# A Multi-Scale Analysis of Single-Family Residential Water Consumption in the Phoenix Metropolitan Area

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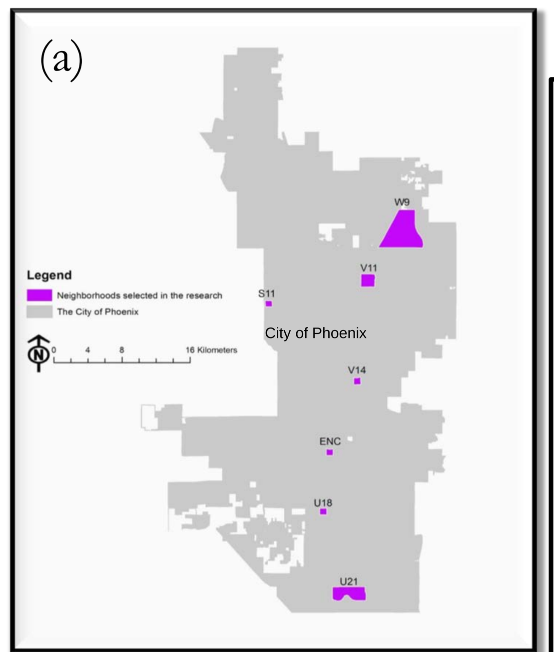
## 1. Introduction

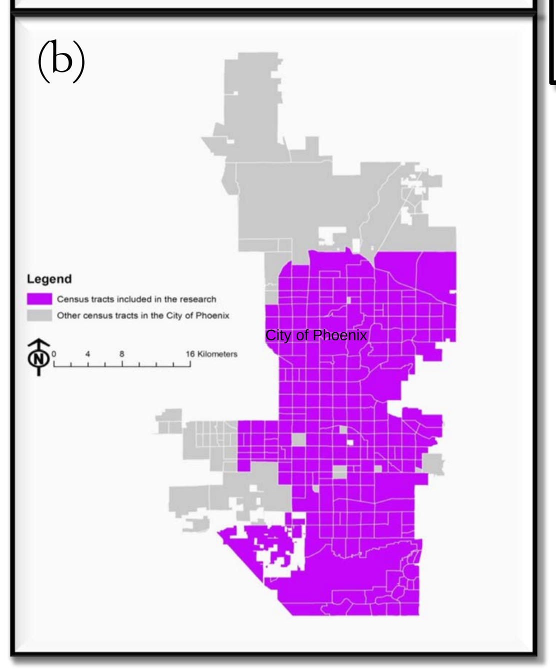
To effectively manage urban water demand, it is imperative to understand the relationship of water use with its determinants. Studies on residential water consumption typically use data on a single spatial scale. Although household scale data are preferred in residential water demand research, especially when econometric models are used to relate residential water use to its determinants, the unavailability of household scale data or high costs to obtain such data often make researchers fall back on aggregated data. To our knowledge, there is no empirical analysis comparing the results of the household scale and an aggregated scale to justify the use of aggregated scale data.

## 2. Objectives

(1) We examine whether the relationship of single-family water use with its determinants changes across the household and census tract scales by using econometric models.
(2) We also examine the regional pattern of this relationship.

## 3. Study Area





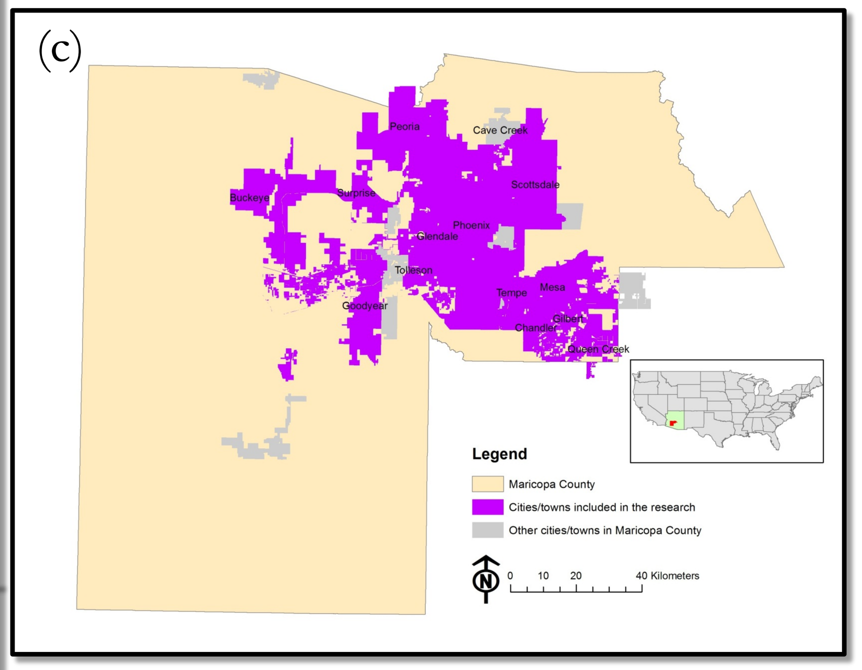


Figure 1. Study area
(a) 7 neighborhoods from which 207 households for the household scale study were selected;
(b) 252 census tracts were included for the census tract scale study;
(c) 10 cities and 4 towns in Maricopa County, Arizona were selected for the city/town scale study

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## 4. Data and Methods

Table 1. Variable definitions and data sources

| Variable | Household scale | | Census tract scale | | City/town scale | |
|---|---|---|---|---|---|---|
| | Definition | Data source | Definition | Data source | Definition | Data source |
| W | Household monthly water use | City of Phoenix | Average household monthly water use | City of Phoenix | Average household monthly water use | Department of Water Resources |
| **Household characteristics** | | | | | | |
| HHS | Household size | Phoenix Area Social Survey | Average household size | US Census 2000 | Average household size | US Census 2000 |
| HHI | Annual household income | | Median annual household income | | Median annual household income | |
| RA | Respondent age | | | | | |
| MA | | | Median Age | US Census 2000 | Median Age | US Census 2000 |
| **Housing characteristics** | | | | | | |
| HA | House age in 2001 | Maricopa County Assessor Database | Average house age in 2001 | Maricopa County Assessor Database | Average house age in 2001 | Maricopa County Assessor Database |
| PS | Pool size | | Average pool size | | Average pool size | |
| LA | Livable area | | Average livable area | | Average livable area | |
| ILS | Irrigable lot size | | Average irrigable lot size | | Average irrigable lot size | |
| FYD | Indicator variables, equal to 1 when front yard is desert, mostly lawn, with some lawn, and patio, respectively | Phoenix Area Social Survey | | | | |
| FYML | | | | | | |
| FYSL | | | | | | |
| FYP | | | | | | |
| BYD | Indicator variables, equal to 1 when backyard is desert, mostly lawn, with some lawn, and patio, respectively | | | | | |
| BYML | | | | | | |
| BYSL | | | | | | |
| BYP | | | | | | |
| **Climate factors** | | | | | | |
| R | Monthly precipitation | AZMET, MCFCD | Average monthly precipitation | AZMET, NOAA, MCFCD | Average monthly precipitation | AZMET, NOAA, MCFCD |
| R*R | Square of monthly precipitation | | Square of average monthly precipitation | | Square of average monthly precipitation | |
| TEMP | Monthly average maximum temperature | AZMET, MCFCD, PRISMS | Mean monthly average maximum temperature | AZMET, NOAA, MCFCD, PRISMS | Mean monthly average maximum temperature | AZMET, NOAA, MCFCD, PRISMS |
| **Water price** | | | | | | |
| MP | | | | | Marginal water price corresponding to average household monthly water use for each city and town | 14 cities and towns |
| **Urban structure** | | | | | | |
| BD | | | Single-family house density | Maricopa County Assessor Database | Single-family house density | Maricopa County Assessor Database |
| %MR | | | Percentage of mesic residential area | CAP LTER, SRP | | |
| **Other** | | | | | | |
| S | Indicator variable, equal to 1 if the month is June, July, August, or September | | Indicator variable, equal to 1 if the month is June, July, August, or September | | Indicator variable, equal to 1 if the month is June, July, August, or September | |
| T | Time trend | | Time trend | | Time trend | |

We use the linear mixed-effects model for panel data. A linear mixed-effects model has an advantage over a pooled cross-sectional ordinary linear regression model because the former includes a subject-specific random variable for controlling the heterogeneity of individuals.

$$Y_{it} = \beta_0 + \beta_1 X_{it,1} + \cdots + \beta_m X_{it,m} + \beta_{m+1} X_{i,1} + \cdots + \beta_{m+n} X_{i,n} + \mu_i + \varepsilon_{it}$$

where:

$i$ is the index to identify each subject (household, census tract, or city/town),

$t$ is the time period,

$Y_{it}$ is the response of the $i$-th subject in the $t$-th time period,

$X_{it,1}, \cdots, X_{it,m}$ are a set of time-related explanatory variables,

$X_{i,1}, \cdots, X_{i,m}$ are a set of time-constant explanatory variables,

$\beta_0, \beta_1, \cdots, \beta_{m+n}$ are parameters that represent the fixed effects of the explanatory variables on $Y_{it}$,

$\mu_i \sim N(0, \sigma_\mu^2)$ is a subject specific portion of the error term that represents unobserved time-constant random effects on $Y_{it}$,

$\varepsilon_{it} \sim N(0, \sigma^2)$ is the other portion of the error term to represent the remaining non-explained variation of $Y_{it}$ that is both subject specific and time-related.

## 5. Results

Table 2. Parameter estimates for models with common variables

| | Household scale | | | | Census tract scale | | | | City/town scale | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Parameter Estimate | 95% Confidence Interval | | Standardized Coefficient | Parameter Estimate | 95% Confidence Interval | | Standardized Coefficient | Parameter Estimate | 95% Confidence Interval | | Standardized Coefficient |
| | | Lower Limit | Upper Limit | | | Lower Limit | Upper Limit | | | Lower Limit | Upper Limit | |
| HHS | 0.0774***(3.88) | 0.0382 | 0.1165 | 0.169 | 0.0906***(7.59) | 0.0672 | 0.1140 | 0.167 | 0.2525***(4.01) | 0.1287 | 0.3763 | 0.245 |
| *ln*(HHI) | 0.339***(6.85) | 0.242 | 0.436 | 0.338 | 0.200***(5.79) | 0.133 | 0.268 | 0.240 | -0.098(-0.41) | -0.5656 | 0.3691 | -0.050 |
| HA | 0.00784***(5.47) | 0.00503 | 0.01065 | 0.242 | 0.00704***(11.03) | 0.00579 | 0.00829 | 0.313 | 0.00673(1.61) | -0.00148 | 0.01494 | 0.158 |
| PS | 0.0046**(2.73) | 0.0013 | 0.0079 | 0.131 | 0.0183***(12.98) | 0.0156 | 0.0211 | 0.482 | 0.0369***(6.31) | 0.0254 | 0.0483 | 0.541 |
| ILS | 0.000071*(2.35) | 0.000012 | 0.000131 | 0.102 | 0.000111***(4.62) | 0.000064 | 0.000158 | 0.102 | -0.000010(-1.19) | -0.000030 | 0.000007 | -0.058 |
| R | -0.1045***(-3.50) | -0.1630 | -0.0460 | -0.074 | -0.1076***(-12.55) | -0.1244 | -0.0908 | -0.152 | -0.0343(-0.63) | -0.1415 | 0.0729 | -0.045 |
| R*R | 0.0729***(5.11) | 0.0450 | 0.1009 | 0.104 | 0.0701***(15.01) | 0.0609 | 0.0792 | 0.177 | 0.0284(0.97) | -0.0291 | 0.0859 | 0.066 |
| TEMP | 0.0120***(16.02) | 0.0105 | 0.0135 | 0.238 | 0.0125***(61.40) | 0.0121 | 0.0129 | 0.530 | 0.0145***(11.00) | 0.0119 | 0.0171 | 0.590 |
| S | 0.0889***(3.76) | 0.04248 | 0.1352 | 0.055 | 0.1051***(15.96) | 0.0922 | 0.1180 | 0.136 | 0.0612(1.42) | -0.0235 | 0.1460 | 0.075 |
| T | 0.00986***(10.73) | 0.00805 | 0.01166 | 0.090 | 0.00655***(25.39) | 0.00604 | 0.00705 | 0.125 | 0.00803***(4.64) | 0.00462 | 0.01144 | 0.144 |
| | | | | | | | | | | | | |
| *N* | 4941 | | | | 6048 | | | | 336 | | | |

Notes: *t*-Statistics in parentheses
$^*p<0.05$; $^{**}p<0.01$; $^{***}p<0.001$

Table 3. Parameter estimates for models with all variables with available data

| | Household scale | | | | Census tract scale | | | | City/town scale | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Parameter Estimate | 95% Confidence Interval | | Standardized Coefficient | Parameter Estimate | 95% Confidence Interval | | Standardized Coefficient | Parameter Estimate | 95% Confidence Interval | | Standardized Coefficient |
| | | Lower Limit | Upper Limit | | | Lower Limit | Upper Limit | | | Lower Limit | Upper Limit | |
| **Household characteristics** | | | | | | | | | | | | |
| HHS | 0.0896***(4.37) | 0.0494 | 0.1297 | 0.195 | 0.1207***(6.89) | 0.0864 | 0.1550 | 0.222 | 0.2355***(3.60) | 0.1067 | 0.3643 | 0.229 |
| *ln*(HHI) | 0.273***(5.63) | 0.178 | 0.368 | 0.272 | 0.191***(4.93) | 0.115 | 0.267 | 0.228 | 0.051(0.30) | -0.2892 | 0.3921 | 0.026 |
| RA | 0.00559(1.89) | -0.00020 | 0.01138 | 0.089 | | | | | | | | |
| MA | | | | | 0.00462(1.85) | -0.00027 | 0.00950 | 0.078 | 0.00198(0.33) | -0.00992 | 0.01388 | 0.029 |
| **Housing characteristics** | | | | | | | | | | | | |
| HA | 0.00351(1.96) | -0.000007 | 0.00702 | 0.108 | 0.00629***(8.06) | 0.00476 | 0.00782 | 0.280 | 0.00940*(2.54) | 0.00212 | 0.01668 | 0.221 |
| PS | 0.0046**(2.92) | 0.0015 | 0.0077 | 0.132 | 0.0172***(11.54) | 0.0143 | 0.0202 | 0.453 | 0.0303***(7.12) | 0.0219 | 0.0386 | 0.444 |
| ILS | 0.000075**(2.66) | 0.000020 | 0.000131 | 0.107 | 0.000067*(2.44) | 0.000013 | 0.000121 | 0.062 | -0.0000027(-0.34) | -0.00002 | 0.000013 | -0.015 |
| FYD | -0.333*(-2.19) | -0.630 | -0.035 | -0.218 | | | | | | | | |
| FYML | -0.175(-1.12) | -0.482 | 0.132 | -0.101 | | | | | | | | |
| FYSL | 0.049(0.32) | -0.255 | 0.353 | 0.026 | | | | | | | | |
| FYP | -0.046(-0.22) | -0.470 | 0.377 | -0.011 | | | | | | | | |
| BYD | -0.045(-0.34) | -0.303 | 0.2142 | -0.023 | | | | | | | | |
| BYML | 0.144(1.13) | -0.106 | 0.394 | 0.083 | | | | | | | | |
| BYSL | 0.139(1.10) | -0.110 | 0.387 | 0.082 | | | | | | | | |
| BYP | 0.171(1.26) | -0.095 | 0.436 | 0.088 | | | | | | | | |
| **Climate factors** | | | | | | | | | | | | |
| R | -0.1046***(-3.50) | -0.1631 | -0.0461 | -0.074 | -0.1076***(-12.56) | -0.1244 | -0.0908 | -0.152 | -0.0333(-0.61) | -0.1410 | 0.0745 | -0.044 |
| R*R | 0.0731***(5.12) | 0.0451 | 0.1010 | 0.104 | 0.0701***(15.02) | 0.0610 | 0.0793 | 0.177 | 0.0286(0.97) | -0.0292 | 0.0864 | 0.067 |
| TEMP | 0.0120***(16.03) | 0.0105 | 0.01347 | 0.238 | 0.0125***(61.43) | 0.0121 | 0.0129 | 0.530 | 0.0147***(11.02) | 0.0120 | 0.0173 | 0.595 |
| **Water price** | | | | | | | | | | | | |
| *ln*(MP) | | | | | | | | | -0.0382*(-2.13) | -0.0735 | -0.0030 | -0.084 |
| **Urban structure** | | | | | | | | | | | | |
| BD | | | | | -0.000110**(-3.11) | -0.000170 | -0.000040 | -0.070 | 0.000245(1.48) | -0.000080 | 0.00057 | 0.078 |
| %MR | | | | | 0.000933(0.98) | -0.000930 | 0.002794 | 0.029 | | | | |
| **Other** | | | | | | | | | | | | |
| S | 0.0886***(3.75) | 0.0422 | 0.1350 | 0.055 | 0.1051***(15.96) | 0.0922 | 0.1180 | 0.136 | 0.0615(1.42) | -0.0237 | 0.1467 | 0.075 |
| T | 0.00986***(10.73) | 0.00806 | 0.01660 | 0.090 | 0.00656**(25.46) | 0.00606 | 0.00707 | 0.125 | 0.00808***(4.63) | 0.00465 | 0.01151 | 0.145 |
| | | | | | | | | | | | | |
| *N* | 4941 | | | | 6048 | | | | 336 | | | |

## 6. Conclusions

- ➢ The household and census tract scale models produce similar results, but different from the city/town scale model. The spatial extent of the city/town scale is much larger than those of the other two scales that are only in the City of Phoenix. The big difference on the city/town scale may be due to spatial heterogeneity in the relationship of water use with its determinants in the different cities and towns in Phoenix metropolitan area.
- ➢ The unique contribution of this research is its conclusion regarding the usability of aggregated scale data as a substitute for household scale data for residential water use research
- ➢ Homeowner association regulations on front yard landscaping help reduce single-family household water use
- ➢ Water prices are inelastic in the Phoenix metropolitan area
- ➢ Single-family residential development may influence single-family water use patterns. Municipal water managers and land use planners should consider better coordination of their respective efforts to ensure urban water sustainability

Next step: To examine the spatial pattern of the relationship between single-family water consumption and its determinants and how this spatial pattern changed over the period of 2000-2009 by using the geographically weighted regression model.