investigate situational factors and consumer attitudes during use. For example, Engelking et al. found that factors determining how much excess water is heated in a kettle ranged from users' uncertainty in future hot-water need to concern about buildup of in-kettle limescale [6].

Once designers understand the product user, they can apply strategies to motivate resource conservation. To support this, Telenko et al. compiled from 20 sources, 76 guidelines corresponding to six general strategies, to help designers create more sustainable products. Of the six strategies, one is to minimize resource consumption during product operation, and 23 corresponding guidelines explain specific best practices to achieve this strategy [7].

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Table 1 Range of behavior-change interventions

	⇐ *User maintains control* ………			……… *User has little/no control* ⇒	
	Information	Feedback	Enabling/Encouraging	Guiding/Steering	Forcing/Automation
Goal	Provide general information to motivate behavior	Provide information specific to user to motivate behavior	Make it easy (or fun) to perform desired behavior	Make it hard NOT to perform desired behavior	Make it impossible to avoid the desired behavior
Example	Message reading, "It takes significant resources to produce clean water. Please turn off faucet when not actively using."	Message reading, "You're using … amount of water per minute, which takes … of energy to clean. Please turn off faucet when not actively using."	Concept showing fish in bowl above sink, where the fishbowl-water level drops when faucet is left on[a]	Concept reducing wastewater outflow so that water fills up sink when faucet is not turned off	Sensor-based automated faucet that turns off in the absence of moving hands

[a] https://inhabitat.com/fishbowl-faucet-encourages-water-conservation-or-else/

For example, relevant to the current work, guidelines include, "Reveal how much resource is being consumed," "Incorporate intuitive controls for resource-saving features," and "Incorporate features that prevent or discourage waste of materials by the user."

The current work is focused on modifying how an individual uses a product to reduce water consumption. As water conservation falls under the umbrella of "pro-environmental behavior," the following sections introduce this field and how aspects can be applied in product design.

1.2 Pro-Environmental Behavior. Many theoretical frameworks aim to represent decision-making processes behind choosing to act pro-environmentally [8]. The term pro-environmental behavior (PEB) describes a person's conscious actions to minimize their negative impact on the environment [9]. The following sections describe how an individual's level of PEB can be measured, and how different motivations can be relevant in design to increase individuals' PEBs.

1.2.1 Measuring Pro-Environmental Behavior. To quantify an individual's level of PEB, self-report measures, e.g., the General Ecological Behavior questionnaire [10] can be used. The General Ecological Behavior questionnaire evaluates PEBs across several domains: energy conservation, mobility and transportation, waste avoidance, consumerism, recycling, and vicarious social behaviors towards conservation. This questionnaire is used frequently to measure an individual's tendency to practice PEBs [11].

1.2.2 Motivating Pro-Environmental Behavior. Individuals may act pro-environmentally due to different motivations. While many interventions that aim to increase PEBs assume that people are motivated by sustainability, this is not the case for many individuals. However, people may perform PEBs because they are motivated to improve their health (e.g., walk or bicycle rather than drive), save money (e.g., use fewer resources for which they must pay), or even to improve others' perception of them (e.g., recycle, but only in public). Thus, Srivastava identified as one dimension of a behavior-change matrix, different sources of motivation, including egoistic, sociocultural, and altruistic motives [12]. The other dimension has to do with the degree of forcefulness of an intervention, as described next.

1.3 Degree of Intervention Forcefulness. Products may incorporate interventions with different degrees of forcefulness, e.g., providing information and feedback, enabling and encouraging, guiding and steering, and finally forcing and automation, as shown in Table 1. The degree of intervention forcefulness also changes the user's level of control [13]. Providing information and feedback alone puts users in control of how they use that information. Forcing and automation, where users have little control, could be argued as infringing on a user's personal freedom [14].

The following sections describe concepts that motivate water conservation along the varying degrees of forcefulness identified above. Understanding the limitations of existing concepts and solutions informs what opportunities are available to further motivate water conservation.

1.3.1 Using Information to Increase Pro-Environmental Behavior. Informational interventions are suitable for addressing a lack of knowledge, but have mixed results on whether they increase the desired behavior. For example, public-awareness campaigns can successfully reduce water use, but their effectiveness may require other concurrent actions, such as bringing together members of the public and suppliers of water-efficient devices [15].

Information alone can increase users' knowledge about consumption, but it may not empower them to modify their use patterns [16]. For example, Sohn and Nam found that even if participants were made aware they were practicing wasteful behavior, that information did not equip them with actions to meaningfully reduce the waste generated [17].

1.3.2 Using Feedback to Increase Pro-Environmental Behavior. Several existing PEB interventions provide feedback, i.e., information specific to users' actions. Smart metering systems that give feedback can be installed in homes to inform users of their water consumption [18,19]. Such systems have been reported to decrease consumption between 2.5% and 28.6% [20].

Bao et al. developed four eco-feedback graphical-display concepts that induce different emotions in users [21]. Of the two concepts involving water conservation, one was for a water faucet and the other for a washing machine. Provided feedback included both quantitative, i.e., how much water was consumed, and figurative, i.e., the state of a fish and a whale in response to water-wasting behavior. They found that inducing negative emotions can motivate immediate PEBs, and inducing positive emotions may motivate users to interact with eco-feedback displays over a longer period [21].

As with informational interventions, feedback interventions rely on individuals' motivation to follow through with the desired behavior. In addition, feedback may be prone to a novelty effect, i.e., people respond as intended until the novelty of that feedback wears off. For example, Stewart et al.'s longitudinal study of a feedback-display shower monitor showed a 27% reduction in water usage at the start of the study [22]. However, after 4 months, participants' shower-water use reverted to original levels, even with the display. Such results suggest that providing feedback alone may not lead to long-term PEBs. Instead, interventions should modify user behavior and habits, rather than provide feedback alone [22,23].

1.3.3 Using Enabling/Encouraging/Guiding/Steering to Increase Pro-Environmental Behavior. More forceful than using

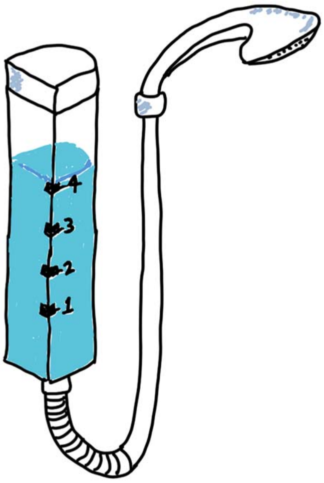

Fig. 1 Discretized-resource shower concept to motivate water conservation, adapted from Srivastava and Shu [24]

information and feedback alone, a strategy that discretizes resources may be used to enable/encourage and guide/steer the desired behavior [24]. For example, a shower concept incorporating the strategy of providing resources in discrete units rather than continuous flow is shown in Fig. 1. The concept features a visible shower tank that contains the water available for a shower. The ability to see the water level decreasing over the shower could enable users to pace themselves and better plan their water usage. The portion of water provided could suggest the appropriate amount of water per shower. Finally, the amount of time required before the tank refills itself could be used to guide/steer the desired water-conserving behavior. A separate shower concept explored the effect of gradually reducing water temperature after a set time [25].

Another steering intervention was developed and tested by Jou et al. through a Wizard-of-Oz sink faucet [26]. Here, a researcher directly controlled the behavior of a faucet described to participants as “smart” or autonomous. Water temperature and pressure were modified based on study participants’ water-use requirements and behaviors. If a participant’s water pressure and temperature were greater than a predetermined threshold, the researchers would lower them. The participant still had control and could override these actions. Water use was observed to decrease by 26.5% with the intervention, and 10.9% immediately after removing the intervention, i.e., when using a regular faucet.

1.3.4 Using Forcing/Automation. Forcing/automation is commonly implemented to reduce water consumption. Low-flow faucets and showerheads are forcing technologies that can significantly decrease water consumption [27]. However, low-flow devices may be used longer and more frequently, offsetting much of the intended savings [15]. Such forcing strategies may reduce consumption more effectively when users do not know that the corresponding products incorporate resource-efficient, e.g., low-flow, technologies [27].

Other interventions are commonly implemented in publicly accessible facilities. For example, timed shower controls, i.e., pressing a button that releases water over a set time, also aim to reduce water usage. Of note, fully automated interventions typically limit the user’s control. For example, a faucet that only provides water at a set temperature, when hands are sensed, may lead to other challenges.

1.4 Context and Intervention Visibility. Benzoni and Telenko found that water-conservation interventions were most effective at reducing water use when presented in the right *context*, and were highly *visible* to users. Context can refer to a user’s existing notions of water conservation [28]. For example, someone who has experienced drought conditions may achieve more water savings with an informational intervention than someone with no water-scarcity experience. Visibility refers to when the intervention appears with respect to resource consumption. Interventions that are present when water is being used (e.g., a feedback display at a faucet) are more effective than a water bill, which provides feedback sometime after usage [28].

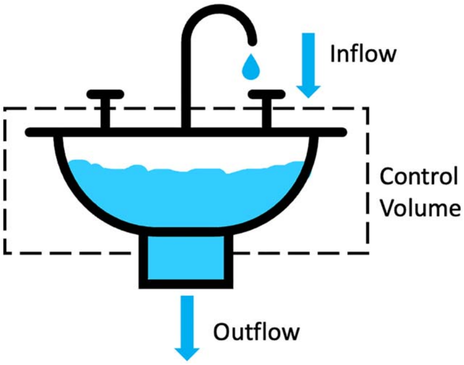

Fig. 2 Water inflow, outflow, and accumulation in a sink as control volume

Bao et al. [21] further elaborated on the importance of visibility with respect to feedback displays. By having a feedback display at a resource point-of-use (e.g., at a faucet), users are more likely to see and interact with the display, and thus lower their water usage.

1.5 Reducing Waste Outflow. As described above, there are known limitations to using information and feedback, or forcing and automation as interventions to increase PEB. Hence, the current work aimed to explore a strategy that steers the user to act more pro-environmentally.

A resource-consumption system can be modeled as three components: the resource inflow into the system, the control volume in which the resource is used, and the resource outflow. Many existing water-conservation strategies aim to limit the resource inflow (e.g., low-flow faucets and showerheads). Instead, the current work explores the effect of reducing resource-outflow rate, i.e., by reducing the rate that wastewater leaves the control volume. Considering the sink in Fig. 2 as the control volume, reducing the rate of wastewater draining from the sink will cause water to accumulate in the sink. This accumulation may then motivate the user to reduce the amount of clean water entering (resource inflow) to avoid overflowing the sink and touching the used water.

The current study focuses on water consumption while handwashing under different outflow rates. A reduced-outflow rate aims to *guide* the user to reduce resource inflow. Unlike with automated concepts, the user still maintains control. However, unlike with information and feedback interventions that have more abstract consequences, failure to respond to the devised intervention may lead the user to have to touch the used water and deal with an overflowed sink.

2 Materials and Methods

While COVID-19 restrictions on in-person research forced an online study, this was also an opportunity to explore the benefits and limitations of virtually simulating a behavioral intervention. Study participants were asked to wash their hands for 20 s at a simulated sink, as shown in Fig. 3. The simulation was coded in p5.js, a JavaScript library. Participants could adjust water pressure, but not temperature. Bias may occur if the participants were aware that the focus of the study is water conservation. Therefore, study instructions focused on removing germs from the simulated hands.

Fig. 3 Top: Simulation in Fully Blocked condition with water pressure set to maximum and countdown at 9.67 s. Bottom: Same simulation with sink overflowing at countdown of 4.38 s.

Handwashing was selected as the target activity, as it was the most straightforward to simulate. It is also a habitual task that is performed multiple times a day, which was actively encouraged during the early days of the pandemic.

2.1 Research Questions.

The current work explores a new strategy to motivate reduced resource consumption, and poses the following research questions:

(1) Does reducing resource outflow affect resource consumption?
(2) Specifically, does limiting wastewater outflow affect water usage in a simulated handwashing activity?

2.2 Pilot Study.

In an earlier pilot study, 35 undergraduate engineering students used a similar simulation, while the current study recruited a larger, more diverse set of participants. In the pilot study, a pop-up warning during the simulation may have interfered with the intervention being studied for some participants, so the warning was removed for the current study. Finally, the pilot study did not show a simulated overflow. In contrast, current-study participants would experience a simulated overflow if the water rose past the rim of the sink, as shown in Fig. 3.

2.3 Simulation Initial Instructions.

Prompts before each simulation stated that to remove as many germs as possible, the Center for Disease Control recommends washing hands for 20 s. Participants were told that there was already soap on their simulated hands. Again, the focus on germ removal was to distract participants from the actual study goal of observing water usage.

Further instructions explained how to increase and decrease the water pressure between five possible levels. Specifically, participants could increase water pressure by pressing the keyboard up-arrow key and decrease it by pressing the down-arrow key. The instructions given in the simulations are in Appendix A.

2.4 Simulation Design.

Once participants were ready to begin the simulation, the tap automatically turned to the highest water pressure, and the hands made a scrubbing motion. This initial, high pressure was intended to force participants into a conscious decision about whether to lower the water pressure. If participants chose to turn the water off during the 20 s, the hands still made a scrubbing motion, and the timer continued to count down. To help convey increased cleanliness, a green tint on the hands gradually disappeared as the simulation progressed. The rate at which the green tint disappeared was independent of the water-pressure level. This accurately represents research showing no significant effect of water pressure on germ removal while handwashing [29].

The timer counted down from 20 s once handwashing began. The simulated water overflowed if it reached the top of the sink. If the tap was turned off while scrubbing, participants were prompted to turn the water on and off for a final rinse. Otherwise, they were asked to turn off the tap to complete handwashing.

2.5 Study Components, Ordering, and Administration.

The study was conducted online using a Qualtrics™ survey. In demographic questions, participants were first asked about their gender, age, and domain of work. Next, a trial simulation enabled participants to become familiar with the interface and water-pressure controls. Then, participants completed the following randomly ordered simulation conditions:

(1) **No-block** outflow (control condition), where the water exits the sink immediately,
(2) **Half-blocked** outflow, where the sink would overflow at the maximum water pressure after approximately 30 s.
(3) **Fully blocked** outflow, where the sink would overflow at the maximum water pressure after approximately 15 s.

Between conditions, participants completed 20 simple-addition arithmetic questions, to reduce carryover effects from one simulation to the next [30]. After completing all the simulation conditions, participants responded to follow-up questions that aimed to clarify their perceptions about the study. Participants were also asked to complete the General Ecological Behavior (GEB) Questionnaire so that they could be classified according to GEB orientation [10]. Attention-check questions were embedded in the questionnaires to identify whether some participants' data should be removed.

Of note, participants' regulatory focus [31] was also measured using a questionnaire [32]. However, no significant effect of participants' regulatory focus on their behavior was found. Thus, regulatory-focus results and discussion are not included below.

2.6 Participants.

Participants were recruited through Amazon Mechanical Turk. Only residents of the United States were included to decrease heterogeneity in water-use behaviors. Elizonda and Lofthouse found that cultural differences in Mexico and the United Kingdom led to different patterns of water conservation and use [33]. Yan et al. also observed ethnic differences in domestic water use [34]. While the United States includes several cultures and ethnicities, limiting the participant pool to its residents at least reduced differences in access to domestic water infrastructure.

A total of 96 participants underwent the study. Several participants' results were immediately removed for not passing attention-check questions intended to ensure that the instructions were followed. Of the remaining 74 participants, there were 31 females and 43 males, all between the ages of 24 and 67.

3 Results

All statistical analyses were conducted in R. Excluded from analyses were outliers, whose data were three or more standard deviations from the mean. This meant that two participants' data were excluded, as they used over 6000 mL of water, whereas on average, participants used 1000–2000 mL of water to complete the simulations. Thus, 72 participants were finally included.

3.1 Mean Simulated Water Use. Simulated water use was calculated as the total amount of water leaving the faucet, regardless of the outflow rate. A repeated-measures ANOVA was used to check whether simulated water use differed significantly between conditions. Results are summarized in Fig. 4. Simulated water use between the conditions differed significantly, $F(2,\ 142) = 12.63$, $p < 0.001$. Post-hoc analysis with Bonferroni-adjusted p-values showed a significant difference in simulated water use between the No-Block and Fully Blocked conditions ($p < 0.01$), and between the Half-Blocked and Fully Blocked conditions ($p < 0.001$). There was no significant difference between the No-Block and Half-Blocked conditions. Participants on average used 14% less simulated water in the Fully Blocked condition than the No-Block condition. An analysis of simulated water use depending on condition order is shown in Appendix B.

3.2 General Ecological Behavior. Of the 50 questions in the General Ecological Behavior questionnaire [11], 42 were used to classify whether participants practice pro-environmental behaviors regularly. Appendix C shows the questions used in this study. Depending on the question, participants either responded yes/no or on a 5-point Likert scale, with an "other" option. To convert responses to numerical values, "always," "often," and "yes" were assigned a value of 1, and "occasionally," "seldom," "never," and "no" were assigned a value of −1. Responses were quantified in the opposite direction for reverse-coded questions, e.g., "At red traffic lights, I keep the engine running." If a participant responded "other," that question was removed from their tally. These responses were converted in the same way that the GEB-questionnaire authors converted their responses. Kaiser and Wilson noted that participant responses become less reliable as response options become more granular, i.e., as the number of response options increases [10].

Participants' scores on all questions were averaged to calculate their overall GEB score. A positive score signified someone who reports practicing PEBs regularly, and a negative score signified someone who did not. Excluding the two outliers described above, 50 participants signified not practicing PEBs in their daily life (negative score), and 22 participants signified practicing PEBs daily (positive score).

Results on overall simulated water usage by GEB orientation and simulation condition are shown in Fig. 5. A robust mixed ANOVA was conducted using the WRS2 package in R, as the data did not have homogeneity of variance and covariance. The main effect of condition was significant ($Q = 9.3015$, $p < 0.001$). The main effect of GEB orientation was not significant ($Q = 3.3526$, $p = 0.0742$). The interaction effect between condition and GEB orientation was also not significant ($Q = 0.4472$, $p = 0.6421$).

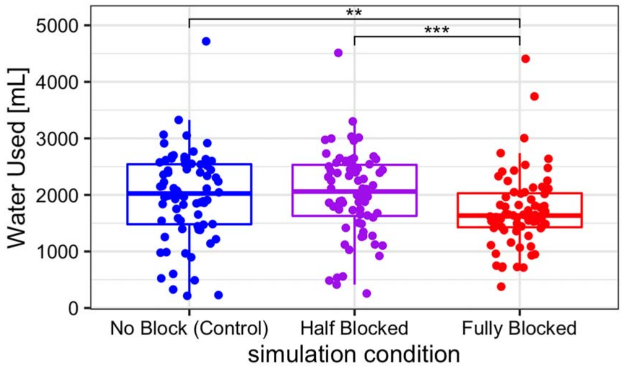

Fig. 4 Simulated water usage at different waste-outflow conditions. **$p < 0.01$, ***$p < 0.001$.

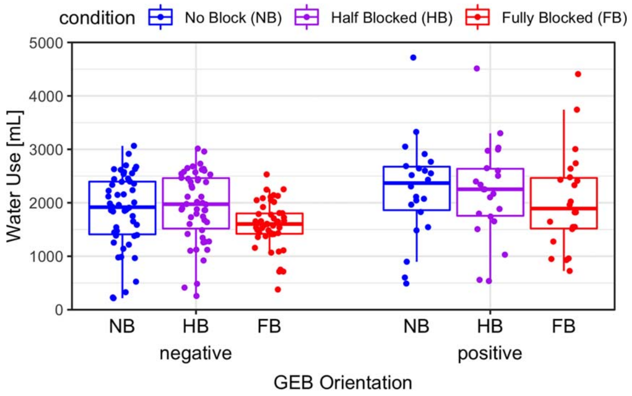

Fig. 5 Simulated water use at different waste-outflow conditions by participants' GEB orientation, where negative denotes not practicing PEBs regularly and positive denotes practicing PEBs regularly

3.3 Change in Simulated Water-Consumption Behavior. Analyzing the time spent at the maximum water pressure provides insight into how participant behavior changed with the intervention. Figure 6 shows the time spent at maximum water pressure for each simulation condition. A Friedman test was conducted on the amount of time spent at maximum pressure between the three conditions. Although the mean time at maximum pressure in the Fully Blocked condition ($M = 2.57$, SD = 2.65) is lower than in the No-Block condition ($M = 3.98$, SD = 5.18), the difference is not significant, $c^2(2) = 1.44$, $p = 0.488$.

Figure 6 shows that many participants chose the maximum water pressure for much of the simulation in the No-Block condition. In the Fully Blocked condition, the interquartile range is much smaller, indicating that more participants reduced the water pressure sooner.

3.4 Self-Reported Water Conservation. Figure 7 shows participants' mean simulated water use in the control condition versus their self-reported water conservation. No participant responded, "strongly disagree" to the statement, "I conserve water daily." Due to a large participant-number imbalance in the response categories, no formal statistical analysis was conducted. However, participants who claimed to conserve water tended to use less water in the control condition than those who claimed to not conserve water.

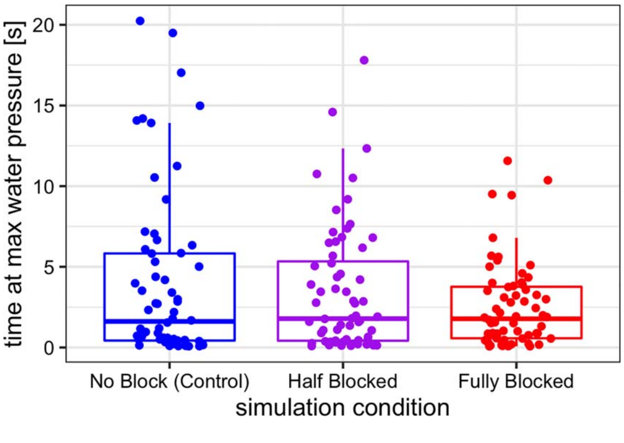

Fig. 6 Time spent at maximum water pressure at different waste-outflow conditions ($p = 0.488$)

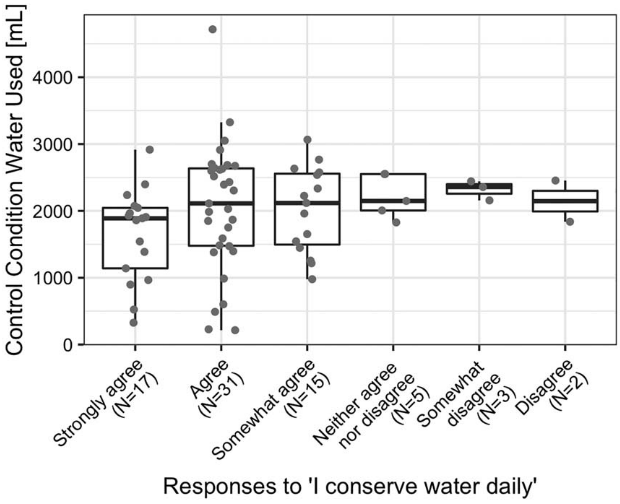

Fig. 7 Simulated water use in control condition by self-reported water-conserving behavior

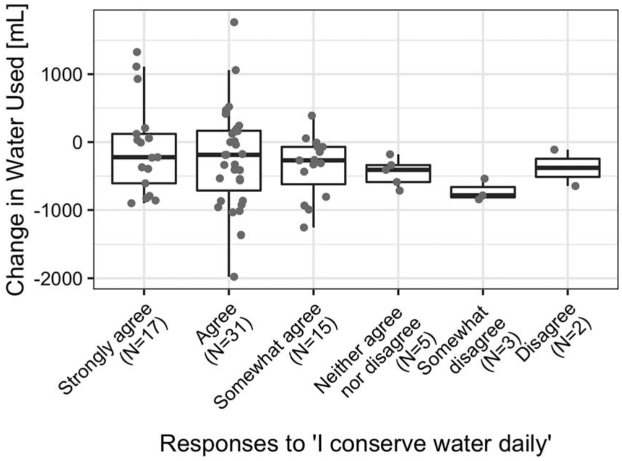

Fig. 8 Difference in simulated water use between No-Block (control) and Fully Blocked conditions, by self-reported water-conserving behavior. Negative value indicates less simulated water was used in Fully Blocked than No-Block (control) conditions.

Figure 8 shows the change in simulated water use between the No-Block (control) and Fully Blocked conditions versus participant responses to "I conserve water daily." A negative change indicates that less simulated water was used in the Fully Blocked condition than in the No-Block control condition. Most participants decreased their average simulated water usage in the Fully Blocked condition. Of note, those who did not claim to conserve water in their daily activities changed their behavior more. This may be because they consumed more water in the control condition, giving them more opportunity to decrease their simulated water use in the intervention condition. However, the relatively few participants in these categories preclude strong conclusions.

4 Discussion

The results are discussed in this section. Also discussed are the generalizability, benefits, and limitations of the reduce-outflow strategy, and the use of online simulation in this study.

4.1 Mean Simulated Water Use. Participants significantly reduced simulated water consumption in the Fully Blocked condition compared to both the No-Block control and Half-Blocked conditions. Thus, the intervention successfully reduced participant water consumption during the handwashing simulation. The significant difference between simulated water use in the Half-Blocked and Fully Blocked conditions suggests that the rate at which water pooled in the sink is important. Perhaps, the rate at which water rose in the sink was not sufficiently salient in the Half-Blocked condition to motivate users to decrease water pressure in response.

The studied intervention was highly salient at the time that participants were handwashing. That is, in the Fully Blocked condition, the simulated rising water was apparent. According to Benzoni and Telenko, intervention visibility is an important determinant of its effectiveness [28]. This may be one reason reducing waste outflow was effective at reducing simulated water consumption.

The intervention is also consistent with Telenko et al.'s guidelines, e.g., optimizing the rate and duration of resource consumption, and showing the amount of resources being used [7]. Reducing waste outflow may have helped users optimize simulated water consumption by "encouraging" them to lower water pressure and/or turn water on only when necessary. Finally, the water pooling in the sink allowed users to visualize the amount of water used, in contrast to informational displays that may only state the numerical volume of water used. Bao et al. noted that individuals may not trust the accuracy of the displayed water-usage amount [21]. Thus, interventions that support users to visualize the amount of water being consumed may be more effective.

There already exist water-conservation interventions that report the amount of water used. However, as noted earlier, information- and feedback-based interventions may not work on those who are unmotivated by the provided information. Furthermore, simply reporting the amount of water used may not convey to users that the amount is excessive, nor does it always provide them with tools to meaningfully decrease consumption. The current intervention adds a nudging element that guides users to the desired behavior. The water level rising in the sink is a direct consequence of setting the water-pressure level higher than required, and users should know how to reduce their consumption in response. Thus, reducing outflow goes beyond typical information and feedback-based interventions.

4.2 General Ecological Behavior. The Fully Blocked intervention condition reduced simulated water use significantly, both for participants who reported, and those who did not report practicing pro-environmental behaviors (PEBs) regularly on the GEB questionnaire. It is ideal that the intervention is effective on individuals regardless of whether they report practicing PEBs, as those who do not may have more potential for improved resource conservation. Even individuals who report practicing PEBs may not behave consistently in sustainable manners. In any case, the intervention's uniform effectiveness supports that it does not rely on user values and motivation.

As shown in Fig. 5, the interquartile range of simulated water use in the Fully Blocked condition for participants with negative GEB orientation is smaller than the interquartile range for positive-GEB-orientation participants. This suggests that the intervention was more consistent in reducing simulated water consumption in participants ($n = 50$) who did not report practicing PEBs daily compared to those who did ($n = 22$). Although the number of positive-GEB participants was limited, this result further supports the intervention's effectiveness without relying on pro-environmental values and intentions. Thus, reducing waste outflow contrasts with many existing water-conservation concepts, which rely on pre-existing user intentions to conserve resources.

However, the appropriateness of the GEB questionnaire to assess water-conservation intentions specifically may be limited. The GEB questionnaire asks about Pro-Environmental Behaviors (PEBs) relating to energy conservation, mobility and transportation, waste avoidance, consumerism, recycling, and vicarious social behaviors towards conservation. While the GEB questionnaire has a few questions on water conservation (e.g., shower behavior), water conservation is not a focus of the GEB. Sønderlund et al. noted differences between behaviors related to energy versus water conservation, and that interventions effective for conserving energy may not be as effective for conserving water [18].

4.3 Water-Conservation Intentions. The data in Figs. 7 and 8 show simulated water use and intervention effectiveness specifically related to water-use intentions. However, no concrete conclusions can be drawn, as some intention categories had only 2 and 3 participants.

Nonetheless, the results suggest that self-reported water-consumption behavior may be inaccurate. Some participants reported conserving water daily, but used the same or more water in the control simulation than those who did not report conserving water daily. Stewart et al.'s shower study found that while participants expressed a willingness to conserve water while showering, this did not translate into actual behavior [22]. The discrepancy between questionnaire responses and measured water use supports that resource consumption should be measured, rather than based on self-reported behavior [35].

4.4 Change in Simulated Water-Consumption Behavior. Ideal water-conserving handwashing behavior involves turning the water off while lathering, and setting a low water pressure while rinsing [36]. Most of the current study's participants spent less time using the maximum water pressure in the Fully Blocked condition than in the No-Block condition. Thus, the intervention guided them to modify their simulated behavior. Responses to follow-up questions confirm that 80% of participants agreed that they decreased the water pressure as the water level rose in the sink. Furthermore, 65% of participants agreed that they turned the water off earlier due to the water rising.

Additionally, Bao et al. [21] suggest that creating cognitive dissonance in the user can motivate them to modify their behavior, as a means of overcoming the dissonance. Cognitive dissonance can be created by catching the user by surprise. While the current-study participants were not asked if they were surprised by the rising water, water pooling in the sink is not what one would typically expect. Thus, the rising water level may have been unexpected, contributing to the change in simulated behavior.

The desired water-conserving behavior may discontinue without the presence of the outflow-reducing intervention. However, the intervention where it exists may help form water-conserving habits. Jou et al. [25] observed continued water-conserving behavior immediately after their intervention ceased. If people were exposed more frequently to such behavior-changing interventions, new, more sustainable habits may form.

4.5 Limitations of Studied Intervention and Possible Countermeasures. While the reducing-outflow intervention was studied virtually, discussed below are likely limitations and possible countermeasures when physically implementing this intervention.

One clear concern is that sinks may overflow. Countermeasures include overflow holes that many sinks already feature. In addition, the sink drain can be configured to only slow or prevent water flow until a certain amount of water (e.g., by weight) had collected.

Another risk is that people may perceive the slow-draining sink as in need of repair, leading to unnecessary maintenance calls. This potential problem can be addressed by information. For example, posted signage reading, "These sinks drain more slowly to encourage you to use less water" may suffice.

If only one of multiple sinks in a public setting drains more slowly, people may learn to avoid using it. Therefore, most if not all sinks in a public setting should implement the same intervention. Accessible sinks could be exempted, as they tend to be shallower, and be used by those who may not be able to turn off the faucet as easily.

Importantly, the intervention should not be noticeable to those who already perform the desired behavior, i.e., people who do not leave the faucet running should not notice water pooling.

Finally, sinks with automated faucets (those that turn on and off automatically) may not require this intervention. However, such faucets require additional resources, e.g., batteries or another source of electricity for motion sensors. In addition, automated faucets may lead people to *not* turn off *manual* faucets, as they become accustomed to walking away from running water.

4.6 Generalizability of Outflow-Limiting Strategy. In the current study, the outflow rate was modified to test whether reduced outflow would decrease simulated water consumption at a sink. Reduced wastewater outflow can also be applied to shower drains to evaluate the water-conserving potential while showering.

Reduced waste outflow may also be applicable beyond water conservation. For example, if the rate of garbage removal is reduced, e.g., during a worker strike, would people decrease the amount of material they buy that may accumulate as solid waste? At a different scale, if a road system has fewer exits or lanes, leading to more congested traffic, would this motivate people to drive less? Finally, beyond liquid and solid matter, would decreased waste-heat removal motivate people to reduce heat-generating activities on products that require heat removal, e.g., electronics and automobiles? Table 2 shows elements of the above examples that correspond to inflow, control volume, outflow, mechanism, and motivation. Of course, fail-safe overrides must be devised.

4.7 Benefits and Limitations of Reduced-Outflow Strategies. The benefit of interventions stronger than information/feedback alone is that people are more likely to perform the desired behavior. With the guiding/steering strategy proposed here, reduced outflow of waste materials or energy, negative consequences may be anticipated and limited. For example, reduced outflow may be limited to predetermined safe levels.

With reduced-outflow interventions, targeted individuals may feel uncomfortable and/or inconvenienced. However, those already performing or guided to perform the desired behavior, e.g., turning off the tap, will not (continue to) feel uncomfortable due to the rising water level. In addition, those who have a strong aversion to touching used water may be strongly influenced, while those who have no such aversion may not be influenced at all.

Table 2 Other potential applications where reducing outflow may reduce resource consumption

Inflow	Control volume	Outflow	Mechanism and motivation
Purchased items	Household	Garbage collected	Reducing garbage-collection rate causes buildup of solid waste. Motivates individuals to buy fewer items
Vehicles	Road	Number of lanes or exits	Reducing the number of lanes or exits causes congestion. Motivates drivers to drive less
Heat generated during use	Device that generates heat during use	Waste heat	Reducing removal rate of waste heat may cause discomfort or damage device. Motivates people to use less heat-generating activity on device

Worth noting is that interventions which may seem less forceful (i.e., encouraging/enabling interventions) will exert different levels of forcefulness on different people. For example, small costs for disposable and reusable bags are used to encourage people to bring their own bags for reuse. However, depending on the financial status or attitude of the individual, a five-cent charge for each disposable bag or a one-dollar charge for each reusable bag may be quite a strong intervention for some and a trivial intervention for others. In addition, each intervention could be framed as both positive or negative, e.g., save $1 by bringing your own bag, or be penalized $1 to buy another reusable bag. With the reduced-outflow strategy, those performing the guided behavior may not experience any forcefulness, whereas those engaging in wasteful behavior may find the intervention forceful.

While interventions using automation are more common, user experience may also be compromised when the automated behavior is not consistent with the user's goal. For example, obtaining the desired temperature and flowrate may be more difficult when filling a water bottle with a sensor-operated faucet. Faucets at public sinks often offer users limited ways to override default settings.

Although designers should avoid sacrificing user experience due to poorly executed design (e.g., non-intuitive user interface, or faulty products), designers already increase inconvenience and discomfort to discourage undesired (e.g., unsafe) behaviors. Goucher-Lambert and Cagan [37] also found that including environmental impact in product decision-making alters product preferences, where functional attributes increase in importance and esthetic attributes decrease in importance. Thus, concepts that effectively reduce resource use, even if uncomfortable to some users, should still be considered. Outflow-reducing interventions will likely be initially implemented in environments where the user of resources may differ from those who pay for them. For example, public-setting paper-towel dispensers often dispense a single paper towel at a time, reducing convenience for those who want to use several paper towels. However, even in this example, the designer must identify and reduce unexpected, negative outcomes, such as increased tearing of paper towels that worsen littering. The initial adoption of such interventions in public spaces may eventually shape private behaviors.

4.8 Versatility of Online Simulations.

The current authors conducted an online study due to COVID-19 restrictions on in-person activities. However, even when in-person studies are more easily conducted, online studies can continue to be used for their benefits. Online studies are already commonplace for crowdsourcing design evaluations of various products [38,39]. Despite the challenges of online studies, more diverse participant pools can be obtained through online platforms. Given the importance of testing PEB interventions on a wide variety of individuals, participant diversity may be more easily accomplished online, compared to recruiting mostly university students. From a research-methodology perspective, iteration in study design is an important element in refining a scientific study. Using online simulations prior to an in-person study can help researchers modify their study for future iterations more efficiently.

4.9 Limitations and Next Steps.

There are, of course, limitations to conducting a virtual simulation that mimics a physical process. Most participants expressed that the simulation was realistic, but there were no real consequences to the sink overflowing. In real life, overflowing the sink results in a mess. In the simulation, 80% of participants still overflowed the sink in the Fully Blocked condition. In an in-person study, fewer participants would likely overflow the sink, and participants would probably choose to reduce the water pressure sooner. However, researchers should anticipate and plan for sink overflow during the study.

In addition to laboratory observations, field evaluations should be conducted to study the intervention in more natural environments [11]. A sink drain that implements this intervention could be installed in public spaces, e.g., institutional washrooms. Parameters such as rate of wastewater outflow can be optimized for specific sinks, depending on the size of the sink and the faucet maximum flowrate. In addition, reduced outflow should be overridden when a sink nears overflow. This intervention may be attractive to public facility owners, who may be more motivated to reduce consumption than facility users. However, as Pakravan and MacCarty [40] noted, sustainable product innovations must be accepted by users to improve sustainability as intended.

Furthermore, to support a water-conservation study, it may be more insightful to use a questionnaire specific to water conservation, instead of the General Ecological Behavior questionnaire. Using a questionnaire specific to the effect being measured, i.e., a questionnaire on water-use beliefs, could predict water consumption more accurately [41].

5 Summary and Conclusions

The United Nations' Sustainable Development Goals highlight the urgency of reducing resource consumption. However, technological solutions should be coupled with an understanding of user behavior, and how users interact with the technology, to be more effective in the long term.

The current work sought to reduce water consumption using a different approach. Many existing water-conservation strategies aim to reduce water inflow, e.g., through a faucet or shower. Instead, this work explored the effect of reducing wastewater outflow, causing water to accumulate, on reducing resource inflow.

Results of an online study, which implemented the reduce-outflow strategy, support that users were successfully motivated to reduce simulated water consumption. Specifically, participants used on average 14% less water to wash their hands in the fully blocked intervention condition than in the no-block control condition. Some participants modified their behavior by setting the faucet at lower water-pressure levels.

Regardless of prior notions and intentions about water conservation, the reduce-outflow intervention was able to decrease simulated water consumption. In contrast, many concepts that aim to promote pro-environmental behaviors rely on the user's intrinsic motivation to conserve resources.

Reducing outflow to conserve resources could be applied to a variety of domains. Studying corresponding interventions in real-world settings will identify factors required for success as well as limitations on effectiveness. Critically, such work must balance the outflow-reduction rate with the desired behavior, to avoid creating larger environmental or other societal problems, e.g., due to reduced sanitation.

Further insights on the reduce-outflow strategy may help inform the development of other enabling/encouraging and guiding/steering strategies. For example, Rea et al. [42] explored whether another such strategy could increase the temperature users set at a thermostat during warm weather. Interventions at different levels of forcefulness are required to address increasing environmental challenges.

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Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

The authors attest that all data for this study are included in the paper.

Nomenclature

General Ecological Behavior (GEB) = Name of questionnaire used to quantify an individual's level of PEB.
Pro-Environmental Behavior (PEB) = Conscious behavior undertaken with intended and/or real effects to benefit the natural environment.

Appendix A: Simulation Instructions

First Simulation Instruction Screen. "The CDC recommends washing your hands with clean water for at least 20 s to prevent the spread of germs.

In this simulation, you are asked to wash your hands for 20 s. There are four water pressure levels. To increase/turn on water pressure, press the up key. To decrease/turn off water pressure, press the down key. Press the 'a' key to continue."

Second Simulation Instruction Screen. "You may assume that you already have soap on your hands.

Although germs are invisible to the naked eye, in this simulation the amount of germs on your hands is represented by a green tint on your hands. Press the 'b' key to continue."

Simulation-Completion Screen. "You have finished washing your hands.

Please open the downloaded .txt file labelled MTurk simulation <0103>, and copy the contents into the Qualtrics survey question box. Once the .txt file has downloaded, you may exit this tab and return to the Qualtrics survey."

Appendix B: Water Use Depending on Condition Order

This analysis examines whether the order in which the conditions were given to participants influenced their behavior, in addition to the main effect of the intervention. Results are summarized in Fig. 9. A robust mixed ANOVA was conducted, using the WRS2 package in *R*, as the data do not have homogeneity of variance and covariance. There was a significant main effect of the condition ($Q = 17.1961$, $p < 0.001$). The main effect of condition order was not significant ($Q = 0.5793$, $p = 0.7154$). The interaction effect between condition and condition order was also not significant ($Q = 1.2718$, $p = 0.3049$).

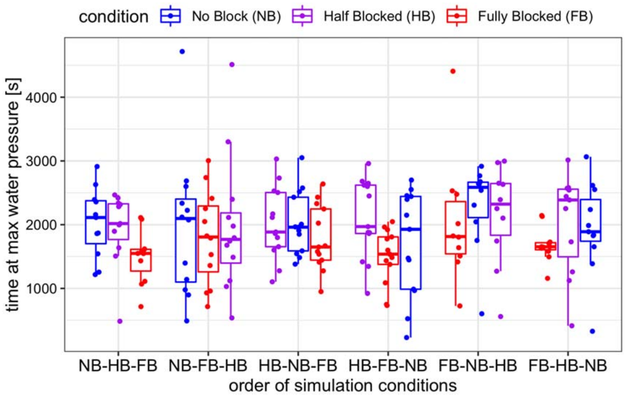

Fig. 9 Simulated water usage at different waste-outflow conditions based on the order in which conditions were presented to participants

The non-significant main effect of order and interaction effect support that the intervention motivated participants to reduce water use, regardless of the order in which conditions were administered to participants.

Appendix C: General Ecological Behavior Questionnaire

Adapted from [10], statements in *italics* were not included in this study's questionnaire.

Energy Conservation

1. I own energy efficient household devices
2. I wait until I have a full load before doing my laundry
3. I wash dirty clothes without prewashing
4. *In hotels, I have the towels changed daily*
5. *I use a clothes dryer*
6. I bought solar panels to produce energy
7. I use renewable energy sources
8. In the winter, I keep the heat on so that I do not have to wear a sweater
9. In the winter, I leave the windows open for long periods of time to let in fresh air
10. In winter, I turn down the heat when I leave my apartment for more than 4 h
11. I prefer to shower rather than to take a bath

Mobility and Transportation

12. I drive my car in or into the city
13. I drive on freeways at speeds under 100 kph (62.5 mph)
14. I keep the engine running while waiting in front of railroad crossing or in a traffic jam
15. At red traffic lights, I keep the engine running
16. I drive to where I want to start my hikes
17. I refrain from owning a car
18. I am a member of a carpool
19. I drive in such a way as to keep my fuel consumption as low as possible
20. I own a fuel-efficient automobile (less than 7 L per 100 km, i.e., less than 3 gallons per 100 miles)
21. For longer journeys (more than 6 h), I take an airplane
22. In nearby areas (around 30 km; around 20 miles), I use public transportation or ride a bike
23. I ride a bicycle or take public transportation to work or school

Waste Avoidance

24. *I buy milk in returnable bottles*
25. If I am offered a plastic bag in a store, I take it
26. I reuse my shopping bags
27. *I buy beverages in cans*
28. I buy products in refillable packages

Consumerism

29. I use fabric softener with my laundry
30. I use an oven cleaning spray to clean my oven
31. I kill insects with a chemical insecticide
32. I use a chemical air freshener in my bathroom
33. *I buy convenience foods*
34. I buy seasonal produce
35. I buy bleached and coloured toilet paper
36. I buy meat and produce with eco-labels
37. *I buy domestically grown wooden furniture*

Recycling

38. I collect and recycle used paper
39. I bring empty bottles to a recycling bin
40. I put dead batteries in the garbage
41. *After meals, I dispose of leftovers in the toilet*

Vicarious, social behaviors toward conservation

42. *After a picnic, I leave the place as clean as it was originally*
43. I am a member of an environmental organization
44. I read about environmental issues
45. I contribute financially to environmental organizations
46. I talk with friends about problems related to the environment
47. I have pointed out unecological behavior to someone
48. I boycott companies with an unecological background
49. I have already looked into the pros and cons of having a private source of solar power
50. I requested an estimate on having solar power installed

Appendix D: Post-Simulation Follow-up Questions

(1) As the water level began rising in the sink, I became more uncomfortable
(2) Seeing the rising water level caused me to decrease the water pressure of the faucet
(3) Seeing the rising water level caused me to turn off the tap earlier than I normally would
(4) Seeing the water I used pooled in the sink helped me understand visually how much water I normally use to complete this task
(5) I try to conserve water during my everyday activities
(6) I can confidently state the volume of water I use for everyday activities such as washing the dishes, showering, brushing my teeth, etc.
(7) Please describe your experience with the simulations (e.g., did you notice the water rising? What did you feel? Was the simulation able to mimic the real experience?)

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