Under Pressure
Transforming the Way We Think About & Use Water in the Home
two-thirds of the earth’s surface is covered by water
Ocean: 96.5%
Polar Ice: 1.7%
Brackish: 1%
Drinkable Water: 0.8%

The amount of water on earth is not changing
The amount of water on earth is not changing but its location, quality and amount per person is changing
As the Earth’s climate changes...

precipitation patterns  glacial and ice snowpack  surface water availability

[Gleick, World Policy Journal, 2009]
As populations grow, per-capita water availability is declining.
water availability disproportionately felt in urban environments

[Barlow, 2007]
This places an enormous strain on drinkable water supplies
growing demand

in 2010, water consumption rose to 938 billion gallons in Beijing. Water supply = 576 billion gallons

[Guardian, Dec 2010]
“china melting snow to meet freshwater demand”
Lake Mead expected to drop below intake pipes in next five years

[Bloomberg News, Feb 2009]
new sources of water
more costly to extract
water utilities
shift focus
governments
This is an area where HCI researchers and designers can help
eco-feedback
sensing and visualizing behavior to reduce environmental impact
Consumption

30 min 25 20 15 10 5 0

Current

Energy 60.5 MPG 204 miles

Reset

OUTSIDE TEMP 61 °F

=50Wh Regenerated
For Hybrid Drivers, Every Trip is a Race for Fuel Efficiency

By Michael S. Rosenwald
Washington Post Staff Writer
Monday, May 26, 2008

Katie Sebastian accuses her friend Evan Hirsche of getting better mileage than she does because he lives in Bethesda and has flatter everyday trips than she encounters in hilly Takoma Park. She suspects the Hirsche family of taking frequent long drives out of town, which also helps them.

"They claim they haven't been out of town in a while," she said, "but I know they have."

Hirsche retorts: "It is well known that Katie is a lead-foot." Their friendly rivalry stems from the Prius effect. Both drive a Prius, the Toyota hybrid with an elaborate dashboard monitor that constantly informs drivers how many miles per gallon they are getting and whether the engine is running on battery or gasoline power. That change driving in startling ways, making drivers change driving habits, then adjusting themselves to new ways of their driving habits, then adjusting themselves to new miles per gallon. "The Prius has 41 mpg," Hirsche averages 43 mpg with his Prius, while Katie Sebastian, who lives in Takoma Park, averages 41 mpg. The drivers have friendly scores, fueled by the Prius hybrid's realtime readiness over their mpg scores, fueled by the Prius hybrid's real-time readiness over their mpg scores, fueled by the Prius hybrid's real-time readiness over their mpg scores, fueled by the Prius hybrid's real-time readiness over their mpg scores. (By Kevin Uhr - The Washington Post)
eco-feedback
sensing and visualizing behavior to reduce environmental impact

you

sensing feedback
water sensing
Municipal Services Statement

Account Number: 100587-00154711
Utility Amount Due: 127.52
Voluntary Donation: 1.00
Total + Voluntary Donation: 128.52
Date Due: 1/8/2007

Gallons delivered: 20,000

Please fold before tearing.

Water feedback

Help to Others voluntary donation program makes it easier to help neighbors in need. Help to Others supports essential human service programs for children, families and seniors. If you do not wish to contribute to this program, simply say "No" or "Only the Utility Amount Due."
10,230 gallons
SAFeway

SAVE MORE AT SAFeway

GROCERY

SFwy PRIZLE STICK
ResPrice 1.79 CardSav .29
BLKBERRY PRES
SFy CANOLA OIL
CEREAL PNT BUTTER
CHILI SAUCE SWT
CHF-B PIZZA
LK GRLC SCE

REFRIG/FROZEN

LUC CHEESE
ResPrice 6.79 CardSav 1.50
SPINACH ARTICHOKE
ResPrice 3.79 CardSav 1.29
3S CRm VEG RSTD
ResPrice 3.79 CardSav 1.29
202.50 SFwy SEL MEDALL FC
ResPrice 7.58 CardSav 1.59
MARGARINE

GEN MERCHANDIS

#SFY BENEFIST TAB

BAKED GOODS

LD COSMIC BROWNIES
ResPrice 5.99 CardSav 1.00
OROweAT RYE
CUSTARD PIE 9IN
ResPrice 5.99 CardSav 1.00
CHOC CREAM PIE
ResPrice 5.99 CardSav 1.00

**** TAX 6.76 BAL 144.25
VF NC XXXXXXXX

CHANGE .00

TOTAL SAVINGS 16.97
NUMBER OF ITEMS = 35
CARD 1627206 19-20-1997 02 07 04

Month: April 2006
Total Food Units: 1527

Total Price: $642
10,230 gallons

- Outdoor: 3,212 gals
- Toilets: 1,872 gals
- Laundry: 1,524 gals
- Showers: 1,176 gals
- Faucets: 1,105 gals
- Dishwasher: 102 gals
- Other: 1,248 gals
waterbot

[Arroyo et al., CHI 2005]
Arroyo et al., CHI 2005

Kuznetsov & Paulos, CHI 2010

upstream
waitek shower monitor

http://www.waitek.co.nz/
Point-of-Consumption Eco-Feedback Displays

sensing and feedback unit co-located at fixture

provides real-time feedback on water usage
Point-of-consumption feedback is the prevailing method for providing water usage feedback at the fixture-level.
Showers and faucets account for ~22% of water use in the average North American home.

[Vickers, 2001]
direct sensing

Toilet: 78.4 gallons
Shower: 52.4 gallons
Bath: 6.5 gallons
Bathroom sink 1: 3.2 gallons
Bathroom sink 1: 4.2 gallons
Bathroom sink 2: 0.8 gallons
Bathroom sink 2: 2.4 gallons

Direct sensing
indirect sensing

- shower 52.4 gallons
- shower 62.4 gallons
- bath 6.5 gallons
- bath 6.5 gallons
- bathroom sink 1 3.2 gallons
- bathroom sink 1 4.2 gallons
- bathroom sink 2 2.4 gallons
- bathroom sink 2 0.8 gallons
- toilet 78.4 gallons

[HydroSense, UbiComp 2009]
indirect sensing

HydroSense attempts to infer fixture-level usage for the entire home from a single point.

[HydroSense, UbiComp 2009]
This data presents new, rich opportunities for...

eco-feedback

sensing and visualizing behavior to reduce environmental impact
What do we do with all this data?
How does HydroSense work?

How did we evaluate it?
hydrosense

- single, screw-on sensor
- identifies fixture usage
- estimates flow

Froehlich et al., UbiComp2009; Larson et al., PMC2010
Traditional water meters measure aggregate consumption.

Requires cutting into pipe to install.
hydro sense implementation

Pressure Sensor → 16-bit ADC → 20 MHz Microcontroller → Class 1 Bluetooth Radio

3D-Printed Enclosure

Images of the hydro sense implementation components.
brief plumbing primer
brief plumbing primer
brief plumbing primer

It’s Samuel Joseph Wurzelbacher!

Joe The Plumber
Fighting for the American Dream
by Samuel I. Wurzelbacher with Thomas N. Tabbach
plumbing primer
incoming cold water from supply line
Water tower

Pressure regulator

Incoming cold water from supply line

Utility water meter

Pressure regulator
pressure regulator

incoming cold water from supply line

utility water meter

pressure regulator

water tower
closed pressure system

water tower

utility water meter
pressure regulator
thermal expansion tank
hot water heater

hose spigot

bathroom 1

kitchen
dishwasher

bathroom 2

incoming cold water from supply line

laundry
Have another toilet as 2nd example rather than kitchen sink.
bathroom sink pressure signal
bathroom sink pressure signal

flow rate related to pressure via Poiseuille’s Law

flow volume

open

Close

Cold Line Pressure (Hose Spigot)
signature dependent on:
- fixture type
- valve type
- valve location in home
hydro algorithm

1. detect that a water event has occurred
2. classify event as “open” or “close”
3. determine source of event (e.g., toilet, shower)
4. provide flow estimate
event detection/segmentation
event detection/segmentation

raw pressure (psi)

smoothed pressure (psi)

derivative (psi/s)

critical change in pressure

time (s)
**event detection/segmentation**

- **raw pressure (psi)**
- **smoothed pressure (psi)**
- **derivative (psi/s)**

Critical stabilization point

**time (s)**
event detection/segmentation

- Raw pressure (psi)
- Smoothed pressure (psi)
- Derivative (psi/s)

Valve open event automatically detected event

Pressure decrease and negative initial derivative

= valve open event
event detection/segmentation

valve open event

raw pressure (psi)

smoothed pressure (psi)

derivative (psi/s)

time (s)
event detection/segmentation

raw pressure (psi)

valve open event

automatically detected event

smoothed pressure (psi)

pressure increase

and

positive initial derivative

derivative (psi/s)

time (s)
event detection/segmentation

- Valve close event
- Valve open event
- Pressure increase
- Positive initial derivative

(raw pressure (psi)

(smoothed pressure (psi)

(derivative (psi/s)

time (s)
fixture classification

unclassified open event

open event library

compare via matched filtering across multiple signal transformations
matched filtering

unclassified waveform

bathroom sink close template

save maximum similarity

bathroom sink comparison result
matched filtering

bathroom sink comparison result
matched filtering

unclassified waveform

kitchen sink close template

new maximum similarity

bathroom sink comparison result
detrended_{unclassified}

matched filter

derivative_{unclassified}

matched filter

cepstrum_{unclassified}

matched filter

detrended_{shower}

matched filter

derivative_{shower}

matched filter

cepstrum_{shower}

possible
events
unclassified open event

open event library

detrended_{unclassified}

derivative_{unclassified}

cepstrum_{unclassified}

detrended_{toilet}

derivative_{toilet}

cepstrum_{toilet}

possible events
unclassified open event

open event library

detrended_{unclassified}

detrended_{toilet}

matched filter

derivative_{unclassified}

derivative_{toilet}

matched filter

cepstrum_{unclassified}

cepstrum_{toilet}

matched filter

possible events
detrended
unclassified

derivative
unclassified

derivative
toilet

derivative
kitchen faucet

cepstrum
unclassified

possible
events

open event library

kitchen faucet

dishwasher

shower

derivative_{shower}

derivative_{toilet}

derivative_{kitchen faucet}
unclassified open event

nearest neighbor match

derivative_{unclassified}

derivative_{shower}

derivative_{toilet}

derivative_{kitchen faucet}

open event library

dishwasher

dishwasher

possible events

kitchen faucet
hydro study #1

goal study feasibility of using pressure to disaggregate water usage

approach controlled experiments across 10 homes
controlled experiments
• 2 researchers per site
• 5 trials per valve

experimental script
• valve opened full stop
• pause for ~5 seconds
• valve closed
controlled data collection
collecting flow data

- 4 / 10 homes gathered flow data
- measure time to fill 1 gallon in a calibrated bucket
data collection stats

- ten test sites
- 706 trials
- 155 flow trials
- 84 total fixtures tested
classification experiments

10-fold cross validation

1. break data into 10 sets of size n/10
2. train on 9 datasets and test on 1
3. repeat for each combination of datasets
4. take mean accuracy
fixture classification results by home

10-fold cross validation
fixture classification results by home

10-fold cross validation

Open Events

Close Events

H1 (12 valves)
H2 (8 valves)
H3 (6 valves)
H4 (5 valves)
H5 (9 valves)
H6 (8 valves)
H7 (8 valves)
H8 (6 valves)
H9 (7 valves)
H10 (7 valves)
fixture classification results
by fixture

- Sinks: 98% (Open), 95% (Close)
- Toilets: 99% (Open), 98% (Close)
- Showers: 96% (Open), 98% (Close)
- Bathtubs: 100% (Open), 100% (Close)
- Clothes Washer: 100% (Open), 100% (Close)
- Dishwasher: 100% (Open), 100% (Close)
flow inference results by home

Within tolerances of domestic water meter accuracy; see [Arregui, 2003]
hydro study

#1 contributions
built and evaluated wireless pressure sensor
first to show that pressure could be used to disaggregate water usage
brushing teeth
shaving
bathing
paw washing
compound events

- incoming cold water from supply line
- utility water meter
- pressure regulator
- thermal expansion tank
- hot water heater
- bathroom 1
- bathroom 2
hydro study

#2

goal

study how well hydrosense can classify real world water usage

approach

5 week deployment in 5 homes
in the first study, pressure waves were manually annotated with “ground truth labels” describing:

- the fixture used
- the water temperature
I’m about to flush the toilet!

Awesome! Marked it. Thanks Mr. Johnson
how can we record real-world water usage?

collect ground truth labels of
wireless buttons
how many times will the **hot** and **cold** water valves be opened and closed while washing these dishes?

tracks the number of times **hot** and **cold** are turned on/off
wireless buttons

FAIL #1
other failed solutions
intel labs shake sensors
FAIL #3
nike+ piezo sensor

FAIL #4
The HydroSense team conducted a set of short, simple experiments investigating whether the Nike+iPod piezoelectric sensor could be used to detect faucet open/close handle movements.
our solution...
design goals

- wireless
- low-power
- water resistant
- detect fixture opens/closes
- track hot only, cold only, mixed

custom direct sensors
automated ground truth labeling method

design goals

**hardware** capabilities
1. wireless communication
2. low-power
3. water resistant

**sensing** capabilities
1. work across fixtures/appliances
2. detect opens/closes
3. discriminate hot/cold/mixed
function across fixtures

kitchen sink

bathroom sink

bath

shower

toilet

laundry basin

washing machine

dishwasher
challenge: fixture diversity

single handle faucet

dual handle faucet
custom ground truth data collection system

- xbee wireless modem
- fixture usage sensor board
- hall effect
- reed switch
- 3-axis accelerometer
- unidirectional ball switch
- omnidirectional ball switch
custom ground truth data collection system

- XBee wireless modem
- Fixture usage sensor board
- Hall effect switch
- Reed switch
- 3-axis accelerometer
- Unidirectional ball switch
- Omnidirectional ball switch

“Wake up” sensors
custom ground truth data collection system

fixture handle position sensors

xbee wireless modem
fixture usage sensor board

hall effect
reed switch
3-axis accelerometer
unidirectional ball switch
omnidirectional ball switch
Accelerometer & Ball Switch Taped on
custom ground truth data collection system
# Deployment Sites

<table>
<thead>
<tr>
<th></th>
<th>House 1</th>
<th>House 2</th>
<th>House 3</th>
<th>House 4</th>
<th>House 5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Residents</strong></td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td><strong>Size</strong></td>
<td>3000 sqft</td>
<td>750 sqft</td>
<td>1200 sqft</td>
<td>700 sqft</td>
<td>750 sqft</td>
</tr>
<tr>
<td><strong>Floors</strong></td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>3&lt;sup&gt;rd&lt;/sup&gt; flr</td>
<td>6&lt;sup&gt;th&lt;/sup&gt; flr</td>
</tr>
<tr>
<td><strong>Fixtures</strong></td>
<td>17</td>
<td>8</td>
<td>13</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td><strong>Valves</strong></td>
<td>28</td>
<td>13</td>
<td>21</td>
<td>13</td>
<td>13</td>
</tr>
</tbody>
</table>
ground truth | labels

manual

automatic

kitchen sink
- cold open
- cold close
- hot open
- hot close

bathroom sink
- cold open
- cold close

Automatic labeling of sink usage
two pressure sensors per home
**hydro**sense data logger

records ground truth sensor data plus two pressure streams for each home

- **Pressure Stream**
  - **Red** = hot line
  - **Blue** = cold line

- **Reed Switches**
  - **High** = active
  - **Low** = inactive
hydroSense data logger
reed switches
hydro deployment infrastructure

**custom** ground truth data collection system

**hydro**sense data logger records ground truth sensor data plus two pressure streams for each home.

**two** pressure sensors

on-site sensing infrastructure

**python web backend**

**hydro**visualizer

**hydro**server

**hydro**analyzer

c# and matlab analysis tools
hydroSense annotations

1. ground truth sensor
2. semi-automated label
3. review annotator
4. verification
5. final label
dual pressure sensor
dual pressure sensor

toilet
bathroom faucet
kitchen faucet
dishwasher
washing machine
bath/shower
bath/shower diverter
5-week dataset

<table>
<thead>
<tr>
<th></th>
<th>House 1</th>
<th>House 2</th>
<th>House 3</th>
<th>House 4</th>
<th>House 5</th>
<th>totals</th>
</tr>
</thead>
<tbody>
<tr>
<td>days</td>
<td>33</td>
<td>33</td>
<td>30</td>
<td>27</td>
<td>33</td>
<td>156</td>
</tr>
<tr>
<td>events</td>
<td>2374</td>
<td>3075</td>
<td>4754</td>
<td>2499</td>
<td>2578</td>
<td>14,960</td>
</tr>
<tr>
<td>events/day</td>
<td>71.9</td>
<td>93.2</td>
<td>158.5</td>
<td>92.6</td>
<td>78.1</td>
<td>95.9</td>
</tr>
</tbody>
</table>
avg num water events/day

- home1: 71.9
- home2: 93.2
- home3: 158.5
- apartment1: 92.6
- apartment2: 78.1
- Overall: 95.9
avg num water events/day

<table>
<thead>
<tr>
<th>Location</th>
<th>Cold</th>
<th>Hot</th>
</tr>
</thead>
<tbody>
<tr>
<td>home1</td>
<td>71.9</td>
<td>64%</td>
</tr>
<tr>
<td>home2</td>
<td>93.2</td>
<td>54%</td>
</tr>
<tr>
<td>home3</td>
<td>158.5</td>
<td>66%</td>
</tr>
<tr>
<td>apartment1</td>
<td>92.6</td>
<td>75%</td>
</tr>
<tr>
<td>apartment2</td>
<td>78.1</td>
<td>36%</td>
</tr>
<tr>
<td>Overall</td>
<td>95.9</td>
<td>60%</td>
</tr>
</tbody>
</table>

- Cold percentage: home1 64%, home2 54%, home3 66%, apartment1 75%, apartment2 36%, Overall 60%.
- Hot percentage: home1 36%, home2 46%, home3 34%, apartment1 25%, apartment2 64%, Overall 40%.
Fixture activity frequency

84.7% of all water events

3 of most active are sinks!

Event frequency

- Kitchen Sink: 5494
- M. Bathroom Sink: 3934
- S. Bathroom Toilet: 1886
- Washing Machine: 1369
- M. Bathroom Bath: 430
- S. Bathroom Toilet: 423
- M. Bathroom Shower: 341
- Dishwasher: 261
- M. Bath Diverter: 261
- Other: 228
- S. Bathroom Bath: 118
- S. Bathroom Shower: 59
- S. Bath Diverter: 47
- Other: 46
22% of all water events were compound.

41.8% of all bathroom sink events were compound.
compound event example

bathroom sink:

- open
- close

time(s)
compound event example

bathroom sink: open close

bathroom sink: open close
compound event example

**bathroom sink:**
- **open** (2-4 seconds)
- **close** (6-8 seconds)

**toilet:**
- **open** (2 seconds)
- **open** (4-6 seconds)
- **close** (6-8 seconds)
beyond template matching

relationship between valve events

duration of water activity
damping ratio

pressure drop

water volume used

time of day

isolation or compound

recency of use

number of uses today

number of uses today
bayesian approach

New algorithm borrows from Bayesian inference in speech recognition

\[
P(S|V) = \prod_{r=0}^{R-1} f_r(S_r | \hat{V}_r) \prod_{n=0}^{N-1} P(v_n | v_{n-1}) \prod_{i \notin \beta} f_p(v_i) \prod_{k=0}^{K-1} \prod_{\langle a,b \rangle \in \beta} f_k(\langle v_a, v_b \rangle)
\]

(i) templates and signal features
(ii) bigram language model
(iii) grammar
(iv) paired valve priors
Bayesian approach

\[ V = \text{pressure signature library} \]
\[ S = \text{sequence of unknown pressure transients} \]

most likely valve sequence

\[
\hat{V} = \arg \max P(V | S) = \arg \max \frac{P(S | V)P(V)}{P(S)}
\]
Bayesian approach

\[ \hat{V} = \text{arg max } P(V | S) = \text{arg max } \frac{P(S | V)P(V)}{P(S)} \]

\[ P(S|V) = \prod_{r=0}^{R-1} f_r(\hat{S}_r | \hat{V}_r) \]

(i) templates and signal features

e.g., matched filtering and stabilized pressure drop
Bayesian approach

\( V = \text{pressure signature library} \)

\( S = \text{sequence of unknown pressure transients} \)

\[
\hat{V} = \arg \max \ P(V | S) = \arg \max \ \frac{P(S | V)P(V)}{P(S)}
\]

\[
= \prod_{r=0}^{R-1} f_r(\hat{S}_r | \hat{V}_r) \prod_{n=0}^{N-1} P(v_n | v_{n-1})
\]

(i) templates and signal features

(ii) bigram language model

E.g., transition probability for toilet open -> bathroom sink open
Bayesian approach

\[ \hat{V} = \arg \max \ P(V \mid S) = \arg \max \ \frac{P(S \mid V)P(V)}{P(S)} \]

\[
\begin{align*}
P(S \mid V) &= \prod_{r=0}^{R-1} f_r(\hat{S}_r \mid \hat{V}_r) \prod_{n=0}^{N-1} P(v_n \mid v_{n-1}) \prod_{i \notin \beta} f_p(v_i) \\
&= (i) \text{ templates and signal features} \quad (ii) \text{ bigram language model} \quad (iii) \text{ grammar}
\end{align*}
\]

e.g., opening of valve \( v_x \) must be followed by closing of \( v_x \)
Bayesian approach

\[ \hat{V} = \arg \max P(V | S) = \arg \max \frac{P(S | V)P(V)}{P(S)} \]

\[ P(S|V) = \prod_{r=0}^{R-1} f_r(\hat{S}_r | \hat{V}_r) \prod_{n=0}^{N-1} P(v_n | v_{n-1}) \prod_{i \notin \beta} f_p(v_i) \prod_{k=0}^{K-1} \prod_{\langle a,b \rangle \in \beta} f_k(v_a, v_b) \]

(i) templates and signal features  
(ii) bigram language model  
(iii) grammar  
(iv) paired valve priors  

\[ e.g., \text{water usage duration} \]
HydroSense classification results
real-world water usage data

- One pressure sensor achieved 75.5% accuracy.
hydroSense classification results

real-world water usage data

- Valve level: 75.5%
- Fixture level: 89.5%

one pressure sensor
hydroSense classification results
real-world water usage data

- Valve level: 75.5%
- Fixture level: 89.5%
- Fixture category level: 95.9%
hydroSensense classification results
real-world water usage data

- Valve level:
  - One pressure sensor: 75.5%
  - Two pressure sensors: 82.4%

- Fixture level:
  - One pressure sensor: 89.5%
  - Two pressure sensors: 93.5%

- Fixture category level:
  - One pressure sensor: 95.9%
  - Two pressure sensors: 97.7%
compound events results
real-world water usage data

Single Sensor
- Isolated
- Compound

Dual Sensor
- Collision

Error Rates (%)

old algorithm  intermediate algorithm  new algorithm

old algorithm  intermediate algorithm  new algorithm
hydroSense training results
real-world water usage data
hydroSense training results
real-world water usage data

Days of Training Data

*error bars = std error
hydro study

#2 contributions demonstrated hydrosense can classify real-world water usage collected one of the most comprehensive datasets of water usage in the world
HydroSense + Reflect²O

Water Usage Sensor

sensing feedback
Two sets of designs:

1. **Design Dimensions**
   Isolate eco-feedback design dimensions in the context of water usage

2. **Design Probes**
   Meant to elicit reactions about how displays would fit within a household and investigate issues such as privacy, competition, family dynamics.
Informal interviews with water experts (e.g., SPU, Amy Vickers)
UW Environmental Practicum on water
Literature review of water resource management, environmental psychology
Our own online survey of water usage attitudes & knowledge (N=656 respondents)

Ideation → Data Gathering → Ideation / Sketch → Pilot Studies → Refinement → Evaluation
Respondents (N=651) dramatically underestimated the amount of water used in common everyday activities.

- toilet: by 15%
- shower: by 30%
- bath: by 55%
- low-flow shower: by 60%
- outdoor yard watering: by 83% to 95%

[Froehlich, UW PhD Dissertation, 2011]
Informal interviews with water experts (e.g., SPU, Amy Vickers)
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Informal interviews with water experts (e.g., SPU, Amy Vickers)
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Our own online survey of water usage attitudes & knowledge (N=656 respondents)

Informed by gathered data
Guided by eco-feedback design space
Iterative Design Process

Sketch

Lo-to-Mid Fidelity Mockup

Higher Fidelity Mockup
Informal interviews with water experts (e.g., SPU, Amy Vickers)
UW Environmental Practicum on water
Literature review of water resource management, environmental psychology
Our own online survey of water usage attitudes & knowledge (N=656 respondents)

Design critique sessions with team
Three sets of pilot studies

Informed by gathered data
Guided by eco-feedback design space

Ideation → Data Gathering → Ideation / Sketch → Pilot Studies → Refinement → Formative Evaluation
Informal interviews with water experts (e.g., SPU, Amy Vickers)
UW Environmental Practicum on water
Literature review of water resource management, environmental psychology
Our own online survey of water usage attitudes & knowledge (N=656 respondents)

Online interactive survey of designs (N=651 respondents)
In-home interviews (10 households, 20 adults)
Two sets of designs:

1. **Design Dimensions**
   Isolate eco-feedback design dimensions in the context of water usage

2. **Design Probes**
   Meant to elicit reactions about how displays would fit within a household and investigate issues such as privacy, competition, family dynamics.
DESIGN SET 1: ISOLATING DESIGN DIMENSIONS

**Design Dimensions Explored**

1. **Data** Granularity
2. **Time** Granularity
3. **Measurement** Unit
4. **Comparison**
Data Granularity

coarse-grain ≤ neighborhood → home → room → activity → fixture category → fixture ≤ valve → fine-grain

DESIGN SET 1: ISOLATING DESIGN DIMENSIONS
Today’s Water Usage in Gallons

Activity View

<table>
<thead>
<tr>
<th>Activity</th>
<th>Usage (Gallons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Showering &amp; Bathing</td>
<td>96</td>
</tr>
<tr>
<td>Hygiene (e.g., shaving)</td>
<td>26</td>
</tr>
<tr>
<td>Toilet</td>
<td>68</td>
</tr>
<tr>
<td>Cooking &amp; Dishes</td>
<td>34</td>
</tr>
<tr>
<td>Laundry</td>
<td>43</td>
</tr>
<tr>
<td>Other Chores (e.g., cleaning)</td>
<td>5</td>
</tr>
<tr>
<td>Watering Lawn</td>
<td>80</td>
</tr>
<tr>
<td>Other Outdoor Use</td>
<td>0</td>
</tr>
</tbody>
</table>

Friday June 15th | 9:30 PM
Today's Water Usage in Gallons

Fixture Category View

Friday June 15th | 9:30 PM

- Showers: 2 gallons
- Bathtubs: 68 gallons
- Toilets: 37 gallons
- Bathroom Sinks: 12 gallons
- Kitchen Sink: 14 gallons
- Dishwasher: 43 gallons
- Laundry Machine: 80 gallons
- Outdoor: 96 gallons
Today’s Water Usage in Gallons
Individual Fixture View

Friday June 15th | 9:30 PM

- Master Bathroom: 26 gallons
- Upstairs Bathroom: 70 gallons
- Downstairs Bathroom: 31 gallons
- Kitchen: 14 gallons
- Laundry: 43 gallons
- Outdoors: 80 gallons
Today’s Water Usage in Gallons
Fixture Category View: Hot vs Cold

Friday June 15th | 9:30 PM

- **Cold Water Usage**
  - Showers: 30%
  - Bathtubs: 2%
  - Toilets: 40%
  - Bathroom Sinks: 41%
  - Kitchen Sink: 12%
  - Dishwasher: 23%
  - Laundry Machine: 77%
  - Outdoor: 0%

- **Hot Water Usage**
  - Showers: 70%
  - Bathtubs: 18%
  - Toilets: 60%
  - Bathroom Sinks: 59%
  - Kitchen Sink: 58%
  - Dishwasher: 77%
  - Laundry Machine: 23%
  - Outdoor: 0%
Measurement Unit

- Resource: 36 gallons of water
- Rate of consumption: 3 gpm
- Cost: 9 cents
- Time: 12 minutes
- Activity: 1 shower
- Metaphor:

DESIGN SET 1: ISOLATING DESIGN DIMENSIONS
This Month’s Water Usage
Fixture Category View | In Gallons

Friday June 15th | 9:30 PM

- Showers: 1,814 gallons
- Bathtubs: 177 gallons
- Toilets: 614 gallons
- Bathroom Sinks: 2,905 gallons
- Kitchen Sink: 1,323 gallons
- Dishwasher: 150 gallons
- Laundry Machine: 2,346 gallons
- Outdoor: 4,310 gallons
This Month’s Water Usage
Fixture Category View | In Dollars & Gallons

Friday June 15th | 9:30 PM
Your Current Water Rate:
1,000 gal = $7.68

$33.10
4,310

$18.02
2,346

$10.16
1,323

$4.72
614

$22.31
2,905

$13.93
1,814

$1.36
177

Dollars

Gallons

Showers
Bathtubs
Toilets
Bathroom Sinks
Kitchen Sink
Dishwasher
Laundry Machine
Outdoor
DESIGN SET 1: ISOLATING DESIGN DIMENSIONS

Data Granularity
- Individual Fixture
- Fixture Category
- Activity
- Hot and Cold

Time Granularity
- So Far Today
- So Far This Week
- So Far This Month

Comparison
- Self Comparison
- To Others
- To A Goal
- Social/Self

Measurement Unit
- In Gallons
- In Dollars
- Dollars / Gallons
- Including Sewage
Two sets of designs:

1. **Design Dimensions**
   Isolate eco-feedback design dimensions in the context of water usage

2. **Design Probes**
   Meant to elicit reactions about how displays would fit within a household and investigate issues such as privacy, competition, family dynamics.
DESIGN SET 2: DESIGN PROBES

Design Probes Explored

Time-Series

Spatial

Aquatic Eco-system

Rainflow

Per-Occupant

Other
DESIGN SET 2: DESIGN PROBES

Design Probes Explored

Time-Series

Aquatic Eco-system

Spatial

Rainflow

Per-Occupant

Other
Daily Patterns of Water Usage

[Adapted from Butler, Building and Environment, 1993]
DESIGN SET 2: DESIGN PROBES

Design Probes Explored

- Time-Series
- Spatial
- Aquatic Eco-system
- Rainflow
- Per-Occupant
- Other

Water Usage in Gallons Today
Water Usage in Gallons This Year
Today's Water Usage in Gallons
Personnel Usage Totals
Other

Design Probes Explored

Rainflow

Aquatic Eco-system

Spatial

Time-Series

Other

Per-Occupant
DESIGN SET 2: DESIGN PROBES

Spatial View

Today’s Water Usage in Gallons

Room View

Bathroom Total: 81.2 gal
- Today: 81.2 gal
- Avg: 108 gal

- Shower: Today 40 gal, Avg 52 gal
- Toilet: Today 30 gal, Avg 37 gal
- Bathroom Sink: Today 10 gal, Avg 16 gal
- Bath: Today 1.2 gal, Avg 3 gal

Kitchen Total: 25 gal
- Today: 25 gal
- Avg: 21 gal

- Kitchen Sink: Today 13 gal, Avg 12 gal
- Dishwasher: Today 12 gal, Avg 9 gal
- Laundry Total: 40.6 gal
- Today: 40.6 gal
- Avg: 31 gal

- Laundry Machine: Today 40 gal, Avg 30 gal
- Laundry Sink: Today 0.6 gal, Avg 1 gal

Friday June 15th | 9:30 PM
DESIGN SET 2: DESIGN PROBES

Design Probes Explored

Time-Series

Spatial

Aquatic Eco-system

Rainflow

Per-Occupant

Other
## DESIGN SET 2: DESIGN PROBES

### Per-Occupant View

#### Personal Usage Totals

<table>
<thead>
<tr>
<th>Person</th>
<th>Overall Usage So Far Today</th>
<th>Showers So Far Today</th>
<th>Last 30 Days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>overall</td>
<td>daily avg</td>
<td>showers</td>
</tr>
<tr>
<td>Son</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>42</td>
<td>59</td>
<td>24</td>
</tr>
<tr>
<td>Mom</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>95</td>
<td>22</td>
</tr>
<tr>
<td>Dad</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>67</td>
<td>129</td>
<td>26</td>
</tr>
<tr>
<td>Daughter</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>65</td>
<td>53</td>
</tr>
</tbody>
</table>
DESIGN SET 2: DESIGN PROBES

**Design Probes Explored**

**Time-Series**

**Spatial**

**Aquatic Eco-system**

**Rainflow**

**Per-Occupant**

**Other**

*Images and diagrams showing various data visualizations and ecological systems.*
DESIGN SET 2: DESIGN PROBES

Aquatic Ecosystem Design Influences

ubifit
Consolvo et al., CHI2008
Consolvo et al., UbiComp2008

ubigreen
Froehlich et al., CHI 2009
DESIGN SET 2: DESIGN PROBES

Aquatic Ecosystem View

- Water savings tracker
- Water savings goal met
- "Frank" the fish meets his mate
- "Frank" the fish
- Frank and his mate have children
- Display is also interactive so fish respond to touch
- And so on...

DESIGN SET 2: DESIGN PROBES

Aquatic Ecosystem View

- Water savings tracker
- Water savings goal met
- "Frank" the fish meets his mate
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- Frank and his mate have children
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- And so on...
DESIGN SET 2: DESIGN PROBES

Design Probes Explored

- **Time-Series**
- **Spatial**
- **Aquatic Eco-system**
- **Rainflow**
- **Per-Occupant**
- **Other**
DESIGN SET 2: DESIGN PROBES

Rainflow View
DESIGN SET 2: DESIGN PROBES

Rainflow  View Movie
DESIGN SET 2: DESIGN PROBES

Design Probes Explored

- Time-Series
- Aquatic Eco-system
- Spatial
- Rainflow
- Per-Occupant
- Other

- Water Usage in Gallons Today
- Water Usage in Gallons This Year
- Today's Water Usage in Gallons
- Your Daily Water Use Compared to State Averages in Gallons
- Per-Capita Comparison
DESIGN SET 2: DESIGN PROBES

Other Design Probes

Geographic Comparisons

Dashboards

Metaphorical Unit Designs

Recommendations
Evaluation
Informal interviews with water experts (e.g., SPU, Amy Vickers)
UW Environmental Practicum on water
Literature review of water resource management, environmental psychology
Our own online survey of water usage attitudes & knowledge (N=656 respondents)

Online interactive survey of designs (N=651 respondents)
In-home interviews (10 households, 20 adults)

Informed by gathered data
Guided by eco-feedback design space

Design critique sessions with team
Three sets of pilot studies

Formative Evaluation
Online Survey

Recruitment
- Online postings and word-of-mouth

Survey Design
- 63 questions (10 optional)
- Question and answer order randomized when possible

Collected Data
- 712 completed surveys (651 from US or Canada)
- Nearly 6,000 qualitative responses
Most people receive information on their water usage from a monthly or bi-monthly bill. We are working on a new type of system that can immediately show people how much water they are using at each fixture in their home. This information could be viewed, for example, on a mobile phone, on a laptop, a digital picture frame, or on an in-home touchscreen display.

In this survey, we'll explore different ways of visually displaying water usage information. Unless otherwise noted, each design is based on an average North American household of four people with two adults and two teenagers.

First, though, we need to ask some demographic questions.
We are also interested in whether people want information on hot water usage vs. cold water usage. Display (a) treats all water usage the same (whether hot or cold), while display (b) breaks down water usage by hot water and cold water amounts.

Like before, please mouse over the thumbnails on the left below to see enlarged versions of the display so that you can easily compare the two designs.

22. Which display do you prefer? *
Click on the image below to make your selection.
In-Home Interviews

Recruitment
- Online postings and word-of-mouth
- Specifically recruited families

Interview Method
- Semi-structured with two researchers
- 90-minutes, 3-phases
- Data coded by two researchers into themes

Participants
- 10 households (20 adults)
- 11 female/9 male
- Diff. socio-economic backgrounds & occupations
- 18 had college degrees
For both the survey and interviews, 90% of participants indicated an interest in conserving water.

Average morning shower uses 400 gallons of water.
Findings
This display lets you more easily identify the specific areas that need attention.

Majority preferred the Individual Fixture Display.
Data Granularity

coarse-grain ≥ neighborhood home room activity fixture category fixture ≤ valve fine-grain

This display lets you more easily identify the specific areas that need attention.

R536

Majority preferred the Individual Fixture Display.
20% preferred the Activity Display
71% of respondents preferred to see both gallons and cost. Seeing the gallon amount triggers the ‘save the environment’ impulse to conserve, while the dollar amount is helpful because almost everyone is motivated by money to some extent. I don't think very well in ‘thousands of gallons’, but $20 I can understand. That’s a case of beer down the drain, if you will.
Comparisons were the most uniformly desired pieces of information of all the dimensions
Self-comparison was most preferred
91%
Emergent Themes

1. Competition and Cooperation
2. Accountability and Blame
3. Playfulness and Functionality
4. Sense of Privacy
5. Display Placement
Competition and Cooperation

You can compare usage to others, and create friendly competition.

It pits the family members against each other rather than encouraging collaboration.

[It] sets up a ‘competitive’ environment that we are trying not to create in our household.
Accountability and Blame

This display could set up a 'competitive' environment that we are trying not to create in our household."

It holds each individual accountable for water usage

There’s no reason to add an element of ‘blame’ to conservation efforts within a family

Would seem to lead to plenty of arguments about usage
Playfulness and Functionality

I like the idea of getting rewards for saving water

I8.2

It’s like unlocking badges in Foursquare. No matter how trivial it can be to make a fish appear on this screen, you still want to do it

I4.1

It doesn’t appeal to me as much. I don’t do Foursquare. This distracts me a little bit and it doesn’t make me think about my usage

I4.2
Useful as an educational tool?
This display could set up a ‘competitive’ environment that we are trying not to create in our household. It would seem to lead to plenty of arguments about usage.
It’s incredibly invasive. And other people’s water consumption is not my business.
Water usage for many purposes can be very personal, and shouldn’t be automatically shared.
This display could set up a 'competitive' environment that we are trying not to create in our household. 

Would seem to lead to plenty of arguments.
Display Location Preferences
If we placed the display here, the kids couldn’t see it.
Display Location Preferences

- kitchen
- near thermostat
- high traffic areas
- accessible when needed
hydroSENSE algorithms

1. minimal training set
2. cross-home training
3. unsupervised learning
EPA estimates that 1 trillion gallons of water are lost due to leaks in homes every year.
can hydrosense be used to detect certain leaks?
behavioral patterns of water usage

<table>
<thead>
<tr>
<th>home1</th>
<th>home2</th>
<th>home3</th>
</tr>
</thead>
<tbody>
<tr>
<td>midnight</td>
<td>6am</td>
<td>noon</td>
</tr>
<tr>
<td>morning routine</td>
<td>gone to work</td>
<td>morning routine</td>
</tr>
<tr>
<td>evening kitchen activity</td>
<td>bedtime routine</td>
<td>evening kitchen activity</td>
</tr>
</tbody>
</table>

How predictable are home water usage patterns?
how can hydrosense be used to support aging in place applications?
Today's Water Usage in Gallons

Individual Fixture View

- Bathroom 1:
  - Hand Sink: 1,145 gallons
  - Toilet: 2,996 gallons

- Bathroom 2:
  - Hand Sink: 1,507 gallons
  - Toilet: 4,328 gallons

- Back Room:
  - Hand Sink: 2,803 gallons
  - Dish Sink: 6,290 gallons
  - Dish Sanitizer: 815 gallons

- Cafe:
  - Sink: 3,254 gallons
  - Espresso Machine: 1,080 gallons
  - Espresso Machine: 961 gallons
  - Coffee Brewer: 3,401 gallons
This Month’s Water Usage in Gallons

Individual Fixture View

<table>
<thead>
<tr>
<th>Fixture</th>
<th>Gallons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evaporative Condenser</td>
<td>85,105</td>
</tr>
<tr>
<td>Ice Machines</td>
<td>2,232</td>
</tr>
<tr>
<td>Hand Sinks</td>
<td>9,859</td>
</tr>
<tr>
<td>Food Sinks</td>
<td>19,985</td>
</tr>
<tr>
<td>Dish Sinks</td>
<td>16,392</td>
</tr>
<tr>
<td>Hose Sprayers</td>
<td>9,343</td>
</tr>
<tr>
<td>Hand Sprayers</td>
<td>5,920</td>
</tr>
<tr>
<td>Produce Spayers</td>
<td>14,780</td>
</tr>
<tr>
<td>Garbage Disposal</td>
<td>24,087</td>
</tr>
<tr>
<td>Urinals</td>
<td>792</td>
</tr>
<tr>
<td>Toilets</td>
<td>5,512</td>
</tr>
</tbody>
</table>
Closing Thought

Eco-feedback displays do not just visualize consumption, they document household activities.
acknowledgements

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**hydroSense**

HydroSense: Infrastructure-Mediated Single-Point Sensing of Whole-Home Water Activity  
Jon Froehlich, Eric Larson, Tim Campbell, Conor Haggerty, James Fogarty, Shwetak N. Patel, *Proc. of Ubicomp 2009*

Disaggregated Water Sensing From a Single, Pressure-Based Sensor: An Extended Analysis of HydroSense Using Staged Experiments  

**WATTt:** A Method for Self-Powered Wireless Sensing of Water Activity in the Home  
Tim Campbell, Eric Larson, Gabe Cohn, Jon Froehlich, Ramses Alcaide, Shwetak N. Patel, *Proc. of UbiComp 2010*

A Longitudinal Study of Pressure Sensing to Infer Real-World Water Usage Events in the Home  

**reflect2O**

The Design and Evaluation of Prototype Eco-Feedback Displays for Fixture-Level Water Usage Data  

Sensing and Feedback of Everyday Activities to Promote Environmental Behaviors  
Jon Froehlich, *UW Doctoral Dissertation 2011*

**other eco-feedback publications**

The Design of Eco-Feedback Technology  
Jon Froehlich, Leah Findlater, James Landay, *Proc. of CHI 2010*

UbiGreen: Investigating a Mobile Tool for Tracking and Supporting Green Transportation Habits  
Jon Froehlich, Tawanna Dillahunt, Predrag Klasnja, Jennifer Mankoff, Sunny Consolvo, Beverly Harrison, James A. Landay, *Proc. of CHI 2009*

Disaggregated End-Use Energy Sensing for the Smart Grid  

GasSense: Appliance-Level, Single-Point Sensing of Gas Activity in the Home  
Gabe Cohn, Sidhant Gupta, Jon Froehlich, Eric Larson, Shwetak Patel, *Proc. of Pervasive 2010*
Questions?

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