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

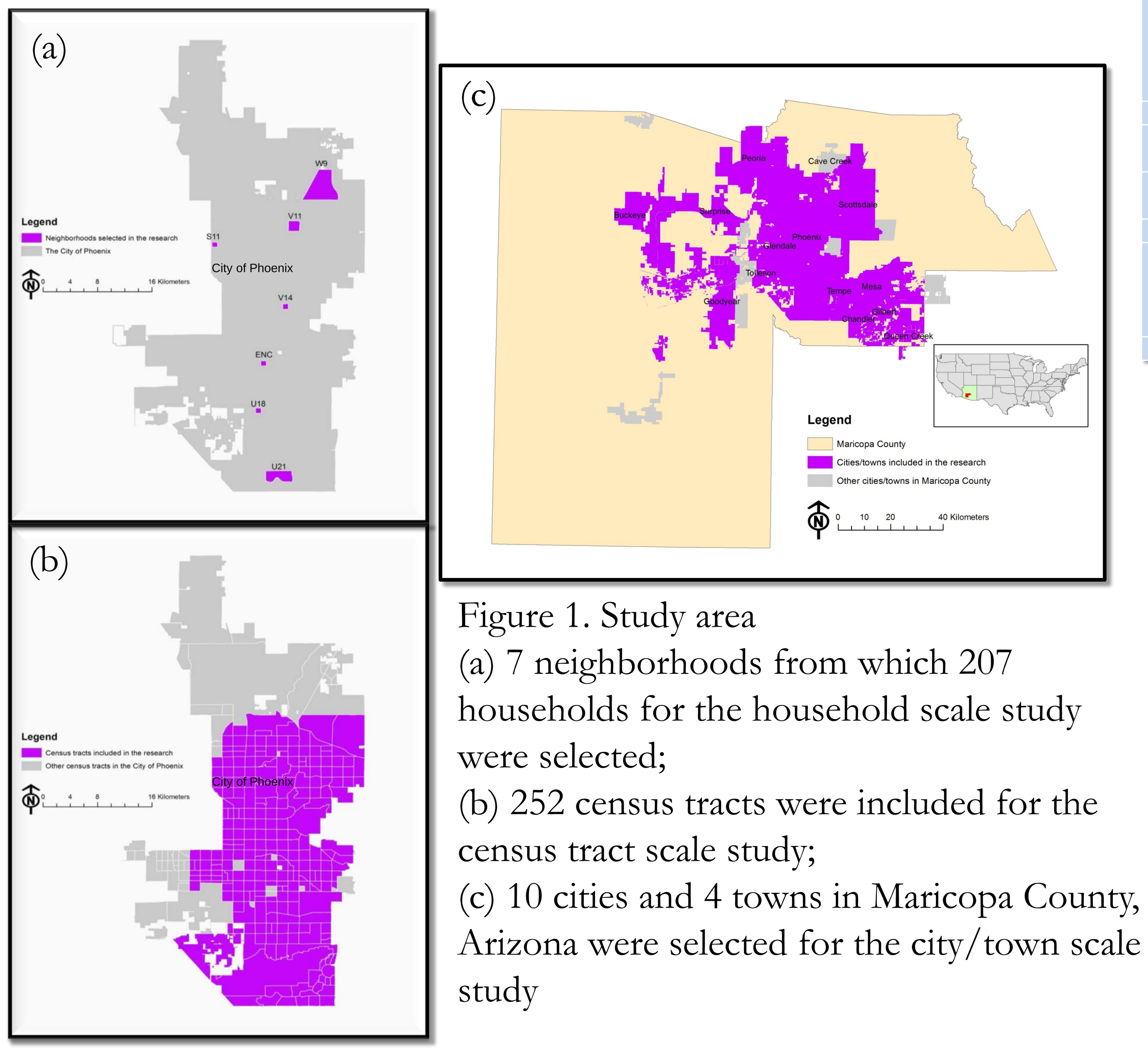

Figure 1. Study area
(a) 7 neighborhoods from which 207 households for the household scale study were selected;
(b) 252 census tracts were included for the census tract scale study;
(c) 10 cities and 4 towns in Maricopa County, Arizona were selected for the city/town scale study

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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.