Infrastructure-Mediated Single-Point Sensing of Whole-Home Water Activity

Jon Froehlich¹, Eric Larson², Tim Campbell³, Conor Haggerty⁴, James Fogarty¹, Shwetak N. Patel¹,²

¹Computer Science & Engineering, ²Electrical Engineering, ³Mechanical Engineering, ⁴Community, Environment, and Planning
water scarcity

Water stress indicator (WSI) in major basins:

Sources: Smakhtin, Revena and Döll, 2004.
barcelona, spain
Lake Mead, Nevada
what are the most consuming water activities in your home?

average indoor household water usage per person/day (70 gpd)

- Toilets
- Clothes Washer
- Showers
- Faucets
- Leaks
- Other Domestic
- Baths
- Dishwasher

Vickers, 2001
• single-point pressure-based sensor of water usage

• identifies water usage activity down to fixture level (e.g., toilet)

• provides estimates of flow at each fixture
the hydro sensor prototype

Pressure Sensor

16-bit ADC

20 MHz Microcontroller

Class 1 Bluetooth Radio

3D-Printed Enclosure

the hydro sensor prototype
brief plumbing primer
brief plumbing primer

- Water tower
- incoming cold water from supply line

Gauge reading:
- 100 psi
- 40 psi

Pressure conversion:
- 1 psi = 6.89 kPa
closed pressure system

- Water tower
- Incoming cold water from supply line
- Pressure regulator
- Thermal expansion tank
- Hot water heater
- Laundry
- Bathroom 1
  - Hose spigot
  - Bathroom 2
  - Kitchen
    - Dishwasher
some possible installation points

water tower

in incoming cold water from supply line

thermal expansion tank

hose spigot

hot water heater

pressure regulator

bathroom 1

dishwasher

kitchen

laundry

bathroom 2
raw bathroom sink signal

- Open valve
- Stabilized pressure drop
- Close valve

Graph showing psi over time (t) with a sudden drop and subsequent stabilized period, followed by a spike and oscillation.
detecting water usage events

1. detect a water event
2. classify event as “open” or “close”
3. determine source of event (e.g., toilet, kitchen sink).
4. provide flow estimate
event detection

raw pressure (psi)

time (s)
event detection

- raw pressure (psi)
- smoothed pressure
- derivative

Critical change in pressure
event detection

raw pressure (psi)

smoothed pressure

derivative

time (s)
event detection

- **raw pressure (psi)**
  - Graph showing raw pressure over time.
  - Detected event highlighted.

- **smoothed pressure**
  - Graph showing smoothed pressure over time.
  - Pressure decrease and negative initial derivative indicated.
  - Red dot at time (s) mark.

- **derivative**
  - Graph showing derivative over time.
  - Red line indicating pressure decrease and negative initial derivative.

**Conclusion**

- Pressure decrease and negative initial derivative at time (s) mark indicate a valve open event.
event detection

raw pressure (psi)

smoothed pressure

derivative

valve open event

time(s)
event detection

raw pressure (psi)

smoothed pressure

derivative

time(s)

valve open event

automatically detected event

pressure increase

= valve close event

and positive initial derivative
example open events

signature dependent on:
- fixture type
- valve type
- valve location in home
fixture classification

- unclassified open event
- open event library

- bath tub
- bath faucet
- kitchen faucet
- dishwasher
- toilet
- shower
test similarity

detrended_{unclassified} 

detrended_{shower}

\textbf{matched filter}

\textbf{matched filter}

derivative_{unclassified} 

\textbf{matched filter}

\textbf{matched filter}

cepstrum_{unclassified} 

\textbf{matched filter}

\textbf{matched filter}

cepstrum_{shower}
unclassified open event

open event library

possible events

detrended

derivative

cepstrum
nearest neighbor match

derivative_{\text{unclassified}}

derivative_{\text{shower}}

derivative_{\text{toilet}}

derivative_{\text{kitchen faucet}}

possible events
raw bathroom sink signal

This is $\Delta P$

stabilized

pressure drop

open

close

time (t)
using $\Delta$ pressure to estimate flow

Poiseuille’s law:

$$Q = \frac{\Delta P \pi r^4}{8 \mu L}$$

Fluid resistance formula:

$$R_f = \frac{\Delta P}{Q}$$

$\Delta P = \text{change in pressure}$

$L = \text{length of pipe}$

$r = \text{radius of pipe}$

$\mu = \text{viscosity of liquid}$

$Q = \text{volumetric flow rate}$
using $\Delta$ pressure to estimate flow

$\Delta P = \text{change in pressure}$
$L = \text{length of pipe}$
$r = \text{radius of pipe}$
$\mu = \text{viscosity of liquid}$
$Q = \text{volumetric flow rate}$

$$Q = \frac{\Delta P}{R_f}$$
acquiring $R_f$

$$R_f = \frac{\Delta P}{Q}$$

$$Q = \frac{\Delta P}{R_f}$$
in-home data collection
home profiles

ten locations
- 8 houses
- 1 apt / 1 cabin

size
- avg: 2,300 sq ft
- min: 750 sq ft
- max: 4,000 sq ft

install point:
- 8 hose bib
- 1 water heater
- 1 utility faucet
experimental protocol

- controlled experiments
- 2 researchers per site
- 5 trials per valve
  - e.g., 5 cold / 5 hot for bathroom sink
- for each trial, valve open for 5 seconds, then closed
collecting flow data

- 4 / 10 homes gathered flow data
- measure time to fill 1 gallon in a calibrated bucket
- this provides $Q$, allowing us to solve for $R_f$

$- R_f = \Delta P / Q$
data collection stats

- ten locations
- 706 trials
- 155 flow rate trials
- 84 total fixtures tested
classification results across homes

• cross validation experiment
• learn similarity thresholds from test data
• classify each event per home using a leave-one-out method
fixture classification results across homes

- Open Events
- Close Events

- H1 (12 valves) 100%
- H2 (8 valves) 98.9%
- H3 (6 valves) 96.8%
- H4 (5 valves) 97.9%
- H5 (9 valves) 100%
- H6 (8 valves) 100%
- H7 (8 valves) 100%
- H8 (6 valves) 100%
- H9 (7 valves) 100%
- H10 (7 valves) 100%

Aggregate 96.8%
Overall 97.9%
fixture classification results across homes

Open Events
Close Events

<table>
<thead>
<tr>
<th>Home</th>
<th>Valves</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1</td>
<td>12</td>
</tr>
<tr>
<td>H2</td>
<td>8</td>
</tr>
<tr>
<td>H3</td>
<td>6</td>
</tr>
<tr>
<td>H4</td>
<td>5</td>
</tr>
<tr>
<td>H5</td>
<td>9</td>
</tr>
<tr>
<td>H6</td>
<td>8</td>
</tr>
<tr>
<td>H7</td>
<td>8</td>
</tr>
<tr>
<td>H8</td>
<td>6</td>
</tr>
<tr>
<td>H9</td>
<td>7</td>
</tr>
<tr>
<td>H10</td>
<td>7</td>
</tr>
<tr>
<td>Aggregate</td>
<td></td>
</tr>
<tr>
<td>Overall</td>
<td></td>
</tr>
</tbody>
</table>

Overall accuracy: 97.9%
fixture classification results across fixtures

- Sinks: 98% Open, 95% Close
- Toilets: 99% Open, 98% Close
- Showers: 96% Open, 89% Close
- Bathtubs: 100% Open, 100% Close
- Clothes Washer: 100% Open, 100% Close
- Dishwasher: 100%
<table>
<thead>
<tr>
<th>Home</th>
<th>Avg Error (GPM)</th>
<th>Stdev Error (GPM)</th>
<th>Avg Error (%)</th>
<th>Stdev Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1</td>
<td>0.17</td>
<td>0.13</td>
<td>7.3</td>
<td>6.7</td>
</tr>
<tr>
<td>(7 valves)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H4</td>
<td>0.19</td>
<td>0.17</td>
<td>5.6</td>
<td>5.3</td>
</tr>
<tr>
<td>(6 valves)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H5</td>
<td>0.13</td>
<td>0.11</td>
<td>4.5</td>
<td>5.5</td>
</tr>
<tr>
<td>(8 valves)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H7</td>
<td>0.67</td>
<td>1.47</td>
<td>22.2</td>
<td>46.0</td>
</tr>
<tr>
<td>(8 valves)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Home</td>
<td>Avg Error (GPM)</td>
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</tr>
<tr>
<td>---------</td>
<td>-----------------</td>
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<td>6.7</td>
</tr>
<tr>
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<td>0.19</td>
<td>0.17</td>
<td>5.6</td>
<td>5.3</td>
</tr>
<tr>
<td>H5 (8 valves)</td>
<td>0.13</td>
<td>0.11</td>
<td>4.5</td>
<td>5.5</td>
</tr>
<tr>
<td>H7 (4 valves)</td>
<td>0.15</td>
<td>0.18</td>
<td>4.5</td>
<td>3.8</td>
</tr>
</tbody>
</table>
acquiring $R_f$

$$R_f = \frac{\Delta P}{Q}$$

$$Q = \frac{\Delta P}{R_f}$$

incoming cold water from supply line

pressure regulator

thermal expansion tank

hot water heater

laundry

bathroom 1

hose spigot

kitchen

dishwasher

bathroom 2
acquiring $R_f$

\[ R_f = \frac{\Delta P}{Q} \]

\[ Q = \frac{\Delta P}{R_f} \]
flow estimation using interpolated $R_f$

After 5 $R_f$ samples, average error is 0.27 GPM
future work: hydrosense 2.0
longitudinal data collection
water feedback interfaces
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jonfroehlich@gmail.com
http://sustain.cs.washington.edu/blog
flow estimation
typical water meters - only provide aggregate information on water usage and require pipe modification for installation.

easy-to-install
matched filtering

save maximum similarity
matched filtering

new maximum similarity
**Municipal Services Statement**

**Account Number:** 100687-00154711

**Utility Amount Due:** $127.52

**Voluntary Donation:** $1.00

**Total + Voluntary Donation:** $128.52

**Date Due:** 1/8/2007

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**Account Activity**

<table>
<thead>
<tr>
<th>Date</th>
<th>Description</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>12/12</td>
<td>Water Quality Fee</td>
<td>0.13</td>
</tr>
<tr>
<td>12/12</td>
<td>City Tax</td>
<td>0.61</td>
</tr>
<tr>
<td>12/12</td>
<td>Sewer Service Charge</td>
<td>7.28</td>
</tr>
<tr>
<td>12/12</td>
<td>Water Consumption</td>
<td>100.00</td>
</tr>
<tr>
<td>12/12</td>
<td>Water Service Charge</td>
<td>2.15</td>
</tr>
<tr>
<td>12/12</td>
<td>1% Disinfectant Fee</td>
<td>11.48</td>
</tr>
<tr>
<td>12/12</td>
<td>Sewer Charge</td>
<td>17.41</td>
</tr>
</tbody>
</table>

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**Billing period:** 12/2006

**Previous meter reading:** 16305

**Gallons delivered:** 20,200

**Date read:** 11/20/2006

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**Service Address:** 7450 S KENWOOD LN

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**Amounts due:**
- Water Consumption: $100.00
- Water Service Charge: $2.15
- 1% Disinfectant Fee: $11.48
- Sewer Charge: $17.41
- Residential Refuse: $7.28

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**53 Cents of every dollar goes toward water treatment costs**

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**Payment Options:**
- Checks payable to the City of Tempe.
- Major credit cards (VISA, Mastercard, American Express, Discover) accepted.

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**Due Date:** 1/8/2007

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**Please fold before tearing**