Smart Meter-Enabled Estimation and Prediction of Outdoor Water Consumption

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Background & Motivation

Smart Meters

- Smart meters allow logging, storage, and transmission of water consumption measurements.
- Water consumption measurements can be processed and analysed like any other signal. More frequent measurements allow more detailed analysis.
- Higher-frequency measurements useful for short-term demand forecasting and giving insight into when and how water is used.

Summer Water Demand in Abbotsford

Abbotsford installed smart meters in 2010 to help with detecting leaks, targeting conservation initiatives, and reducing meter reading costs.

Abbotsford is particularly concerned with **peak demand** , which occurs in July and August, in order to reduce need for infrastructure upgrades.

Outdoor water consumption is an important component in peak demand in summer:

- Watering restrictions: Two days a week per household, 6:00 am to 8:00am.
- Other initiatives: seasonal water rates, education about efficient irrigation.

Outdoor Water Consumption

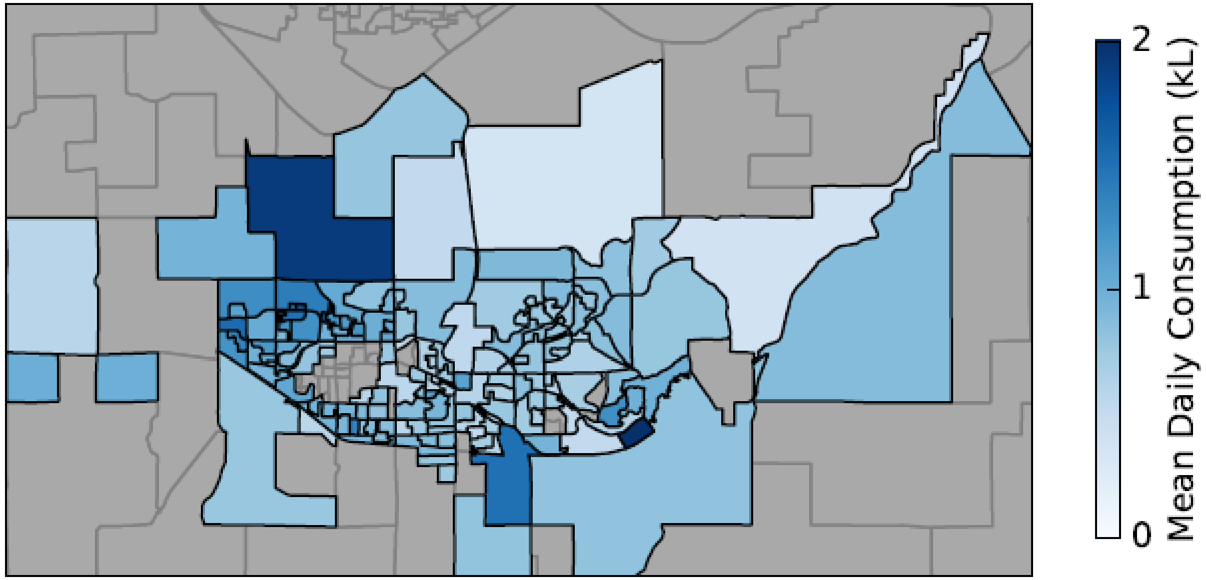
Outdoor water consumption is a important component of peak demand from residential households. Therefore, it is useful to be able to:

1. Identifying outdoor water consumption from already-available data (hourly measurements of total consumption for a household).
2. Predict future outdoor water consumption. This work focuses on next-hour prediction (useful mostly for operational purposes).
3. Explain what factor influence outdoor water consumption and how it varies between households.

Dataset

Datasets - Abbotsford

- Hourly water consumption data for 8229 single family residences from September 2012 to August 2013
- Daily rainfall and temperature
- Property assessment data for individual households
- National Household Survey (NHS) data at small neighbourhood (dissemination area) level



Summer water consumption by dissemination area

Identifying Outdoor Water Consumption

Previous work: Disaggregation

Disaggregation: Breaking a measurement of total water consumption into end uses (such as running taps, showers, irrigation).

Most approaches to identifying individual end uses limited by metering frequency and availability of ground truth. Equipment and installation costs limit study sizes.

Previous work: Outdoor Water Consumption

Identifying **outdoor** consumption is somewhat more straightforward because it has clear seasonal patterns and many uses are high-volume (lawn irrigation, filling pools).

Simple approaches subtract monthly consumption in winter from monthly consumption in summer. Drawbacks: indoor consumption may have slight seasonal patterns, and these approaches cannot show timing of outdoor consumption over hours or weeks.

Previous Work: Cole & Stewart (2013)

Intuition: Outdoor uses are high-volume, so it's possible to determine upper limit on plausible indoor usage in one hour

Hourly outdoor consumption:

$$y_{outdoor} = \begin{cases} 0, & y_{total} < 300L \\ y_{total}, & otherwise \end{cases}$$

Limitations: Sharp changes in outdoor consumption around threshold, validation for threshold

Approach

Maintain basic assumptions from Cole and Stewart: Outdoor uses are high volume and occur primarily in summer

Estimate in a way suitable for prediction:

$$y_{outdoor} = \max(y_{total} - t, 0)$$

$$y_{indoor} = \min(y_{total}, t)$$

How to identify and validate t? Patterns in water consumption (weekly, seasonal, by household characteristics)

Indoor Water Consumption

Most indoor uses are <100 L. Possibility of concurrent uses put plausible upper limit for indoor consumption around 200-400 L in a single hour.

Average usage per **day** is 731 L. High use per hour indicates likely outdoor consumption.

End Use	Volume
Faucet	4.9 L/min
Toilet	13.2 L/flush
Shower	65 L/shower
Clothes Washer	154 L/load
Dishwasher	37 L/load

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End Use	Volume
Faucet	4.9 L/min
Toilet	9.8 L/flush
Shower	62 L/shower
Clothes Washer	117 L/load
Dishwasher	23 L/load

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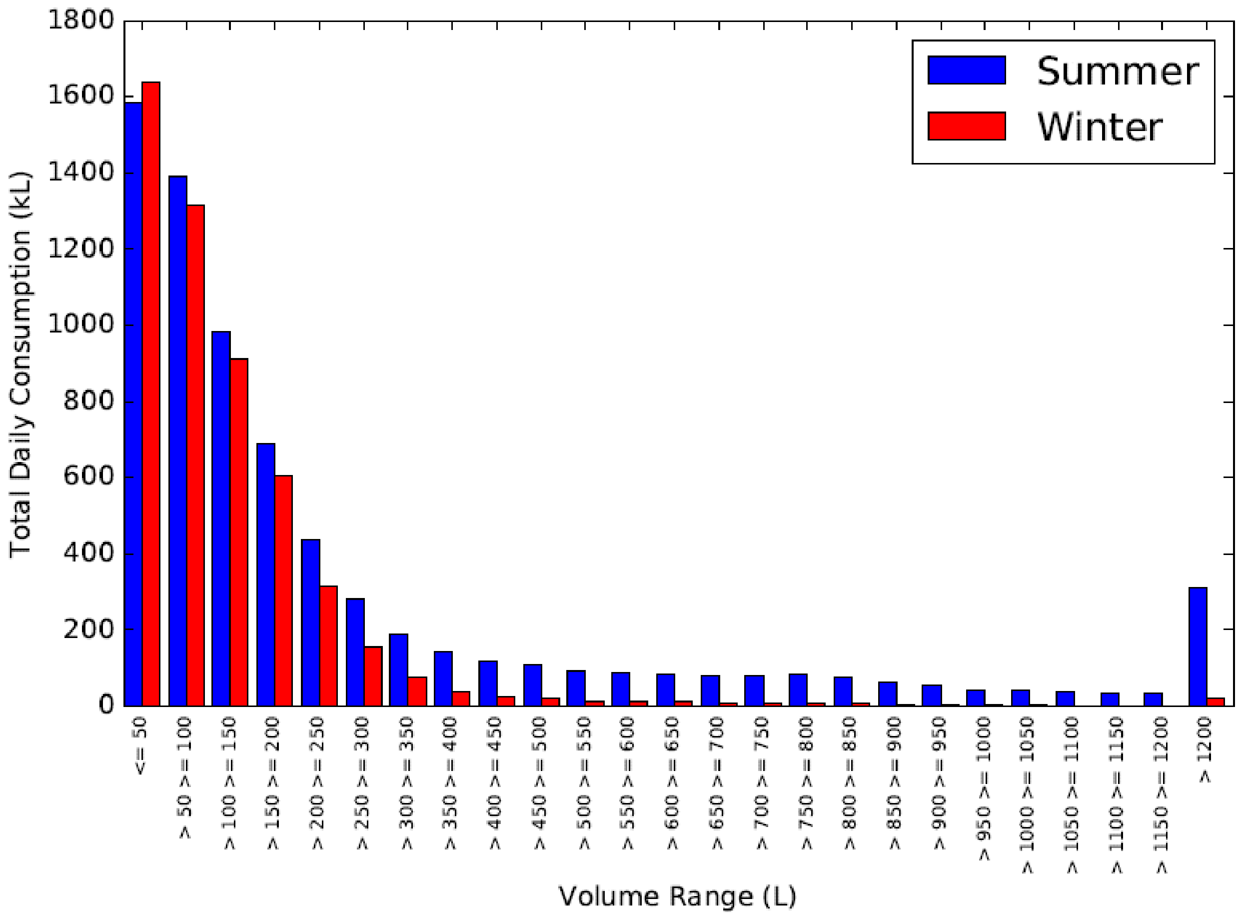
Seasonal Consumption

Consumption at low hourly volumes is similar in summer and winter

Consumption at higher volumes (>300L) much more frequent in summer



Evaluating Thresholds

Seasonal patterns and water requirements for indoor end-uses suggest a 'good' threshold is around 300L.

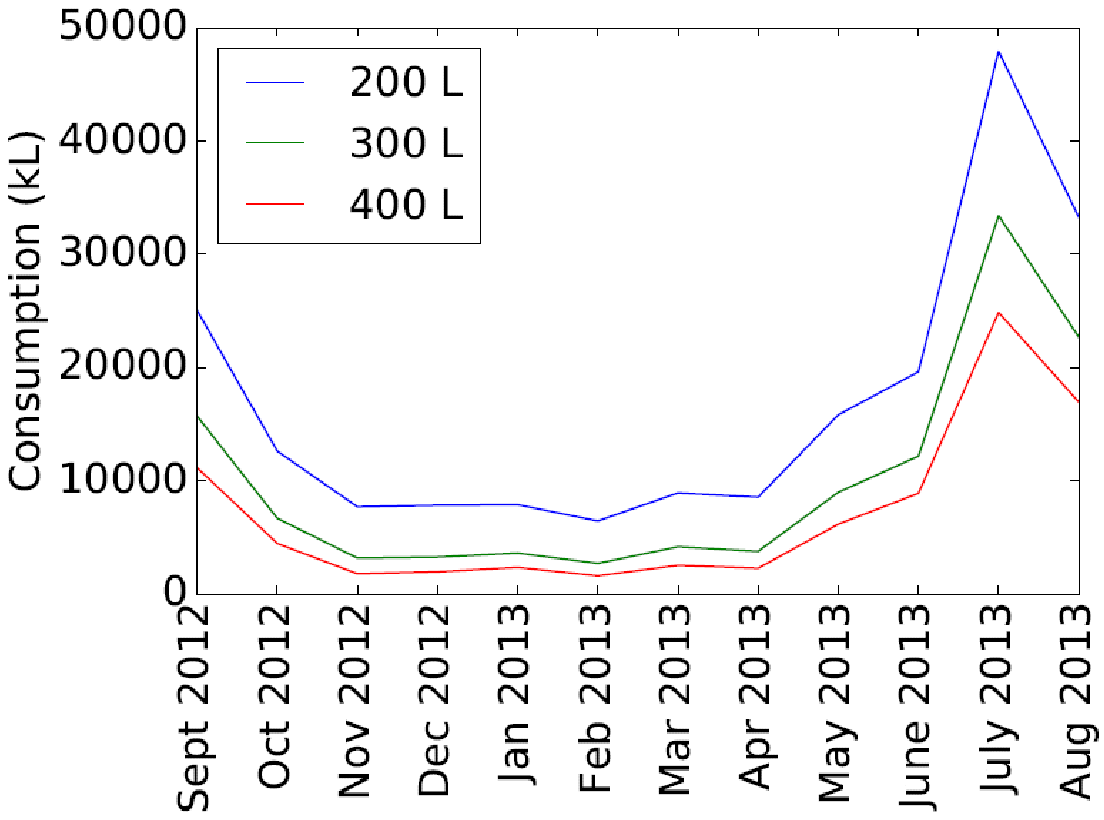
Alternative thresholds were tested to determine robustness: 200 L, 300 L, 400 L.

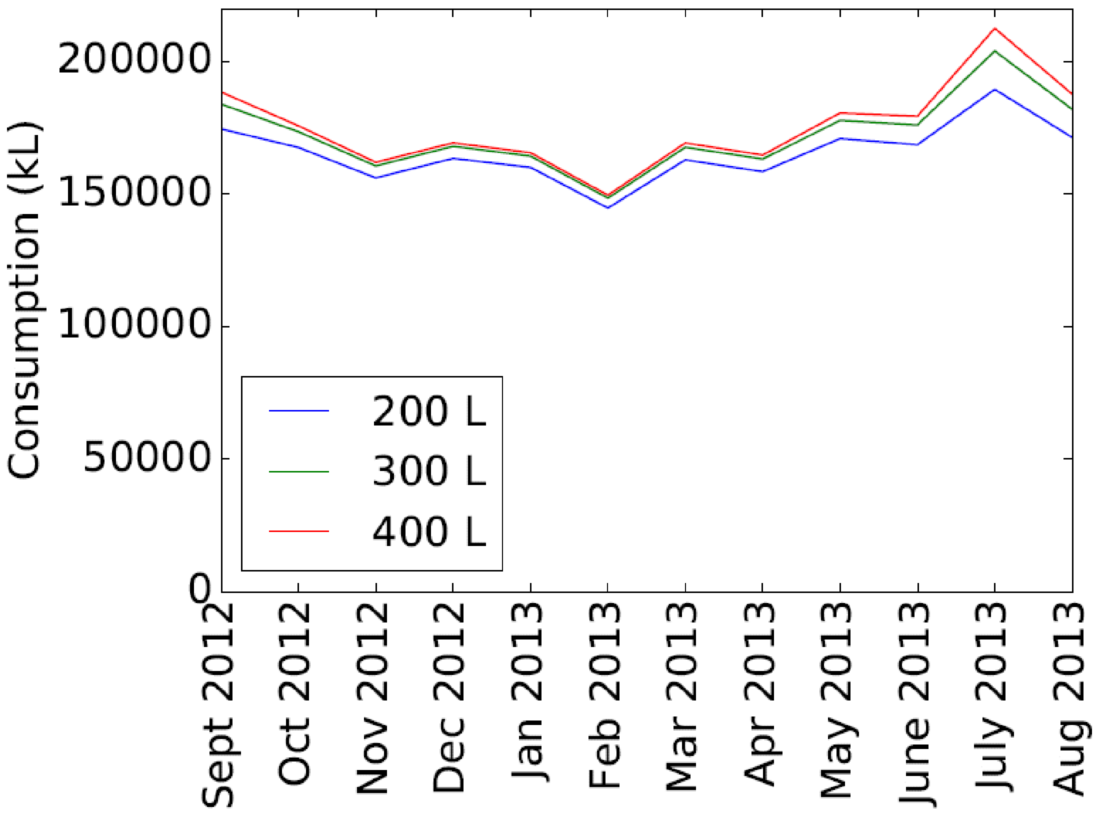
"Common sense" assumptions about outdoor water consumption:

- Occurs primarily in the summer
- Greater on days when automatic irrigation is permitted
- Relatively independent of household size

Seasonal Patterns

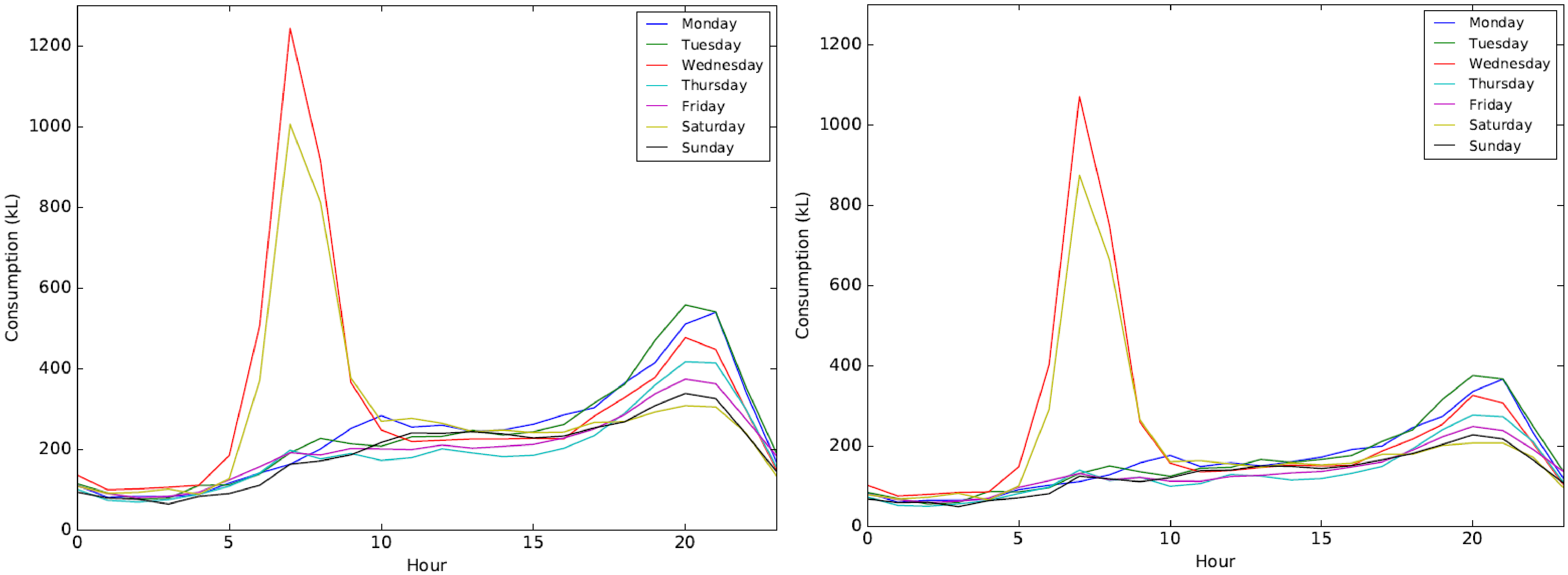
Expect low outdoor water consumption is winter and only slight seasonal pattern for indoor water consumption



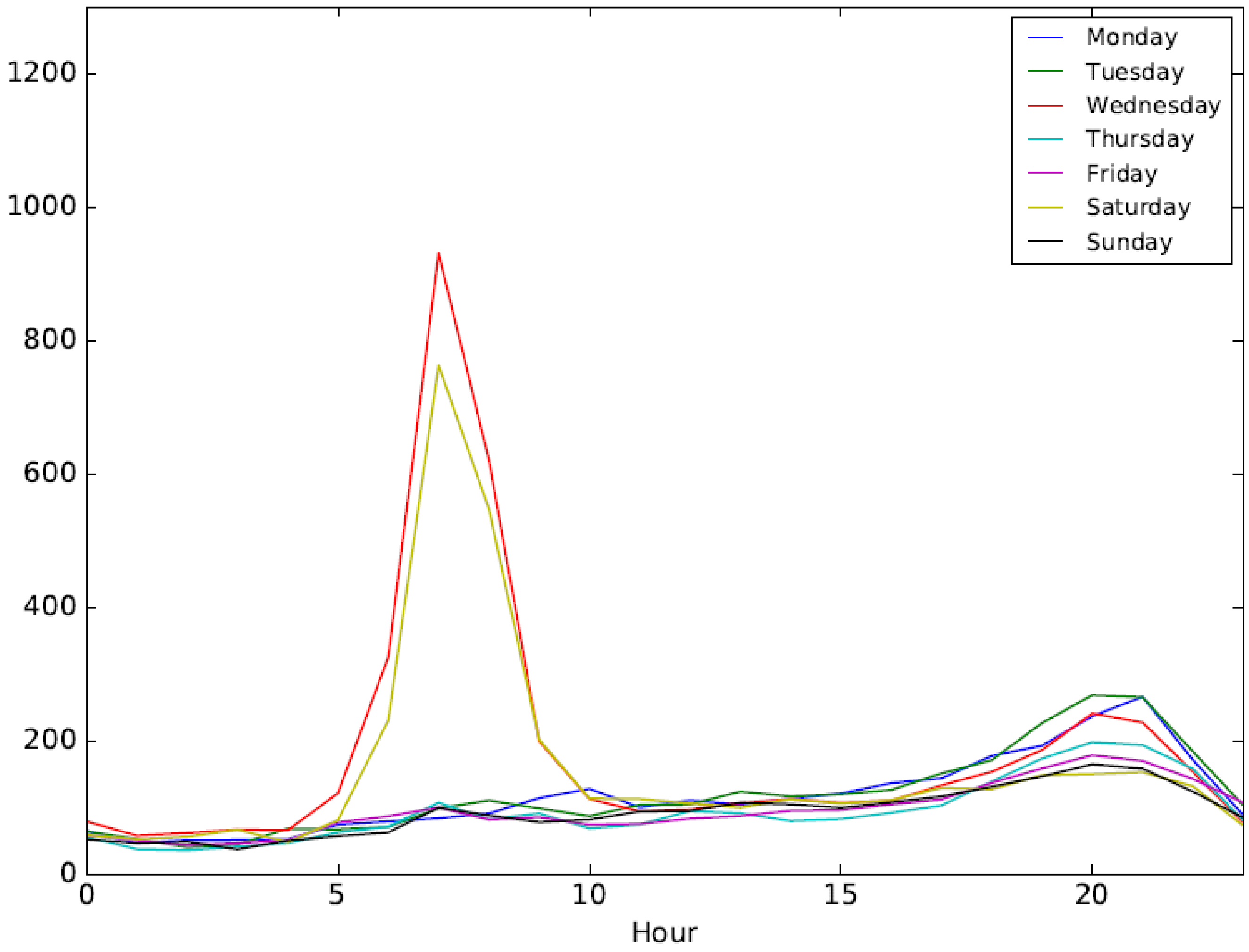


Restrictions (200 L and 300 L Threshold)

Lower thresholds show higher consumption in evening (likely indoor)

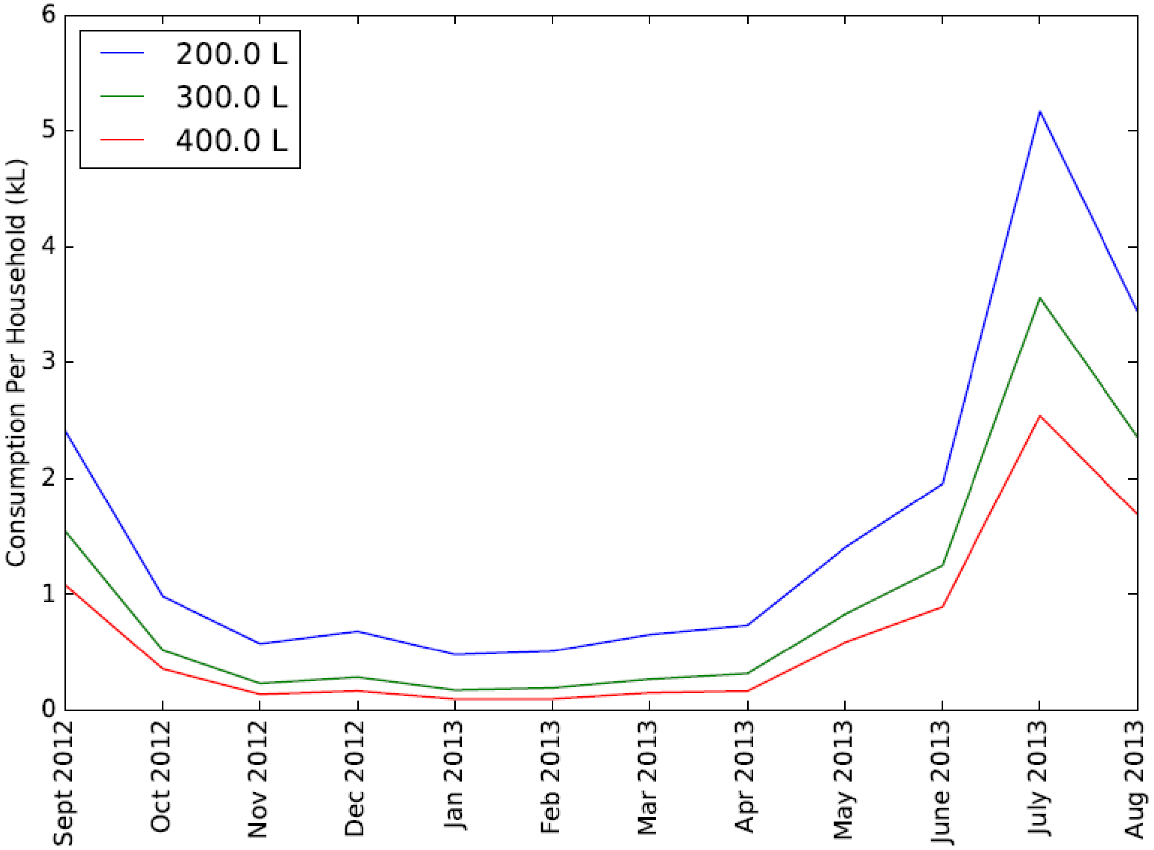


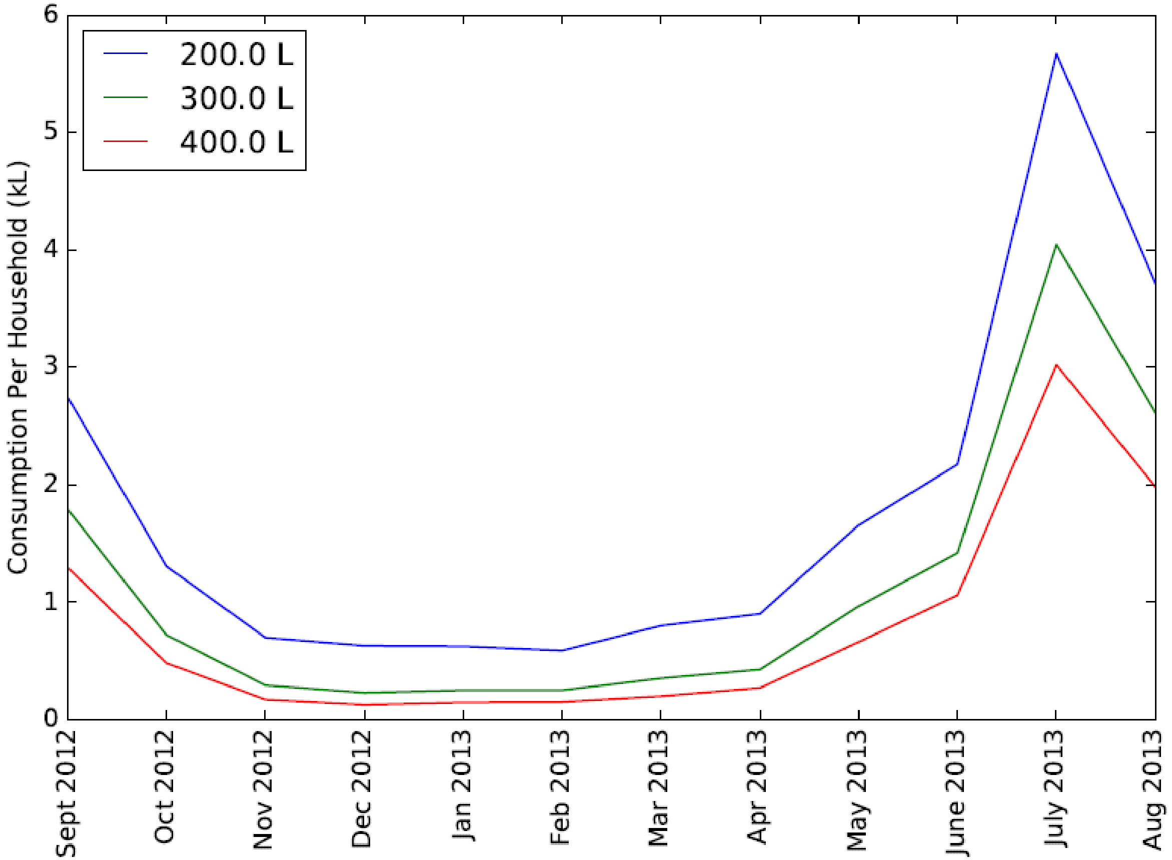
Restrictions (400 L)



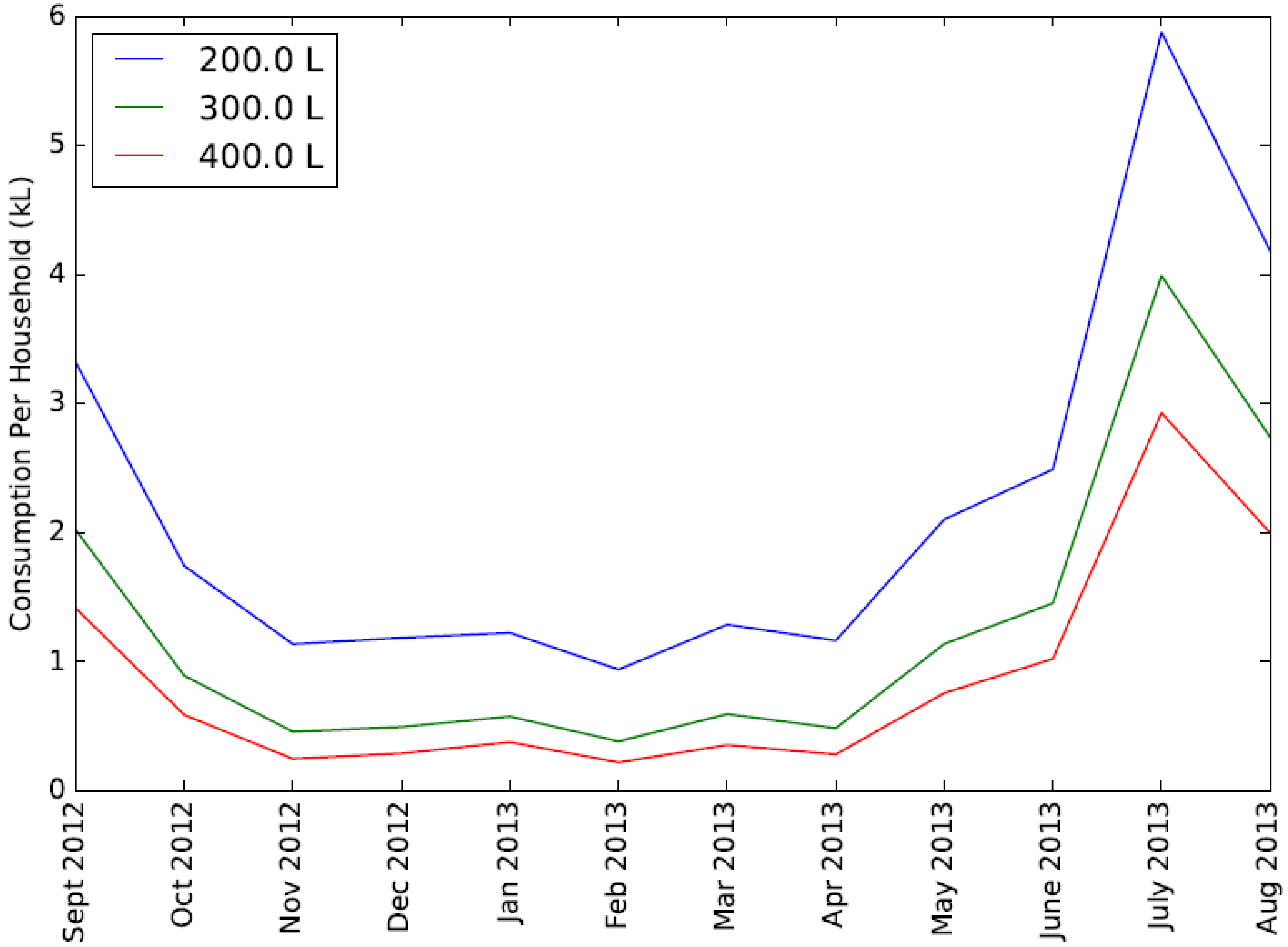
Household Size (1 & 2 , 3 bedrooms)

Number of bedrooms used as estimate of household size. Similar seasonal patterns of water consumption for different household sizes at all thresholds.





Household Size (4 Bedrooms)



Final Threshold

All threshold produce reasonable seasonal patterns, but there are tradeoffs between capturing the largest amount of outdoor consumption and capturing only outdoor consumption.

A 300 L threshold was used to produce the estimate of outdoor consumption used in other parts of this work:

- Reasonable seasonal pattern, with minimal winter water consumption
- Reflects watering restrictions
- Not significantly related to household size

Predictive Models

Related Work: Predicting Water Consumption

- Most previous work is on predicting **total** water consumption, typically for a large area (city-level or large neighbourhoods).
- Walker et al. (2015) use ANNs to predict total consumption at household level, inaccurately predicts magnitude.
- Previous work on **peak** consumption at a weekly level (Boudagis et al. 2005; Adamoski and Karapataki 2010).
- Taylor (2012) predicts **outdoor** consumption at a city level and monthly timescale

Problem

Short term modeling used for **operational** purposes by water utilities.

Predict next-hour **outdoor** water consumption in summer for small neighbourhoods (dissemination areas) from previous values of outdoor water consumption and other variables:

$$y_t = f(y_{t-1}, y_{t-2}, y_{t-3}, \dots, x_1, \dots, x_n)$$

Can be modeled as a supervised learning problem.

Models: ensembles of regression trees, chosen for interpretability.

Model Features

Previous values of water consumption: $y_{t-1}, y_{t-2}, y_{t-3}, y_{t-168}$

Other variables:

Category	Feature	Description
weather	rainfall (current)	rainfall amount
	rainfall (last 3)	rainfall amount for previous 3 days
	rain occurrence (current)	true for days when rain occcured
	rain occurrence (last 3)	true when rain occurred over last 3 days
	temperature (current)	daily high temperature
	temperature (previous)	high temperature for previous day
date	weekday	true for weekday
	watering	true for days when sprinklers are permitted
property	lot size	average lot size
	bedrooms	average number of bedrooms
	value	average value of houses
	pools	percentage of houses with pool
demographic	income	median household income
	household size	average household size

Models

Outdoor$_1$: predicts outdoor water consumption using single model for all days

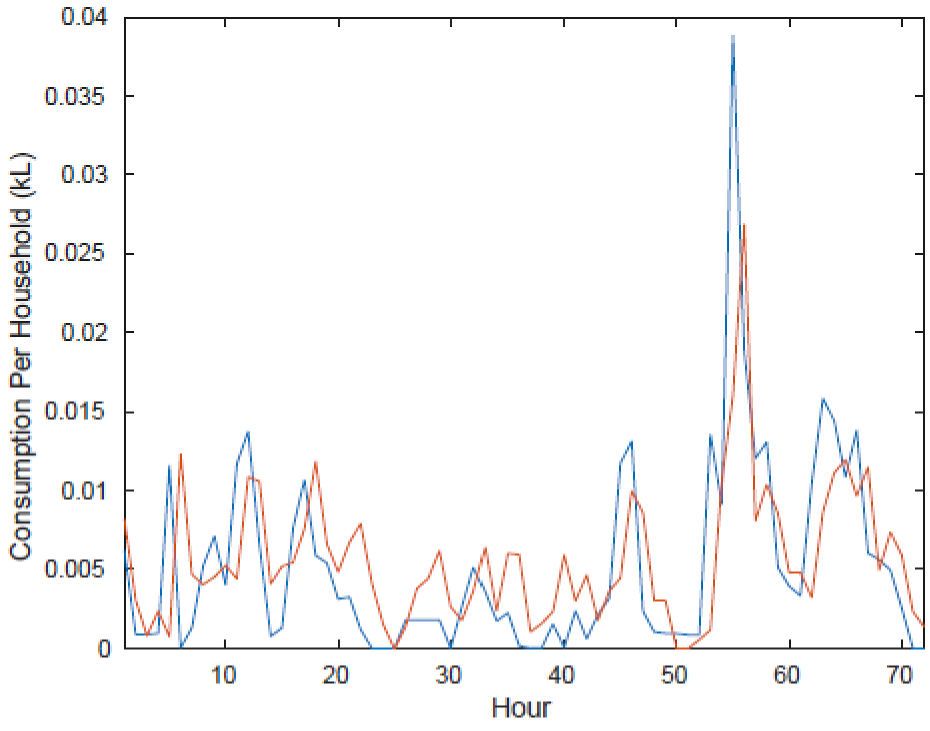
Outdoor$_2$: predicts outdoor water consumption with submodels for weekends and weekdays

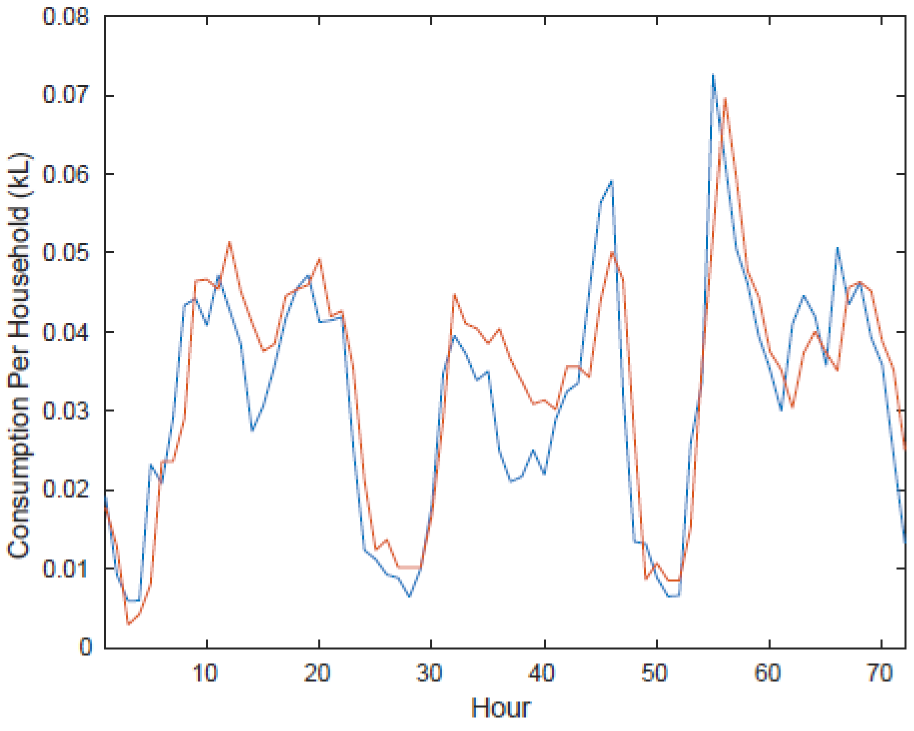
- $Outdoor_{weekday}$
- $\text{Outdoor}_{\text{weekend}}$

Total: predicts total water consumption using single model for all days

Model Performance

Outdoor1 and *Total* models for largest dissemination area

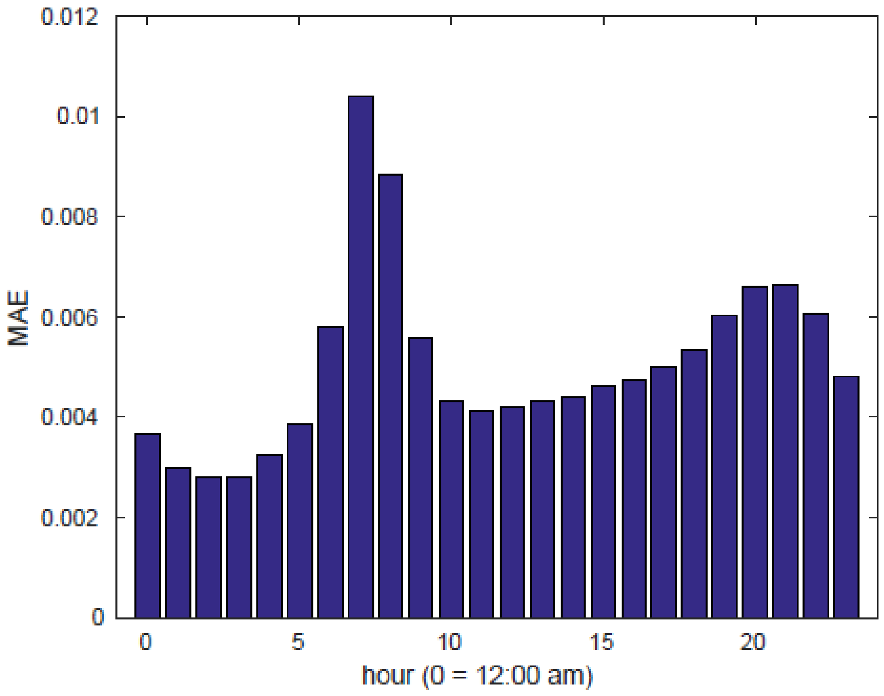




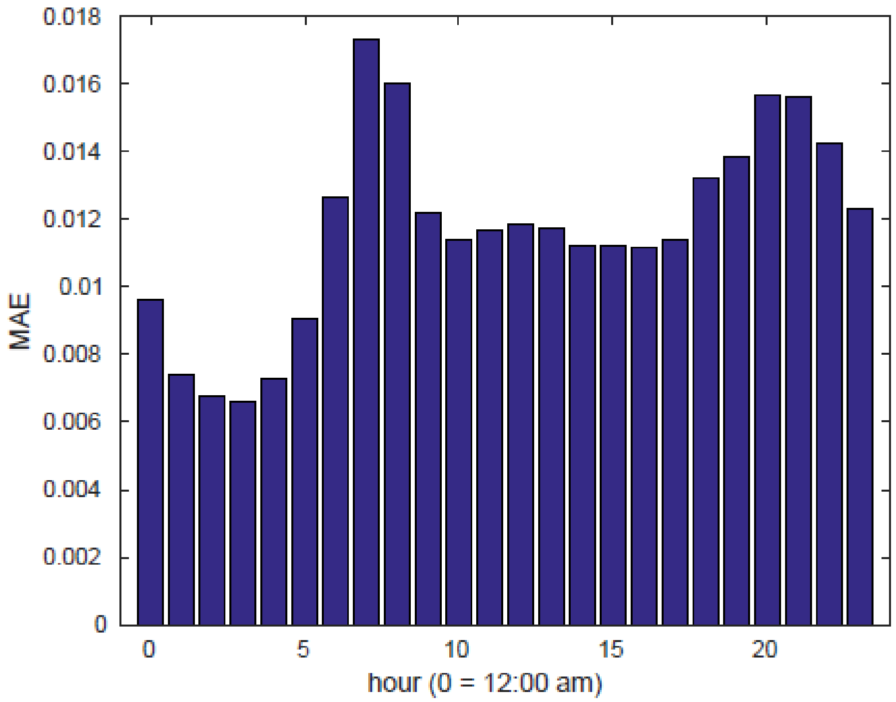
Timing of Model Errors

Greatest errors at times when irrigation is permitted

Absolute error: $|y_t - \hat{y}_t|$



MAE per hour for *Outdoor*$_1$



MAE per hour for *Total*

Summary of Results

- Similar results for $Outdoor_1$ and $Outdoor_2$ models
- Highest errors on weekends and watering days
- Average errors significantly higher than median

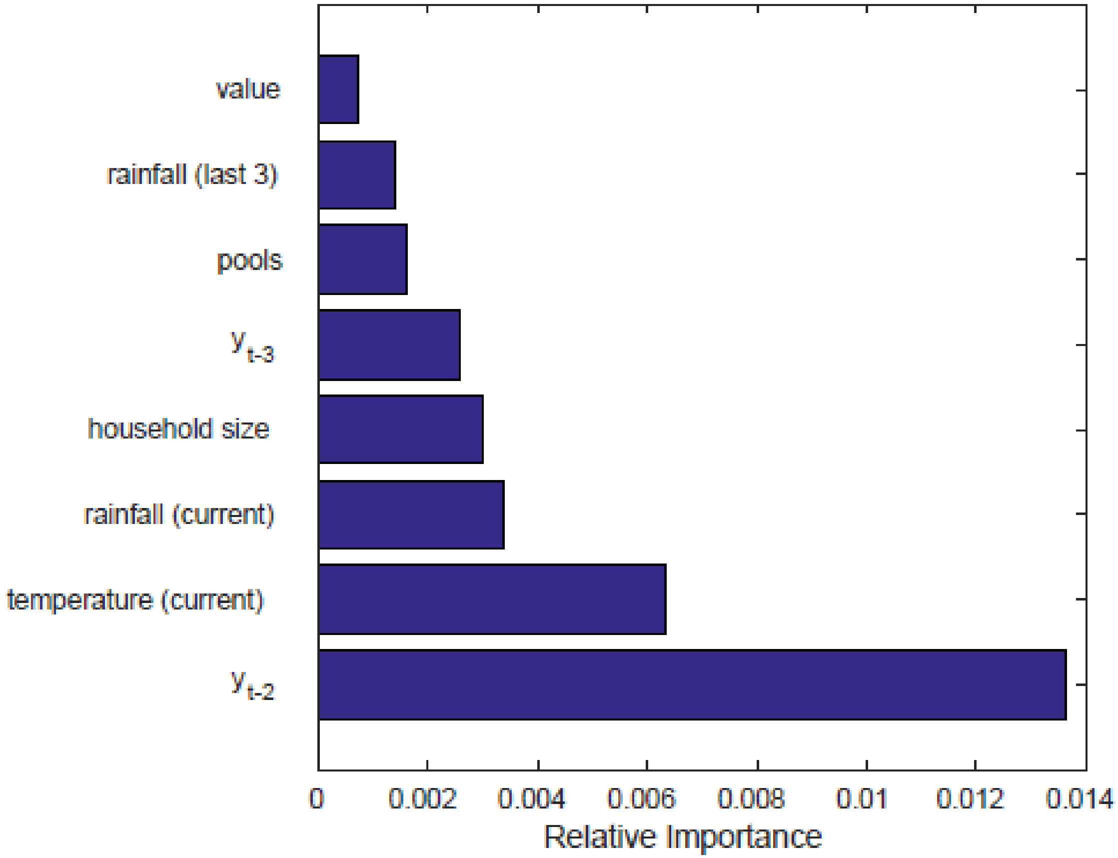
	Average	Median	75th percentile	90th percentile
Outdoor1	$5.054*10^{-3}$	$2.819*10^{-3}$	$6.453*10^{-3}$	$1.212*10^{-2}$
Outdoor2	$5.050*10^{-3}$	$2.795*10^{-3}$	$6.431*10^{-3}$	$1.212*10^{-2}$
Total	$1.172*10^{-2}$	$8.648*10^{-3}$	$1.626*10^{-2}$	$2.486*10^{-2}$

Mean Absolute Error (kL)

Interpretability

Variable importance: measure of the reduction in error from each feature.

Most significant predictor for all models is y_{t-1}, followed by y_{t-168}.



Relative variable importance for $Outdoor_1$

Predictive Models Summary

The strongest predictors are previous values of water consumption, suggesting significant variability not captured by demographic variables.

Accuracy for operational purposes should be balanced against data required. Hourly predictions would be useful for operational forecasting.

Although it's not clear the accuracy of this model is sufficiently high for operational purposes, it is the first work that predicts at this scale.

Explanatory Factors

Previous Work: Explanatory Factors

Previous work has found many factors influence **total** water consumption:

- weather (rainfall and temperature)
- income
- lot size
- pool ownership

Where **outdoor** water consumption has been studied explicitly, it has either been estimated by subtracting winter water consumption (not necessarily accurate at a household level), or through end use studies.

Findings have varied by climate and demographics of location studied.

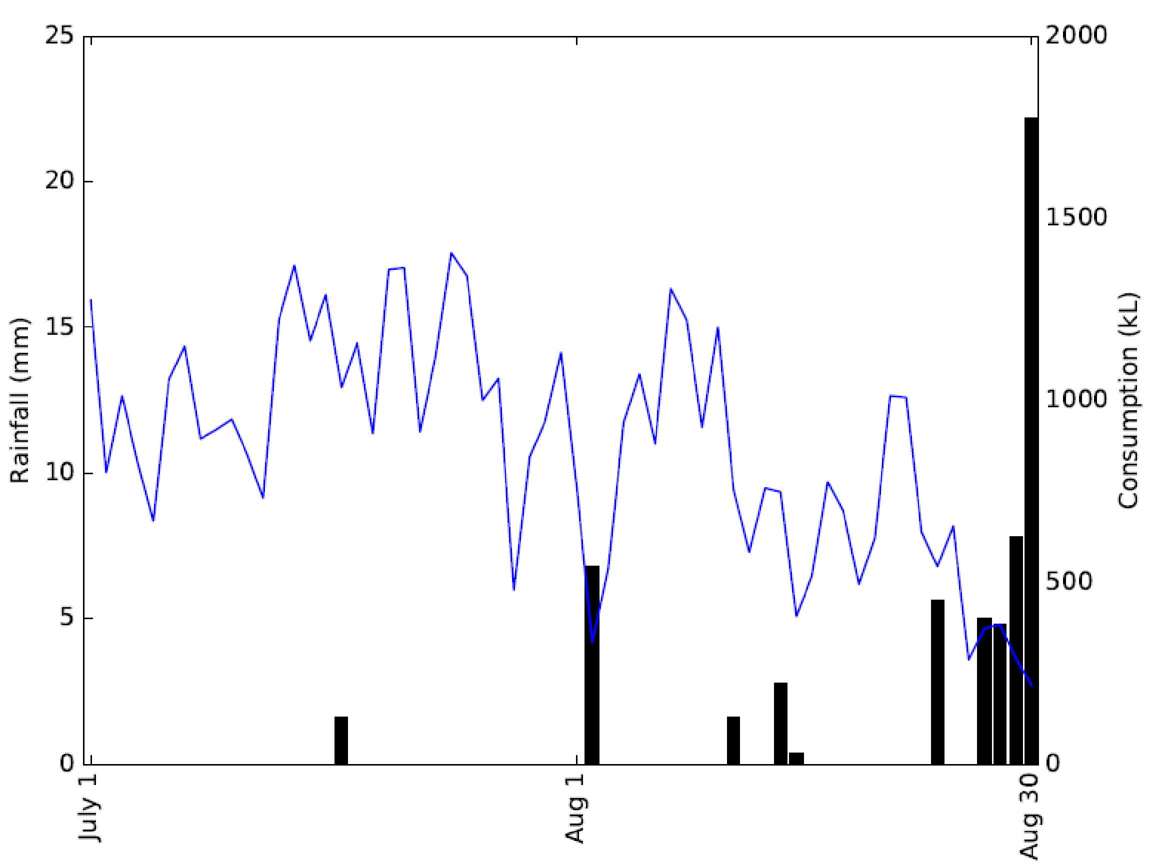
Influence of Rainfall

July:

- 1037 kL outdoor consumption
- 1.6mm rainfall

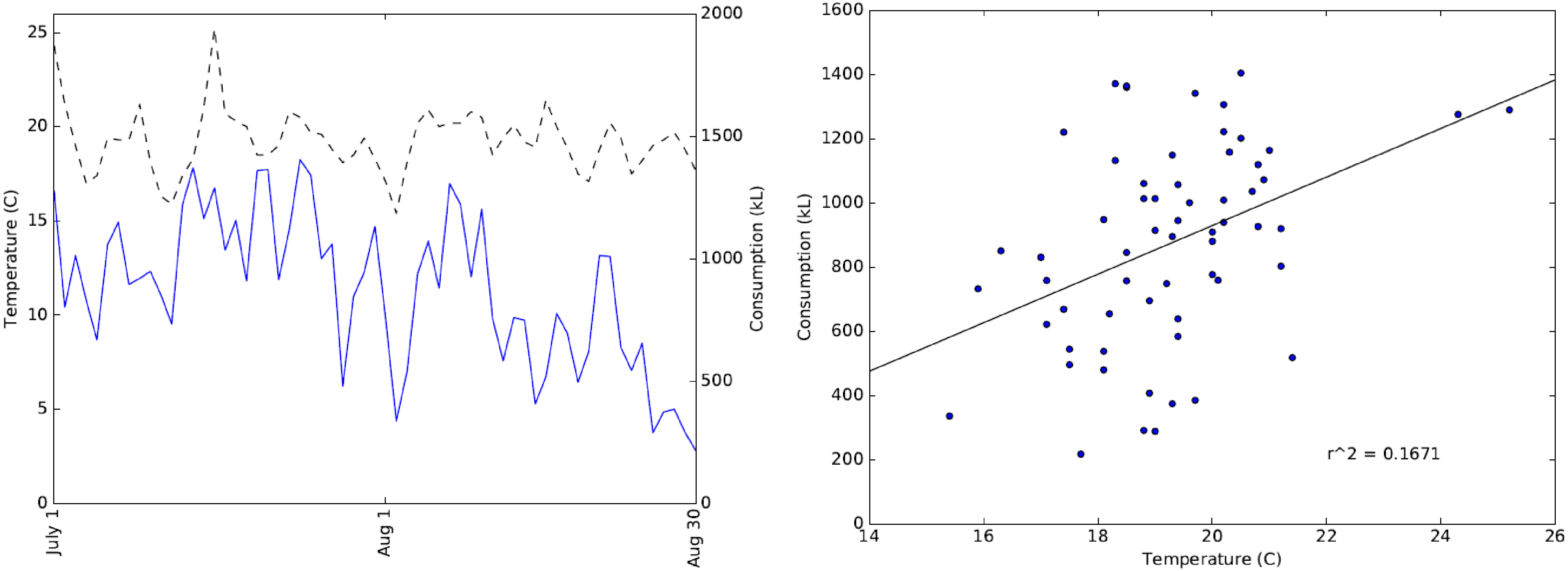
August:

- 698 kL outdoor consumption
- 57 mm rainfall



Temperature

There is a weak positive correlation between temperature and outdoor water consumption (r = 0.409; ρ = 0.401).



Explanatory Factors at Neighbourhood Level

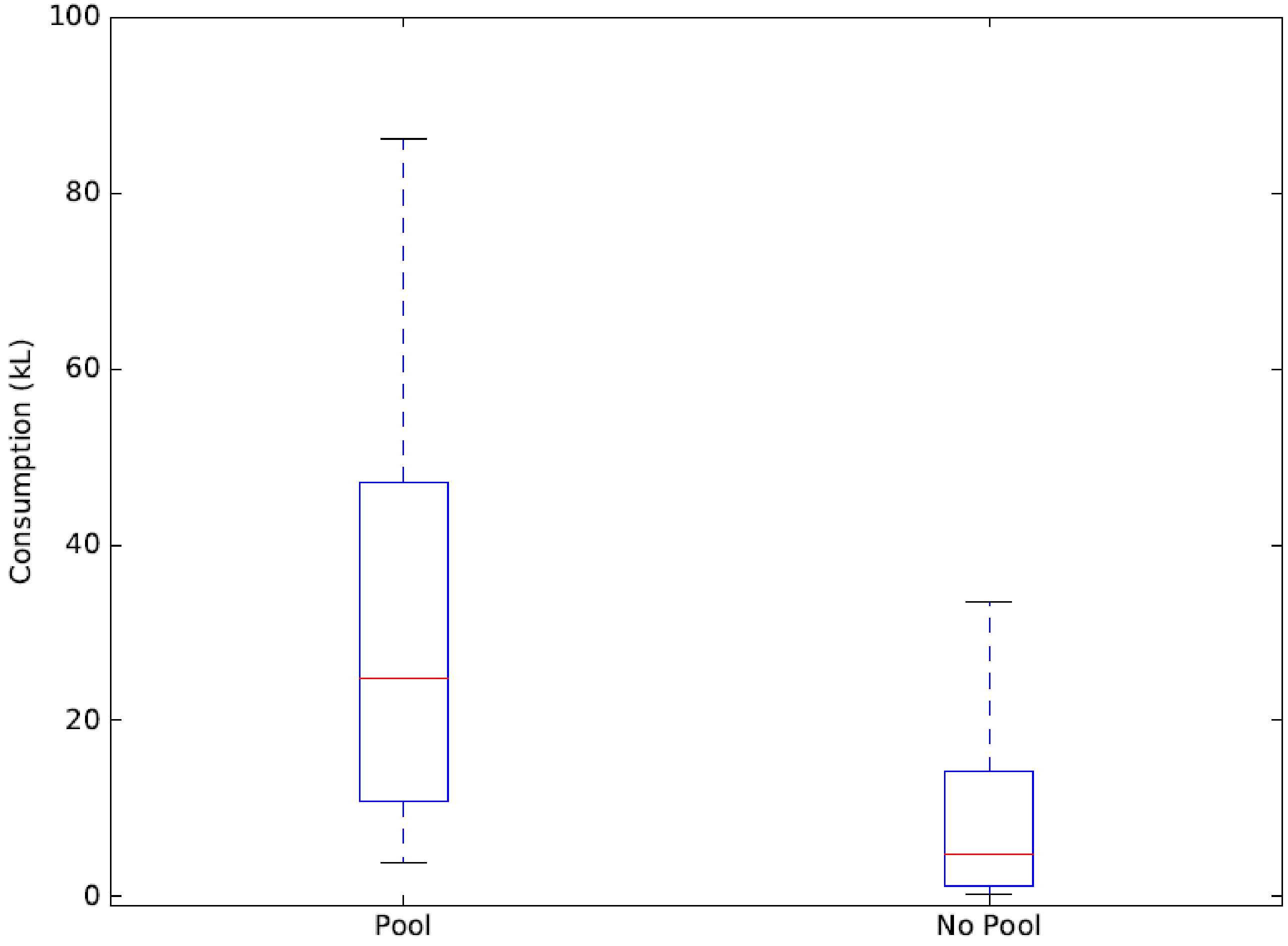
Weak relationships with outdoor water consumption:

- income ($r = 0.0939$, $\rho = 0.122$)
- lot size ($r = 0.423$; $\rho = 0.0745$)
- pool ownership ($r = 0.145$; $\rho = -0.0396$)

Explanatory Factors at Household Level

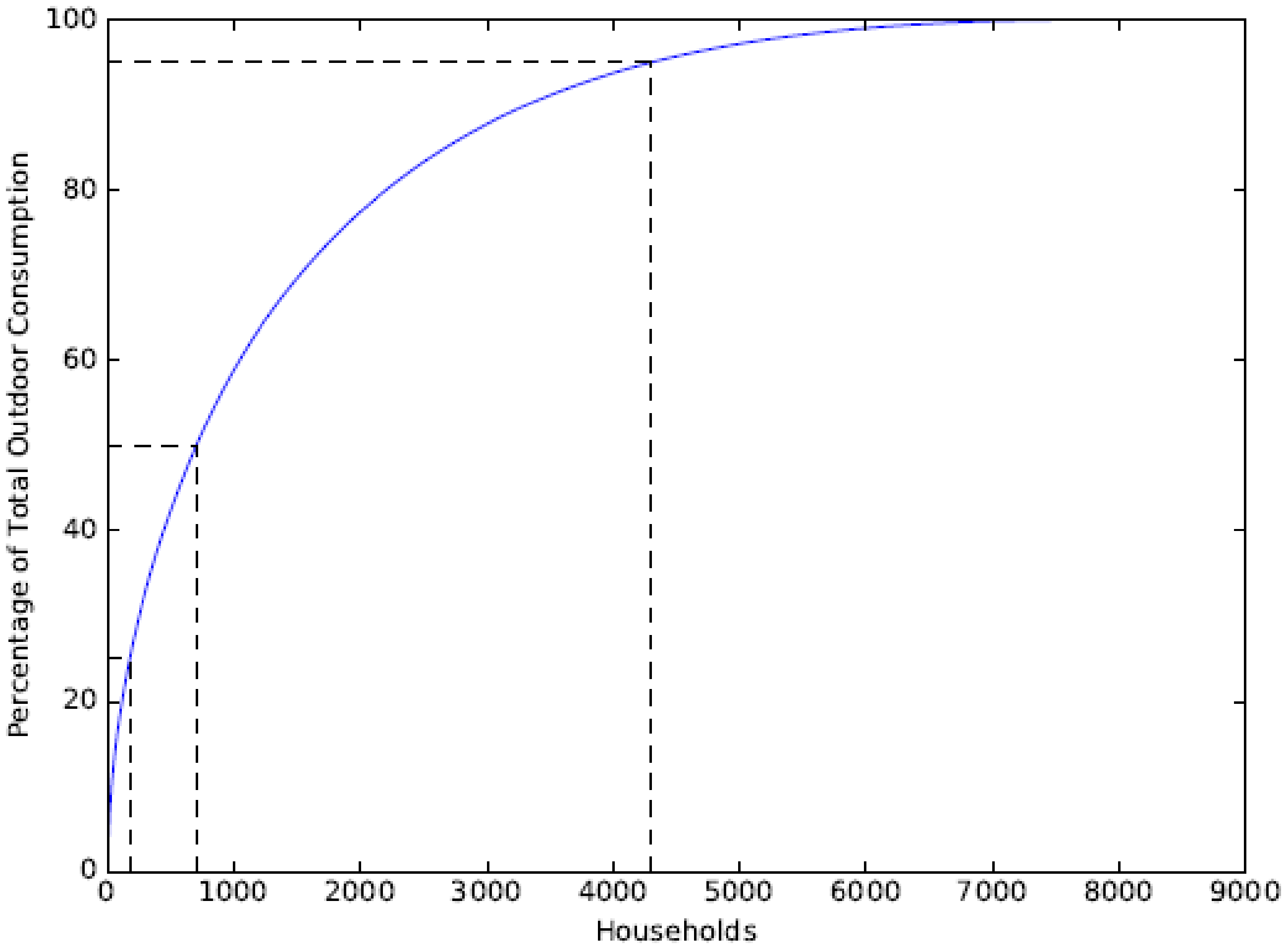
Very weak correlation with lot size (r = 0.144; ρ = 0.0817) for 703 households using the most outdoor water

Pool ownership affects water consumption at the household level (median 24.7kL for households with pools, 4.7kL for households without pools)



Variability in Outdoor Consumption

- 174 households use 25% of outdoor water
- 704 households use 50% of outdoor water
- About half of households use 95% of outdoor water



Explanation: Summary

Outdoor water consumption is partially explained by weather, but less impact for demographic factors

Individual variability could be an important factor in determining the potential effectiveness of demand management efforts

Conclusion & Future Work

Conclusion & Future Work

- It is possible to identify outdoor water consumption sufficiently accurately for explaining outdoor consumption and identifying consumers who use large amounts of outdoor water.
- Predictive models generally predict direction of change but not clear they are sufficiently accurate for operational purposes in practice.
- Future work could focus on the scale at which outdoor water consumption becomes predictable