WATER CONSERVATION FACILITATED BY PHASIC FEEDBACK THROUGH SMART DEVICES

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LIST OF SYMBOLS AND ABBREVIATIONS

NEP	New Ecological Paradigm Survey [1]
LCA	Life Cycle Analysis
GFCI	Ground Fault Circuit Interrupt

SUMMARY

On average Americans consume 99 gallons of water per person at home each day. This is more than six times the necessary amount of water to have a comfortable life, 13.2 gallons per day. This excess usage results in avoidable stress on water reservoirs, and material and energy resources for the processing and delivery of water. Despite much technological advancement, such as low-flow aerators, household water consumption remains much higher than necessary. The underlying problem is human behavior. To change behavior, researchers have developed and studied a range of intervention systems aimed at creating water conservation. They have achieved savings from 0-28%. These studies were limited by small sample sizes, short deployments, and providing only basic usage feedback. This thesis describes the development and pilot testing of a prototype phasic usage feedback device aimed at creating water conservation at the kitchen sink.

Our device was informed by the pros, cons, and pitfalls of existing eco-persuasive technologies. The kitchen sink was the chosen point of intervention due to its relatively high visibility throughout the day, and due to the often large potential to save water by adjusting habits. We found that efficient dishwashing methods can save up to 80% of the water used by less efficient methods to achieve the same task.

While most smart user-centered devices in literature and on the market, such as Fitbit and Nest, provide a simple usage feedback, i.e. a meter or indicator showing how much water one is using/has used, or “steps taken/calories burned”, the device described in this thesis utilizes a behavioral change model of feedback. The feedback type changes over time based on the Trans theoretical Model of behavior change. The feedback

includes a standard quantitative usage feedback, but also relies heavily on educational and prescriptive messages displayed while the sink is determined to be idle. Although researchers have suggested the use of the Trans theoretical Model to smart devices on theoretical grounds, it has not been implemented or tested until now.

The phasic feedback device was tested in volunteers’ homes during the Fall of 2016 and the Spring of 2017. The study employed two test groups, one test group with the phasic feedback device, and one control group with a non-phasic, traditional feedback device. Each household had their device for a total of 10 weeks in the fall and 7 weeks in the spring. A total of 12 households participated with five as control groups, with non-phasic devices installed, and seven as test groups with phasic devices.

Interactions between the device and user attitudes were also investigated. To measure any differences in subjects' pro-ecological attitudes and how participant’s eco-attitudes may correlate to the device’s efficacy, New Ecological Paradigm (NEP) surveys we administered at the beginning and end of the intervention. A qualitative survey was also administered after the experiment to understand what the participants did and did not like about the many aspects of the device and feedback. This feedback allowed us to ascertain what degree of accuracy the device’s volume estimations were perceived to be.

Data collected from the pilot studies showed the phasic groups saved an average of 57%, and 50% of their weekly water than the control group, whose weekly usage increased 17% and decreased 2% throughout the Fall 2016 and Spring 2017 pilot studies respectively. The NEP surveys indicated a negligible shift in pro ecological attitudes.

CHAPTER 1. INTRODUCTION

Sustainable user behavior is crucial to conserving resources, and designers are seeking to integrate resource conservation guidance into engineered systems. Recent advances in transducer and microprocessor technology allow for the development of personal usage feedback systems in homes and other areas. These technologies are now used commercially in cars and homes for energy consumption feedback, in wearables for personal health feedback, and in academia by researchers to provide users resource usage feedback; such as telling someone how much water or electricity they used over a given period of time and in general behavioral feedback. Though there have been a handful of studies, UpStream, Show-Me, the WaiTek shower monitor, surrounding eco feedback technologies aimed at creating water conservation, few of these studies examine the design of the feedback, and none incorporate psychological models for behavior change into the provided feedback [2]–[4]. This thesis adds to the growing body of knowledge in eco-feedback systems, and explores the relative efficacy of water usage feedback based on a phasic model for behavior change, called the Trans theoretical Model [5], versus traditional usage-only feedback at the kitchen sink.

1.1 The Opportunity and Need for Water Conservation

Worldwide, 663 million people do not have access to clean water, and 6 to 8 million people die annually due to water-related diseases [6]. Global demand for water is growing at double the rate of the population. The U.S Government Accountability Office predicts that 40 out of the 50 continental states will experience water shortages in at least one region over the next 10 years, and that the USA is on the brink of a water crisis [7]. Despite such projections, water is largely treated as an infinite resource by the citizens of wealthy nations. Many consumers fail to understand the process through which water must go before exiting the tap in one's home, the high associated environmental cost of these processes, and the dwindling supply of potable water [8].

This misunderstanding of water's value, coupled with the hidden water costs of many in-home processes leads US consumers to demand far more water than is necessary or reasonable for a comfortable life. The average American uses about 98 gallons per day at home, including irrigation. In comparison, the average European consumes about 53 gallons per day, while the average Sub-Saharan citizen consumes 3-5 gallons per day [9]. Peter Gleick concluded that the basic water needs for a human to reasonably, drink, bathe, prepare food, and maintain a sanitary environment is about 50 liters a day, or 13.2 gallons [10]. These estimates do not account for the production of one's food or lawn maintenance.

How so much water is used is an important question, with a unique answer for each person and region. Mayer et al. [11] found that indoor water usage is generally broken down as leaks 13.7%, showers 16.8%, toilets 26.7%, clothes washer 22%, and faucets 15.7%. Including outdoor use, about 50-70% of domestic water is used watering lawns and gardens [11]. Though at-home water use only accounts for about 11% of the total US freshwater withdrawals, this type of usage is generally the most intimate and may be the best reflection of a user's attitude towards water. Further, these withdrawals do not always reflect *consumption* which is the amount of water lost (evaporated, redirected to different watersheds, polluted), and not all of these withdrawals need to be processed and reprocessed as domestic usage does. In the electricity generation sector, which accounts for 40% of the USA's freshwater withdrawals, typically only 3-9% of the total withdrawn water is *consumed* [12]. This means that the relative significance of the domestic sector's withdrawals are larger than may seem as all of this water is processed at least two times: once for distribution, once for wastewater treatment and reintroduction.

Because it is the most intimate water use, affecting indoor water usage may be the best way to change a user's core belief system with respect to water, resulting in significant savings in other sectors of use. However, even if far reaching effects are not achieved, the potential for indoor water savings in the domestic sector alone is massive. Amy Vickers [13] estimates that a 30% reduction in US household water usage would result in a savings of more than 5.4 billion gallons a day, and over $4 billion annually.

1.2 Interventions for Water Conservation

In recent years many new technologies for saving resources in-home have been developed and even commercialized [14]. For water, these methods primarily take the form of water-efficient appliances and appliance "add-ons", such as faucet and shower aerators. Though ten states in the US now require new housing to be built with water-efficient appliances, there are still tens of millions of inefficient, old-fashioned appliances being used in America [15]. Thus it is important to reach homeowners, and enable them to conserve water as effectively as possible. A system or device that “reaches out and affects” a user is termed an intervention.

Researchers have developed and tested many intervention systems aimed at creating water conservation. These interventions have taken many forms in academia, such as physical mail, online portals, pamphlets, signs, and electronic feedback devices. This last category, devices, has only been possible since the widespread use of microcontrollers has become popular and sensor technology has advanced to allow for small, cheap sensors and microprocessors to become easily available. Electronic devices allow for the greatest amount of information to be disseminated, and also are the only format which allow for real-time water usage feedback to be provided to users. Online portals may allow some degree of usage feedback, but users have been found to seldom log in to their accounts [16].

A few devices give water usage feedback at the sink such as Upstream, Waterbot [2], [17]. The study of Waterbot did not record how users’ behaviors changed, and UpStream had very mixed results from a short public deployment, -33% -- +125%. However, devices deployed in showers, such as Show Me and WaiTek have consistently shown high water savings, from 10-27% saved in shower volume [3], [4]. The range of device successes, combined with conclusions from a broad review of water interventions, provided in Chapter 3, suggest that a device which combines education, theories of behavior change, and live usage feedback may achieve greater savings than previous interventions.

In order to persuade users to adopt water-wise habits we developed a device that provides dynamic feedback seeking to motivate water conservation by providing specific information tailored to distinct phases of behavior change. These phases are described in the Trans theoretical Model (TTM) of behavior change. The TTM describes six phases a person goes through before enacting lasting behavior change, and has been used to create behavior change in many areas including health, fitness, and addiction recovery [18], [19].[18], [19]. Thus, this study aims to discern what levels of behavior change can be achieved using phasic feedback compared to a non-phasic counterpart. Behavior change is defined as water volume used at the kitchen sink. Further the study tests if phasic feedback influences pro-ecological attitudes, and how these attitudes affect or correlate to the user's behavior.

1.3 Thesis Organization

The rest of this thesis will be structured as follows;

Chapter 2: Review of Intervention Studies Aimed at Water Conservation reviews the academic literature about different interventions which sought to create behavior change favoring water conservation. Eighteen studies are described, reviewed, and tabulated here. These interventions resulted in 0-28% reduction in water volume for the targeted area (overall, shower, faucet). Further an analysis of the studies taken together provides recommendations for future water intervention systems. The two main factors found to contribute to a water interventions success were; the visibility/accessibility of the intervention, and the climate context an intervention is deployed in. Furthermore, incisive criticisms of persuasive technologies indicated that a phasic approach that incorporates human psychology to feedback could further advance conservation efforts and improve feedback efficacy [20]. This review led to the development of the phasic water feedback device developed and tested in this thesis.

Chapter 3: Design provides an overview of how and why the device works. There is a recap of the device oriented intervention in literature followed by a high-level description and justification of the design of the phasic feedback device. This description includes a list of components in the device and their functions. Finally there is a description of the code/control in the device and a description of the feedback and feedback framework which is provided to the participants in the study. The device achieved a degree of accuracy higher than reportedly achieved by similar devices, and the sensing method for predicting water flows was greatly improved upon.

Chapter 4: Phasic Device Study Methodology describes the pilot study of the device in six households from September-December (Fall) 2016 and the subsequent January-April (Spring) 2017. This section explains the details of the study itself; including the methods for measuring the device's efficacy both qualitatively and quantitatively.

Chapter 5: Results from Device Pilot Studies gives a description and summary of the recorded results from the first pilot study. This section illustrates and discusses the water use data, environmental attitude measurements and qualitative feedback received. In this study, we achieved an over 50% recorded water volume reduction in the phasic experimental groups compared with the non-phasic control groups. The participants reported only a slight increase in pro-ecological attitudes, with the phasic group having zero net change. From the open ended survey we learned that the users overall had positive experiences with the device, and that the phasic groups were engaged by the information displayed, while the non-phasic groups were less so.

Chapter 6: Conclusions and Future Work summarizes the conclusions; that the phasic device groups conserved more water than the non-phasic groups, but that their self-reported pro-ecological attitude shift was less. A list of device, and data limitations is also given with a variety of potential design solutions.

CHAPTER 2. LITERATURE REVIEW

To ensure that there is enough potable water to meet the rising global demand many researchers have developed intervention methods aimed at promoting water conservation in the home. These intervention methods generally rely on informing water users and may be classified as either antecedent or consequential. Current intervention studies, applied from a range of a few days to eight months, reveal a wide range (2% to 28%) of water savings [21]. The results indicate that higher levels of savings require more investigation and understanding of what design affordances and contextual factors are most influential. Two factors are highlighted in the following review paper: an intervention's visibility and the climate context in which the intervention was conducted. This chapter provides a comprehensive review of eighteen intervention methods and a sub-review of household water sensing systems, which may facilitate feedback. The findings of current research are synthesized to provide recommendations for future work. In particular, point-of-use interventions, and contextual immediacy are important attributes of successful systems.

2.1 Review Intro

In recent years many new technologies for saving resources in-home have been developed and even commercialized [14]. For water, these methods primarily take the form of water-efficient appliances and appliance "add-ons", such as faucet and shower aerators. Though ten states in the US now require new housing to be built with water-efficient appliances, there are still tens of millions of inefficient, old-fashioned appliances being used in America [15]. Thus it is important to reach homeowners, and enable them to conserve water as effectively as possible. A system or device that "reaches out and affects" a user is termed an intervention.

Intervention systems take two primary forms: before-use; termed antecedent, and after-use; termed consequential. Common antecedent interventions are educational, such as pamphlets containing water-saving tips, and consultation, such as goal-setting. Consequence interventions primarily take the form of usage tracking and comparison (feedback), and may sometimes take the form of reward/penalty systems. Feedback is a complicated mechanism and has many facets which may affect a consumer's response. How one displays data can have a large effect on the overall success [22]. Further, usage feedback is reliant on some system of monitoring consumer's water usage. The reliance on monitoring poses a technological/infrastructural barrier to feedback systems, which may be overcome through the use of many types of sensing systems, pre-existing and novel, detailed in section 2.6.

2.2 Method

The goal of this review is to identify why some water interventions succeed while others do not. This review also serves to provide a summary of a range of interventions and their test results. This section describes the processes by which the reviewed studies and interventions were collected and evaluated. Exclusion criteria are also discussed.

2.2.1 Selection Procedure

To find the papers reviewed here various data-bases were searched -- Google scholar, Georgia Tech library system, and Wiley Online -- leading to many journal and conference papers associated with interventions for water conservation. The references of each paper were examined in order to find relevant publications, as was the list of "cited-by" papers. This is called the "snowball" method and has been shown to effectively reveal high quality papers [23].

In order to be included in this review the study had to either propose a product with a functioning prototype aimed at affecting user behaviour, and/or the study had to measure the effects of an intervention system or method aimed specifically at household water behaviour. Most studies developed their own intervention system, but one work examined what factors contributed to the success of an external governmental campaign [24]. Due to the consistency and quality of peer-reviewed academic studies, all reviewed studies are published academic papers.

2.2.2 Evaluation Criteria

To evaluate the effectiveness of an intervention, studies generally do one or both of the following; measure the change in net water consumption versus a control, and/or measure subject-reported changes in behavior and consumption. The inclusion of a behavior change survey provides insight into how or what the intervention succeeded or failed to affect. These reported behavior changes imply some activities have a higher elasticity than others and provide insight into how an intervention system may be optimized. Many reviews do their own analyses on a studies' dataset to normalize the data. The results reported in this study are reported directly if the reviewed results are easily understood in either percentage or volumetric change compared with a control. If the results were volumetric, the only extra analysis done here was converting from volumetric to a percentage change. This is done to give the reader a comparable understanding of each paper without bias or error introduced by additional processing, and because the raw datum from each study are not easily available.

The decision not to do additional data analysis introduces a degree of comparison error, as the sets may be normalized differently, as they use different controls, measurement systems etc. In order to combat any misrepresentation, each study will have included in its analysis the method of data collection, the sample size, and the type of control; compared with baseline data acquired pre-intervention, or compared with non-intervened parties. In the summary section there is a table detailing all of the studies reviewed here, with the most crucial information displayed.

A more in depth discussion of the specifics of the studies may be found in the following sections. Section 3 will deal with antecedent interventions, Section 4 will discuss consequential interventions, and finally the device oriented solutions will be discussed in Section 5. After the intervention discussions there will be a review of the different sensing methods in Section 6 which may be applied in various ways to create new interventions and intervention systems.

2.3 Antecedent Interventions

Antecedent interventions attempt to influence user behavior before the behavior is carried out. They work by supplying information in order to change the user's attitude towards water use, how much an individual feels his/her actions affect the big picture (i.e.

one's locus of control), and provide action strategies which in turn causes and enables the user to conserve water [25].

The main forms these take, in order of discussion, are tips and information pertaining to water and/or water usage (electronic, physical mail, pamphlets, signage), invoking cognitive dissonance (through surveys), or social interventions which rely on using groups and dialogue to facilitate learning and conservation. A government program in Queensland was also considered to be a social intervention due to the widespread communication and community leverage it had.

2.3.1 Tips and Information

Five studies tested the effectiveness of antecedent interventions in the form of tips or information. Each study features an experimental group provided with only water-saving tips and/or water related education, without any other form of intervention[26]–[30]. Most of these studies found that antecedent information did not lead to water conservation. The only exception to the results was in one study of information released in a drought region. This drought context seemed to increase the effectiveness of information-based interventions. Additionally, information at the point-of-use seems to be more effective than pamphlets as well. This sub-section reviews each of the five studies in more detail.

The first study, by Thompson and Stoutemyer, [29] examined the difference in effectiveness of education, in the form of informational pamphlets, about the long-term effects of water usage (describing water usage as a 'commons dilemma' as defined by

Garritt Hardin, 1968 [31]) versus education about the economic effects of water use. There were 171 households in this study broken into four groups, a commons education group (CE), an economic incentive education group (EIE), a participation control group who received just conservation tips and knew their water usage was being monitored (PC), and finally a no contact control group (NCC), whose water usage was anonymously recorded. Both education groups also pledged to conserve water and were given a pamphlet detailing water conservation strategies. Their results show that a 'commons' education caused more conservation behavior than an economic education in only one of the two socioeconomic areas studied, implying that participants value cooperation over menial economic advantage [29]. The no contact control group also reduced water consumption during the course of the study and achieved savings between 20% and 50%.

The second study, by Schultz et al. [27], was focused on understanding which factors among tips for saving, social comparisons, and 'injunctive' -- meaning the comparisons message had an 'happy' or 'sad' face on them -- comparisons are most motivating for conservational behavior. Their ANOVA revealed no difference between the group given only information and tips compared with the control group. This implied that without another motivator, information alone is impotent for changing behaviors, even in those who report strong feelings towards conserving water. The feedback aspect of this work will be discussed later in the consequence intervention section.

Schultz et al.'s findings about the information-only group are corroborated by Ferraro et al.'s findings [26]. In Ferraro et al.'s 2014 study 26,000 residents of Cobb County, GA were split into three groups and sent a single letter: (1) one given tips and information, along with a message imploring conservation of water, (2) another given the same as (1) but with a weak social comparison stating that the participant was either higher or lower than average and (3) the final group was given both of the previous conditions along with a strong social comparison, detailing exactly how much more or less water a participant used compared with the average. In the first year the savings were 0.5%, 2.7% and 4.8% respectively, but in the following year this diminished to 0%, 0%, and 1%, respectively. Looking only at the first year it is easy to see that information alone had only a fifth and a tenth of the impact that a more detailed message had [26].

In the fourth study, by Kurz et al., 166 households were divided up into three groups, one given attunement labels to place on water-intensive appliances, the second was given social comparative feedback, and the third was given only information pamphlets containing the same information that was posted on the labels respectively [30]. Kurz et al. found a large reduction in water consumption for the attunement labels group, about 23% total savings, and ANOVA tests revealed no significant reductions for the other two comparison groups. This indicates that information, if consumed out of the context of usage (reading the pamphlet when received) is much less effective than having that same information displayed at the point of use (attunement labels).

The fifth and final information only study, by Fielding et al., reviewed occurred during a drought and public service campaigns and had results which starkly contrast with the previous two works' results [28]. Studying behavior in a drought-stricken region of southeast Queensland, Australia, researchers divided 221 households into three groups: (1) an information only group, (2) a social norm (i.e. "X% of people conserve water") plus information group and (3) a group given tailored end-use feed-back from smart meters with information. During the 3-month intervention period all groups achieved about 10% total water usage reduction (11.3L/person/day). After the intervention, all groups continued to reduce consumption, however group one, the information only group, achieved the highest peak savings of about 13.3% (15L/p/d) three months after the intervention. The groups eventually returned to pre-intervention usage levels, possibly due to flooding the area experienced after the study was completed. The success of information only group in this one out of five studies reviewed may be correlated to the pre-existing drought condition and water-saving campaign conducted by the Queensland Water Commission (QWC) from 2006 to 2009, discussed in section 3.3. This discrepancy between the Queensland study's 13% and the much lower savings of previous four studies' indicates that the context of intervention plays into its effectiveness, which is discussed further in Section 2.3.4.

2.3.2 Cognitive Dissonance

Cognitive dissonance is the uncomfortable sensation of being shown that one holds inconsistent beliefs, attitudes, and/or actions, and may motivate an individual to change one or more of these categories in order to make them consistent[32].Two studies reviewed successfully used surveys to invoke cognitive dissonance to motivate water savings.

In Dickerson's 1992 study, a group of 80 swimmers were split into four groups. A control group was given no survey before entering a communal locker-room to shower, and three groups were each given a different survey before entering the room [33]. One survey had a pledge to save water in it. Another survey evoked mindfulness of usage by asking about how much water one uses and/or about her shower practices. The final survey evoked a state of cognitive dissonance by asking if the swimmer believed in water conservation, followed by questions with answers that imply that the subject sometimes wasted a resource she had just claimed to value.

The swimmers' showers were then discreetly monitored. The mindful and commitment survey groups both spent about 18% less time showering than the control, while the dissonance group spent 26.9% less time than the control. Further, all of the surveys asked whether one turned the water off while soaping, and each of the three survey groups subsequently had 14/20 swimmers turn off the shower while soaping, in contrast to the 7/20 observed in the control. Though this study observed a subset of the general population, the results allow the reasonable conclusion that cognitive dissonance can be more effective at motivating immediate behavior change than commitment or mindfulness of usage.

Aitken, McMahon et al. [34] hand-delivered surveys to 273 households containing tips on water saving. These surveys were either structured to invoke cognitive dissonance or paired with social comparative feedback. Both groups were shown artificial water use averages for households of similar size. These averages were 10% lower than actual averages to enlarge the gap between attitude and performance. The participants' water usage was then recorded over a three-week period, and once again after this period. Directly after the intervention, the participants in the dissonance group who started at high usage levels lowered their water usage by 7.5% while the participants with initially low usage levels achieved 2.8% savings. In contrast, the comparative feedback groups achieved a 4% reduction from high usage users, but low usage users rebounded and increased usage by 7%. After three weeks the high usage groups had reduced total usage by 6% and 4% for cognitive dissonance and comparative feedback respectively. The low usage groups both returned to pre-intervention levels after three weeks. As in Dickerson (1992), the results imply that cognitive dissonance is effective at motivating immediate behavior change [33].

2.3.3 Social Intervention

Staats et al.'s 2004 study specifically intended to "effect durable change" and intended the scope of the behavior changes to span all types of resource consumption [35]. Thus this study is dissimilar to the other studies included in this review in that the intervention targeted water consumption as well as electricity consumption, natural gas consumption, solid waste, and other resources. The researchers targeted 38 behaviors common to material and energy resources that are deemed high impact. To help the participants change these behaviors, they were divided into "eco-teams". Survey responses from the participants tracked the behavior changes, as well as self-measured and reported physical quantities of resources consumed (i.e. the participants checked their own water meters).

The Eco-teams were made up of 6-10 acquaintances, each member made a series of pledges to try to make changes to a variety of actions and record his/her progress. The teams met each month to discuss and compare their progress. They were given information about other eco-teams' progresses. The active meetings lasted for about 8 months, at which point the active part of the study ended, and the participants retook a survey they had taken a year prior, reporting on their 38 behaviors and consumption patterns after the active period. One year later, participants took the same survey a third and final time. The average score of the participants had further improved, a full year after the intervention withdrawal. The water specific results showed a 2.8% overall reduction after the first 8 months and a 6.7% overall reduction at after the additional year [35].

Walton et al. studied the Queensland Water Commission (QWC) over the years 2006 through 2009. This study is unique in this review in that the researchers did not formulate the intervention method, but instead analysed the impact and methods of a public campaign [24]. The Target 140 (T140) was a successful eight month campaign conducted by the QWC in order to promote drastic water conservation in response to "the worst drought in 100 years". The objective of the campaign was simple; reduce the per capita water consumption of the Brisbane and surrounding Southeast Queensland to 140 litres per person per day (l/p/d). The campaign succeeded in reducing average consumption from about 165 to 129 l/p/d. This success is especially striking because before the drought began residents used an average of 300 l/p/d, which attenuated to 165 l/p/d before the T140 campaign, thus the residents were already experiencing ‘conservation weariness’ when the T140 began. Further, once the restrictions were lifted and the campaign over, residents continued to use less than 140 l/p/d, implying that there had been a durable shift in the values and attitudes of the people.

To achieve such success the QWC did a couple of things; they convinced the population that their own usage made up 70% of the district’s total water usage, that small personal changes could have large effects, and that the drought they were fighting was severe. To distribute this information, they ran commercials showing the dams at low capacity, they had billboard ads put up with various images and phrases. Another effective idea in the campaign was to champion a single behavior, ‘the four minute shower’. To encourage residents to cut shower lengths down to four or fewer minutes they highlighted how much water shorter showers at scale could save, and they distributed over 1.1M shower timers. The 140 l/p/d goal was carefully chosen to give a meaningful and measurable personal objective to each citizen, and because the campaign took place after significant restrictions it focused on indoor water usage (while restrictions along generally curtail outdoor usage).

2.3.4 Antecedent Interventions: Major Findings

Information distribution is the most common form of antecedent intervention and has nominal effects. Information alone, without a drought context, is often ineffective at motivating change [27], [30]. The only studies which showed significant effects resulting from information alone were Fielding et al.’s work in a drought context, and the Queensland Target 140 campaign (analysed by Walton et al.), both of which occurred in a drought stricken region. These two successful studies viewed together show that when a population directly understands the need or benefit of water conservation, they will be willing to change their water behaviors [24].

Another two factors which contributed to the success of the T140 campaign were the social scale, and the concreteness in objective. Both of these factors were also present in Staats et al.'s experiment with eco-teams. Thus a concrete goal system (140l/p/d, 38 behaviours, 4-minute shower) may be an effect part of teaching conservation, while social pressures may be effective as motivation to conserve.

The contrast implies that people need to be motivated and taught how to conserve water, not only taught how to. This motivation may come in the form of education, climate necessity, social pressures, or by inciting a state of cognitive dissonance [24], [28], [29], [33], [35]. Nevertheless, some studies found that social comparison information is not as effective as information in a drought context or cognitive dissonance.

Invoking cognitive dissonance, in particular, was shown to be effective at creating change immediately and in the short term [33], [34]. This observation is significant as it implies that an individual's own beliefs may be leveraged to achieve behavior change, despite the fact that behavior is often only loosely linked to attitude [36].

2.4 Consequence Interventions

Consequence interventions utilize "feedback", where a user is given information about his/her specific usage, and come in two primary forms: reinforcement, and information. Informational feedback means that a user is simply given data about his or her usage. Attari et al. [37] and Beal [38], have independently confirmed that people often have little idea of how much water they use, or what the most effective means of conservation are. Thus informational feedback may inform people of the consequences of their actions, enabling them to better their habits. Reinforcing feedback is given in the form of an attitude expressed by the system, as a result of the gathered data. For instance, a happy face displayed when a user acts in a way supported by the intent of an intervention. Very often reinforcement feedback is given with informational feedback.

Brynjarsdottir et al. [20] pointed out many issues with using 'persuasive technologies' as a means for achieving sustainable behaviors (discussed further in Section 9: Recommendations), especially criticizing informational feedback as making the assumption that if given data users will then logically reduce consumption by informational processing. However, informational feedback may be important to help users understand how much water (or any resource) they are using.

Feedback delivery systems also play a role in feedback effectiveness and can be boiled down into two major types; point-of-use (in-situ), and not point of use. Each method has advantages and disadvantages and focus on different aspects of behavior change. In-situ feedback generally focuses on a single area of usage (specifically whatever the point of use it is near is) where non-point of use feedback motivates general change.

2.4.1 Non-Point-of-Use Feedback

In the three studies reviewed in this section, subjects were provided with one or more types of feedback, often with control groups to delineate which feedback had what effect. The feedback was delivered peripherally to the participants, via mail, or the internet, and not at the point of use, as in the following section.

The first study, conducted by Erickson et al. in 2012, used a website that allowed 303 households in Dubuque, Iowa, USA to monitor their water usage in near real time over a 15 week period. The website also provided techniques, as well as social and historical comparisons of usage [16]. The 303 households studied achieved an overall 6.6% reduction in consumption compared with the experimental control group during first 9 weeks of pilot study. Only 35% (106 of 303 households) of the participants reported actually logging into (using) the portal website, thus putting the cause of the reduction into question. In response to polls after the study, 49% of participants reported they “kept forgetting”, and thus failed to use the portal. Of the portal users, 61% reported making a change to either their home infrastructure or water-use practices during the study. Overall, 57% of the participants reported having made physical changes to their household water infrastructure, while 73% reported they had changed their water usage practices since the study began (with or without actually using the portal) [30]. Because so many more people made changes to their lifestyle in one way or another without actually consulting the website, the results may be due in part to the Hawthorne effect [39], wherein people know they are in a study and thus act accordingly.

The second study, conducted by Schultz et al. in 2014, gave either postal or web based feedback to a group of 301 participants. Forty four of these participants received no feedback, while the remaining 257 were split roughly into three groups, each receiving feedback by web or mail. The test groups were distinguished as follows, (1) information-only group; the households were given tips and information regarding methods of reducing water consumption, (2) descriptive norm group; the households received identical information as (1) as well as personalized information about their own usage, and a comparison of their usage to that of similar households. The last group (3) was the aligned norm group, this group was given the same information as (1) as well as the feedback and comparison given in (2) with an attached happy/sad face, expressing social approval/disapproval [27]. Each group only received a single packet of information, and the effect of that information was recorded on a daily basis during the week following the date the information was provided.

Group 1 (antecedent info only) showed no significant change compared to the control group, as discussed previously in the Section 3. Groups 2 and 3 (with personal performance feedback) showed, respectively, a 26% and 16% decrease in usage compared with control. These results indicate firstly that applying a judgement to data is counter-productive for motivating savings, and secondly that appealing to one’s actual usage habits is critical to motivate behavior change. Like the web portal from Erickson et al., the Schultz et al. study also had extremely low online access rates, only 18% (26 of the 141 participants) of the internet based material households actually accessed the website at least once.

The final study, conducted by Geller et al. in 1983, provided daily and weekly written feedback alone or with water-savings devices, education, or both for 5 weeks [40]. There were 129 households, and 8 groups, each with between 15 and 18 households. Interestingly, this study had the highest savings in the devices-only group. The feedback-only group increased water consumption by 1.36%, while the no-intervention group managed to reduce consumption by 3.4%. The feedback provided had the previous day's water usage compared to the median, the percentage change compared with the baseline data (measured for five weeks before the intervention) and smiling/frowning faces depending on the usage change. In this study the devices only group achieved the highest savings (9.5%), followed by devices and feedback (7.7%), and devices and education (6.9%). Education alone had almost no effect (0.7% reduction).

2.4.2 Point-of-Use Feedback: Device Interventions

Point-of-use feedback is given by a physical device installed near a water consuming appliance. Devices operate on similar psychological principles to both feedback and antecedent based interventions. Devices are extremely visible high frequency feedback interventions. The majority of devices reviewed here operate in a way that simply allows users to know or visualize their water consumption during the time of use. These devices are either ambient, meaning the user gets an abstract idea of his/her usage, or indexical, meaning s/he receives an actual numerical value of his/her usage. Many of the reviewed studies do not have experimental data justifying the design, but are included to fully outline the range of device implementations.

All of the devices reviewed here are intended to reduce water consumption either in the shower or at a faucet, each of which account for about 20% respectively of the water used in home [41]. Faucet and shower water usage is targeted because the volume used in each instance is highly dependent on the user's attitude and awareness.

Arroyo et al.'s Waterbot was the forerunner of device oriented water intervention systems. In this study the group developed four iterations of the device, however in this chapter only the most relevant iteration will be discussed, the Waterbot. This device attached to the spigot of a faucet, and included a two bar display (indicating current usage and average usage respectively), a speaker, as well as different coloured LED's which change the water color according to the water temperature (the LED component alone is one of the iterations, Heatbot) [17].Waterbot combines many strategies to affect the user's water usage: positive and negative reinforcements, 'just-in-time prompts' accomplished by audio feedback, and social/historical comparison via the bar graph (with other users of the same faucet). The pilot study of Waterbot took place over two months in a laboratory environment with 15 users, the change in water usage was not reported. Overall the users reported not becoming annoyed with Waterbot; 12 of 15 were still engaged after two months, and some wanted more sounds integrated into the system.

"UpStream", conducted by Kuznetsov and Paulos, included faucet mounted devices as well as the shower displays. They used microphones attached to Arduino microcontrollers to monitor flowrates in a closed pipe at a very low (less than $40) price point [2]. They reportedly achieved a less than 10% error in measuring volumetric flowrate, at 0.2 gallon resolution. This device suite is shown in Figure 1.

Their pilot studies took place in a semi-public dorm setting and in a private single home setting. The dorm setting experiment had inconclusive results. The faucet display actually caused an increase of between 25%-133% in water volume usage compared to the control over the duration of the pilot study, attributed to dorm users' curiosity with the system. The shower display had statistically insignificant results in the dorm setting. The users apparently did not understand the display immediately so they ran the faucet heedlessly to see how the display changed [2].

In the privatized setting the ambient shower display reduced water usage by nearly two gallons (~17% of total shower volume) per shower, while the numeric display achieved 1 gallon saved per shower (~8%). The ambient display was not attention intensive and was easy to understand, whereas the numeric display required more effort and its granularity in reporting usage caused some confusion. While the participants stated that the numerical display was more 'information rich', it did not provide a benchmark for comparison while the ambient red LED output was easily interpreted. Users also reported simply enjoying the ambient display more than the indexical, some implying they wished to keep one in their homes after the experiment's conclusion. Users also reported that the numerical display caused them to think about and estimate their usage during other water-related activities, like washing dishes.

"Show-me" by Kappel and Grechenig is a device that attaches, in-line, to shower plumbing and resulted in a 20% reduction in showering water use. The pilot study of Show-me was conducted in 4 households, where it was installed for 3 weeks [3]. The device uses a tower of LEDs to indicate how much water has been used in a single shower. The rising LEDs emulate the look rising water, giving the user an abstract idea of how much water s/he has used in a given shower. This method of feedback is non-intrusive and non-judgmental; no lights turn red, or indicate fault. Further it allows users to set goals however they want, like reducing a shower by two LEDs – corresponding to a 10 liter per shower savings. The participants reported the device prompting discussion about water usage, and even settling an argument one group was having about length of shower versus volume water used.

Figure 1 - "Show-me" (left) and "Upstream"(Right)

Willis et al. tested a device similar to "Show-me" that used an indexical display with numerical usage, attached to the showerhead. Their study was conducted in Australia, involved 151 households and took place over 2 years. 44 of the households were equipped with the indexical display. Those given the displays achieved an average of 27% reduction in shower volume, about 10% of total water usage. One interesting point they highlighted was the payback period of 1.67 years of the device they used (a

WaiTEK shower monitor) [4]. The participants' feelings about the devices were not recorded.

2.4.3 Consequence Interventions: Conclusions

The two types of feedback intervention differentiated here are point-of-use and non-point-of use. The difference is how the user receives feedback, and what the feedback is in reference to. Point-of-use is displayed at a specific point of use, shower or faucet, and the information displayed is only pertinent to the appliance. Non-point-point-of-use is generalized feedback, giving information about total water use and is disseminated in this review by physical mail or an online portal.

The feedback displayed by either type may contain three primary pieces of information; information, social comparison, and/or judgement. These are defined as such; direct information about usage, for example "you used 10L in this shower". Social comparison may show how an individual's specific usage compares to a relevant average (national, similar household, ideal). Judgment messages are given by expressing some sort of positive or negative message in conjunction with information. An example is a sad face shown with a high usage.

For the three non-device feedback interventions, the biggest barrier to success seemed to be the medium of communication. Only 35% and 18% of the groups provided with web resources actually logging into them at least once [16], [27].This low usage rate implies that the average water savings each study achieved was not 'maximized', and that there is much potential for improvement. The results of Schultz et al.'s study, despite low web usage rates, show that people are motivated to reduce their water usage when shown their own usage rates in the context of similar households (26% reduction), though are de-motivated by feedback with injunctive judgment embedded in it (16% reduction). This same ‘de-motivation’ may also be responsible for the failure of Geller et al.’s feedback, which always included a smiling or sad face [40].

Device interventions have been shown to consistently have significant impact on the targeted behavior. The Show-Me and Alarming Display (WaiTEK shower monitor) both achieved 20% or more reduction in shower volume, while the Upstream shower devices achieved between 1 and 2 gallons, 3.8-7.6 L liters, saved per shower (about 8%-17% the low end of range being attributed to the indexical display, the high end, ambient). The feedback given by the participants about the UpStream devices also indicated that ambient displays are more pleasant to interact with regularly than are indexical. This is corroborated by Ham and Midden’s work on ambient displays’ cognitive load [42].

2.5 Review of Water Sensing Systems Capable of Providing Disaggregated Feedback

The “grocery list problem” is posed as such; it is very hard for a person to cut the cost of groceries if individual items’ prices are unknown. In order to reduce the cost of the groceries, one would need to resort to a guess and check method, eventually finding a list that was within the desired budget. This is how most modern water bills are given; a bill is sent out each month with the cost and often aggregate quantity of water used. The consumer of this water generally has no idea how or when s/he used the resources, and is thus ill-equipped to curtail such usage. However, if the water bill each month said that a specific toilet used 35% of the total water used that month, one may easily conclude that either the toilet is either leaking or tremendously wasteful and proceed accordingly. This sort of feedback is called ‘disaggregated feedback’ and has been shown to be effective at helping consumers curtail their electricity usage [43]. The primary barrier to providing this sort of feedback is the high cost of implementing a system capable of gathering such information [44].

The company Aquacraft developed the first system capable of obtaining disaggregated data, Trace Wizard. This device used flow trace analysis, where a device measures the flowrate in the water main with a 0.1Hz frequency. Then training data acquired from each appliance is used to match their ‘flow traces’ with measured ones allowing the system to determine what appliance was causing a certain increase in flow [45]. The first academic water-flow sensing system capable of providing disaggregated water-use information was done by Fogarty and Hudson in their 2006 study “Sensing from the Basement…”. This was accomplished by attaching microphones to the exterior of water pipes in a home’s water infra-structure. The microphones were able to determine whether water was flowing through a pipe whose destination was known. [46]. They did not try to predict the volume of water used, but instead focused on identifying the water activities, for use in monitoring the elderly’s daily activities for signs of faltering health.

In 2008, Kim et al. [47] placed vibration sensors (gyroscopes) on pipes, and recommended attaching a computer to the house water meter (or interface with smart meters, if they are installed) allowing for the prediction of actual water volume used in each instance. They set up the system on a testbed only. The gyroscopes communicated wirelessly with a computer which then read a water meter, allowing it to calculate how much water was used in a particular instance. Using the same flow sensing system, Martin et al. developed a self-powered system, called DoubleDip which utilizes the thermal gradients in the pipe to power the sensors. DoubleDip was tested at five locations and was able to generate enough energy to self-power even on cold water pipes [48].

Froelich and Fogarty et al.'s 2009 study "HydroSense: Infrastructure-Mediated Single-Point Sensing of Whole-Home Water Activity" succeeded in making a device capable of determining the volume of water used, and the specific appliance which used with a single pressure sensor attached to a houses water-infrastructure, typically an outdoor hose spigot [49]. They achieved 97.9% accuracy in identifying 'fixture events', while also determining the water volume used in each event to about the same precision as an industrial water meter. This was not done at the time of usage, but used machine learning to analyse the signatures after the data were taken. Campbell et al. developed a self-powered system, WATTR, that uses the changes in water pressure in homes to create rotational motion to power the sensor, which was fundamentally HydroSense [50].

Thomaz et al. [51] took the same system as HydroSense and implemented a higher-learning functionality. They developed an algorithm that could recognize what specific activity was being performed, for example differentiating between washing hands and washing dishes. The pilot study had 23 participants, each performing a variety of different activities, and achieved 72% accuracy at identifying which activities were being performed.

Srinivasan et al. [52] created WaterSense, a sensing system that uses motion sensors attached at each point of use (i.e. on the faucet, shower, washer) in conjunction with a flowmeter attached to the water main to gather disaggregated water usage information. WaterSense, unlike Hydrosense or NAWMS, reportedly does not need training data and still achieved 80-90% accuracy.

2.6 Criticisms/Analyses of Eco-Persuasion; He et al. & Brynjarsdottir et al.

In the previous and subsequent section(s) He et al.'s work, and Brynjarsdottir et al.'s work has been and will be mentioned many times [5], [20]. In this section, a summary of each paper as it is relevant to this work will be given. The theory and ideas in each were instrumental in the inspiration and development of the phasic device. Many of the authors' recommendations are incorporated into our design as a means of testing the hypotheses through physical experimentation.

2.6.1 He et al.: "One Size Does Not Fit All…"

Motivation is defined in He et al.'s paper as the inquiry into the why of behaviour. In validated psychological literature, there are a few classification systems describing behaviors, specifically Rokeach's Behavior Ideals and Preferences for Experiences, and Maslow's Preference for Experience Low to High Level [53].These basic blocks of motivation are believed to be foundational to humans' attitudes, beliefs, and values. Such factors are then linked, albeit sometimes unconsciously, to an individual's actions. The values and preferences may be used as building blocks to inform the development of persuasive technologies, and used as fundamental points of leverage that a persuasive technology uses. The three classifications are in Table 1, which is adapted from He et al.'s paper [5], [53]. The Ideals and preferences in Table 1 are provided to give a broad picture of what motivates people to act., which is adapted from He et al.'s paper [5], [53]. The Ideals and preferences in Table 1 are provided to give a broad picture of what motivates people to act.

Table 1 - Values from He et. al

Behavioural Ideals (Rokeach)	**Preferences for Experiences (Rokeach)**	**Preferences for Experiences - Low to high level (Maslow)**
Capable: Competent, effective	**A comfortable life**: a prosperous life	**Physiological**: Homeostasis and appetites
Helpful: Working for the welfare of others	**Freedom**: independence and free choice	**Safety**: Security of body, employment, resources, family, health, property
Honest: Sincere and truthful	**Health**: physical and mental well-being	**Love/belonging**: Affection and belongingness, be accepted
Imaginative: Daring and creative	**Inner harmony**: freedom from inner conflict	**Esteem**: Self- respect, self-esteem, esteem of others
Independent: Self-reliant; self-sufficient	**A sense of accomplishment**: a lasting contribution	**Self- actualization:** To find self-fulfilment and realize one's potential
Intellectual: Intelligent and reflective	**Social recognition**: respect and admiration	
Logical: Consistent; rational	**Wisdom**: a mature understanding of life	

Obedient: Dutiful, respectful	**A world of beauty**: beauty of nature and the arts
Responsible: Dependable and reliable	

Motivation is required for the user to then go through the stages of behaviour change as outlined in the Trans Theoretical Model (TTM) which is also called Stages of Change Model [5]. The stages one must go through before achieving behavior change are as follows;

1. *Precontemplation* – Subject does not believe his/her behavior needs to change. Believes benefits outweigh adverse effects. S/he believes his/her behavior is in alignment with attitude and beliefs.
2. *Contemplation* – Subject recognizes behavior may be more adverse than positive, begins to consider changing behavior
3. *Preparation* – Subject plans change
4. *Action* – Subject begins to enact behavior change
5. *Maintenance, Relapse, Recycle* – Subject maintains behavior change, prevents relapse. Moves back to previous stage (recycles) in the event of a relapse

The goals of sustainable behavior change are described primarily as *durability* (not needing many interventions to maintain) and *generalizability* (spills into other areas). Further, the goals should ideally be *intrinsically* motivated, meaning for the satisfaction inherent to the behavior, rather than towards a "separable" outcome (*extrinsic*).

Traditional non-phasic feedback does not create an intrinsic desire to save water, as the user is responding purely to the quantification of his or her usage. Further non-phasic feedback has not been shown to create non-durable behavior change, and phasic approaches could achieve this aim [2], [3].

There are a variety of motivation techniques, and most are used in conjunction with one another. Each is unique and familiar, with advantages and disadvantages. Some commonly used motivation techniques, and drawbacks of each are as follows

Attitude Model - assumes pro-ecological behavior will automatically follow pro-environmental attitude. Drawbacks; (1) does not consider stages, mainly aims at people in contemplation/preparation phase (2) does not consider other factors such as time and convenience.

Rational-Economic Model – assumes people will make pro-environmental decisions if they are economically advantageous. Main drawback is that many resource consumption activities in-home are not highly economically impactful.

Information Model – appeals to the responsibility in someone, provides information about why a problem is a problem and assumes actors will then work to change it. This model does not target well pre-contemplators or contemplators, as it assumes that one is open to suggestion with respect to his/her attitudes about conservation.

Positive Reinforcement – assumes that positive behavior may be conditioned by providing positive stimulus after a desirable action. This model, to be effective, must be paired with other strategies; else it is often short lived and fundamentally creates extrinsic motivation.

2.6.2 Brynjarsdottir et al.; "Sustainably Unpersuaded…"

In this work, the Brynjarsdottir et al. offered a 'critical analysis' of 86 papers tagged "environmental" and "sustainability" submitted to the Conference on Human Factors in Computing Systems (CHI) in the years 2009-2011, 36 of which were also concerned with "persuasion" [20]. The stated objective of Brynjarsdottir et al.'s paper is to explain how many systems are "modernist" and may narrow one's view of sustainability. They also provide suggestions on ways to improve eco persuasion systems.

The authors state that "awareness" is often a reported goal for systems that sense usage and provide feedback. This objective is in spite of the fact that there is often only a very loose causal relationship between awareness and behavior, and thus awareness is an ineffectual goal. Further though studies have shown eco-feedback systems increase efficiency of the targeted behavior, they do not often stop the adoption of unrelated resource-intensive practices. This is an example of how such an eco-feedback system may achieve a narrow goal (making the targeted behavior more efficient), but ultimately not help the user to behave more sustainably overall.

The authors summarize a few major criticisms of sustainable human computer interaction (HCI). Focusing on "individual and simple acts" and "defining sustainability too narrowly" limits interventions to changing measurable activities, and may narrow the subjects' ideas of sustainability. Per example, the studies they analysed always tended to change harmful behaviors, rather than try to actually eliminate harmful behaviors. Targeting a behavior is often in order to allow for changes to be measurable and metrics of success possible to record and report. Specifying a specific problem behavior may serve to influence someone that the best they can do is better a harmful behavior rather than stop the behavior all together.

The authors' third criticism is that most interventions assume their subjects are rational actors swayed by information. This issue was discussed by He et al. as a designer's misunderstanding of how information may be perceived depending on where a person is on his/her path to behavior change. It is inaccurate to assume that all people want to change their behavior but simply need informatics to motivate them. Often there are deeper reasons to why a person chooses to act in the way they do.

The fourth criticism is that the design is "too distant from lived use"; meaning that the devices are designed by people and are generalized for many types of people. Thus they may not deal with socio-cultural peculiarities well, and do not take into consideration "the nuance and complexity of everyday activities" and are generally designed for a specific user group, most often "middle- to upper-class, urban consumers".

The fifth and final intervention specific criticism is "trouble dealing with dynamics of change over time". This states that interventions are often rigid and do not adapt to changing circumstances, and that users' attention flags as soon as they absorb the lessons provided. At this point in the paper the authors specifically mention He et al.'s work as state that even such [phasic] approaches may fail to counteract the "ways an individuals' preferences and practices form a moving target".

Finally Brynjarsdottir et al. give three specific suggestions on how future persuasive sustainable systems may address some of their concerns. First, "broaden understanding of persuasion"; by this the authors explain that the focus of a system should be less about rhetoric and more about providing a learning process, without dogmatism, from which a user may draw his/her own conclusions, which will be more informed and ideally sustainable. Second, "include users in the design process", this may be achieved in many ways, and is often done in iterative design phases. This approach also helps to make designs more accessible and separate undue authority from designers. The final suggestion is to "move beyond the individual", citing that "unsustainability arises from complex iterations among individuals, social groups, corporation…" and that future interventions may benefit by targeting such groups and communities.

2.6.3 Incorporation into Design

These two papers influenced greatly the design of the phasic feedback devices developed. Firstly the framework by He et al. was adapted to suit water conservation, greatly aiding the feedback provided. Brynjarsdottir's paper was one of the few who offered many criticisms of such systems, which are very popular in academia, and such criticisms were incorporated as best as possible within the time constraints available.

Two of the suggestions were incorporated as follows;

1. Broaden understanding of persuasion: the device was not highly prescriptive, and began the early phases with broad and interesting ideas about water. This method was supposed to facilitate a more organic interest in water conservation, and did not just begin by trying to convince users of anything.
2. Include users in the design process: this is hard to do, but after the experiment, as mentioned in Chapter 3, users were asked in person, and in informal online surveys for design improvements, which are intended to be made in the next iteration should funding be available.

The criticisms Bryanisjattidor et al. made were taken into consideration in our device as well. The targeted behaviors were defined narrowly out of metric necessity; however the information provided by the device was not only about personal water use but included broader educational points. Further, an attempt was made to measure how targeting sink behaviors influences overall water consumption. The third and fourth criticisms are both directly addressed by using a dynamic feedback framework. This experiment itself was a sort of test of the fifth “trouble dealing with the dynamics of change over time”, as that is exactly what the phasic feedback device was intended to overcome. The results show that, at least compared with traditional rigid sensing and feedback systems, the phasic model had significantly more behavior change over longer periods of time, while users quickly lost interest in the rigid counterparts.

2.7 Conclusions from Intervention Review

In order to achieve maximum efficacy, intervention designers should consider mental context and visibility. Visibility refers to the timeliness and ease of access to information, such as having information visible at the point of task. Context refers to situational awareness, such as a user who is aware of the consequences because of his/her actions.

In the successful information only-studies wide-spread drought seems to have primed the participants to begin saving water, all they needed to save water was the knowledge of how to do so. For example info/tips were administered in a drought context in Fielding et al.'s work in Queensland and the participants achieved significant water savings [28].Conversely, the handful of studies whose information-only groups showed no change may have been unprepared to save water, thus providing details on how to conserve was ineffectual at motivating behavior change. It may be more effective to first give participants information about the environment, and the current successes conservation before then giving them tips about how to conserve water.

He et al. [5] discuss how one may apply the trans-theoretical (stages of behavior change) model to persuasive technologies specifically discussing electricity savings, though the model may be easily adapted to water. They focus on the idea of different approaches to users at different points in their respective paths to behavior change, citing five specific phases; pre-contemplation, contemplation, preparation, action, and maintenance. This phased approach may emulate somewhat the effect of living in a drought-stricken region by heightening one’s awareness of the problems associated with excessive water usage.

Feedback should be given in a positive or neutral manner. Providing objective information and allowing the subjects to draw their own conclusions before trying to change their behavior more accurately reflects persuasion defined by Brynjarsdottir et al [20]. Coercion has been shown to actually attenuate results, shown by Schultz et al. where the experimental group whose feedback had an opinion expressed on it conserved significantly less (26%, 16% respectively) than the group given identical feedback without any opinion [27].

Social feedback may only be useful to show a participant that his/her usage is above the norm for similar persons. In Aitken et al.’s [34] work the participants shown that they used relatively more water were motivated to conserve, whereas the participants shown to use less water were not motivated, and in some cases used more water. These results may be due to the social pressure to conform, and/or due to a state of cognitive dissonance incited by one’s realization that his/her usage is higher than average. Perception of peers’ water usage has been shown to affect one’s own usage habits. Verdugo et al. [54] showed that those who perceived their peers ‘wasting water’ tended to have worse conservation behaviors.

Interventions should be very easily accessible, requiring little or no effort on the subject’s part in order to communicate any information effectively. The success of devices such as the “Show-me” and the WaiTEK alarming display may be attributed to the high visibility of such systems; the user is automatically made aware of his or her usage, and the potential to conserve [3], [4]. An alternative explanation of the curtailments could be the Hawthorne effect; the participants were aware they were in a study and that their actions were being recorded so they acted in a way that would satisfy the researchers [39]. The use of attunement labels on appliances (high visibility) achieved high savings, whereas the same information in packet form (low visibility) achieved no statistically significant savings [30].

Mail-based feedback has the obvious shortcomings of delay, bulk, and inconvenience of opening/reading the contents. Both web-based feedback studies observed the intrinsic barrier to information posed by accessing a web medium. These extra steps may be overcome by integrating a passive widget, or plug-in to a sensor system. Web portals with user accounts and passwords are fairly inaccessible. Though the Dubuque Portal achieved some degree of success, its information was not displayed easily (low visibility) and the participants in the study largely did not use it at all [16]. People are generally unwilling or unable to regularly access internet portals, even when they volunteer to partake in a study known to be about conservation and the internet medium as in the Dubuque Portal.

Thus the two factors which seem most important for the success of an intervention are the context in which it is deployed, and its visibility. The context may be the user's predisposition to conservative behaviors, or foreknowledge of environmental consequences bestowed on her by living in a drought-stricken region, or by an educator. The visibility of an intervention is simply how easily and frequently a user is affected by an intervention (very high with labels, devices, or large campaigns, very low with a web-portal requiring a password). Lastly, these two factors do not constitute the intervention itself, but are attributes of any intervention.

2.8 Review Summary

From the review of interventions aimed at water conservation two primary factors were highlighted as contributing to an interventions success (or lack thereof). First, the accessibility or visibility of an intervention; Any intervention that was not easily visible or required effort to view was generally ineffective, such as a web portal which required logging in [16]. Thus interventions needed to be overt and passively visible on a regular basis; like alarming displays or attunement labels [30].

The second is the climate context in which the intervention was deployed. For example, tips and information in a non-drought stricken area proved ineffective, whereas they were equally as effective as a smart meter feedback system in a drought stricken region of Australia. This conclusion leads one to believe that if an intervention can "prime" the participants to save, the information provided by the intervention will have a greater impact of the participants' actions.

This review led to the discovery of a gap in the existing literature; phasic feedback, and testing for lasting change. Up until now, no intervention system attempted to provide users with dynamic feedback that change over time. And very few tested how durable any changes were post-intervention. Thus we hypothesize that by incorporating the conclusions from this review; creating a highly visible device whose objective is to emulate climate context through informational and usage feedback, and base such feedback framework on the Trans Theoretical model, we will be able to create conservational behavior at the sink greater than that generated by a device which provides traditional rigid feedback as do the devices discussed in this review.

	Author(s)	Type of Intervention	Sample Size	Duration of Intervention	Effect During Intervention	Long-Term Effect
1	Thompson, Stoutemyer (1991)	Paper-based education, 3 mailing to 3 groups: 1. About long term effects of conservation, commons metaphor and personal efficacy 2. About individual economic advantage as a result 3. No education all groups received conservation tips, and a pledge.	171 Households	2-month	Dubious results	
2	Schultz, Messina, Tronu *et al*. (2014)	Web and Mail distributed Tips/Information with 1. Normative comparison 2. Aligned Normative comparison	301 Households, Only 172 given feedback	One message, following week monitored	1. Info/Tips only: 0% 2. Info/Tips + Feedback with Normative Comparison: 26% 3. Info/Tips + Feedback with Normative + happy/sad face: 16%	No data
3	Ferraro, Miranda, Price (2014)	Mail to home: 1. Tip sheet giving information only 2. 1+weak social norm treatment: asking conservation and saying the county uses too much water 3. 2+Direct comparison of monthly consumption versus neighbor average in bold	26,000 households, ~12,000 per treatment, 72,000 control	1 Message	Year 1: 1. -0.5% 2. -2.7% 3. -4.8% Year 2: 1. 0% 2. 0% 3. -2.6% Year 3: 1. 0% 2. 0% 3. 1%	See effect during intervention
4	Kurz, Donaghue, Walker (2005)	1. Information leaflets 2. attunement labels on appliances 3. socially comparative feedback (biweekly mail slips)	166 households	3.5 Months	Labels: 23% water savings Information & Comparison: no significant savings	still lowered 1 month after removal
5	Fielding, Spinks *et al*. (2013)	1. Water-savings tips and info alone 2. 1 + descriptive norm manipulation; 3. 1 + tailored end-use feedback, acquired via smart meters (f=.2Hz)	221 Households	3 Months	Average: 11.3L/Person/day, about 10% total water savings for all groups	3 Months: Groups 1 and 2 reached a peak savings of almost 15L/day 12 months: back to pre-intervention levels
6	Dickerson (1992)	Survey pre-shower with varying questions: 2X2 cognitive dissonance	80 Female Swimmers	1 shower	Mindful only: 17.7% less than control (control = 100%) commitment only: 17.93% less than control both(hypocrisy): 26.9% less than control	No data
7	Aitken, McMahon *et al* (1994)	Survey combined with paper (hand delivered) a) Dissonance b) Feedback both with tips	273 Households	3 weeks	1. Dissonance: High usage -7.5% Low usage: -2.8% 2. Feedback: high: -4% Low: +7%	3 weeks after intervention: 1. Dissonance: High: -6% . Low: -0% 2. Feedback: High: -4% Low: 0%

Table 2 - Summary of Interventions Aimed at Water Conservation

	Author(s)	Type of Intervention	Sample Size	Duration of Intervention	Effect During Intervention	Long-Term Effect
8	Staats, Harland, Wilke (2011)	"EcoTeam" method: included group meetings/discussions, feedback, informational pamphlets	150 participants	1 year	2.8% Water Use Reduction	6.7% water reduced three years after
9	Walton, Hume (2011)	Large-scale community intervention; billboards, leaflets, retrofitting 508K devices, main habit was "4-minute shower"	1.1M	8 months	28% Water use reduction	One year later still down 27.2%
10	Erickson *et al* (2012)	Website Providing: 1. Feedback on Water Usage (T=3hr), 2. Normative & Historical Comparison	303 Households (only 35% actually checked the website at least once)	15 weeks	6.6% reduction total consumption	No data
18	Geller, Erickson, Buttram (1983)	Education, Daily Feedback, Low Cost conservation devices	129 Households	35 days	Device only: -9.5% Devices + Feedback: -7.7%, Devices + Education: -7% Device + Education + Feedback: -9% Feedback: +1.34% Control: -3.4%	No Data
11	Kappel, Grechenig (2009)	Point of Use Ambient Feedback (shower)	4 Households	3 Weeks	-20% (10 L) per Shower	None: no data shown however
12	Willis *et al*. (2010)	Point of Use Indexical Display (Shower)	151 Households, 44 with Shower Display	2 years	Shower: -27% or about -10% total water use (-40.85L/Household/day)	Remained installed
13	Kuznetsov, Paulos (2010)	Point of Use Ambient/Indexical Display(s) (faucet & shower)	1. Used Publicly 2. 3 apartments with 2 people (N=6)	1. Unspecified (Data indicates few days) 2. 4-7 Days	1. Faucet: +25-133% Shower: -30% 2.Faucet: No data Shower: 10%-20%	No Data
14	Laschke, Hessenzahl *et al* (2011)	Point of Use Calendar Projection (Shower)	2 families	1 Month	Slight, inconsistent change	No data
15	Hammerschmidt *et al* (2013)	Auditory Device (Shower)	No data	None	No Data	No Data
16	Arroyo, Bonanni, Selker (2005)	Point of Use Indexical/Ambient Display (Faucet)	10 Diverse Outside Peoples, 15 People in Lab	2 months	No Data	No Data
17	Togler, Hemmert, Wettach (2009)	Point of Use Dynamic System (Faucet)	No data	None	No data	No data

Table 2 contd. - Summary of Interventions Aimed at Water Conservation

CHAPTER 3. DESIGN OF PHASIC DEVICE

This section describes the design of the phasic feedback device.

Of the 17 water intervention studies reviewed, six were device oriented however there has not been an academic paper studying a device which leverages the aforementioned psychological elements and provides a dynamic feedback in order to achieve such behavior change. The most relevant academic papers about such devices are discussed in the following section. In the paper "One Size Does Not Fit All" He *et al.* describe a feedback framework tailored to take into consideration a popular psychological model for behavior change called the trans-theoretical model for behavior change (TTM) [5]. This model describes behavior change as happening gradually and in distinct parts, beginning in a stage called "pre-contemplation", which leads then into "contemplation", then into "preparation", then into "action", and finally into "maintenance". In He et al.'s paper a description about different goals and methods associated with each phase of behavior change which may most effectively help persuade a user to continue to the next phase, ultimately achieving a permanent behavior change. Thus this framework was adapted to achieve water conservation at a specific faucet in home.

3.1 Technical Review

We chose not to have our device physically attach to a faucet as our device needed to be installable on any sink. Arroyo et al.'s Waterbot provided auditory and visual feedback for the user of a single sink [17]. It illuminated an LED bar located next to a permanently illuminated one that indicated the 'average' usage of that faucet in abstract terms. Usage data was not recorded.

Our design used a similar though more precise sensing method employing piezo electric sensors rather than microphones as in Kutsenov et al.'s device suite, UpStream, consisted of a faucet device as well as a handful of shower oriented devices. These devices used microphones to sense noise from pipes and estimate water flow rate. The devices reported water volumes with 10% error at 0.1 gallon, 0.37 L, increments. The faucet device provided only abstract feedback, in the form of a green or red light. While deployed in a college dormitory for one day, the faucet devices achieved a range from -33% reduction to a +125% increase in water usage at each faucet [2].

An open source project published on Instructables.com by Will Buchanan about the development of an in-situ water monitor for faucets. Ultimately decided this device used a modified Hall Effect monitor attached to a water main dial to measure instantaneous water usage, in conjunction with piezo-electric sensors on specific faucets to determine which was on. The hardware selection provided in his Instructable guided my own sensor and amplification circuit selection, though our final products are dissimilar as his does not provide any in-situ feedback but instead logs the data externally [55].

There are no, at the time of this document being written, devices which provide more information than simple real-time usage data. Thus there is a gap in the literature this device aims to fill with respect to devices that take into consideration the point at which a user may be in his or her path towards behavior change, and furthermore a gap in devices which attempt to educate their users as well as inform them of real-time water usage data. This gap was also highlighted in the paper “Sustainably Unpersuaded” which criticized many sustainable persuasive technologies as making many fallacious assumptions about the intended audience of such devices. Thus our group intended to take into considerations our own perceived gap in the literature, He et al.’s prescriptions for behavior change, and Bryanisjattidor et al.’s criticisms of persuasive sustainable technologies [5], [20].

3.2 Functional Requirements

The device needed to be installed at any sink, work and record data continuously for at least 70 days, and effectively display information while in three distinct states; 1. Sink OFF (idle) 2. Sink ON (active) 3. Sink JUST TURNED OFF (just off), and be made by a single graduate researched and an undergraduate assistant. Thus the functional requirements are outlined in Table 3.

Table 3 - Functional Requirements for Device

Functional Requirement	**Design Component**
Safe to use near running water	The device needs to be water resistant and failsafe in the event of a potential short circuit
Detect, estimate, save water usage	Must be able to reliably detect water flow being on, and estimate water flow rate to a competitive degree, and save such information
Display any information	User must be able to easily read and understand any data output by the device in all three states (idle, active, just off)
Small-scale Manufacturable	At least ten devices must be made by a single graduate student and an undergraduate assistant
Inexpensive	$20-80 per device

3.3 Design Description

The purpose of the device is to give the user of a kitchen sink feedback, before, during, and after the sink is used. Thus it must sit adjacent to the kitchen sink, and be easily visible to nearby kitchen occupants. Inside the device is an Arduino Mega equivalent, a custom PCB shield, and a 20 x 4 blue/white LCD screen visible through the clear acrylic exterior of the device. Extending from the device's interior are three wires, a 2-pin power cable, a piezoelectric sensor with two lead wires (bundled together), and a single wire which is used to provide the board with an earth ground.

3.3.1 Component Selection

An Arduino Mega equivalent was used for the controller as the final code exceeded the memory capacity of the Arduino Uno and Arduino Yun. This decision was also aided by the extremely low price-point of $4 per unit, compared with the prohibitively expensive $65/unit Yun, we were able to get by purchasing from a third party manufacturer.

The 6 KHz piezoelectric transducer used in all the devices was one of many different transducers tested; it is shown in Figure 2. We also tested microphones, as used in UpStream, and a few other piezoelectric transducers. We connected each these unamplified transducers to an oscilloscope and monitored their outputs while the transducers were attached to various sinks. The ability to be easily attached to the faucet itself by wrapping with electrical tape was a requisite for all sensors considered. When attached to an oscilloscope the microphones had no detectable response while the piezoelectric transducers had a visible response, thus we chose the piezoelectric sensors. We then attached these sensors to the amplification circuit depicted in Figure 4 and determined which gave us the most stratification of signal for varying flow rates on common sinks. Though crude, this method proved effective and we eventually chose the 6 KHz piezoelectric sensor. None of these transducers cost more than $3 per unit, thus price was not a deciding factor in this process, though gyroscopic transducers (at $5-10 each) might be used if piezoelectric sensors do not provide the resolution needed.

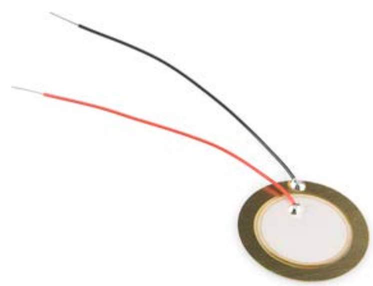

Figure 2 - Piezoelectric transducer used to detect sink vibrations

To mitigate any chance of electrocution, the whole unit was plugged into an outlet through a ground fault circuit interrupt (GFCI) adapter. The GFCI adapter flips a mechanical switch to stop the flow of electricity to the unit if it detects an imbalance of current in and out. The adapter we chose is pictured in Figure 3.

Figure 3 - Ground Fault Circuit Interrupt Adapter

3.3.2 Circuit Description

The piezoelectric transducer output an average maximum signal of about 150mV. This signal needed to pass through an amplification circuit before being read and recorded by the microcontroller. All of the circuits described in this section were first prototyped on a breadboard and then etched into PCBs, which can be seen in Figure 4. The amplification circuit itself was a simple op-amp system, using a low power single rail op-amp (LM6432) powered by 5V and 0V. The amplification ratio was 10kOhm over 562 Ohm, a gain of about 17.5. This gain was optimized by trying to make the maximum output voltage of the signal a bit less than 4.5V such that there would be no saturation on the analog read pin (max 5V readable). A voltage divider was placed between the transducer leads to shift the signal to center. The signal output was wired to analog pin 0 (A0) on the microcontroller. The diagram is shown in Figure 4.

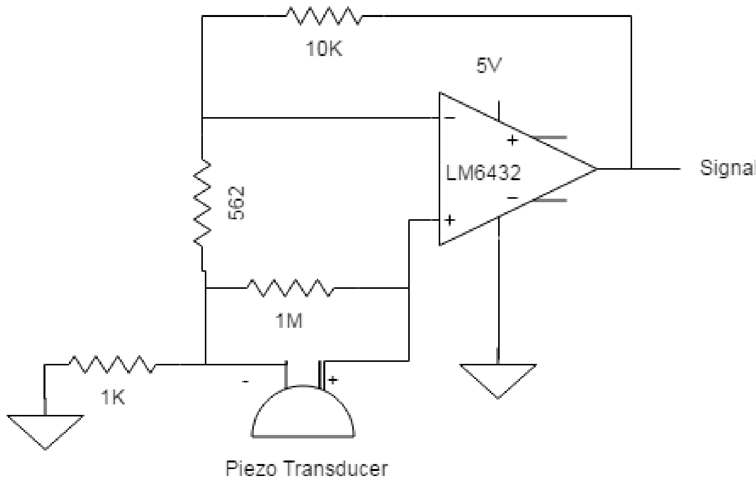

Figure 4 - Amplification Circuit on PCB

The Micro-SD card read/write unit was a micro-SD 6-pin writing board coupled with an 8GB micro-SD card. This board was soldered to the PCB as described on Adafruit and the appropriate Arduino library commands interfaced with it [56]. Being an Arduino Mega, the variable pin was set to 52 (rather than 12 as on an Uno). The 20x4 character LCD white on blue display was chosen to be easily programmable, as well as compact and a similar size as the Mega board. This size proved sufficient to display all information we desired to display and was also very legible from many distances. The LCD screen was wired per its supplier, Adafruit, instructions.

3.3.3 Device Housing

The housing of the system was composed entirely of laser cut eighth-inch thick clear acrylic, with a 35 degree angled top for optimal visibility of the screen. The controller and screen are both supported by slide-in acrylic “shelves”. These keep the screen at a 35 degree angle, and the controller and electrical components half an inch from the bottom of the inner cavity such that they would be out of contact with any water that may come inside of the packaging. These shelves replaced the original idea of 3D printing an interior component holder, which is beneficial for getting rid of an additional manufacturing step and added volume of the component.

The interior corners were all sealed with acrylic epoxy, and the two-layer base, shelves, and top were attached with clear packing tape. The tape was necessary to allow for easy access to the components while inside of a participant’s home, and was also waterproof and relatively invisible. Two and a half full exteriors could be laser cut from a single piece of 12”x24”x ⅛” piece of acrylic and assembled by hand very quickly. The total size of the exterior is 4”x4.5”x2.5”, with a half inch protrusion from all sides in the bottom quarter inch from the base. There are also seven rubber feet stuck to the bottom of the base to raise the unit off of the surface of the counter and provide it with greater static friction, making it harder to accidentally knock over. A picture of the full device is shown in Figure 5.

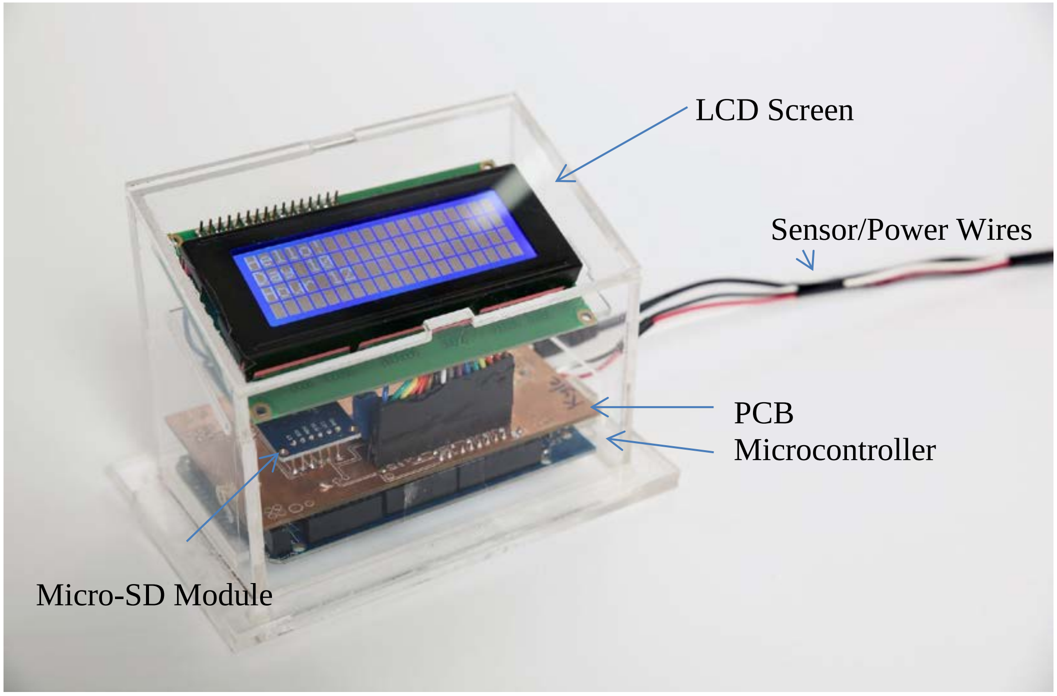

Figure 5 - Final Device Photo - Active Screen / Pre-Contemplation

3.4 Sensor Calibration

This section provides additional detail on the sensor reading calibration process and environmental variables that affect data accuracy and consistency. This is different than the actual flow-signal calibration process described in the previous sections in that this calibration process was to achieve a higher signal-to-noise ratio and get the readings to be consistent and responsive enough for human interaction for a single flow rate.

3.4.1 Improving Accuracy and Consistency

In order to devise the optimal sensor attachment and active filtering parameters, various configurations were tested. The device needed to be able to deliver a stable sensor reading for a visibly stable water flow rate. This section describes how the raw sensor output was processed in order to achieve a low noise signal that may then be converted into water use estimates through the process described in Section 3.4.2.

The first configuration tested was raw sensor output read at intervals of about 0.1s. The readings proved to be extremely noisy as pictured Figure 6 thus more software processing was needed. To smooth this signal, the raw sensor output was put into a running array and a running standard deviation and average of the array were taken. The number of samples per array was tested at 5, 10, 20, 30, 50, and 100. Fifty and 100 sample arrays were too slow, the resulting averages and standard deviations of such large arrays had lag up to 0.5s, which caused significant inaccuracies in small sink usages. 20 samples was the best array size, as it gave good delineation and stable readings for various flow rates.

Either the running average or the running standard deviation can be used to develop a flow rate estimation at sinks. A few test sinks in this study yielded higher accuracy using with the standard deviation method, and Evans et al. publish had a high degree of accuracy in-lab doing a flow rate estimation using the standard deviation of a gyroscope [57]. Thus we chose to use the running standard deviation of the signal as the flow estimation signal.

The graphs in Figure 6 and Figure 7 show three and four different flow rates as time series sensor data. Both graphs were generated from the same faucet, three months apart. The first shows how the output looked toward the beginning of the sensor calibration phase, and the second shows a near final output. The final output has significantly lower noise, and a clearer delineation between flow rates compared with the initial sensor data. The graph in Figure 7 show four flows each of which correspond to a data point used in the signal-flow calibration curve shown in Figure 9.

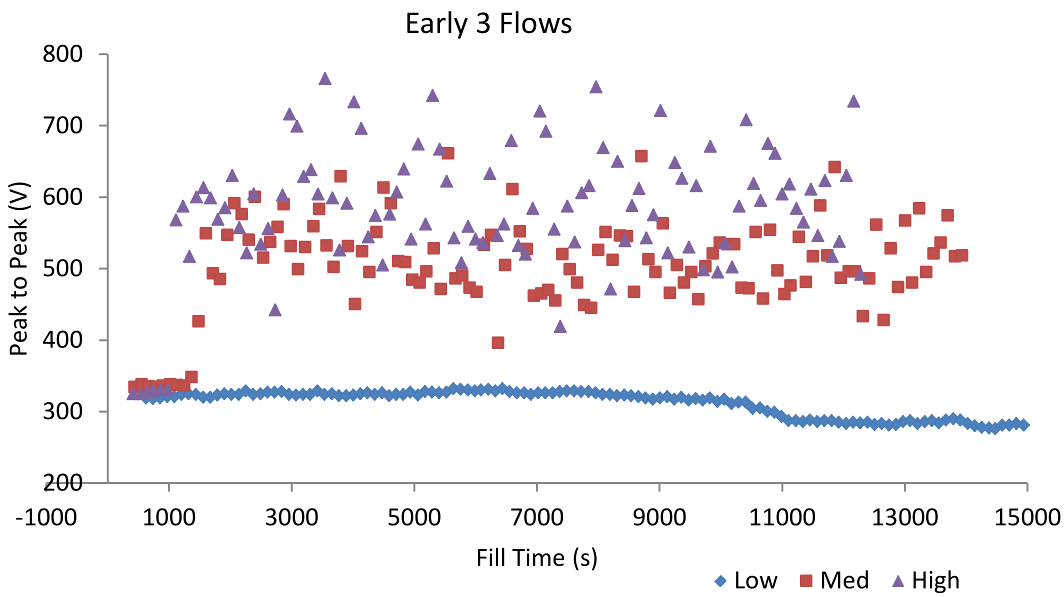

Figure 6 - This graph shows an early trial, each line is the transducer reading at a different flow rate. Medium and High flow are very hard to discern here

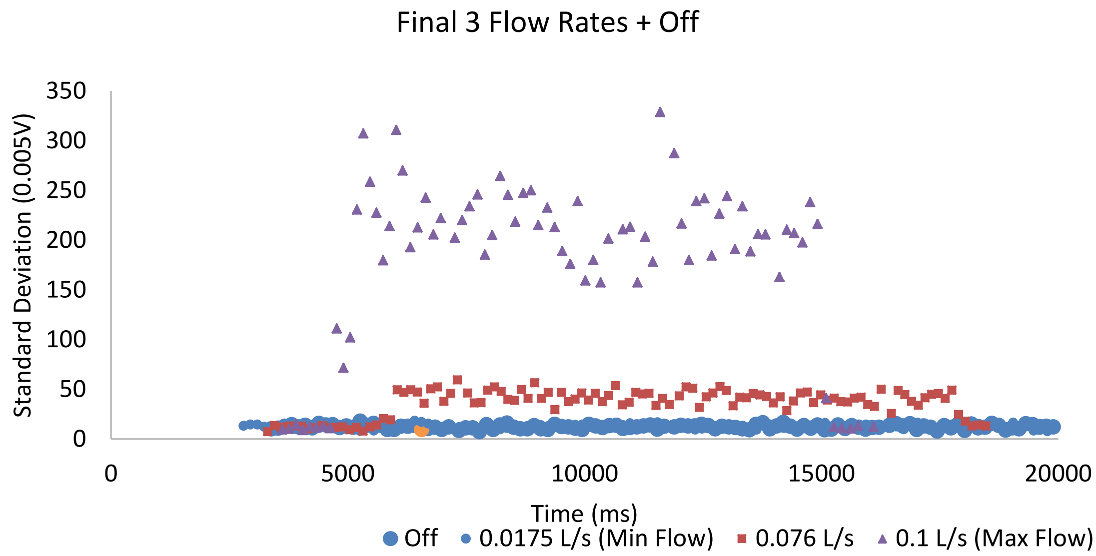

Figure 7 - This graph shows three flow rates at the same sink as the previous graph, much more differentiated

In the first graph, Figure 6, the raw output for the medium and high flow rates is hard to tell apart, and their range of fluctuation was almost 400 units (0.005V). In the second graph, Figure 7, the raw output is evaluated using the standard deviation of 20 samples. The medium and high flow rates are more delineated when measuring the standard deviation rather than the running average. The high flow rate has a fluctuation of about 100 units, and the medium has a 20 unit fluctuation. This resolution allowed for the generation of an accurate signal-flow curve (R^2 > 0.8), shown in Figure 9. When testing the calibrated device using the signal-flow curve in Figure 9 (which was generated from the data points in Figure 7 as well as some non-pictured flow rates) we achieved nearly 95% water volume accuracy. During the three months between generating these two curves the sampling rate and window were honed and adjusted. Further we found that constantly measuring the standard deviation of the signal was a more reliable method to track flow rates. Using standard deviation is rigidly justified in [57] Evan et al.'s work. They were able to achieve 97% accuracy in estimating flow rate through a pipe measuring the standard deviation of signals from gyroscopic sensors in a controlled lab environment.

3.4.2 Signal – Water Flow Calibration during Installation

The Arduino program used to control the whole system is calibrated at each individual sink during an installation visit at each of the participants' homes. During this visit a researcher records training data corresponding to measured flow rates, then corresponds the data to the flow rates and generates a first or second order polynomial, which may be uni-, bi-, or tri-linear depending on the vibrational behavior of the sink. In similar studies, such as Upstream, the designers assumed a linear vibration-flow profile, interpolated between two or three known flow rate data points. We found the linear relationship to largely be sufficient; however in some cases it is neither sufficient nor accurate. An example of a linear and a bi-linear calibration curve is shown in Figure 8 and Figure 9. This curve was generated from the same sink data as that shown in Figure 7. The small parabolic bump around 40 on the X-Axis of Figure 9, though inaccurate for that small section, results in negligible error (<5%) for flow prediction.

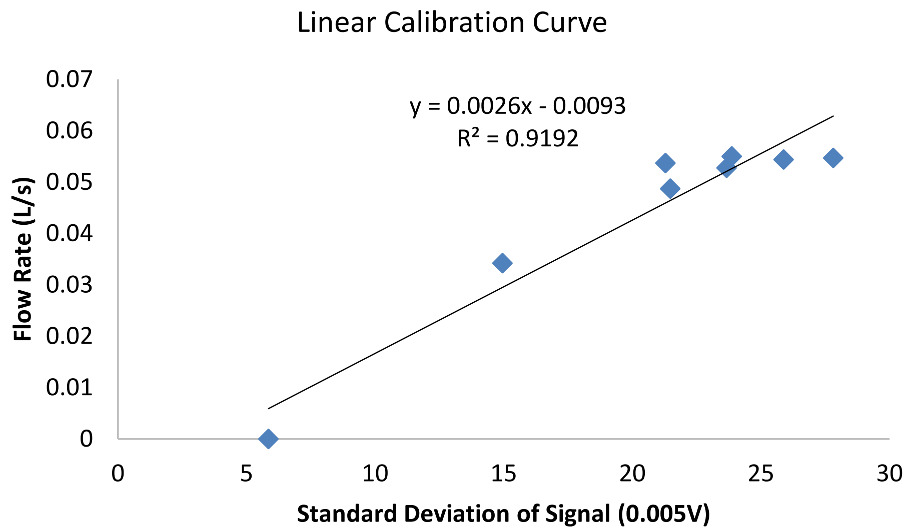

Figure 8 - Example of actual linear calibration curve

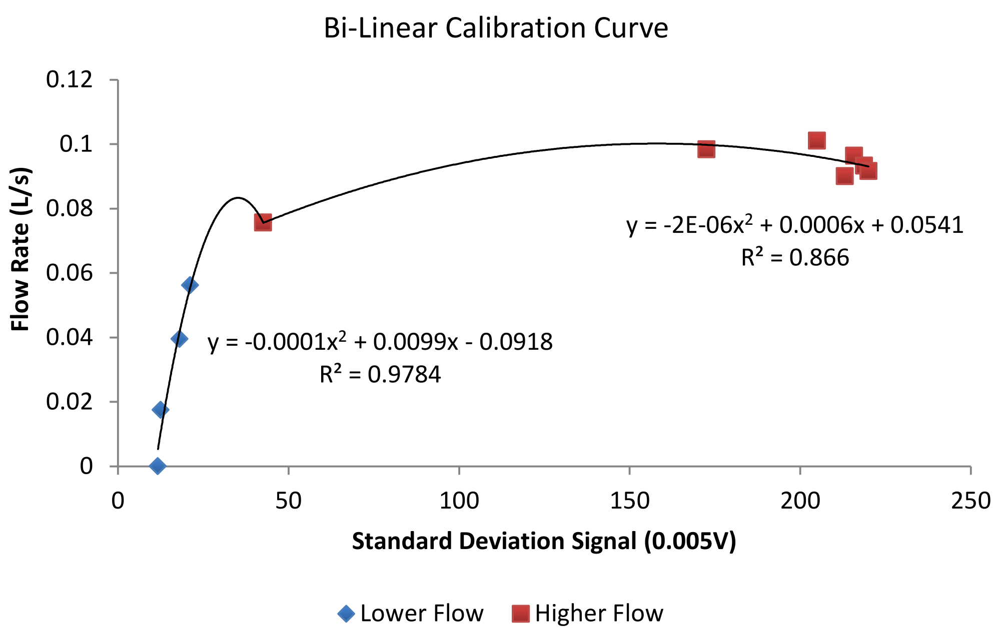

Figure 9 - Actual bi-linear curve used to calibrate a device for testing

From Figure 8 and Figure 9 it can be seen that some faucets have very different vibrational profiles. However, by splitting the nonlinear curve in Figure 9 we were still able to calibrate the sink with reasonably high accuracy, as signified by the R^2 value. Naturally, more calibration data points would provide a curve with a higher regression coefficient, however we found between five and ten data points to be sufficient for our needs. We generally strove to achieve an Rˆ2 value of greater than 0.75.

3.4.3 Drift

If a signal drifts over time, then the calibration curve will need to be changed regularly. To test for drift, I installed a transducer at my home sink and took readings a week apart, and generated a calibration curve for them. Figure 10 shows two curves taken a week apart.

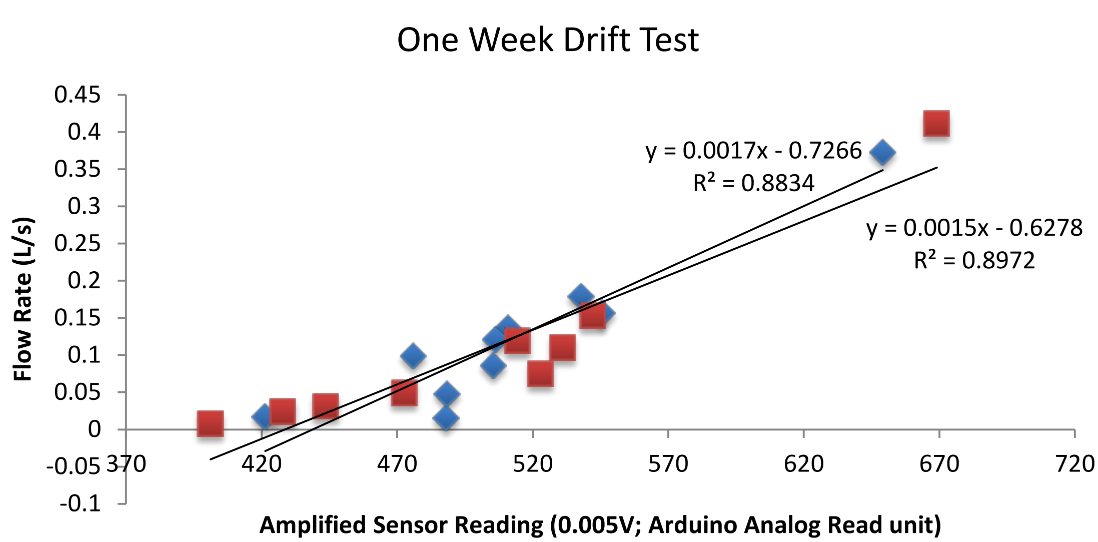

Figure 10 - Drift test, two curves made from data taken a week apart

Though the two curves are not the same, they are very close and drift due to any environmental factors was reasonably not accounted for as it would require more labour and researcher visits to recalibrate the devices regularly.

3.4.4 Hot Flow

When exposed to extreme temperature fluctuations, piezoelectric transducers tend to change their response curves. We generated two calibration curves at a single faucet using both very hot water (about 175F) and room temperature water (about 72F). The two curves had very different profiles, as shown in Figure 11.

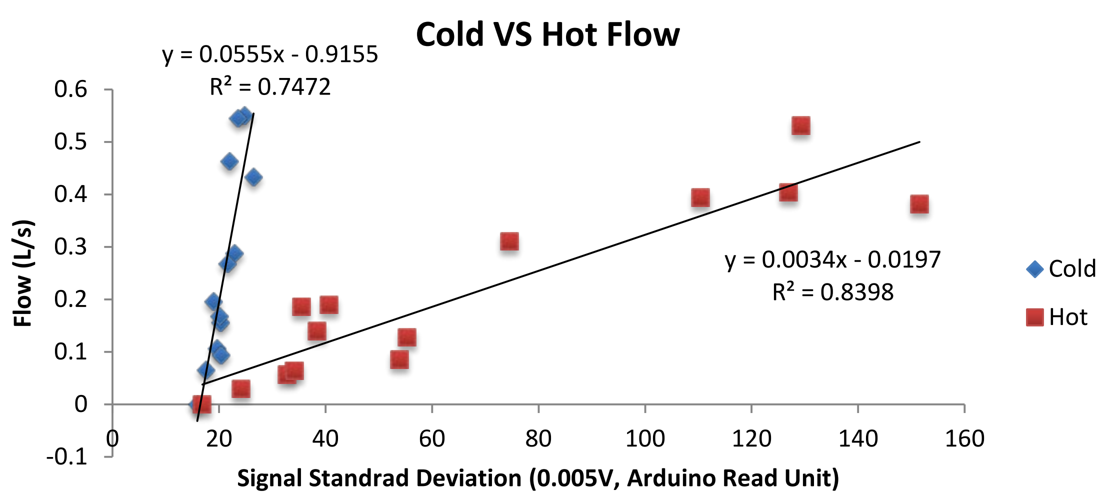

Figure 11 - Calibration Curves for Hot and Cold Water

The two curves were extremely different. As this was discovered after the devices had largely been physically finalized we chose to calibrate all sinks to room temperature water. In order to compensate for temperature we would need an additional few sensors and a much more complicated calibration system. In a pre-test installation, no issues were raised regarding inaccuracies surrounding hot water usage. This may be because the hot water we used in this trial was far hotter than most sinks generate. Finally, as our intention is to achieve water conservation, it can be seen that a *low* hot flow calibrated for cold water will read as a *high* cold water flow. Thus it skews the data towards accepting the null hypothesis; that a phasic device will not achieve conservational behavior change.

3.5 Code/Control Description

This section describes the Arduino code that controls the device, the code itself may be found in the appendix. This serves to give an idea as to how the device operates on a low-level. Arduino scripts follow this basic structure; first, library and variable declarations, then a “void setup ()” section which runs a single time upon the device’s being booted up, then a “void loop ()” section which runs continuously until the device is powered down. Any sub-functions must be declared independently after the “void loop ()” section.

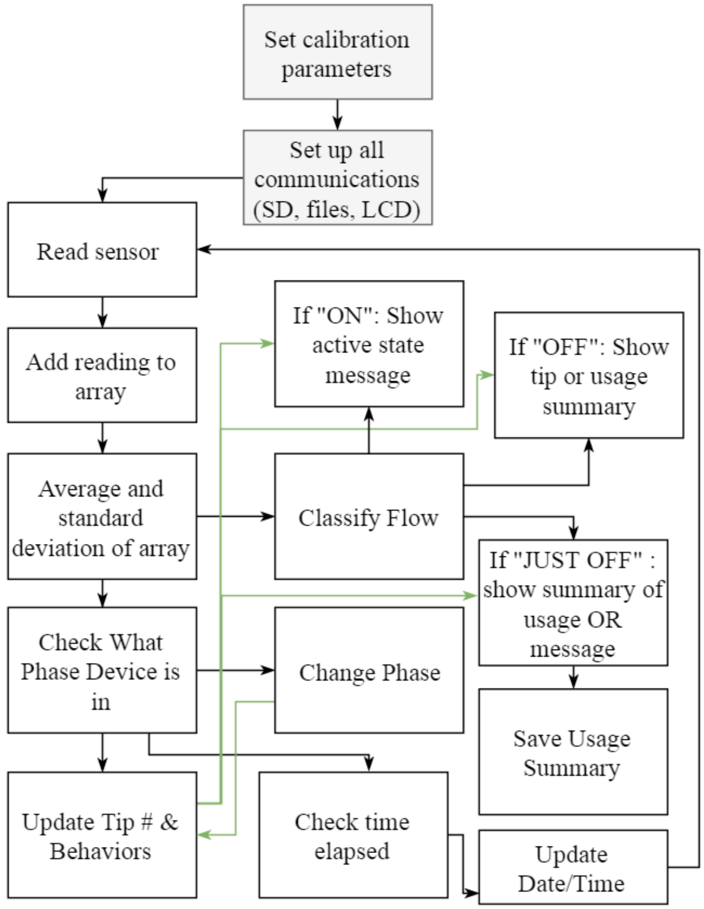

Figure 12 - Code overview. Void setup () in grey boxes, void loop () in white. Green arrows indicate information

At the beginning of the code, with all the variable declarations, there is a set of variables which must be found and set for each sink the device is to be deployed on. These variables describe the vibrational profile of the sink, allow for accurate water flow estimation, and limit error. These variables are signified in the appendix with a "CALIBRATE []" commented out next to them. Many of these variables are found by running a Processing script which saves all the Arduino output to a .txt file. This file is then analyzed in Microsoft Excel, and the variables are determined uniquely for each installation.

In the "void setup ()" section of the code all necessary systems are initialized (SD card, LCD screen, serial communication), and the long term storage variables are checked against files on the SD card and input. This step allows for important variables such as number of days running to be consistent even if the device is powered off and on and all the variables are reset to their defaults. Such a check is very important as the phases of the device are determined by how many days the device has been installed for. Each such step also has embedded error messages to ensure that all necessary data were saved correctly.

The main body of the code, "void loop ()", first takes a reading from Analog input A0. It then adds the reading to an array of readings which generates a standard deviation of the last 20 readings. A running average of the readings themselves are also made and processed to output a peak-to-peak (PTP) over a 150ms window. The PTP is generated in the event that a sink has a better vibration profile from the raw readings rather than the noise in the signal. During the experiment no sink showed better PTP results than standard deviation.

The processed signal is then put into an exponentially weighted moving average (EWMA); this eliminates most noise and makes the readings more reliable and less "jumpy". The EWMA signal is then analyzed to determine what state the sink is in. The three states are "IDLE", meaning the sink has been OFF for over 15 seconds, "ACTIVE" meaning the sink is currently ON, and "JUST OFF" meaning the sink has been on in the last 15 seconds and is now off. What the display shows during these states is described in the following, Section 3.7, in Table 2.

Depending on which state the faucet is determined to be in the program will display different things on the LCD screen. If the sink is ON or “active”, then the flow-rate will be calculated, and some information pertaining to that will be displayed depending on what PHASE (which change every 7 or 14 days) the device is in on that say. If the sink is JUST OFF, then the device will save a summary of that single instance of usage onto the SD card, and will also update each of the arrays. The five arrays are all 70 dimension arrays, each entry of which corresponds to a single piece of datum about a particular day. If the sink is OFF or “idle” then the display will show information about water, tips about how to use water in-home more efficiently, and/or a summary of that day’s usage depending on what phase the device is in. After the appropriate information is displayed on the LCD the device checks what phase it is in, sets the behavior accordingly, saves all data and starts the loop over again.

3.6 Phasic Feedback Framework

In this section the feedback given to the user by the device will be explained. The phases of feedback will also be described, in function and in conception as an adaptation from The *et al.*’s work. Each of the phases is specifically detailed in Table 2, at the end of this section. The tips referred to in the table are listed in the appendix, *Section A1*. We chose the advancement of the phases to depend entirely on time passed, rather than based on the user activity, for simplicity and in order to guarantee that each subject is exposed to each phase.

The framework for the phasic feedback was derived from *The et al.*'s paper "One Size Does Not Fit All". He *et al.* postulate that persuasive technologies which employ feedback based on well-established psychological theories pertaining to behavior change in phases will achieve greater behavior change than those that provide just usage feedback to their users. The assumption behind behavior change associated with pure usage-informational, non-phasic, feedback is that each individual is a rational actor with an inherent desire to conserve water. However, if the user either is not rational, does not believe his/her locus of control to be very large, or simply does not wish to conserve water, then providing him or her with usage data will be ineffectual at creating behavior change. Thus by gradually engaging the user, and "waking him/her up" to the benefits of conservation, it is hypothesized that phasic behavior change will create greater, more lasting behavior change. The actual phases are outlined in Table 4. A more in depth summary of He et al.'s work may be found in section 2.6.1

Table 4 - Feedback Phase Description

Phase	He et al.'s goal	Adapted Goal	Days	Device Actions
1. Baseline	N/A	Try to understand how participants behavior is without feedback	14	**Active**: Display "Baseline Day [Day #] [Hour #]" **Just off:** Display "Baseline [Day #]" **Idle**: Display "Baseline [Day #]"
2. Pre-contemplation	- Plant the "seeds of change" - Address barriers to action	Get users thinking about water, current state of water supply	7	**Active**: "Hello!" **Just Off**: "Goodbye!" **Idle**: Change every 8 hours. Tips 1-10
3. Contemplation	Tip the balance in favor of behavior change	Show water situation on earth, show advantages of conservation	7	**Active**: High flow detected: "High flow is good for filling pots, cups, and water bottles." - Low flow detected: "Low flow is good for most uses." **Just Off**: "Goodbye!" **Idle**: Tips 9-18. Change every eight hours.
4. Preparation	Support individuals in building a plan that is acceptable, accessible, effective	- Give goal building blocks - Develop awareness of usage	7	**Active**: OFF--------------MAX bar display **Just Off**: Water volume estimate "You just used about ## L." **Idle**: Tips 15-31, change every 4 hours.
5. Action	Reinforce action	- Allow users to monitor usage -Encourage conservation	14	**Active**: Big text, saying HIGH, MED, LOW or OFF--------------MAX bar display **Just Off**: Usage estimate - - "You just used ## L." - "Today's usage is ###% of yesterday's so far." - "Today's usage so far ### L." **Idle**: Tips 25-52, change each hour. - Daily usage - Today/Yesterday usage

6. Maintenance	Provide support, encourage user	Provide support, encourage user	20	**Active**: “Hello!” **Just Off**: “You just used about ### L.” - “Today’s usage so far ### L.” **Idle**: Tips 1-52, change hourly

Upon installation, the phase of feedback the device gave was termed a “Baseline” phase. This phase lasted two weeks, and the purpose of it was simply to accustom the user to having a device installed at their sink to mitigate the “Hawthorne Effect” (behavior change due to one’s knowledge of being monitored), and to gather information on the user's sink usage when no information was being given to the users.

The next phase the device entered, termed “Pre-contemplation”, assumes that a user may be “unaware, unwilling or discouraged to change problem behavior” and tailors the feedback given in this phase accordingly [5]. There is no information output during the ACTIVE or JUST OFF phase, simply “Hello” and “Goodbye” such that the user knows the device is working. The information provided in the idle phase are mainly “fun facts” about water, to get the user thinking about water in general, such as “Water is the only substance found on earth naturally in three forms”.

After seven days, pre-contemplation then gives way to “Contemplation” phase. In this phase a user is assumed to be more open to thinking about the problem of water usage, yet may still have mixed feelings about his or her role or responsibility in the water system. In this phase, more general pieces of information about the current, regional, water situation are made plain, such as “Georgia has been in a severe drought since October 2016”. The idea here is to make the user think not only about water in general, but about the water system he or she participates in and his or her own actions’ consequences. Further, the information provided is intended to make the users realize that water is a valuable resource that is often scarce and should be conserved.

After seven days, pre-contemplation changes to the “Preparation” phase. At this point the participants are assumed to be thinking about water, and the urgency of conservation. Thus the device provides feedback intending to help the user take concrete steps towards changing daily actions to achieve water conservation. The device still provides many non-actionable pieces of information relating to water scarcity, but most of the information provided is specific to actions, such as giving an estimated volume of water used at the faucet each time the device recognizes an instance of water usage.

After seven days in the preparation phase the device enters the “action” phase. Now it assumes the user is trying to change his or her habits in order to conserve water and provides only actionable tips on doing so. Further, it provides a few different displays of water flow while the sink is on, such a bar indicating how high the flow is from OFF to MAX.

After fourteen days in this phase, the device enters its final phase; the “maintenance” phase. The users are assumed to have made changes, and the device plays a more passive role in maintaining any changes. In this phase all the tips and information are cycled through while the sink is idle, reminding the user of all the information provided. The device does not provide information when the sink is on, but does provide a summary of usage upon the sink being turned off.

After 20 days of being in the maintenance phase the device re-enters the baseline phase to ensure that no single participant is given more feedback than another due to misalignment of uninstall dates. This baseline state is the same as the first baseline state.

3.7 Summary of Design Chapter

The final device was constructed of an Arduino Mega equivalent, a custom PCB shield with various circuits and a micro-SD module, a 20x4 LCD display, and a 6 kHz piezoelectric transducer. All of this was encased in a laser cut and epoxy-glued clear acrylic packaging, and plugged in through a ground fault circuit interrupt (GFCI) adapter for safety. The total cost of each device was about $60, a full bill of materials may be found in Appendix A6.

A major challenge was recognizing the need for (after many noise issues) and installing a peripheral earth-ground wire to mitigate added noise into the sensing system from the otherwise floating ground. The technology in the device designed and built in this thesis was inspired by works done by Kutsenov et al. and Will Buchanan [2], [55]. These two projects used similar detection methods and provided some groundwork on component selection.

By calibrating the sensor system and doing much testing, we were able to achieve a higher resolution than reported by either Kutsenov or Buchannon, of about 10% average error for many types of sinks, reporting on a 0.05L increment. Kutsenov et al. reported a 10% error reporting on a 0.2 Gal (25.2 fl. Oz, 0.74L) increment. For most purposes of reporting water usage at a sink, a 0.2 gal (about a full glass) is too large a unit, thus our improvement on the increment reporting was significant [2].

The feedback framework was an adaptation of the framework outlined in The et al.'s paper "One Size Does Not Fit All". This feedback framework was based on addressing different goals depending on what phase of behavior change a user is purported to be in. The phasic model for behavior change specifically used was called the Trans theoretical Model of Behavior change, and had five distinct phases, plus a baseline. The phases were baseline (no feedback), precontemplation, contemplation, preparation, action, and maintenance.

CHAPTER 4. PILOT STUDY METHODOLOGY

4.1 Research Goal

The goals of the phasic device experiment are 1) to compare the efficacy of phasic feedback delivered by pervasive displays, 2) to motivate conservation behaviors in home, like efficient dish washing, and 3) see how specific behavior-targeted feedback affects other water using habits and thus overall water consumption. These experiments occurred during two pilot studies. One was in Fall 2016, lasting ten weeks, and the second in Spring 2017, lasting seven weeks.

4.2 Fall 2016 Methodology

The Fall 2016 study took place over 70 days in 6 volunteer households. The households were divided into experimental (phasic, N=4), and control (non-phasic, N=2) groups. A device was installed at the primary kitchen sink on day 1, and uninstalled on day 70 or after. After this initial visit the primary function of the device is to simply provide the user of the sink, or inhabitant of the kitchen, with data pertaining to that specific faucet's usage, and in the case of the four non-control groups, tips and facts about water and water usage. Throughout the 70-day experiment the device cycled through seven different modes of feedback, explained in detail later in this section. The device logged all detected faucet uses during this 70 day period. During the two install/uninstall visits a survey was administered to track any reported shifts in pro-ecological behavior change. A final electronic survey was also administered online to get open-ended design feedback. Figure 13 gives an overview of the experiment timeline.

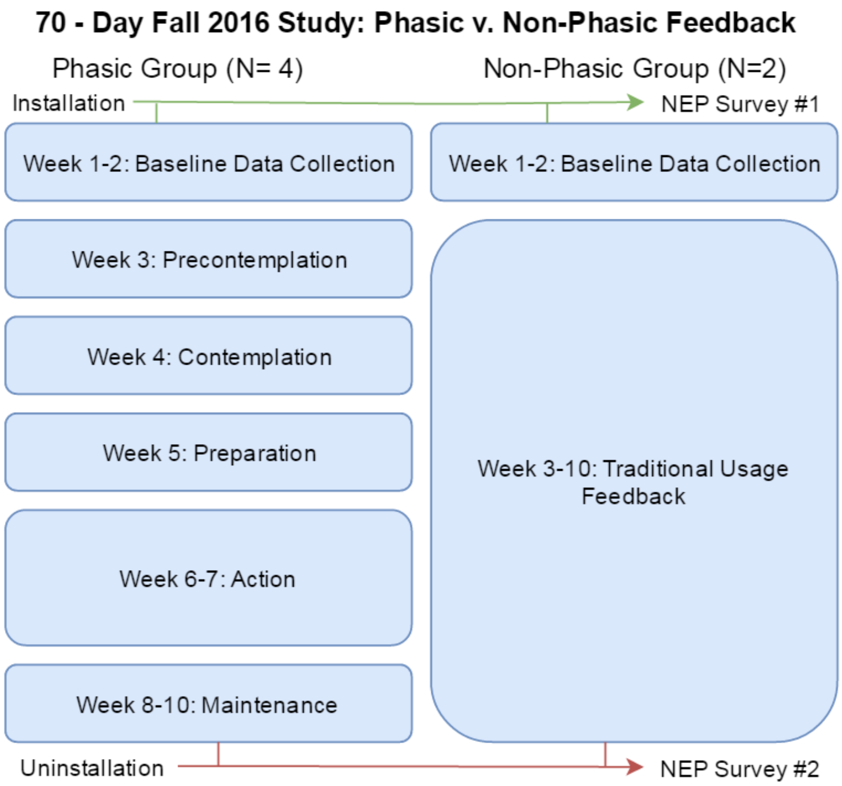

Figure 13 - Experimental Overview

To recruit volunteers to participate in this study, flyers were posted on and near the Georgia Tech campus. The flyers briefly described the study and mentioned compensation. Those interested were told to email an official Georgia Tech email address generated for the study alone. Before being accepted as participants in the study, responders to the email filled out an online survey making sure they were viable candidates. The criteria for the volunteers were as such; 1) within reasonable driving distance of Georgia Tech, 2) had a primary kitchen sink, 3) consented to reporting water billing information. One volunteer paid a flat rate for his utilities and thus could not provide granular billing information. A few people who lived in dormitories or with minors were screened out.

Six responders qualified to be participants, and a single device was installed in each of their homes at their kitchen sinks. All of the principal volunteers, those who actually contacted the researchers, were students; five of the six were currently enrolled at Georgia Tech. Including their housemates a total of 16 people lived full-time in the residences the devices were deployed at.

4.2.1 Quantitative Assessment of Behavior Change

For the duration of the device being installed, every detected sink usage was logged to an 8GB micro-SD card, and the data saved for each instance were: day of use, approximate time of use, duration of use, two types of sensor data describing use, and estimated water volume used. The device also filled a 5x70 matrix of datum on the micro-SD containing this information summed per each day of the device's deployment. This data are used to determine how the sink usage behavior changed during the course of the device's installation.

To get an idea of what a participant's sink usage is like without any feedback the device does not display any tips or information during the first one or two weeks of intervention, for the Spring and Fall study respectively. This period of time is called the "Baseline" phase. It also serves to help ameliorate any extra behavior change that is due to the simple fact of being monitored, called the Hawthorne Effect.

Each volunteer was asked to report his or her water billing information. This information came as specific water volume used, or total amount as charged by the management of his or her apartment complex. If a volume was not reported then the volume was estimated using current water pricing in the specific Atlanta zip code in which the volunteer lived. This data allowed the researchers to determine if and how a volunteer's overall water usage changed throughout the duration of the experiment. Many households in apartment did not have direct access to their water billing information and instead paid a lump sum. Thus the data concerning total water volume used is incomplete, and will only briefly be discussed. Which households lack this data will be made clear.

4.2.2 Testing Interactions with User Attitude

Pro-ecological attitude is defined as how much a person believes themselves to value environmental concerns. To measure this attitude, Dunlap et al. developed a survey called the New Ecological Paradigm Survey (NEP) [1].The NEP survey was used to check for sample bias: comparing the participants in our study with the general population as sampled by the NEP study (N=676), and to test three hypotheses: (1) that interventions may be effective when users have more pro-environmental attitudes (2) that behavior change interventions change user attitudes and to make sure that the two sample groups are neither more or less pro-environmental than the general population.

Also important to the analysis of the device's performance is the more abstract effects it had on the opinions and attitudes of the participants. In order to measure these changes three surveys total were administered to the volunteers. Two of these surveys were the same “New Ecological Paradigm” (NEP) survey, with three extra questions added pertaining to water usage awareness specifically, a total of 18 questions. The first three questions are shown in Figure 14.

Statements	Circle Your Opinion of Each Statement				
We are approaching the limit of the number of people the earth can support	Strongly Disagree	Mildly Disagree	Unsure	Mildly Agree	Strongly Agree
Humans have the right to modify the natural environment to suit their needs	Strongly Disagree	Mildly Disagree	Unsure	Mildly Agree	Strongly Agree
When humans interfere with nature it often produces disastrous consequences	Strongly Disagree	Mildly Disagree	Unsure	Mildly Agree	Strongly Agree

Figure 14 - Example of first three questions from NEP survey

The full 18 question survey may be found in the appendix. The survey was 18 questions long (three were added to the original 15 question NEP about water usage specifically), and the answer format was a five option Likert scale, from Completely Agree to Completely Disagree. Each question relates to one of five categories of pro-ecological attitude, or to awareness of his/her water usage. The categories from the NEP are limits to growth (“A” in Figure 22), antianthropocentrism (“B”), fragility of nature’s balance (“C”), rejection of exemptionalism (“D”), and possibility of an eco-crisis (“E”). Additionally, three questions were added to ascertain the individual’s opinion of his or her own water usage, these are under the category “Water Awareness” (“F”) in Figure 21. The two NEP surveys were administered at the first and last visit to the volunteers’ home (during which the device was installed and uninstalled respectively). These surveys were intended to measure any shift in environmental attitudes in the volunteers during the course of the experiment.

4.2.3 Open Ended Survey

The third and final survey administered was a qualitative survey administered online after all of the devices had been collected asking general questions such as “How was the overall experience with the device?” This survey sought insight into trends in water usage correlated to opinions of their experience as well as to inform a potential next generation of devices on user-perceived shortcomings. The result of all surveys is reported in the qualitative results sections, Section 5.2 and 5.3.

4.3 Spring 2017 Methodology

A second pilot study was conducted in Spring 2017. It included six households: three phasic feedback experimental groups, and three non-phasic control groups. This study differs slightly from Fall 2016 due to a compressed timeline. The baseline, and the maintenance phases shortened from two and three weeks to one week each. The total duration of the study is 49 days. The control group is only affected by this in that the baseline phase is one week rather than two. An overview of this adjusted timeline is shown in Figure 15. All details about quantifying behavior change are identical to those specified in sections *4.2.3* and *4.2.4*, and will not be repeated in this chapter.

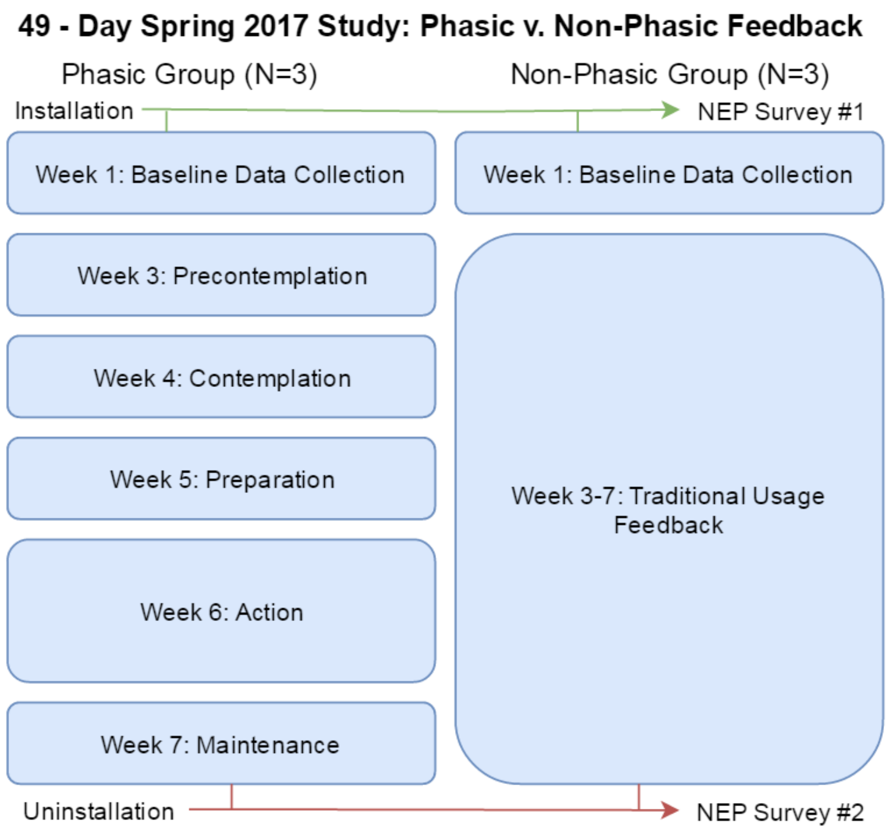

Figure 15 – Spring 2017 Experimental Overview

4.3.1 Volunteer Recruitment

Again due to the compressed timeline we sped up the recruitment process by posting an advertisement for the study in the Mechanical Engineering Graduate Association (MEGA), and resorting to friend-of-friend networks. Thus we were able to gain seven volunteers in about a week, and we were able to install the devices over the following week and a half. The volunteers were all Georgia Tech students, four graduate and two undergraduate. Each household had two to four residents.

4.3.2 Maintenance and Issues

There were three reports of devices acting incorrectly. Two were solved easily, one by a visit, and the other by restarting the device. The third was a recurring issue which led to the revelation that some component in the circuit of the device was malfunctioning, albeit slowly over time. The symptoms of this were the LCD screen becoming slowly brighter until it became unreadable and erratic. This device was uninstalled and this seventh household was removed from the study, as the reinstallation of a device would have occurred too late in the timeline.

4.4 Study Methodology Summary

The pilot study took place over 70 days in 6 households. Four of these households were experimental groups given phasic devices, the other two were control groups given rigid feedback devices. All volunteering households were students, graduate and undergraduate, at Georgia Tech or Georgia State University. The study tests the efficacy of phasic feedback compared with non-phasic feedback by recording actual faucet usage data, how/if phasic feedback affects user's pro-ecological behaviour measured via the NEP surveys, and if there is any correlation between changes in attitude and changes in behaviour.

At the beginning and of the study, during the installation and uninstallation visits, a modified New Ecological Paradigm survey was administered to notice any shift in reported pro-ecological attitudes. During the course of the device being installed, it logged each sink usage and gave feedback in fact/tip and usage form to the users. This feedback changed on a weekly or bi-weekly basis. After the uninstallation, the participants were given an online, 10 question survey. This survey contained more open ended questions about the participants experience with the device.

CHAPTER 5. RESULTS FROM PILOT STUDIES

This section is a report and discussion of the results from the Fall 2016 pilot study. This study involved six households, and each device was deployed for at least 70 days. All data displayed or discussed in this chapter is with respect to those full 70 days. The study lasted from September 2016 to December/January 2017; no devices were installed more than three weeks apart.

5.1 Fall 2016 Pilot Study

This section describes the results from the first pilot study, conducted from September to December of 2016.

5.1.1 Data Exclusion

In the early phase of the device installation erratic behavior was observed in many devices. This behavior was not evident during preliminary tests. After analyzing the issues, the problem was identified as noise introduced to the system due to the floating ground the power source used. To remedy the problem, a wire was either soldered to the ground of the PCB, or was plugged into the ground pin of the microcontroller, and then pinned under an outlet screw. This method worked to relieve the issue on four of the six devices which were installed.

The only additional maintenance trips were to replace a sensor whose leads became unattached, and various trips to raise the "OFF" noise floor, making it slightly harder to trigger an “ON” state and thus allowing less vibrational noise to trigger the device. There were a total of seven maintenance trips for the Fall 2016 study.

Two of the devices still recorded large amounts of noise. This was likely due to the outlet frame in these two households not being properly grounded, or due to a loose attachment of the earth ground wire to the devices. The participants at these households did report the erratic device behavior, and a researcher visited these houses and conducted maintenance. However, upon reviewing the data it is clear that the devices continued to work improperly as they recorded many impossible quantities of water used. Thus it is necessary for the quantitative data recorded in these two devices to be excluded from the data analysis. The following results are data from the remaining two control (non-phasic feedback) groups, and two experimental (phasic feedback) groups.

5.1.2 Overall Usage Change

In order to compare how the households changed their water usage over time, we needed to normalize the data. Each household had a different number of residents, and the estimated number of liters used per household per day varied from 2L per day to 55L/day. The normalization technique employed is as follows; the total water used by a particular household throughout the entire study was summed, and then the percentage of this total used is reported on a weekly basis. The normalization allows for the change in usage to be visualized on a comparable scale since some houses used more water by volume than others. Figure 16 is a graph showing the average percentage of total water used each week for the non-phasic control groups and the experimental phasic groups.

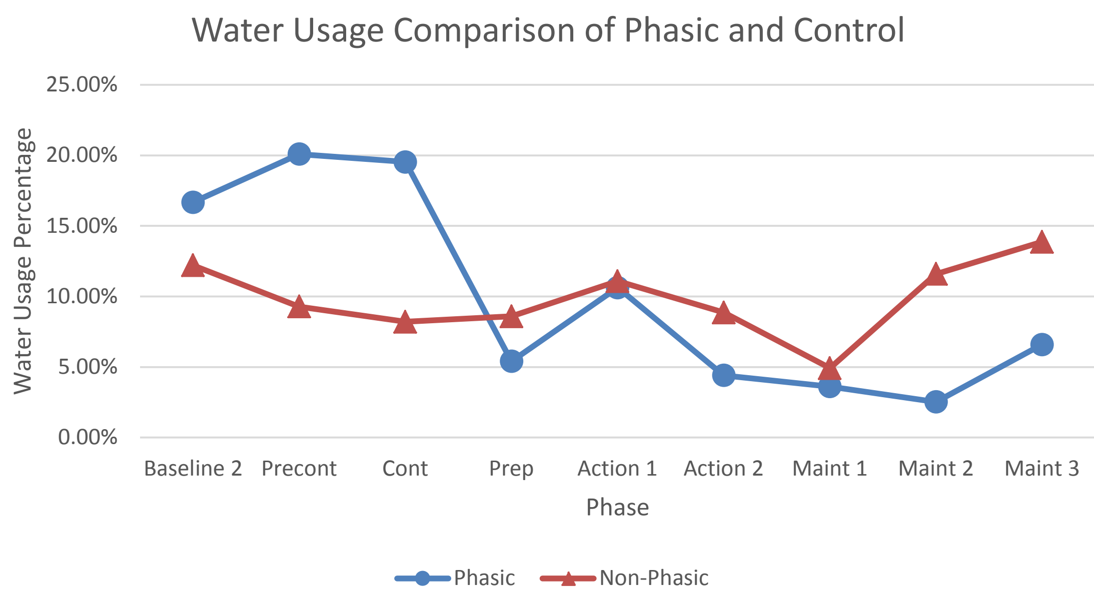

Figure 16 – Phasic groups lower usage significantly more than non-phasic

Shown in Figure 16, the phasic group reduced water consumption from 17% of total water used in a week during the baseline phase to 3% and 7% per week in the maintenance phase, a 58% relative reduction. The control group drifted up from 12% in the baseline weeks to 14% during the course of the intervention, a 17% relative increase in usage. Overall, the control group maintained usage rates between 8-15 percent per week, while the test group had a marked decrease over time. Though these results are promising, they are not statistically significant (p=0.54, two-tailed variance unknown) and warrant further study.

5.1.3 Individual Sink Usages Histogram Analysis

To visualize the change in sink usage, individual sink usage data were sorted into bins and put in histograms. Thus one can detect mean shifts in quantities of water used in each phase. We expect the adoption of the tips provided by the device to result in a shift toward the y-axis (leftward shift), indicating that on average the sink usages became lower volume, if not less frequent. A histogram for each group, two phasic experimental and two non-phasic control is shown in Figure 17 through Figure 20. All usages above 2.5 L were summed and put as a single point at 2.5L. The histograms are grouped in intervals of a quarter liter, and frequency results for each bin are posted at 0, 0.25-0.5L and so on. Thus any point at 0 is for all usages from 0-0.25L any point at 0.25L is for all usages from 0.25-0.5L etc.

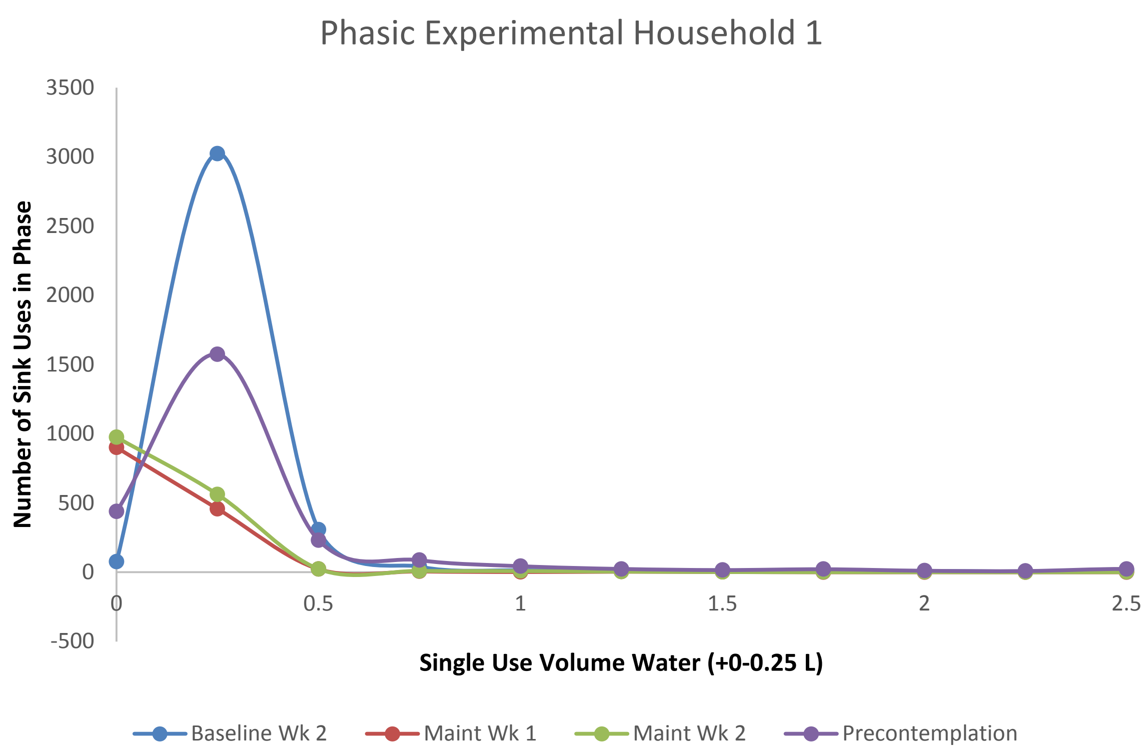

Figure 17 - Expected "leftward" movement, unexpectedly high number of usage, may be due to vibrational noise. All points are bins; 0 is for 0-0.25L, 0.25 for 0.25-0.5L

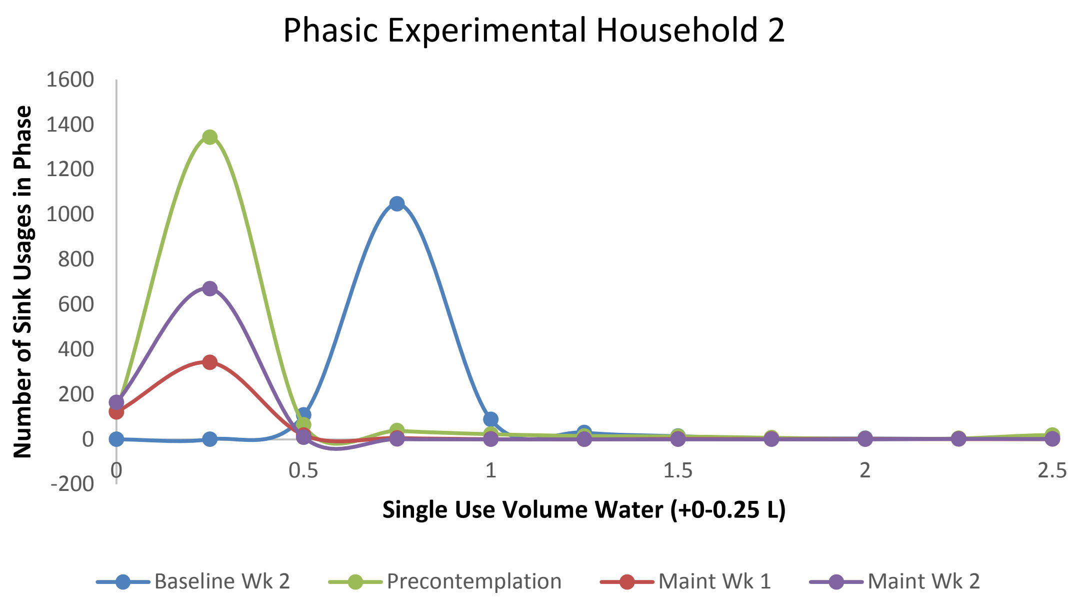

Figure 18 – Leftward mean shift, high number of total uses

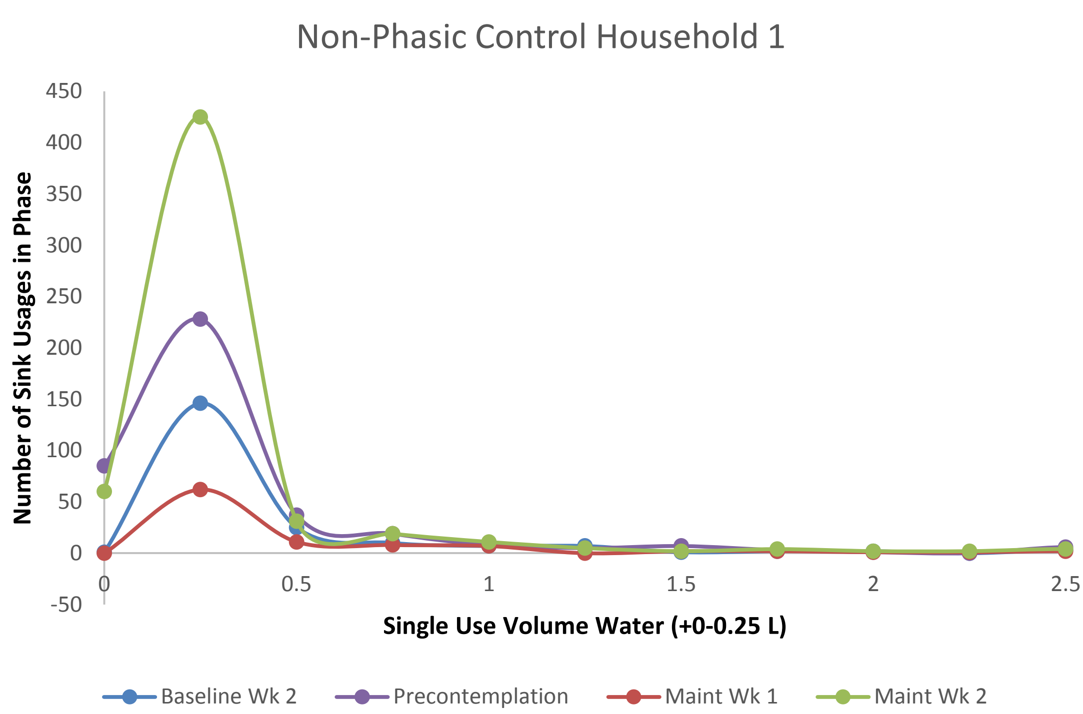

Figure 19 - Control group with sporadic weekly usages

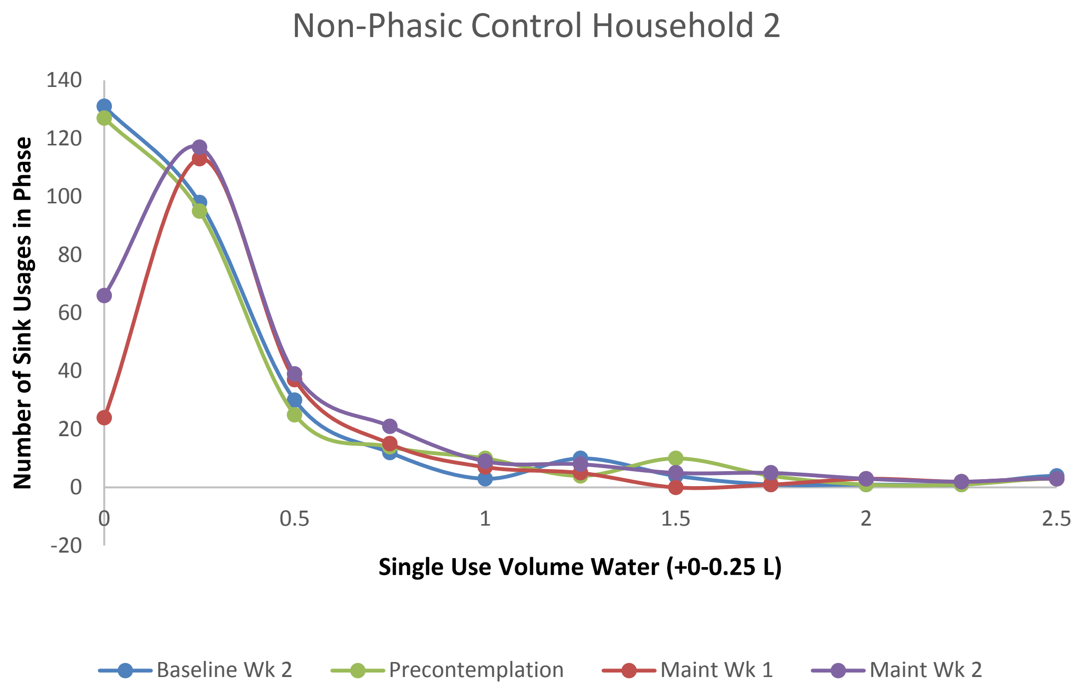

Figure 20 - Control group shows fewer usages, higher volumes

The histograms show some interesting results. The two control groups had only two members in each household, whereas the phasic groups had four and three. The larger number of users may account in part for the dramatically higher number of usages per week. Vibrational noise and lower signal to noise ratio for the given faucets may also contribute to higher low volume readings.

There is not a consistent trend seen in all four groups, however the expected leftward shift is present in both phasic groups. When comparing the baseline week 2 reading with maintenance week 2 usages in a two tail T-test assuming unequal variances, we could not reject the null hypothesis for any of these mean shifts, so the results are not statistically significant.

5.1.4 Changes in Pro-Ecological Attitude

As mentioned in Section *4.2.1*, the New Ecological Paradigm (NEP) survey was administered at the beginning and end of the study about 70 days apart. This survey served three purposes: 1) to compare the attitudes of the research participants to more representative samples, 2) to test for interaction between attitude and behavior change, and 3) to identify any shift in pro-ecological attitudes or opinions. The questions in this survey were relevant to one of five pro-ecological categories, three questions per category. We averaged the responses to these questions to understand how the participants were or were not skewed and how/if they changed. Figure 21 and Figure 22 are two graphs displaying how the participants in our study changed their answers to the NEP survey after 70 days of having a device installed.

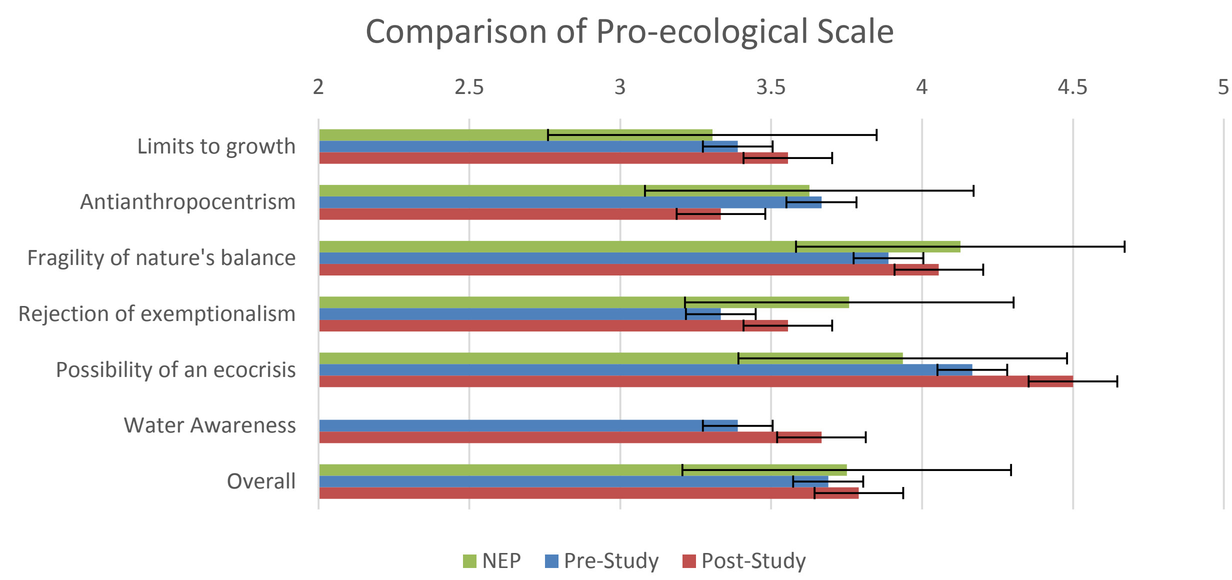

Figure 21 - Comparing NEP study group, all participants (N=6) before and after the Fall 2016 70-day intervention

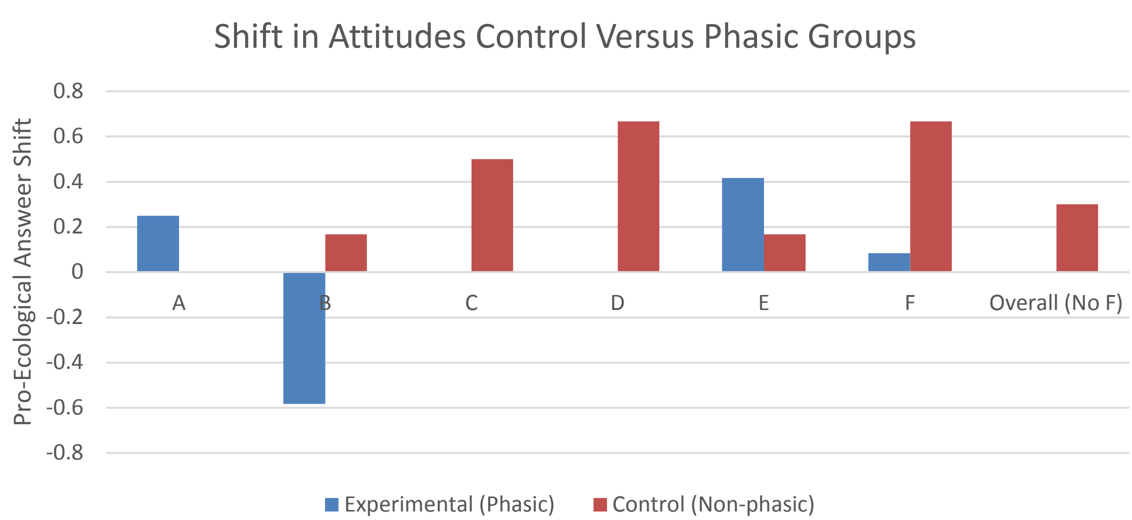

Figure 22 - Graph showing how the phasic groups changed their responses compared with the control group. Phasic N = 4, Control N = 2

In Figure 21, there are three separate groups shown, all participant groups pre-intervention, all participant groups post-intervention, and the dataset used in the original NEP paper. In Figure 22, change in attitude is reported in points. The numbers reported are the average pro-ecological change in answers for the six households for all three questions in a given category, each on the Likert Scale, 1-Completely Disagree being the lowest, and least pro-ecological, and 5- Completely Agree being the highest and most pro-ecological. In the actual survey, affirmation with odd numbered questions and disagreement with even questions was the most pro-ecological. However, for ease of communication we inverted the responses are reported inverted such that a 1 is always the least pro-ecological, and 5 is always the most.

The results do not suggest a statistically significant (p=0.629) change in pro-ecological attitude. The specific changes in survey responses are given in percent change and in actual Likert unit shift. The percent indicates how much the groups average answers shifted toward or away from answering in a fully-pro-ecological way (100% being all answers in NEP survey were most pro-ecological). Positive change always reflects pro-ecological answer shift.

From Figure 21 one may see there was an increase in pro-ecological attitudes across all participants in three of the five areas, “limits to growth” (+3% or +0.17 out of 5), “possibility of an eco-crisis” (+6% or +0.33 out of 5), and “rejection of exceptionalism” (+4%, +0.22), while decreasing slightly in “fragility of nature’s balance” (-1% or -0.05 out of 5), and dramatically in “antianthropocentrism” (-6% or -0.33).

Overall, the trend shows that after the 70-day intervention period pro-ecological attitudes were narrowly increased (+2%).

The category we added, "F – Perceived Water Awareness" showed a large increase in pro-ecological attitude (+6%, +0.33). Interestingly the self-reported increase was much larger in the non-phasic control group than in the phasic experimental group. This difference may because the non-phasic control group was solely given information about their own usage, whereas the phasic group was shown many different facts about water usage in general. The non-phasic group may have overestimated their awareness, or the tips may have distracted the phasic group from their personal usage information.

Figure 22 shows that the non-phasic control group improved their reported attitudes more than the phasic experimental group. Overall there was no change for the phasic group and a large positive change for the control group (+6% or +0.33) in the original five NEP categories. Furthermore, the non-phasic control group reported a positive change for water awareness (+7% or +0.38), while the phasic experimental group reported a decrease (-3% or -0.15). It is interesting to note that in no category did either of the two control group show a decrease in overall pro-ecological attitude, while the responses from the phasic groups showed no pattern.

5.1.5 General User Response to Device

A 10 question open ended online survey was administered after the devices were uninstalled. This survey had questions about the perceived accuracy of the estimations, the experience with the device overall, and more open ended questions, such as, "What was the least useful aspect of the device?”. Answers were either in a five unit Likert scale form, or comment. This survey aimed to gain design insights that may not have been readily observable during the install/uninstall visits, and to gauge participants’ feeling about their experience with the device.

Three users, one from the non-phasic control group, and two from phasic experimental group, reported their overall experience with the device to be “5 - Great”, while two responders, one non-phasic and one phasic, chose “4 - Good”. All five responders said the accuracy of measurements given by the device were “3 – Reasonable”. The consistency of these responses across both phasic and non-phasic groups implies a positive experience with the device overall.

There was a lot of enthusiasm from phasic group participants about the actual tips and information displayed; both non-phasic control groups cited displaying water usage as the most useful aspect of the device while all three phasic group responders cited the facts and tips as the most useful aspect of the device, while going on to recall their favorite specific tip in a later question. The specific tips cited were “Atlanta has the most expensive water in the country”, “A drop every five seconds is roughly a gallon a day”, and the final tip was an active state, while the sink was on and determined to be using a “High” flow a message saying “High flow is good for fillings pots and bottles”.

When asked “How engaging was the device throughout the experiment?”?”, all three phasic responders favorably mentioned reading the facts or tips every day (“I enjoyed reading the advice and facts generated by the device during use", "Very engaging", "Very interesting to check out the message every day").

In contrast, one non-phasic control said "not engaging at all" and another said "I would look at it multiple times a week to see what amount of usage it was displaying". This disparity in reported engagement for the non-phasic control device supports a crucial part of the hypothesis, namely that giving a static feedback quickly becomes uninteresting while a daily changing tip/fact, combined with weekly changing active functions serves to maintain interest in users.

The "least useful aspect of the device" was reported to be "errors in reading" three times, and "light too bright in evening" by a phasic group. One responder declined to answer this question. The area needing most improvement, consistent with the least useful aspect, was "more accuracy" from two phasic groups, "more interactive feedback", "more instructive feedback on how to conserve" from the two non-phasic control groups, and "less bright light" from one phasic group. The actual usage feedback was not the most useful part of the phasic groups who received tips and information, and both non-phasic households asked for more instructive feedback (as they received none).

5.2 Spring 2017 Pilot Study

The results from the shorter Spring 2017 study were largely consistent with the Fall 2016 results, though the shape of the usage curve was less conclusive. All results reported in the following sections are displayed and have been processed in an identical way as in the Fall 2016 results, thus an in-depth explanation of the results will be omitted and only a summary of the changes, with corresponding figures will be reported in this section. The phasic group saved 50% water volume from during the maintenance phase compared with the baseline phase, each a week long. The phasic group overall slightly positively changed their pro-ecological attitude, +0.25 Likert units (out of 5) or +4%, while the control group shifted +0.033 Likert Units, or +0.06%, where positive indicates an increase in pro-ecological attitude. The participants had significantly lower pro-ecological attitudes, 41.5% Pro-ecological in Spring 2017 versus 69% pro-ecological as in the Fall 2016 study.

5.2.1 Data Exclusion

The Spring 2017 study had only a single maintenance visit to a phasic household whose device lost connection to the SD card. This resulted in the loss of three days of data. This same household, however, had an inverse exponential vibrational profile, with a low R^2 value corresponding the signal to flow. The calibration curve is shown in Figure 24.

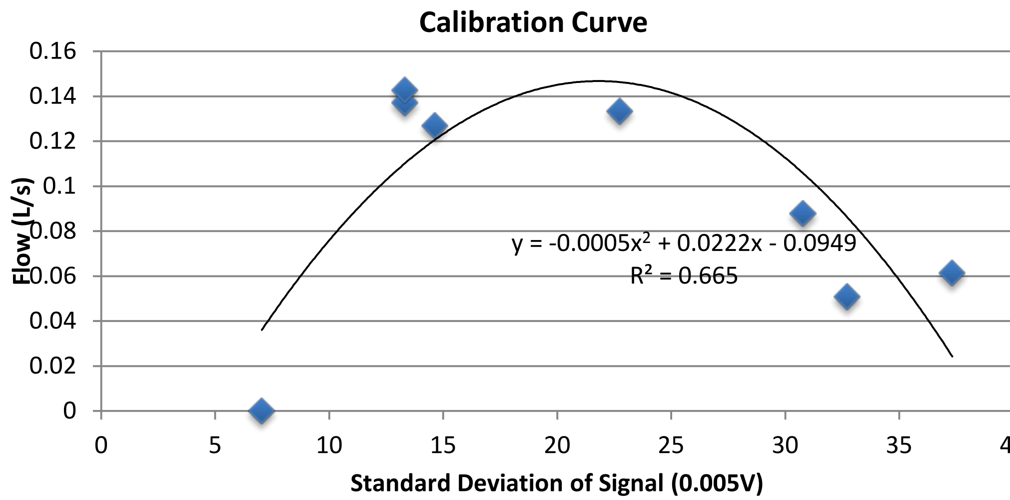

Figure 23 - Inverted exponential shape of calibration curve caused faulty device activity

The code was written to estimate flow with positive sloped calibration curves, and was altered to try to accommodate this vibrational profile. Based on the data, the participant's reported impression of the accuracy, and the low R^2 value (the next lowest R^2 value was 0.72, followed by 0.92 and greater), this data set will be omitted from future discussion.

5.2.2 Overall Usage Change

Through the course of the 49-day intervention the phasic group lowered faucet volume usage by 50% while the non-phasic group lowered their average usage by 2%. However, in the second to last week of the study, Action Phase week two, the phasic group only reduced usage by 17%, while the control group reduced 30% compared with the baseline phase. The shape of usage was a bit noisier in this pilot study than in the Fall 2016.

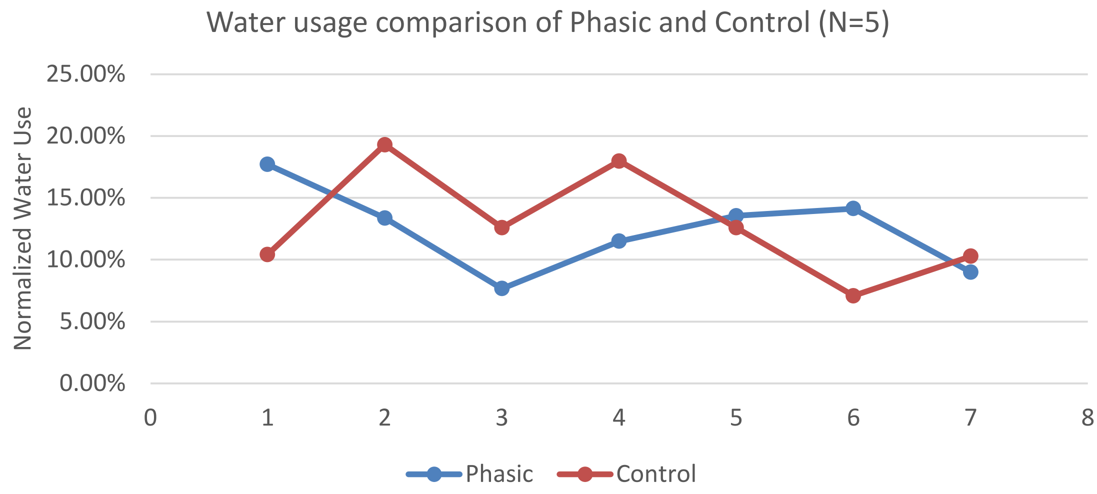

Figure 24 - Spring 2017 Weekly Usage

5.2.3 Changes in Pro-Ecological Attitude

The participants in the Spring 2017 pilot study showed a small increase in pro-ecological attitude overall and the non-phasic group showed no change, contrasting with the Fall 2016 results where the non-phasic group showed small pro-ecological shift, and the phasic group showed no change. The participants were much less pro-ecological overall, both pre- and post-study than the participants in the Fall 2016 population. The processing and presentation of the results are the same as in the Fall 2016, and may be read much the same.

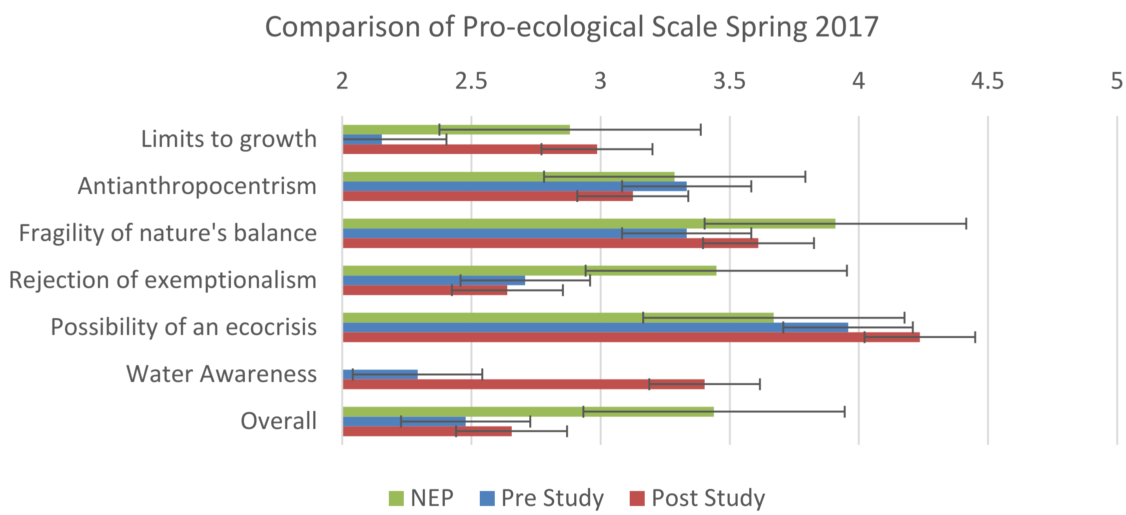

Figure 25 - Spring 2017 Participant Pro-Ecological attitude compared with NEP (N=665) before and after study

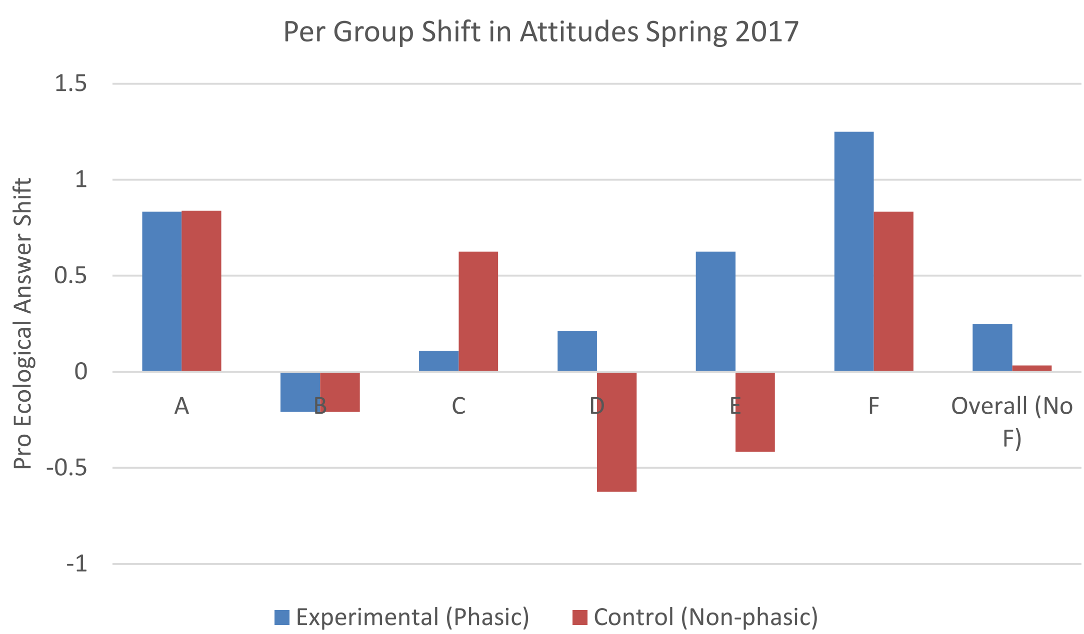

Figure 26 - Spring 2017 Pro-Ecological Attitude shift, slightly more pro-ecological after study

The shift in pro-ecological was by category inconsistent with the Fall 2016 participant's shift, but the overall changes and shape is consistent. The major difference is that in the Spring 2017 study the non-phasic group showed almost no change (+0.6%) and the phasic group showed a +5%. In the Fall 2016 study the non-phasic showed a +5% and the phasic group showed no overall change in pro-ecological attitude.

5.3 Summary of Results

The devices were deployed in six households over 70 days (Fall 2016) and another six households over 49 days (Spring 2017). In the Fall 2016 Study, the two households given non-corrupt phasic devices reduced their daily usage at the faucet significantly compared with the two control groups, about a 70% difference in change from the baseline phase to maintenance. In the Spring 2017 Study two phasic groups saved 48% more water than the three non-phasic control groups. This change was not consistently reflected in the results of the New Ecological Paradigm (NEP) survey results. In the Fall 2016 Study the phasic groups showed far less positive pro-ecological attitude shift than the control groups in the, the opposite being true for the Spring 2017 study (phasic slight increase in pro-ecological attitude, non-phasic remaining same). This result is supports the idea that one's ecological attitudes have a poor causal relationship with one's ecological actions [58].

From the open ended follow-up survey, we learned that the phasic groups found the devices quite interesting while the non-phasic control groups did not. Further, the main issue with the devices is their accuracy in estimating water volumes. This estimation issue may have been exacerbated by late installation of ground-earth wires, which corrected much erroneous behavior after the behavior was experienced by the participant.

CHAPTER 6. CONCLUSIONS AND FUTURE WORK

The hypotheses which were tested in this thesis were 1) phasic feedback will motivate more conservation than non-phasic feedback delivered by pervasive displays, 2) phasic feedback including education aspects will create pro-ecological attitude change. The Fall 2016 pilot study had complications leading to the exclusion of two out of six participating households. The Spring 2017 pilot study had much fewer complications, though the improper calibration of one device led to the exclusion of one out of six participating households.

The phasic devices achieved a large decrease in volume usage during the course of the 70-day study. The two phasic groups in the Fall 2016 study reduced their usage by 57% while the two control groups increased theirs by 17% on average, while the two phasic groups in the Spring 2017 study reduced their usage by 50% compared with a 2% increase in the three non-phasic groups. These results are compelling, though not statistically significant, likely due to the small sample size.

These results support our hypothesis that phasic feedback creates more behavior change than does traditional non-phasic feedback. This conclusion is supported by the open-ended results survey responses. These responses confirmed that each of the phasic groups in the Fall 2016 found the device engaging or very engaging throughout the 70 days, whereas both control groups reported the device being not interesting or only checking it weekly.

The behavior changes were not reflected in the New Ecological Paradigm (NEP) surveys administered at the beginning and end of the intervention. The results were mixed, showing a decrease in pro-ecological attitude in some areas with an increase in others. In the Fall 2016 study the phasic groups showed no pro-ecological attitude change while the control groups averaged a 6% more pro-ecological response. In the Spring 2017 study the phasic group had a 5% increase in pro-ecological attitude, with the three non-phasic groups showing no change. These results are inconclusive as the results show a general positive trend but the variance is large. Further there are flaws with administering the same survey twice while a researcher is present.

The reduction in water used coupled with the inconclusive NEP results further supports the idea that there is a non-causal relationship between reported Pro-ecological attitude and conservational behavior. This has been shown in previous studies [25].

The Fall 2016 and Spring 2017 pilot studies imply that phasic feedback is a promising area of exploration, and that front end demand management may help close the gap between water needed to live a comfortable life, and water consumed in reality.

6.1.1 Largescale Impact

Drawing upon Jeong et al.'s LCA of the Atlanta Metropolitan Water Delivery system for the environmental cost of each cubic meter of water, we estimate that reducing faucet usage by 50% through the widespread implementation of devices like ours in a single metropolitan area such as Atlanta (about 5M residents) would result in an annual savings of 37 GWh of electricity, 3,600 tonnes CO_2 emissions, 4,740 tonnes Phosphorus emission as water pollution, and 54,900 tonnes Nitrogen as water pollution [8]. The extrapolation of these estimates to include a larger population has tremendous implications. To give a complete picture of the impact this device would have, when also accounting for the operating costs of the device, a life cycle analysis was also done on the device itself, in *Section 6.1.2*.

6.1.2 Device LCA

Calculating the environmental payback period (the point at which the effects from the device mitigate the effects from creating the device) is very important for considering the final utility of such a technology. Chun Qi Lim, an undergraduate research assistant who worked closely on this project, performed an LCA on the device, and calculated the CO2 payback trends for different levels of behavior change shown in. This was assuming a four person household, each using 100 gallons a day, with the usage broken down as usual, 50% outdoor, 20% of the remaining 50% used at the faucet.

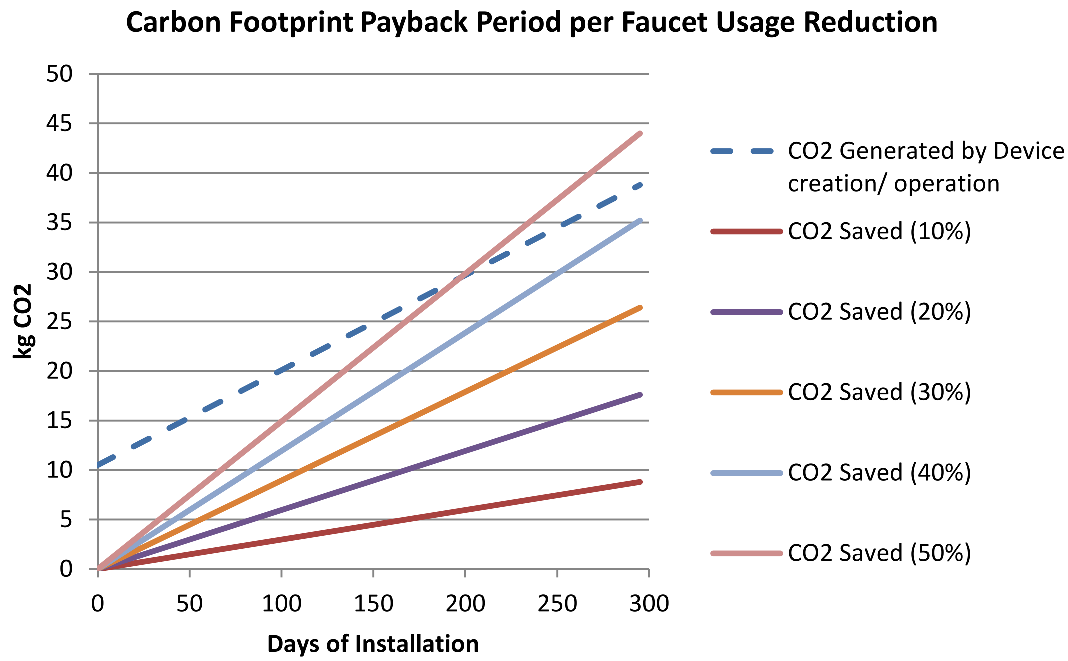

Figure 27 – CO2 payback period

This graph shows that a reduction of 50% water volume at the faucet may reach a net zero carbon footprint after about 30 days of installation. However, if the behavior change is created by the 70th day, and the device is uninstalled, the payback period will be over by the 124th day. The average cost of water in Atlanta is $160 per month, so applying the same math as above; the device has a **7.5 month** economic pay-back period if it achieve a 5% total reduction in water volume usage.

6.2 Future Work

As of this being written, a proposal has been submitted for this project to gain funding for another year of development and testing as a part of the EPA's People, Prosperity and the Planet (P3) Award competition. This proposal is primarily concerned with the redevelopment of the device; the areas of improvement will be discussed in the following section.

One major way to broaden the scope of impact for this device is to replace the sensor and calibration system with an inline flow meter installed directly below ones sink. This would allow for the succinct and fast installation of the device at any sink, by anybody.

6.2.1 Design Limitations

Though a degree of success was experienced in the pilot study, its algorithm was customized to user behavior and requires further aesthetic and functional development. The device redesigns incorporate the experiences reported by the participants in the pilot study, combined with the researchers' own understandings of the devices shortcomings. By solving the devices shortcomings and redesigning the experiment, a much larger range of people will be able to participate, significantly increasing the validity of the results and the chances of creating a more wide-reaching commercialized product.

<u>1. Bulky Calibration/Installation Step:</u>

Currently, the device takes between 30-60 minutes to calibrate and is tedious. The researcher must first use electrical tape to affix to sensor to the faucet. The tension of the tape greatly influences the flow, and the researcher must use care to watch the readings while adjusting the flow to ensure that the tape is neither too tight nor too loose. A researcher turns on a faucet with sensors attached to it and fills a known quantity of water. The device outputs many different pieces of information including timestamps and various sensor readings while the faucet is on. These pieces of information are saved to a .txt file by a Processing script, as Arduino has limited functionality for exporting data. This process is repeated 4-8 times at various flow rates. The researcher then imports these .txt files into Excel and correlates the average flow of the particular fill, with the average sensor reading (standard deviation of 20 sensor readings). The average flow is found by dividing the measured mass of water by the measured milliseconds the sink is on, as indicated by the shape of the signal versus time in the .txt file.

Solution(s):

To mitigate the complications and inconsistencies associated with the current tape used to affix the sensor, a universal sensor mount with a specific tightness setting needs to be developed. Exactly what form this unit will take is as of yet unclear, though we have developed several test cases made to fit the most commonly sized sinks. Generally, a rubber strap and a triangular cross-sectioned piece in which the transducer fits snugly is the basic framework, though the unit is going to be subject to design.

We would like to explore using an inline flowmeter, made by Adafruit, to allow the device to create its own best fit line. It would create a large array, with the x-column being sensor readings, and the y-column being the measured flow rate over a given time interval (likely 150ms as that is the current reading window). The device could then use some linear regression C packages to generate the appropriate coefficients, and choose whichever line has the highest R^2 value for the particular dataset.

If the previous solution does not pan out as planned, another solution which would be less accurate, but require less additional hardware would be a function that allows the Arduino to be told how much water was used during a particular instance. This process could be completed with prompts from the screen and could make the calibration possible without the laptop and Processing script. In order to manually activate calibration, the device would need an interactive feature, likely a button. This button would also be used in a few other circumstances as detailed later on.

2. Increased Intelligence of Feedback:

The current system of feedback changes phases after a set period of time passes, a week, or two weeks in the case of the action phase. To improve this, an actual behavior shift may be detected which would indicate a user actually “graduated” from one phase of behavior to the next. Such intelligence would likely be coupled with a failsafe maximum time allowed to be spent in a phase, to ensure that each participant had gone through every phase by the close of the experiment. This increased intelligence is only possible now that a pilot study has been concluded and it is possible to discern some information about how people use their sinks, and may be used to indicate what a reasonable amount of time one must take in order to achieve a mean shift in usage over to indicate “graduation”. More details about this process will be gleaned as the current dataset is analyzed further.

<u>3. Less false positives of flow:</u>

An analysis of the data shows clear periods of time where ambient vibration was misdetected by the transducer as sink flow, causing erroneous data to be collected. This is likely due to things like dishwashers, kitchen appliances, pipes, garbage disposals, and the like.

Solution:

The addition of a second sensor (such as a motion sensor) aimed at the handles of the faucet could serve as a second verification of valid flow. The vibrations would only be registered as a valid flow if the second sensor system also verified the presence of a user at or near the sink. Further, vibrational profiles of sinks in use were not made, and if the resonant frequency range of most sinks could be found then we could also put a band pass filter after or before the amplification circuit to filter out vibrational noise that is picked up by the transducer.

<u>4. Power source redesign:</u>

Currently, the device has a large ground fault circuit interrupt (GFCI) attached to the plug between the plug and the outlet. This is to ensure that in the circumstance that the device would become submerged and would shock the user; the GFI mechanically switches to an OFF position, rendering the submerged device safe. Secondly, the device has peripheral earth ground wire that attaches to a screw in the outlet to stabilize the amplification voltage. This earth ground is necessary as the amplification circuit is magnifying a very small signal; about 150 mV, to about 4.5V, such that it may be read in high resolution by the analog read on the Arduino. A typical "floating ground" in a two prong power source adds too much noise to the reading. This noise cannot be calibrated out, as the device grounds itself through the computer when it is being calibrated. The only power sources we tested that provide a low enough noise voltage to the circuit are either from a computer or from a large laptop power source (prohibitively large and expensive). Thus, after much experimentation and testing of various power sources, the solution found was the addition of an actual wire soldered to the ground of the PCB shield, which is then attached to an earth grounded piece of external hardware, typically the actual outlet housing.

Solution:

Two things need to happen to mitigate the use of the GFCI adapter: the device needs a thorough electrical examination to get an actual estimate of the risk it poses; as such an analysis was not done due to lack of resources in the prototype's development. This analysis may reveal that the microcontroller's built-in safety circuits are sufficient, or that we may rely on the fact that most outlets near sinks are equipped with GFCI adapters. If the analysis does not reveal this, then we will need to find a way to integrate a GFCI into the proprietary power source we will design and have manufactured to the correct specifications.

This power source redesign will be necessary to include an earth ground in a low voltage power source (the third pin of a plug is an earth ground; they are not often included in low voltage power sources). Surprisingly, such a power source is very hard to find, even by certified electronics professionals who aid Georgia Tech researchers in developing such devices as ours.

5. Casing redesign:

The case that is currently used functions very well, though it has a few issues which could be greatly improved. Firstly, while it certainly is water resistant and the majority of the connections are made with airtight epoxy, it was never properly waterproof tested. Further, to access a few important parts of the device, like the SD card or the power source, it is necessary to remove the upper acrylic from the lower. To accommodate this, the top and bottom are currently fixed with clear packing tape. This serves surprisingly well and is almost invisible, but it is still inconsistent between each device and not at all a feature of a commercial product.

Solution:

A case designed by an experienced industrial design student will be more ergonomic, allowing for better access to necessary components in the system while also being more attractive and waterproof. Exact features of its ergonomics will be determined through human factors research and participant observation and interviews.

6. Improved display, added ambient feedback:

The 20x4 LCD works fairly well, though users reported it is too bright. It also requires 16 wires to operate, and has limited display functionality: 80 character slots total, only 8 custom characters allowed. With additional knowledge from new team members more advanced in Arduino coding, it is possible to replace these displays with graphical displays which are controlled with 3-5 wires, allowing for shrinkage of the device and simplification of the PCB. These displays may also show different graphics which may help make the feedback more attractive and higher resolution.

Secondly, a 2-neopixel ambient feedback system, which communicates with the users simply by lighting up certain colors to indicate different things or flow rates, had already been developed but was not integrated into the final device in time for its deployment in the pilot study. Ambient feedback capabilities will be added to the second iteration of the device.

6.2.2 Data Limitations

The main limitation of the data is the small sample size. With four non-corrupted data sets for the Fall 2016, and six for the Spring 2017 pilot study, the results are not highly generalizable. However the data shows promising results for the continuation of this study on a larger population.

Because the households were all student households rather than the typical American family, their sink activities are likely different than the norm. That being said, when compared with the 647 responders in the New Ecological Paradigm Survey development study our sample population, pre-intervention, was not more pro-ecological overall.

6.2.3 Other Applications

The results from this study may be used to inform the physical and virtual design of future feedback systems aimed at creating behavior change. The phasic feedback framework may be applied in many different fields of behavior change technologies like FitBit.

APPENDIX.

A.1 All Tips

Table 5 – PC: Precontemplation, C: contemplation, P: Preparation, A: Action , M: maintenance

Phase	**Tip #**	**Idle**
PC	1	The water from your tap could contain molecules that dinosaurs drank.
PC	2	There is more water in the atmosphere than in all of our rivers combined.
PC	3	Water is the only substance found on earth naturally in three forms.
PC	4	Water regulates the temperature of the body.
PC	5	70% of the human brain is water
PC	6	The first water pipes in the U.S. were made from hollowed logs.
PC	7	Water expands by 9% when it freezes.
PC	8	Water dissolves more substances than any other liquid.
PC/C	9	Groundwater serves about 80% of the population, and 4% is already polluted.
PC/C	10	Only 1% of Earths water is drinkable
C	11	Water needs to meet over 100 quality standards before reaching your tap
C	12	Saving 1% of your water reduces your monthly bill by 2.5% or more
C	13	Three quarters of all Americans live within 10 miles of polluted water
C	14	A person can only live about a week without water.
C/P	15	New dishwashers use as little as 4 gallons per cycle, 1/5 of avg hand wash
C/P	16	There are a number of ways to save water, and they all start with you.
C/P	17	Nearly 97% of the world's water is undrinkable.
P	18	There are many opportunities to reuse water around the house.
P	19	The United States uses about 3.5 billion gal. of fresh water every day.
P	20	1 out of 6 gallons of water leak from utility pipes in the US.
P	21	North Georgia has been in a severe drought since September 2016
P	22	Lake Lanier is metro Atlanta's main water source, supplying 4M+ people.
P	23	One drip every second adds up to five gallons per day!
P	24	Challenge yourself to see how little water you can use!
P/A	25	70% of U.S. counties are in danger of water shortages by 2050.
P/A	26	Daily usage
P/A	27	The last gallons of water used a month can cost more than twice the first.
P/A	28	When washing your hands, turn the water off while you lather.

P/A	29	Wet the sponge or cloth, rather than the dish, when washing by hand
P/A	30	Run the dishwasher only when it is full to save up to 1000 gallons a month.
A	31	Wash greasier dishes last to clean all dishes more easily.
A	32	Avoid running water while scrubbing dishes
A	33	Think ahead! Defrost items in the fridge overnight instead of in water.
A	34	Try to use the garbage instead of the garbage disposal
A	35	Only run the dishwasher when it is full
A	36	Don’t let the faucet run while cooking.
A	37	Cook in the smallest appropriate pan. Large pans need more water.
A	38	Rinse tupperware by shaking a small amount of water inside.
A	39	Don't let regular dishes sit in greasy pans. It will take longer to clean.
A	40	Wipe dishes instead of rinsing them before putting in the dishwasher.
A	41	Avoid running water while washing or scrubbing items in the sink.
A	42	Fill the sink or use a water basin to wash dishes by hand.
A	43	Cook food in as little water as possible to help it retain more nutrients.
A	44	Minimize use of kitchen sink garbage disposal units.
A	45	Don't let the faucet run while you clean vegetables.
A	46	Dirty dishes can be rinsed under low flow from the faucet.
A	47	Soap and scrub all dishes before rinsing together.
A	48	Atlanta has the most expensive water of any USA city.
A	49	Thirty-six states in the US are anticipating water shortages by 2016.
A	50	A comfortable life only needs about 15 gallons of water a day.
A	51	Water use has grown at over twice the rate of population in the last century.
A	52	Designate a single glass to drink out of for the day to wash less dishes.

A.2 NEP Survey Adapted From Dunlap et al. [1]

Listed below are statements about the relationship between humans and the environment. For each one, please indicate whether you STRONGLY AGREE, MILDLY AGREE, UNSURE, MILDLY DISAGREE, or STRONGLY DISAGREE with it.

Statements	Circle Your Opinion of Each Statement				
We are approaching the limit of the number of people the earth can support	Strongly Disagree	Mildly Disagree	Unsure	Mildly Agree	Strongly Agree
Humans have the right to modify the natural environment to suit their needs	Strongly Disagree	Mildly Disagree	Unsure	Mildly Agree	Strongly Agree
When humans interfere with nature it often produces disastrous consequences	Strongly Disagree	Mildly Disagree	Unsure	Mildly Agree	Strongly Agree
Human ingenuity will insure that we do NOT make the earth unlivable	Strongly Disagree	Mildly Disagree	Unsure	Mildly Agree	Strongly Agree
Humans are severely abusing the environment	Strongly Disagree	Mildly Disagree	Unsure	Mildly Agree	Strongly Agree
The earth has plenty of natural resources if we just learn how to develop them	Strongly Disagree	Mildly Disagree	Unsure	Mildly Agree	Strongly Agree

Plants and animals have as much right as humans to exist	Strongly Disagree	Mildly Disagree	Unsure	Mildly Agree	Strongly Agree
The balance of nature is strong enough to cope with the impacts of modern industrial nations	Strongly Disagree	Mildly Disagree	Unsure	Mildly Agree	Strongly Agree
Despite our special abilities, humans are still subject to the laws of nature	Strongly Disagree	Mildly Disagree	Unsure	Mildly Agree	Strongly Agree
The so-called "ecological crisis" facing humankind has been greatly exaggerated	Strongly Disagree	Mildly Disagree	Unsure	Mildly Agree	Strongly Agree
The earth is like a spaceship with very limited room and resources	Strongly Disagree	Mildly Disagree	Unsure	Mildly Agree	Strongly Agree
Humans were meant to rule over the rest of nature	Strongly Disagree	Mildly Disagree	Unsure	Mildly Agree	Strongly Agree
The balance of nature is very delicate and easily upset	Strongly Disagree	Mildly Disagree	Unsure	Mildly Agree	Strongly Agree
Humans will eventually learn enough about how nature works to be able to control it	Strongly Disagree	Mildly Disagree	Unsure	Mildly Agree	Strongly Agree
If things continue on their present course, we will soon experience a major ecological catastrophe	Strongly Disagree	Mildly Disagree	Unsure	Mildly Agree	Strongly Agree

My own personal actions have a direct impact on the environment	Strongly Disagree	Mildly Disagree	Unsure	Mildly Agree	Strongly Agree
I feel I am doing enough to conserve water	Strongly Disagree	Mildly Disagree	Unsure	Mildly Agree	Strongly Agree
I know about how many gallons of water I use each day	Strongly Disagree	Mildly Disagree	Unsure	Mildly Agree	Strongly Agree

Figure 28 – Full NEP Survey with added three questions about "Water Awareness"

A.3 Full Phasic Code Including Comments

```
// include the library code:
#include <LiquidCrystal.h>
#include <SD.h>
#include <SPI.h>

// initialize the library with the numbers of the
interface pins
LiquidCrystal lcd(7, 8, 9, 10, 11, 12);

const int numReadings = 20;
const int ptpTime = 150;
const int idleSwitch = 10; //10 = 1.6 seconds of
showing per tip 1900 for 5 min
const int activeSwitch = 2; //to make active screen not
fresh too fast
double lam = 0.5; //set according to data
const int stdDevReads = 20; //If using Std Dev also
File myFile;
File UseSum;
double CurrentFlow = 0; //calc flow real quick

//NEED TO ALSO KNOW MAX/MIN FLOW
POSSIBLE, anything higher than MAX
//should be ignored or called MAX.
double FlowEWMA[6] = {0, 15, 25, 35, 45, 60}; //
thresholds for the 5 flowtypes is one on left until
reaches right {off, vlow, low, med, high, vhigh}
CALIBRATE[ ]
double EWMA = 389; //initialize to 'off' value
CAILBRATE[ ]
double MaxFlow = .125; //should be in L/s, set to
MAX FLOW from sink
CAILBRATE[ ]
double stdDEWMA = 6; //off value
CAILBRATE[ ]

bool useEWMA = false; //true for ewma , false if stdD
CAILBRATE[ ]

double thresh[3] = {100, 600}; //set to split code into
one, two or three polynomials. 0-thresh[0], thresh[0]-
thresh[1], thresh[1]-inf                CAILBRATE[ ]

//ceAx^2+ceBx+ceC=flow 0-thresh[0]
CAILBRATE[ ]
double ceA = -0.004;
double ceB = .0888;
double ceC = -0.3594;

//ceA1X^2+ceB1x+ceC1 = flow //for chunking at
given threshold thresh[0]-thresh[1]
CAILBRATE[ ]
double ceA1 = 0;
double ceB1 = 0;
double ceC1 = 0;

//ceA1X^2+ceB1x+ceC1 = flow //for chunking at
given threshold >thresh[1]
CAILBRATE[ ]
double ceA2 = 0;
double ceB2 = 0;
double ceC2 = 0;

float stdD = 0; //all std dev only
float dev[stdDevReads];
int stdIndex = 0;
```

```
int ok = 1; // just for trimming of beignning data
int readings[numReadings];      // the readings from the analog input
int readIndex = 0;              // the index of the current reading
int total = 0;                  // the running total
int average = 200;              // the average
int count = 0;
int activeCounter = 0;
int idleCounter = 0;
double mxm = 0;
double mnm = 0;
double ptp = 0;
int inputPin = A0;
long now1 = 0;
long FlowTime[6];
int whichFlow = 0;
String lastFlow = "Off";
String flowNow = "Off";
String flow = "Off";
int flowCount = 0;
long OnTime = 0;
int JustOffAction = 0;

//PHASES
int PhaseNow = 0;
int PhaseDay[5] = {14, 21, 28, 35, 49}; //BL, PC, C, PR, A, M 50 days total
int whichAction = 0; //0: Big text 1: Waste not want not 2: Raining
int whichTip = 5;
bool tipSwitch = false;
long actionTip = 0;
int lastTip = 0;
long summaryDisplay = 0;

bool justOff = 0;
bool On = 0;
unsigned long startUse = 0;
unsigned long endUse = 0;
unsigned long thisElapsed = 0;
double thisEWMA = 0;
double thisStd = 0;
double thisEWMAAvg = 0;
double thisStdAvg = 0;
double thisAvgFlow = 0;
unsigned long thisCounter = 0;
float thisWater = 0; //remember what units you used here
float thisWaterSTD = 0; //basically can choose one or both of these estimations
//stuff for daily/weekly breakdown
unsigned long HourCheck = 0;
unsigned long DayCheck = 0;
int Yesterday = -1;
int Today = 0;
int thisHour = 0;
long checkTime = 0;
unsigned long todayOnTime = 0;
unsigned long todayTimeEWMA = 0;
unsigned long todayAvgEWMA = 0;
unsigned long DailyOnTime[70] = {0};
unsigned long DailyTimeEWMA[70] = {0};
unsigned long DailyStdDevTime[70] = {0};
double DailyWater[70] = {0};
int DailyUses[70] = {0};

byte drop[8] = { //create drop image for LCD char
  0b00000,
  0b00100,
  0b01110,
  0b11111,
  0b11111,
  0b01110,
  0b00000,
  0b00000
};

byte Full[8] = {
  0b11111,
  0b11111,
  0b11111,
  0b11111,
  0b11111,
  0b11111,
  0b11111,
  0b11111
};
byte MCenter[8] = {
  0b11111,
  0b11111,
  0b11111,
  0b11111,
  0b11111,
  0b01110,
  0b00100,
  0b00000
};
byte MTop[8] = {
  0b00000,
  0b10001,
  0b11011,
  0b11111,
  0b11111,
  0b11111,
  0b11111,
  0b11111
};
byte WBottom[8] = {
  0b11111,
  0b11111,
  0b11111,
  0b11111,
  0b11111,
  0b11011,
  0b10001,
  0b00000
};
```

```
byte Wcenter[8] = {
  0b00000,
  0b00100,
  0b01110,
  0b11111,
  0b11111,
  0b11111,
  0b11111,
  0b11111
};
byte GRight[8] = {
  0b00000,
  0b00000,
  0b00000,
  0b00000,
  0b11111,
  0b11111,
  0b11111,
  0b11111
};
byte ECenter[8] = {
  0b00000,
  0b11111,
  0b11111,
  0b11111,
  0b11111,
  0b11111,
  0b11111,
  0b00000
};


void setup() {

  // initialize serial communication with computer:
  Serial.begin(9600);
  while (!Serial) {
    ;
  }

  // initialize all the readings to 0:
  for (int thisReading = 0; thisReading <
numReadings; thisReading++) {
    readings[thisReading] = 0;
  }

  for (int thisReading = 0; thisReading < stdDevReads;
thisReading++) {
    dev[thisReading] = 0;
  }

  // set up the LCD's number of columns and rows:
  lcd.begin(20, 4);
  lcd.print(F("Phasic 15 Final"));

  //create all custom characters for BIG TEXT
  lcd.createChar((byte)0, Full);
  lcd.createChar(1, MCenter);
  lcd.createChar(2, MTop);
  lcd.createChar(3, WBottom);
  lcd.createChar(4, Wcenter);
  lcd.createChar(5, GRight);
  lcd.createChar(6, ECenter);
  lcd.createChar(7, drop);

  //initialize SD
  if (!SD.begin(53)) {
    Serial.println(("SD Failed"));
    lcd.clear();
    lcd.print("SD Failed. Try again.");
    delay(30000);
    return;
  }
  lcd.clear();
  lcd.print("SD Initialized");
  delay(100);

  //Open file, make sure it worked
  myFile = SD.open("AllOn.txt", FILE_WRITE);
  if (myFile) {
    lcd.clear();
    lcd.write("File opened");
    myFile.println("New Data:");
    myFile.close();
    delay(100);
  }
  else {
    lcd.clear();
    lcd.write("File failed to open");
    delay(30000);
  }

  if (CheckArrays()) {
    lcd.clear();
    lcd.write("Memory ready.");
    delay(100);
  } else {
    lcd.clear();
    lcd.write("Arrays not intialized.");
    delay(3000);
  }
  Today = whatDay();
  thisHour = whatHour();
  lcd.clear(); //delete after calibration step
  lcd.write("Turn on faucet!");
  delay(500);
}


void loop() {

  // TAKE READING AND CALCULATE
STANDARD DEVIATION AND RUNNING
AVERAGE -=-=-=-=-=-=-=-=-=-=-=-
  total = total - readings[readIndex]; // subtract the last
reading:
  readings[readIndex] = analogRead(inputPin); // read
from the sensor:
```

```
  total = total + readings[readIndex]; // add the reading
to the total:
  readIndex++; // advance to the next position in the
array:
  average = total / numReadings; // calculate the
average

  dev[stdIndex] = readings[readIndex - 1]; //add
reading to running stdDev
  stdD = standard_deviation(dev, stdDevReads); //calc
stdev
  stdIndex++;

  if (stdIndex >= stdDevReads) {
    stdIndex = 0; //return to beginning of running std
dev calc
  }

  if (readIndex >= numReadings) { // if we're at the
end of the array...
    readIndex = 0; // ...wrap around to the beginning:
  }

  //PTP Calculations gather max and min
  if (count <= ptpTime) {
    //check if average is max or min, cut super high
    if (average >= mxm && average < 800) {
      mxm = average; // high values for ptp
    }
    if (average <= mnm) { //low values for ptp
      mnm = average;
    }
  }

  //Demarcate buffer data, for DAQ DELETE FOR
REAL one
  if ( ok == 1) {
    lcd.clear();
    lcd.write("OK");
    Serial.println("Start Here:");
    ok = 0;
    lcd.clear();
  }

  // EWMA CALCULATED -------------------------------
------------------------ EWMA CALCULATED ----------
---------------------------------------------
  if (count >= ptpTime) {
    ptp = mxm - mnm; //set ptp
    EWMA = lam * ptp + (1 - lam) * EWMA ;//EWMA
Calculation
    stdDEWMA = lam * stdD + (1 - lam) *
stdDEWMA;

    Serial.print(millis()); //Serial output for
Processing/DAQ ----- // out for real one
    Serial.print("\t");
    Serial.print(EWMA);
    Serial.print("\t");
    Serial.println(stdD);

    //Check if flow was just TURNED ON (from off)
    if (flowNow != "Off" && On == 0 && lastFlow ==
"Off") {
      //turn flow state ON
      On = 1;
      startUse = millis();
      thisStd = 0;
      thisEWMA = 0;
      //Which just off action?
    }

    //Check if flow was just TURNED OFF (from any
state) -------- JUST TURNED OFF STATE CHANGE
    //Save newline for this use
    if (On == 1 && flowNow == "Off") {
      //Turn state OFF
      On = 0;
      justOff = 1;
      //calculate length of last usage
      endUse = millis();
      thisElapsed = endUse - startUse;
      //save all of it in one nice 5 column file
      UseSum = SD.open("UseSums.txt",
FILE_WRITE);
      if (UseSum) {
        thisEWMAAvg = thisEWMA / thisCounter;
        thisStdAvg = thisStd / thisCounter;
        //estimate water as a second order polynomial
        if (useEWMA) { //EWMA Used for flow calc
          if (thisEWMAAvg <= thresh[0]) {
            thisAvgFlow = (ceA * thisEWMAAvg *
thisEWMAAvg + ceB * thisEWMAAvg + ceC); //
STD DEV (ceA * thisStdAvg * thisStdAvg + ceB *
thisStdAvg + ceB);
          } else if (thisEWMAAvg > thresh[0] &&
thisEWMAAvg <= thresh[1]) {
            thisAvgFlow = (ceA1 * thisEWMAAvg *
thisEWMAAvg + ceB1 * thisEWMAAvg + ceC1);
          } else {
            thisAvgFlow = (ceA2 * thisEWMAAvg *
thisEWMAAvg + ceB2 * thisEWMAAvg + ceC2);
          }
        }

        else { //stdD Used
          if (thisStdAvg <= thresh[0]) {
            thisAvgFlow = (ceA * thisStdAvg *
thisStdAvg + ceB * thisStdAvg + ceC);
          } else if (thisStdAvg > thresh[0] && thisStdAvg
<= thresh[1]) {
            thisAvgFlow = (ceA1 * thisStdAvg *
thisStdAvg + ceB1 * thisStdAvg + ceC1);
          } else {
            thisAvgFlow = (ceA2 * thisStdAvg *
thisStdAvg + ceB2 * thisStdAvg + ceC2);
          }
        }
```

```
      if (thisAvgFlow > MaxFlow) { //can never go
mroe than emasured max flow
        thisAvgFlow = MaxFlow;
      }
      if (thisAvgFlow < 0) { //or below 0 flow...
        thisAvgFlow = 0;
      }

      thisWater = thisElapsed * thisAvgFlow;
//CHOOSE WHICH METHOD TO CALCULATE
WATER
      thisWater = thisWater/1000;
      //Check what day / hour it is
      UseSum.print(Today);
//DAY:HR:TIME:EWMA:STDD:H2O
      UseSum.print("\t");
      UseSum.print(thisHour);
      UseSum.print("\t");
      UseSum.print(thisElapsed);
      UseSum.print("\t");
      UseSum.print(thisEWMAAvg);
      UseSum.print("\t");
      UseSum.print(thisStdAvg);
      UseSum.print("\t");
      UseSum.println(thisWater);
      UseSum.close();
      //Add values to the daily totals
      DailyOnTime[Today] += thisElapsed;
      DailyTimeEWMA[Today] += thisEWMAAvg *
thisElapsed;
      DailyStdDevTime[Today] += thisStdAvg *
thisElapsed;
      DailyWater[Today] += thisWater; //OR this
Water, or some combo!!! <------------- DAILY H2O
calc.
      DailyUses[Today]++;
      if (!SaveArrays()) { //Save arrays or show error
        lcd.clear();
        lcd.write("Arrays not saved,");
        lcd.setCursor(0, 1);
        lcd.write("please contact");
        lcd.setCursor(0, 2);
        lcd.write("gtwaterstudy@gatech.");
        lcd.setCursor(0, 3);
        lcd.write("Or 6263908943");
        delay(30000);
      }
    }
    else { //save use sum or show error
      lcd.clear();
      lcd.print("ERROR UseSum not opened");
      delay(30000);
    }

    //Reset all values to 0
    thisEWMA = 0;
    thisStd = 0;
    thisCounter = 0;
    startUse = 0;
    endUse = 0;
  }

  //ACTIVE STATE =====================
ACTIVE STATE ===================
ACTIVE STATE ================= ACTIVE
STATE =============== ACTIVE STATE
===============
  if (On) {
    thisStd += stdD; //to determine the average STD
and EWMA of this usage, for calculating total used
    thisEWMA += EWMA;
    thisCounter ++;
    activeCounter++;
    if (activeCounter > activeSwitch) {

      if (useEWMA) { //EWMA Used for flow calc
        if (thisEWMAAvg <= thresh[0]) {
          CurrentFlow = (ceA * EWMA * EWMA +
ceB * EWMA + ceC);
        } else if (thisEWMAAvg > thresh[0] &&
thisEWMAAvg <= thresh[1]) {
          CurrentFlow = (ceA1 * EWMA * EWMA +
ceB1 * EWMA + ceC1);
        } else {
          CurrentFlow = (ceA2 * EWMA * EWMA +
ceB2 * EWMA + ceC2);
        }
      }
      else { //stdD Used
        if (thisStdAvg <= thresh[0]) {
          CurrentFlow = (ceA * stdDEWMA *
stdDEWMA + ceB * stdDEWMA + ceC);
        } else if (thisStdAvg > thresh[0] && thisStdAvg
<= thresh[1]) {
          CurrentFlow = (ceA1 * stdDEWMA *
stdDEWMA + ceB1 * stdDEWMA + ceC1);
        } else {
          CurrentFlow = (ceA2 * stdDEWMA *
stdDEWMA + ceB2 * stdDEWMA + ceC2);
        }
      }

      if (CurrentFlow > MaxFlow) { //make sure not
less than 0 or more than possible
        CurrentFlow = MaxFlow;
      }
      if (CurrentFlow < 0) {
        CurrentFlow = 0;
      }

      if (whichAction == 0) { //Baseline
        lcd.clear();
        lcd.setCursor(0, 0);
        lcd.print("Baseline Phase");
        lcd.setCursor(0, 1);
        lcd.print("Day ");
```

```
        lcd.print(Today);
        lcd.setCursor(0, 2);
        lcd.print("Hour ");
        lcd.print(thisHour);
      } else if (whichAction == 1) { //Hello!
        lcd.clear();
        lcd.setCursor(0, 0);
        lcd.print("Hello!");
        lcd.setCursor(0, 1);
        lcd.print("Day ");
        lcd.print(Today);
        lcd.setCursor(0, 2);
        lcd.print("Hour ");
        lcd.print(thisHour);
      } else if ( whichAction == 3) { //Waste not, want
not
        lcd.clear();
        lcd.setCursor(0, 0);
        lcd.print("Is the water running");
        lcd.setCursor(0, 1);
        lcd.print("in the background?");
      } else if (whichAction == 4) { //Low flow / high
good for
        if (whichFlow == 3 || whichFlow == 4 ||
whichFlow == 5) {
          lcd.clear();
          lcd.setCursor(0, 0);
          lcd.print("High flow is best");
          lcd.setCursor(0, 1);
          lcd.print("for filling pots,");
          lcd.setCursor(0, 2);
          lcd.print("cups, and ");
          lcd.setCursor(0, 3);
          lcd.print("waterbottles");
        } else {
          lcd.clear();
          lcd.setCursor(0, 0);
          lcd.print("Low flow is good");
          lcd.setCursor(0, 1);
          lcd.print("for most uses.");
        }
      } else if ( whichAction == 5) { //bar from off to
max
        lcd.clear();
        lcd.setCursor(0, 0);
        lcd.print("Flow: ");
        lcd.print(CurrentFlow);
        lcd.print("L/s");
        lcd.setCursor(0, 2);
        lcd.print("OFF");
        lcd.setCursor(3, 1);
        for (int i = 3; i <= 16 * (CurrentFlow /
MaxFlow); i++) {
          lcd.setCursor(i, 1);
          lcd.write((byte)0);
          lcd.setCursor(i, 2);
          lcd.write((byte)0);
          lcd.setCursor(i, 3);
          lcd.write((byte)0);
        }
        lcd.setCursor(17, 2);
        lcd.print("MAX");
      }  else if ( whichAction == 6) { //BIG TEXT
        lcd.clear(); // Populate LCD Screen with Live
Usage Information
        lcd.write("Flow:");
        lcd.print(CurrentFlow);
        lcd.print("L/s");
        lcd.setCursor(0, 1);
        //Just to print the big text
        displayBigtext(whichFlow);
      }
      activeCounter = 0; //reset active timer, to make
sure the screen does not refresh too fast.
    }
  }

  //IDLE STATE ********************** IDLE
STATE ********************** IDLE STATE
********************** IDLE STATE
********************** IDLE STATE
**********************
  else {
    idleCounter++;              //next active, random is
(min, max-1)
    //JUST OFF ACTION STATE +++ +++ +++ +++
+++ JUST OFF ACTION STATE +++ +++ +++ +++
+++  JUST OFF ACTION STATE +++ +++ +++ +++
+++  JUST OFF ACTION STATE +++ +++ +++ +++
+++
    if (justOff) {
      if (JustOffAction == 0) { //baseline day prints
same thing
        lcd.clear();
        lcd.setCursor(0, 0);
        lcd.print("Baseline Day ");
        lcd.print(Today);
      }
      if (JustOffAction == 1) { //print goodbye after
turn sink off
        lcd.clear();
        lcd.setCursor(0, 0);
        lcd.print("Goodbye!");
      }
      if (JustOffAction == 2) { //estimate
        //Display the right after breakdown
        lcd.clear();
        lcd.setCursor(0, 0);
        lcd.write("You just used about ");
        lcd.setCursor(0, 1);
        lcd.print(thisWater);
        lcd.write( " liters.");
      }
      if (JustOffAction == 3) {
        //Say how much you have used today versus
yesterday
        //convert to percentage
        lcd.clear();
```

```
        lcd.setCursor(0, 0);
        lcd.write("Today's usage so far");
        lcd.setCursor(0, 1);
        lcd.write("about ");
        lcd.print(DailyWater[Today]);
        lcd.write(" L.");
      }
      if (JustOffAction == 4) {
        // Another justoff action state
      }
      if (idleCounter > 93) { //ten seconds
        //No longer "just turned off"
        justOff = 0;
        thisElapsed = 0;
        thisEWMAAvg = 0;
        thisStdAvg = 0;
        idleCounter = 0;
      }
    } else {
      if (idleCounter > idleSwitch) { // ::::::::::::::::
IDLE TIPS :::::::::::::::::::::: IDLE IDLE IDLE
::::::::::::::::::::::
        char thisTip [8] = "###.TXT";
        //int whichTip = random(1, 12); //MAX+1 and
Min should be range of tips for given state
        //convert random int into char array for being
called filename for each tip
        if (whichTip > 0) {//convert tip number to char
array and call on sd card
          thisTip[0] = whichTip / 100 + '0';
          thisTip[1] = (whichTip % 100 / 10) + '0';
          thisTip[2] = whichTip % 100 % 10 + '0';
          displayText77(thisTip);
        } else if (whichTip == 0) { //baseline
          lcd.clear();
          lcd.setCursor(0, 0);
          lcd.print("Baseline Day ");
          lcd.print(Today);
        }  else if (whichTip == -1) { //display daily use
          lcd.clear();
          lcd.setCursor(0, 0);
          lcd.write("Today about ");
          lcd.print(DailyWater[Today]);
          lcd.setCursor(0, 1);
          lcd.write("liters have been");
          lcd.setCursor(0, 2);
          lcd.write("used at this sink.");
        }
        idleCounter = 0;
        //SET PHASE
______________________________ SET PHASE
____________________________ SET PHASE
____________________ SET PHASE
____________________
        //in the set phase area I need to have each phase
specify what range of tips to be used
        // which action and post action screens to be
used.
        if (Today < PhaseDay[0]) { //BASELINE
PHASE
          //No tips just display date
          whichTip = 0;
          PhaseNow = 0;
          JustOffAction = 0;
          whichAction = 0;
        }

        else if (Today >= PhaseDay[0] && Today <
PhaseDay[1]) { //PRECONTEMPLATION
          if (thisHour = 0 && !tipSwitch) { //change tip
at 12AM
            whichTip++;
            tipSwitch = true;
          } else if (thisHour = 14 && tipSwitch) { //and
at 2PM
            whichTip++;
            tipSwitch = false;
          }
          if (whichTip == 11) {
            whichTip = 1;
          }
          PhaseNow = 1;
          JustOffAction = 1;
          whichAction = 1;
          //Tip range 1-10
        }

        else if (Today >= PhaseDay[1] && Today <
PhaseDay[2]) { //CONTEMPLATION
          PhaseNow = 2;
          JustOffAction = 1;
          whichAction = 4;
          if (thisHour = 0 && !tipSwitch) { //change tip
at 12AM
            whichTip++;
            tipSwitch = true;
          } else if (thisHour = 14 && tipSwitch) { //and
at 2PM
            whichTip++;
            tipSwitch = false;
          }
          if (whichTip == 18) {
            whichTip = 9;
          }
          //Tip range 9-17
        }

        else if (Today >= PhaseDay[2] && Today <
PhaseDay[3]) { //PREPARATION
          JustOffAction = 2;
          PhaseNow = 3;
          whichAction = 5;
          if (millis() - actionTip > 14400000) { //change
tip every 4 hours
            whichTip++;
            actionTip = millis();
          }
```

```
        if (whichTip == 31) {
          whichTip = 15;
        }
        //tip range 15-30
      }

      else if (Today >= PhaseDay[3] && Today <
PhaseDay[4]) { //ACTION
        if (millis() - actionTip > 3600000) { //change
tip each hour
          whichTip++;
          actionTip = millis();
        }
        if (whichTip == 53) {
          whichTip = 25;
        }
        whichAction = random(5, 7);
        JustOffAction = random(2, 4);
        PhaseNow = 4;
        //tip range 25-52
      }

      else { //MAINTENANCE Goes until device off
        PhaseNow = 5;
        JustOffAction = random(2, 4);
        whichAction = 1;
        if (millis() - actionTip > 3600000) { //change
tip each hour
          whichTip = random(1, 53);
          actionTip = millis();
        }
      } // maintenance ned
    } //idle tip end
  }//closed here
}
//ok from here down
OnTime = 0; //reset ontime
for (int i = 0; i < 4 ; i ++) { //sums how much time
the sink has been on for this run
  OnTime += FlowTime[i];
}

// classify flow into 6 categories
if (useEWMA) {
  flow = classifyFlow(EWMA);
} else {
  flow = classifyFlow(stdDEWMA);
}

//the flow has changed to a new kind, and the time
spent at
if ( flow != flowNow) {
  flowCount ++;
  //make sure flow has changed for 3 periods before
switching
  if (flowCount >= 3) {
    lastFlow = flowNow;
    flowNow = flow; //the current flow is registered
    now1 = millis(); //reset to a normalized 0 after the
flow changed
    flowCount = 0;
  }
}

  mxm = 0; //reset PTP
  mnm = 0;
  count = 0; //reset count
} //end of the output step (count) ------------------------
------------------------------------------------ END OF
LOOOOOOOOP END OF LOOOOOOOOP
**************
 count++; //add to count for PTP window
 if (millis() - checkTime > 180000) { //jus to make
sure the day and hour are checked every 3 mins
   checkTime = millis();
   thisHour = whatHour();
   Today = whatDay();
 }
} // should be loop

void displayBigtext(int flownumber) {
 if (flownumber == 0) {
   printOff();
 }
 else if (flownumber == 1 || flownumber == 2) {
   printLow();
 } else if (flownumber == 3) {
   printMed();
 } else if (flownumber == 4 || flownumber == 5) {
   printHigh();
 } else {
   return;
 }
}

String classifyFlow(double EWMA) //outputs the
Flow string type, also adds up how long -----------
CLASSIFY FLOW
{ //the flow is at a certain rate
 String flowRate = "Off";
 if (EWMA < FlowEWMA[1]) {
   whichFlow = 0; // move register
   flowRate = "Off"; //Name the flow rate
 }
 if (EWMA >= FlowEWMA[1] && EWMA <=
FlowEWMA[2]) {
   FlowTime[1] += millis() - now1;
   whichFlow = 1;
   flowRate = "Very Low";
 }
 if (EWMA > FlowEWMA[2] && EWMA <=
FlowEWMA[3]) {
   FlowTime[2] += millis() - now1;
   whichFlow = 2;
   flowRate = "Low";
 }
```

```
  if (EWMA > FlowEWMA[3] && EWMA <=
FlowEWMA[4]) {
    FlowTime[3] += millis() - now1;
    whichFlow = 3;
    flowRate = "Med";
  }
  if (EWMA > FlowEWMA[4] && EWMA <=
FlowEWMA[5]) {
    FlowTime[3] += millis() - now1;
    whichFlow = 4;
    flowRate = "High";
  }
  if (EWMA > FlowEWMA[5]) {
    FlowTime[4] += millis() - now1;
    whichFlow = 5;
    flowRate = "Very High";
  }
  return flowRate;
}

float standard_deviation(float data[], int n) //Standard
Dev to be used when needed
{
  float mean = 0.0, sum_deviation = 0.0;
  int i;
  for (i = 0; i < n; ++i)
  {
    mean += data[i];
  }
  mean = mean / n;
  for (i = 0; i < n; ++i)
    sum_deviation += (data[i] - mean) * (data[i] -
mean);
  return sqrt(sum_deviation / n);
}

int whatDay() { //reads a file called Day and outputs
the 1-2 digit int ---------------------- WHAT DAY ------
------
  File Day;
  String inString = "";
  int i = 0;
  int LastDay = 0;
  //read what day it remembers it being from Days.txt
  Day = SD.open("Days.txt");
  if (Day) {
    while (Day.available()) {
      char inDay = Day.read();
      inString += inDay;
    }
  } else {
    lcd.clear();
    lcd.print("Error open Days");
    delay(30000);
  }
  Day.close();

  LastDay = (int)inString.toFloat();
  inString = "";
  return LastDay;
}

int whatHour() { //reads a file called Day and outputs
the 1-2 digit int ------------------ WHAT HOUR
  File Hour;
  File Day;
  String inHour = "";
  String inString = "";
  int LastHour = 0;
  int LastDayRead = 0;
  //read what day it remembers it being from Days.txt
  Hour = SD.open("HOUR.TXT");
  //Read hour file
  if (Hour) {
    while (Hour.available()) {
      char hourread = Hour.read();
      inHour += hourread;
    }
  } else {
    lcd.clear();
    lcd.print("ERROR Hour File");
    delay(30000);
  }
  Hour.close();
  LastHour = (int)inHour.toFloat(); //Set Last Hour to
read from file
  inHour = "";
  //Has time elapsed to change the file?
  //Is there an hour difference between current millis()
and last
  //HourCheck?
  if ((millis() - HourCheck) > 3600000) { //change
back to 24 and delete modifier
    HourCheck = millis();
    LastHour++;
    if (LastHour == 24) { //keep it on 24hr clock, if day
changed, change day
      LastHour = 0;
      Day = SD.open("Days.txt"); //open and read day
      if (Day) {
        while (Day.available()) {
          char inDay = Day.read();
          inString += inDay;
        }
        LastDayRead = (int)inString.toFloat();
        inString = "";
        LastDayRead++; //change day
      } else {
        lcd.clear();
        lcd.print("ERROR Read Day");
        delay(30000);
      }


      SD.remove("Days.txt");
      Day = SD.open("Days.txt", FILE_WRITE);
      if (Day) {
        Day.print(LastDayRead);
```

```
      } else {
        lcd.clear();
        lcd.print("ERROR Day File");
        delay(3000);
      }
      Day.close();
    }
    SD.remove("HOUR.TXT"); //change hour file if
hour passed
    Hour = SD.open("HOUR.TXT", FILE_WRITE);
    if (Hour) {
      Hour.print(LastHour);
    }
    else {
      lcd.print("Error changing Hour");
      delay(30000);
    }
    Hour.close();
  }
  return LastHour;
}

void displayText77( char OpenFile[8]) { //tip names
should be in format "###.txt", and have an empty final
character
  int idx = 0;
  int y = 0;
  int x = 0;
  char tRead;
  char tLast;
  char tPrinted;
  File tipFile;

  tipFile = SD.open(OpenFile);
  lcd.clear();
  if (tipFile) {
    while (tipFile.available()) {
      tPrinted = tLast;
      tLast = tRead;
      tRead = tipFile.read();
      if (idx >= 1) {
        if (x == 19) {
          if (tPrinted == ' ') {
            lcd.print(' ');
            x++;
          } else if (tRead != ' ' && tLast != ' ' && tPrinted
!= ' ') {
            lcd.print("-");
            x++;
          }
        }
        if (x == 20) {
          y++;
          x = 0;
        }
        lcd.setCursor(x, y);
        if (x == 0 && tLast == ' ') {
          ;//do nothing and skip this char
        }
        else {
          lcd.print(tLast);
          x++;
        }
      }
      idx++;
    }
    tipFile.close();
  } else {
    lcd.clear();
    lcd.print("File not found");
    tipFile.close();
  }
}

bool SaveArrays() { //seems to work at 12PM 9-21,
except saves it three times...
  /*need to save each of the six arrays, in this order, to
the sd file Array.txt
    unsigned long DailyOnTime[70] = {0};
    unsigned long DailyTimeEWMA[70] = {0};
    unsigned long DailyStdDevTime[70] = {0};
    double DailyWater[70] = {0};
    int DailyUses[70] = {0};
  */
  if (!SD.remove("ARRAYS.TXT")) {
    lcd.clear();
    lcd.print("ERROR Remove array"); //remove old
one to make new one
    delay(5000);
  }
  File Array = SD.open("Arrays.txt", FILE_WRITE);
  if (Array) {
    for (int i = 0; i <= 69; i++) { //DailyOnTime
      Array.print(DailyOnTime[i]);
      if (i < 69) { //dont print on last one
        Array.print("\t");
      } else {
        Array.print("\n");
      }
    }
    for (int i = 0; i <= 69; i++) { //DailyTimeEWMA
      Array.print(DailyTimeEWMA[i]);
      if (i < 69) { //dont print on last one
        Array.print("\t");
      } else {
        Array.print("\n");
      }
    }
    for (int i = 0; i <= 69; i++) { //DailyStdDevTime
      Array.print(DailyStdDevTime[i]);
      if (i < 69) { //dont print on last one
        Array.print("\t");
      } else {
        Array.print("\n");
      }
    }
    for (int i = 0; i <= 69; i++) { //DailyWater
      Array.print(DailyWater[i]);
```

```
      if (i < 69) { //dont print on last one
        Array.print("\t");
      } else {
        Array.print("\n");
      }
    }
    for (int i = 0; i <= 69; i++) { //DailyUses
      Array.print(DailyUses[i]);
      if (i < 69) { //dont print on last one
        Array.print("\t");
      } else {
        Array.print("\n");
      }
    }
    Array.close();
    return true;
  }
  else {
    return false;
  }


}

bool CheckArrays() {
  /* Need to have a file that reads each array from the
file, and fills it in (in case of unplug)
      in this order, each entry is seperated by a \t and
each array is seperated by a \n
    unsigned long DailyOnTime[70] = {0}; ArrayNo =
0
    unsigned long DailyTimeEWMA[70] = {0};
ArrayNo = 1
    unsigned long DailyStdDevTime[70] = {0};
ArrayNo = 2
    double DailyWater[70] = {0}; ArrayNo = 3
    int DailyUses[70] = {0}; ArrayNo = 4
  */
  File Array;
  String inString = "";
  int NewlineCounter = 0;
  int TimesRan = 0;
  int ArrayNo = 0;
  long startTime = 0;
  int i = 0;
  Array = SD.open("ARRAYS.TXT");
  lcd.clear();
  lcd.print("Checking arrays");
  lcd.setCursor(0, 1);
  if (Array) {
    while (Array.available()) {
      lcd.setCursor(0, 1);
      lcd.print(TimesRan++);
      char inChar = Array.read();
      if (inChar == '\n') { //see if the array is over
(demarcated by \n)
        ArrayNo++;
        i = 0;
        continue; //dont write this char to anything
      }
      if (ArrayNo == 0) {
        if (inChar != '\t') {
          inString += (char)inChar;
        } else { //the character was a \t, so write and
move to next
          DailyOnTime[i] = (unsigned
long)inString.toFloat();
          inString = ""; //after writing the stroing to an
array, reinitialize that beezy!!!
          i++;
        }
      }
      if (ArrayNo == 1) {
        if (inChar != '\t') {
          inString += (char)inChar;
        } else { //the character was a \t, so write and
move to next
          DailyTimeEWMA[i] = (unsigned
long)inString.toFloat();
          inString = "";
          i++;
        }
      }
      if (ArrayNo == 2) {
        if (inChar != '\t') {
          inString += (char)inChar;
        } else { //the character was a \t, so write and
move to next
          DailyStdDevTime[i] = (unsigned
long)inString.toFloat();
          inString = "";
          i++;
        }
      }
      if (ArrayNo == 3) {
        if (inChar != '\t') {
          inString += (char)inChar;
        } else { //the character was a \t, so write and
move to next
          DailyWater[i] = inString.toFloat();
          inString = "";
          i++;
        }
      }
      if (ArrayNo == 4) {
        if (inChar != '\t') {
          inString += (char)inChar;
        } else { //the character was a \t, so write and
move to next
          DailyUses[i] = (int)inString.toFloat();
          inString = "";
          i++;
        }
      }
    }
    return true;
  }
  else {
```

```
    return false;
  }

}

void printOff() {
  //write O
  lcd.setCursor(0, 1);
  lcd.write((byte)0);
  lcd.write((byte)0);
  lcd.write((byte)0);
  lcd.setCursor(0, 2);
  lcd.write((byte)0);
  lcd.write(" ");
  lcd.write((byte)0);
  lcd.setCursor(0, 3);
  lcd.write((byte)0);
  lcd.write((byte)0);
  lcd.write((byte)0);
  //Write F
  lcd.setCursor(4, 1);
  lcd.write((byte)0);
  lcd.write((byte)0);
  lcd.write((byte)0);
  lcd.setCursor(4, 2);
  lcd.write((byte)0);
  lcd.write((byte)6);
  lcd.write(" ");
  lcd.setCursor(4, 3);
  lcd.write((byte)0);
  lcd.write(" ");
  lcd.write(" ");
  //Write F
  lcd.setCursor(8, 1);
  lcd.write((byte)0);
  lcd.write((byte)0);
  lcd.write((byte)0);
  lcd.setCursor(8, 2);
  lcd.write((byte)0);
  lcd.write((byte)6);
  lcd.write(" ");
  lcd.setCursor(8, 3);
  lcd.write((byte)0);
  lcd.write(" ");
  lcd.write(" ");
}

void printMed() {
  //write M
  lcd.setCursor(0, 1);
  lcd.write((byte)0);
  lcd.write((byte)2);
  lcd.write((byte)0);
  lcd.setCursor(0, 2);
  lcd.write((byte)0);
  lcd.write((byte)1);
  lcd.write((byte)0);
  lcd.setCursor(0, 3);
  lcd.write((byte)0);
```

```
  lcd.write(" ");
  lcd.write((byte)0);
  //Write E
  lcd.setCursor(4, 1);
  lcd.write((byte)0);
  lcd.write((byte)0);
  lcd.write((byte)0);
  lcd.setCursor(4, 2);
  lcd.write((byte)0);
  lcd.write((byte)6);
  lcd.write(" ");
  lcd.setCursor(4, 3);
  lcd.write((byte)0);
  lcd.write((byte)0);
  lcd.write((byte)0);
  //Write D
  lcd.setCursor(8, 1);
  lcd.write((byte)0);
  lcd.write((byte)0);
  lcd.write(" ");
  lcd.setCursor(8, 2);
  lcd.write((byte)0);
  lcd.write(" ");
  lcd.write((byte)0);
  lcd.setCursor(8, 3);
  lcd.write((byte)0);
  lcd.write((byte)0);
  lcd.write(" ");
}

void printHigh() {
  //write H
  lcd.setCursor(0, 1);
  lcd.write((byte)0);
  lcd.write(" ");
  lcd.write((byte)0);
  lcd.setCursor(0, 2);
  lcd.write((byte)0);
  lcd.write((byte)0);
  lcd.write((byte)0);
  lcd.setCursor(0, 3);
  lcd.write((byte)0);
  lcd.write(" ");
  lcd.write((byte)0);

  //write I, no serif
  lcd.setCursor(4, 1);
  lcd.write((byte)0);
  lcd.setCursor(4, 2);
  lcd.write((byte)0);
  lcd.setCursor(4, 3);
  lcd.write((byte)0);

  //write G
  lcd.setCursor(6, 1);
  lcd.write((byte)0);
  lcd.write((byte)0);
  lcd.write((byte)0);
  lcd.setCursor(6, 2);
```

```
  lcd.write((byte)0);
  lcd.write(" ");
  lcd.write((byte)5);
  lcd.setCursor(6, 3);
  lcd.write((byte)0);
  lcd.write((byte)0);
  lcd.write((byte)0);

  //write H
  lcd.setCursor(10, 1);
  lcd.write((byte)0);
  lcd.write(" ");
  lcd.write((byte)0);
  lcd.setCursor(10, 2);
  lcd.write((byte)0);
  lcd.write((byte)0);
  lcd.write((byte)0);
  lcd.setCursor(10, 3);
  lcd.write((byte)0);
  lcd.write(" ");
  lcd.write((byte)0);
}

void printLow() {
  //write L
  lcd.setCursor(0, 1);
  lcd.write((byte)0);
  lcd.write("  ");
  lcd.setCursor(0, 2);
  lcd.write((byte)0);
  lcd.write("  ");
  lcd.setCursor(0, 3);
  lcd.write((byte)0);
  lcd.write((byte)0);
  lcd.write((byte)0);
  //Write O
  lcd.setCursor(4, 1);
  lcd.write((byte)0);
  lcd.write((byte)0);
  lcd.write((byte)0);
  lcd.setCursor(4, 2);
  lcd.write((byte)0);
  lcd.write(" ");
  lcd.write((byte)0);
  lcd.setCursor(4, 3);
  lcd.write((byte)0);
  lcd.write((byte)0);
  lcd.write((byte)0);
  //Write W
  lcd.setCursor(8, 1);
  lcd.write((byte)0);
  lcd.write(" ");
  lcd.write((byte)0);
  lcd.setCursor(8, 2);
  lcd.write((byte)0);
  lcd.write((byte)4);
  lcd.write((byte)0);
  lcd.setCursor(8, 3);
  lcd.write((byte)0);
  lcd.write((byte)3);
  lcd.write((byte)0);
};
```

A.5 Bill of Materials

Table 6 – Device BOM

Part Description	Number	Cost
Acrylic 6"X12"X1/8"	1	$5
20x4 LCD	1	$18.95
8GB Micro SD Card	1	$5
Resistors	5	$0
Capacitor	1	$0
Jumper Wire	16	$0.08
Micro SD Module	1	$3.50
Mega Equivalent	1	$4.50
PCB	1	$0
Op-Amp	1	$2
6.2kHz Piezo	1	$1.50
Power Supply	1	$8
GFCI Adapter	1	$10
Total		$59

A6. NEP Survey Response Data

Table 7 – Fall 2016 NEP Survey Responses

	P1	P2	P3	P4	NP5	NP6	Average Overall
Overall (no F)	-0.4	-0.133333	0.476190	0.066666	0.333333	0.2666	0.1015873
Overall (F)	-0.388888	0.055555	0.277777	0.055555	0.333333	0.2777	0.10185185
A	-0.666666	0.666666	1.333333	-0.33333	0	0	0.16666667
B	-1.333333	-0.333333	-1.666666	1	0.666666	-0.3333	-0.33333333

	P1	P2	P3	P4	NP5	NP6	
C	0.333333	-0.333333	NA	-1	0.333333	0.66667	0
D	-0.666666	-0.666666	1.333333	0	0.666667	0.66667	0.22222222
E	0.333333	0	0.666667	0.666667	0	0.33333	0.33333333
F	-1	0.666667	0.666667	0.666667	1	0.3333	0.38888889

Pre

	P1	P2	P3	P4	NP5	NP6	
Overall (no F)	4.4	3.066667	3.666667	3.533333	3.53333	3.93333	
Overall (F)	4.388889	3.055556	3.722222	3.38889	3.44444	3.83333	
A	4.333333	2.333333	3	3.666667	3.333333	3.66667	3.38888889
B	5	2.666667	4.666667	3	3	3.66667	3.66666667
C	4.333333	3.333333	4	4.333333	4	3.33333	3.88888889
D	3.666667	3.666667	2.333333	3	3	4.33333	3.33333333
E	4.666667	3.333333	4.333333	3.66667	4.33333	4.66667	4.16666667
F	4.333333	3	4	2.666667	3	3.33333	3.38888889

Post

	P1	P2	P3	P4	NP5	NP6	
Overall (no F)	4	2.93333333	4.142857	3.6	3.866667	4.2	
Overall (F)	4	3.111111	4	3.44444	3.777778	4.11111	
A	3.666667	3	4.333333	3.33333	3.333333	3.6667	3.55555556
B	3.666667	2.333333	3	4	3.666667	3.33333	3.33333333
C	4.666667	3		3.33333	4.33333	4	3.86666667
D	3	3	3.666667	3	3.66667	5	3.55555556
E	5	3.333333	5	4.33333	4.33333	5	4.5
F	3.333333	3.666667	4.666667	3.33333	4	3.66667	3.77777778

A5. Household Usage Data

Table 8 – Fall 2016 Phase Average Household Use (L) P: Phasic NP: Non-phasic, Red: corrupt

WaterUse (L)

Participant	UseSum						
	Baseline	Precont	Cont	Prep	Action	Maint	Average
P1	757.7	863.37	416.2	1592.8	1929.8	1758	1219.645
P2	36.185	33.85	20.19	14.41	6.132	6.43	19.532833
P3	9.81	51.82	40.568	2.9	21.21	13.18	23.248
P4	254.9	1190	588.4	599.5	763.8	667.2	677.3
NP5	16.655	13.79	14.205	8.6733	11.22	8.817	11.96
NP6	9.78	9.72	12.09	10.21	10.75	20.4	13.5

Participant	Baseline	Precont	Cont	Prep	Action	Maint	Average
P1	757.7	863.37	416.2	1592.8	1929.8	1758	1219.645
P2	42.8425	26.67	24.435	15.299	6.43815	6.627	20.385275
P3	11.415	47.5	54.839	1.957	21.505	18.575	25.965167
P4	254.9	1190	588.4	599.5	763.8	667.2	677.3
NP5	15.6775	13.73	14.52	8.33665	13.185	8.6585	12.04
NP6	9.1525	10.695	9.104	12.495	10.455	20.605	13.65

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