QUANTIFYING IMPACTS OF WATER DEMAND MANAGEMENT IN A SMALL MUNICIPALITY

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Research questions

- Some municipal water utilities are simultaneously confronting declining demand and dwindling supplies
  - How have utility price and non-price action impacted demand?
- What tools are available to assess municipal water demand?
  - Time-series analysis; econometric modeling; spatial analysis
- This study uses premises-level administrative water use data from Clovis, New Mexico to investigate these questions
  - Most studies focus on large cities – this study is distinct because it focuses on a small one

Presentation organization

- Brief literature review
- Background
- Data
- Econometric estimation & rebate cost effectiveness
- Conclusions & further research

Literature review

Literature review 1

- Many studies that have estimated residential water demand:
  - Arbues and Barberan (2004). Comparison of empirical approaches
  - Kenney, et al. (2008). Demand management & drought Aurora, Colorado
  - Arbues, Villanua, and Barberan (2010). Impact of household size
  - Price, Chermak, and Felardo (2014). Rebates and cost-effectiveness in Albuquerque, New Mexico
  - Ouyang, et al. (2014). Geographic scale in Phoenix, Arizona
  - Brelsford and Abbott (2017). Las Vegas, Nevada; declining demand and acknowledgement of spatial effects

Literature review 2

- This research adds to the literature in several ways:
  - Provides empirical demand estimates for small- to mid-sized western municipalities confronting declining supplies & climate change
  - Estimates efficacy of price and non-price demand management policy
  - Estimates cost effectiveness of rebate programs
- Not able to cover in this presentation:
  - Application of time series analysis methods to municipal water demand data
  - Utilization of spatial panel econometrics in water demand estimation context

Background

Clovis, New Mexico

- Small arid city in east-central New Mexico
- Rapidly growing population: up 32% from 2000 to 2015
  - Still fewer than 40,000 persons by 2015
  - Major industries: agriculture, manufacturing, state and local government, nearby Air Force base
- Climate: generally warm and relatively dry
  - Average temperature ranges from mid-30° F in winter to mid-70° F
  - Annual precipitation averages about 15 inches per year
  - Severe drought conditions in 2006 and 2011-2014
- Single declining water source: Ogallala Aquifer (part of High Plains Aquifer)
- Private water utility (EPCOR) supplies city; demand is declining

Data

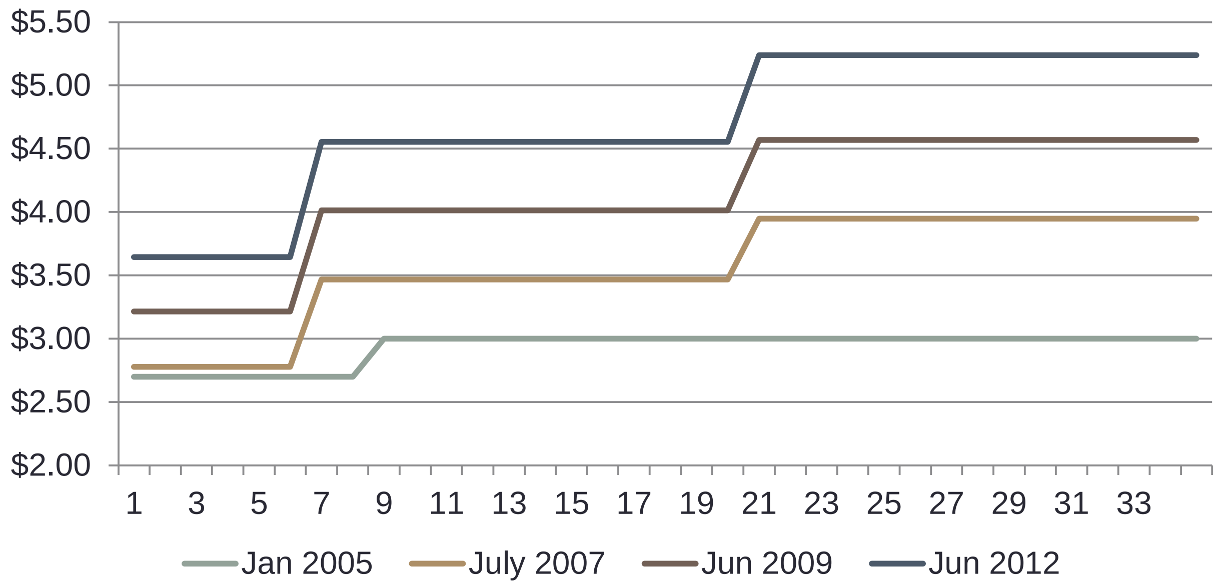
Descriptive statistics

Table 1. Variable Definitions and Descriptive Statistics

Variable	Description	Period	Unit	Mean	Std. dev.	Source
WU	Average daily household water use	Month	Gallons	323.6	653.51	EPCOR
AvgPrice	Average water price	Month	$/Gallon	0.003	0.002	EPCOR
ToiletPrem	Premises toilet rebate indicator	Month	1/0	0.03	0.18	EPCOR
Washer	Washing machine rebate indicator	Month	1/0	0.02	0.13	EPCOR
Landscape	Landscape rebate indicator	Month	1/0	0.01	0.08	EPCOR
Income	Average household income in county	Ann.	Dollars	40,945	1.02	US Census (ACS)
HHSize	Average household size in county	Ann.	Persons	2.61	0.08	US Census (ACS)
Permits	Number of single family building permits	Month	Permits	10.37	5.47	BBER & Clovis
Temp	Average monthly temperature	Month	Fahrenheit	56.80	14.86	NOAA
Precip	Average total monthly precipitation	Month	Inches	1.28	1.44	NOAA
Vegetation	Vegetation index	Ann.	Unitless	12.72	9.16	USGS
PDSI	Palmer Drought Severity Index	Month	Unitless	-0.28	2.45	NOAA

Rate adjustments and conservation rebates

- Price based on increasing block rate schedule
  - EPCOR has initiated 3 rate adjustments since 2006
- Three types of rebates granted by EPCOR (2008 to 2015)
  - Toilet rebates: 1,686 granted to 927 premises
  - Washing machine rebates: 459 granted
  - Landscaping rebates: 334 granted



Econometric estimation

Demand estimation model

- $Q = \mathrm{f}(p, X; v)$
  - Quantity, Q, is a function of price, p, a set of knowable factors, X, and factors unknown to the econometrician, v
- Fixed effects instrumental variable econometric model (FE-IV) is employed
  - FE accounts for time-independent idiosyncratic premises characteristics
  - IV controls for endogenous price
  - Analysis at the record level (roughly 13,000-15,000 premises, for 120 months or about 1.6 million observations)

Empirical model

$$\ln \mathrm{WU}_{it} =$$

$$B_0 + B_1 \ln\widehat{\mathrm{AvgPrice}}_{it} + B_2 \mathrm{Temp}_{it} + B_3 \mathrm{Precip}_{it} + B_4 \ln\mathrm{Income}_{it} + B_5 \mathrm{HHsize}_{it} + B_6 \mathrm{VegIndex}_{it}$$

$$+ B_7 \mathrm{BldPermit}_{it} + \sum_{j=1}^{3} \delta_j \mathrm{Rebate}_{jit} + \sum_{k=1}^{11} \theta_k \mathrm{Month}_k + \sum_{l=1}^{3} \gamma_l \mathrm{MeterSize}_{li} + v_i + \varepsilon_{it}$$

Note: i = premises; t = time

Regression results for full model:

- Month and meter size controls suppressed
- Although only about 15,000 premises in any given month, 17,000 premises identified
- R^2 is 0.28 in model 1.

Table 2. 2SLS Regression Results (Full Model)

Variable	Model 1	Model 2	Model 3	Model 4
lnAvgPrice	-0.534***	-0.584***	-0.448***	-0.494***
	(0.0076)	(0.0074)	(0.0084)	(0.0083)
ToiletPrem	-0.083***	-0.080***	-0.079***	-0.078***
	(0.0042)	(0.0041)	(0.0049)	(0.0049)
Washer	-0.060***	-0.060***	-0.048***	-0.048***
	(0.0059)	(0.0058)	(0.0069)	(0.0068)
Landscape	-0.100***	-0.094***	-0.009	-0.019
	(0.0071)	(0.0071)	(0.0114)	(0.0113)
lnIncome	0.568***	0.301***	0.387***	0.064*
	(0.0268)	(0.0264)	(0.0295)	(0.0296)
Hhsize	-0.009	0.067***	0.055***	0.029*
	(0.0122)	(0.0123)	(0.0134)	(0.0134)
BldPermit	0.007***	0.006***	0.004***	0.004***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Temp	0.010***	0.010***	0.010***	0.010***
	(0.00001)	(0.00001)	(0.00002)	(0.00002)
Precip	-0.012***	0.005***	-0.006***	0.005***
	(0.0004)	(0.0008)	(0.0007)	(0.0008)
PDSI		-0.018***		-0.015***
		(0.0003)		(0.0003)
VegIndex			-0.001***	0.000
			(0.0001)	(0.0001)
Constant	-3.658***	-2.111***	-1.114***	2.111***
	(0.2554)	(0.2862)	(0.2827)	(0.2862)
Obs.	1,575,980	1,575,980	1,173,761	1,173,761
Premises	16,904	16,904	15,533	15,533
R^2	0.280	0.292	0.254	0.265

Observations:

- Inelastic demand
- Rebates are effective at reducing demand
- Water is a normal good
- Household size and building permits positively correlated with water demand
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Interpreting marginal effects 1

- Price and income: log-log, so price and income estimated coefficients are elasticities. % increase in price gives % decrease in water use.
- Price elasticity from full and subset models:

	Full Model	Toilet Rebate	Washer Rebate	Landscaping Rebate
Price Elasticity	0.5	0.4	0.3	0.7

Interpreting marginal effects 2

- Rebates: not straightforward, log-dummy. Given by Kenney (1981):

$$\alpha_j = 100\left[\exp\left(\hat{\delta}_j - \frac{\hat{V}(\hat{\delta}_j)}{2}\right) - 1\right]$$

	Toilet Rebate	Washer Rebate	Landscaping Rebate
Marginal Effect (%)	-9.3	-9.2	-4.7
Change in Gallons per Day	-35.3	-37.7	-19.2

Effect for premises receiving landscaping rebate is for average rebate-receiving rebate (1960 ft^2).

Cost effectiveness of rebates

Table 4. Change in Water Use Due to Low-flow Device and Levalized Cost

Rebate Type	Marginal effect per device (percent)	Change in water use (gal/day)	Rebate value per device ($)	Device lifespan (years)	Cost r=5% ($/1000 gal.)	Cost r=7% ($/1000 gal.)	Cost r=10% ($/1000 gal.)
ToiletPrem	-7.52	-28.57	150	25	0.97	1.15	1.44
Washer	-9.21	-37.70	150	12	1.17	1.28	1.45
Landscape (100 ft^2)	-0.24	-0.98	40	25	7.55	8.96	11.19

Conclusions & future steps

Conclusions

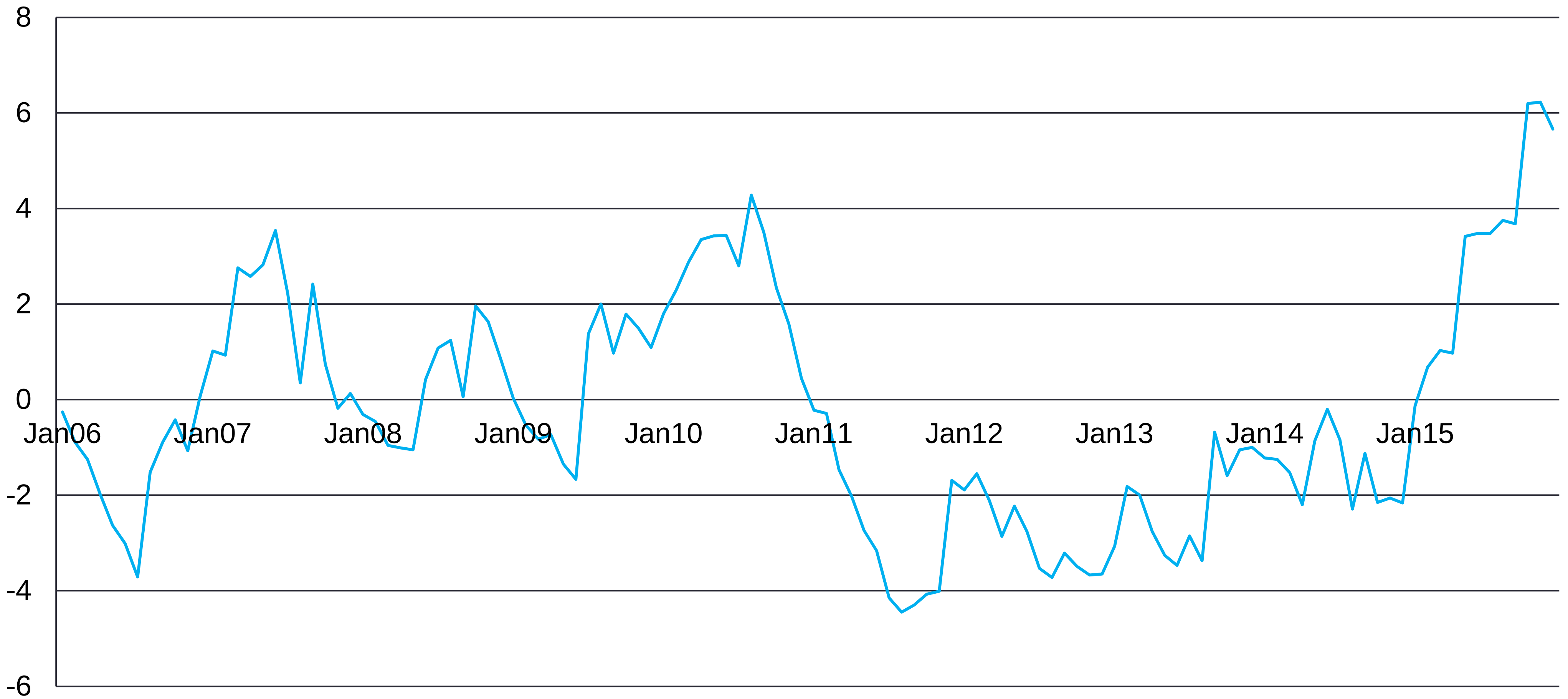
- Price inelastic at current prices
- Rebate programs reduce demand
  - However, premises receiving rebates are higher water users even post-rebate
  - Toilet rebates are most cost-effective, landscaping rebates least cost-effective
- Possible to quantify responsiveness to weather and climate conditions
- Other elements also likely contributing to reduced demand but could not be quantified
  - I.e. housing stock age, latent characteristics, plumbing improvements, preferences

Further research

- Some results not discussed:
  - Seasonal trends and breakpoints with qualitative analysis
  - Water use based on premises age
  - Spatial panel econometrics
  - Various robustness checks
- Addition of variables to explain demand
- Impact of different types of demand management investment (such as advertising)
- More fine-grained analysis of climate, socioeconomic, and and vegetation variables
- Change to water use preferences
- Willingness to pay to ensure uninterrupted water supply (or willingness to accept interruptions)

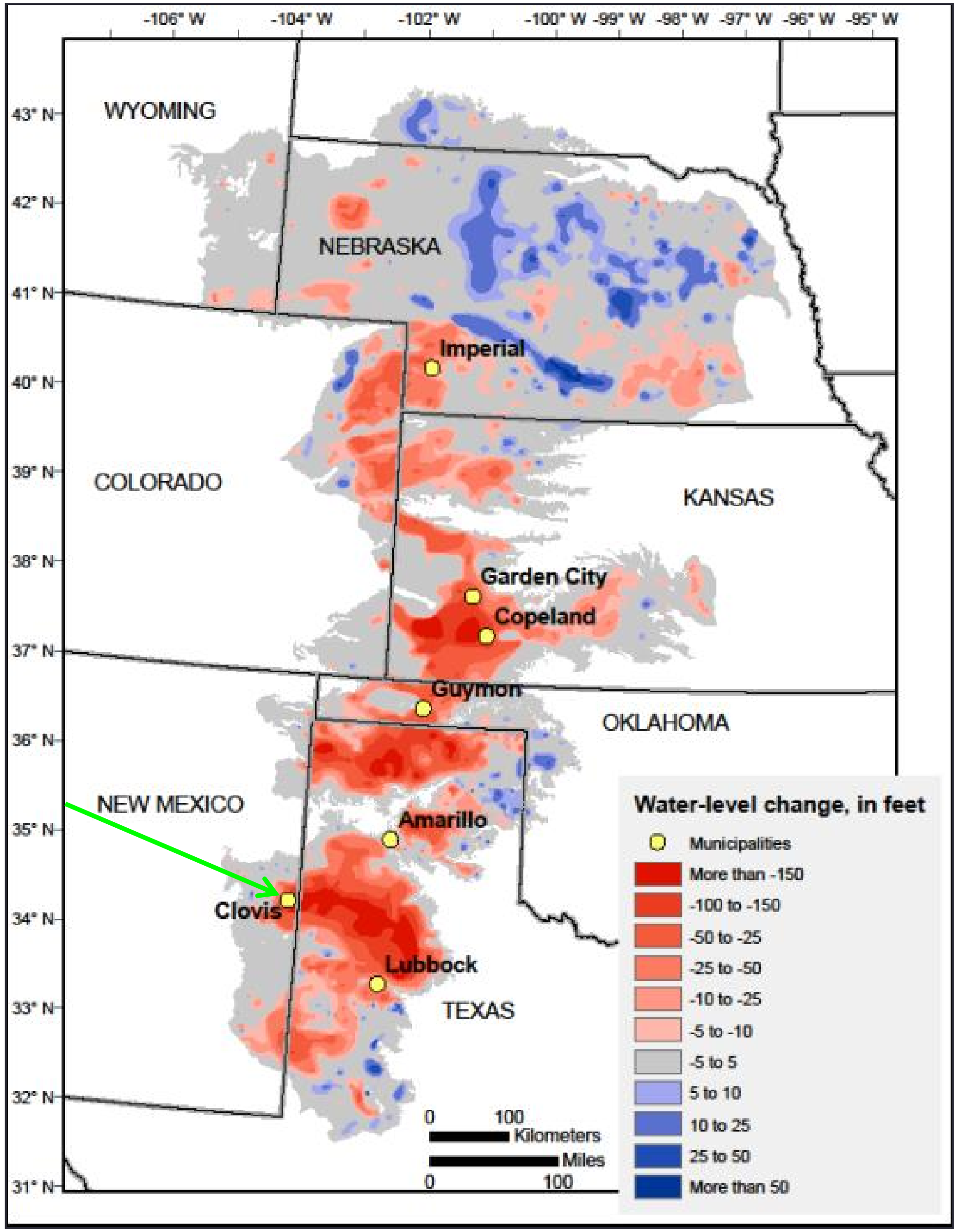
Extra

Palmer Drought Severity Index



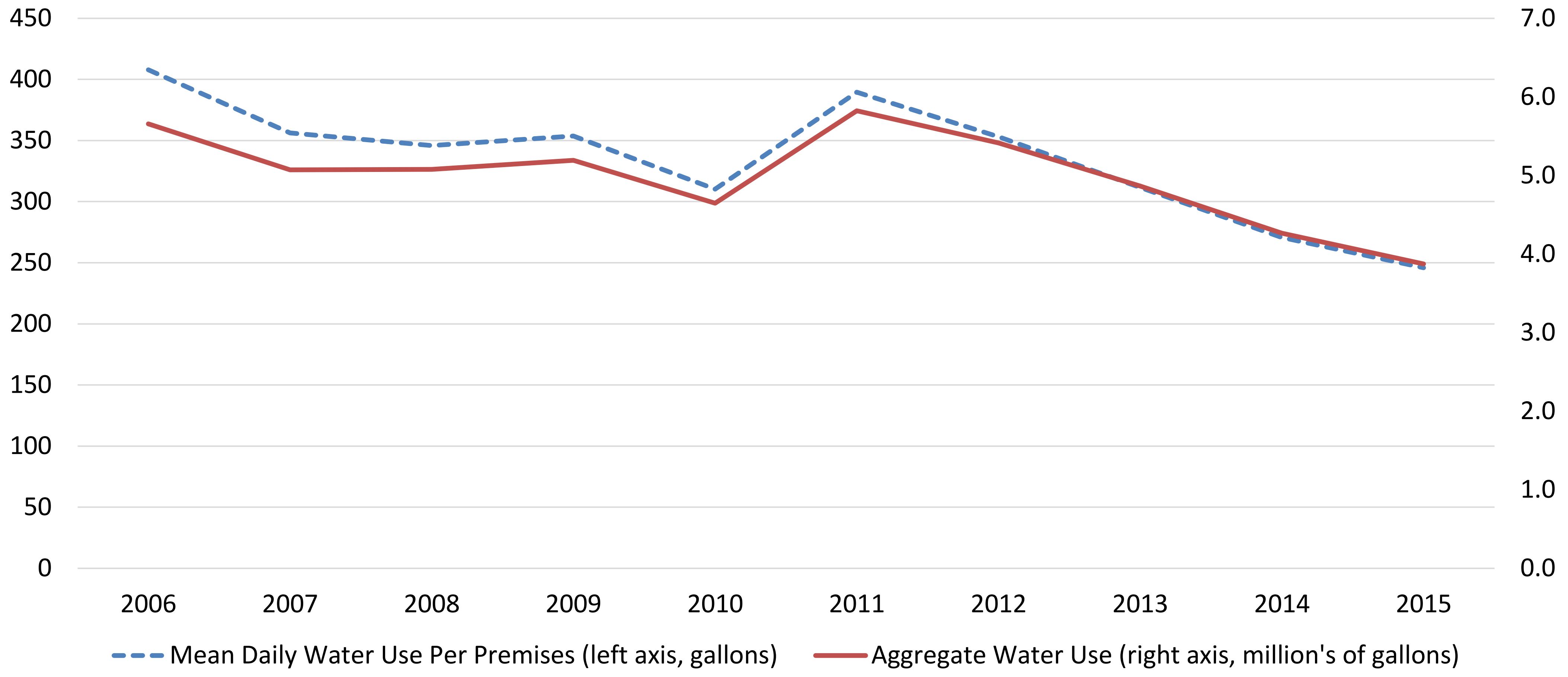
Declining High Plains Aquifer: predevelopment to 2013

- The Ogallala Aquifer is a part of the High Plains
- Average aquifer declines of 15 feet over the last several decades
- Municipalities in New Mexico, Texas, Oklahoma, and Kansas have fared worse



Source: High plains aquifer boundary from Qi (2010); water level change from McGuire (2014). Map based on USGS digital data.

Clovis water use



Sources of data

- Premises, use, price, and rebate administrative data from EPCOR
  - For demand estimation: average gallons used per day for each month
  - Approximately 13,000-15,000 premises per month for 120 months
- County-level socioeconomic data: US Census, American Community Survey (household size and income)
- Climate data: NOAA (temperature & precipitation); drought data, USDA
- Vegetation data: NOAA/USGS Earth Explorer (1 sq-km overlay; annual data); Specifically, AVHRR

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Premises comparison

Table 3. Gallons Used Per Day Per Premises: Non-Rebate & Rebate Comparison

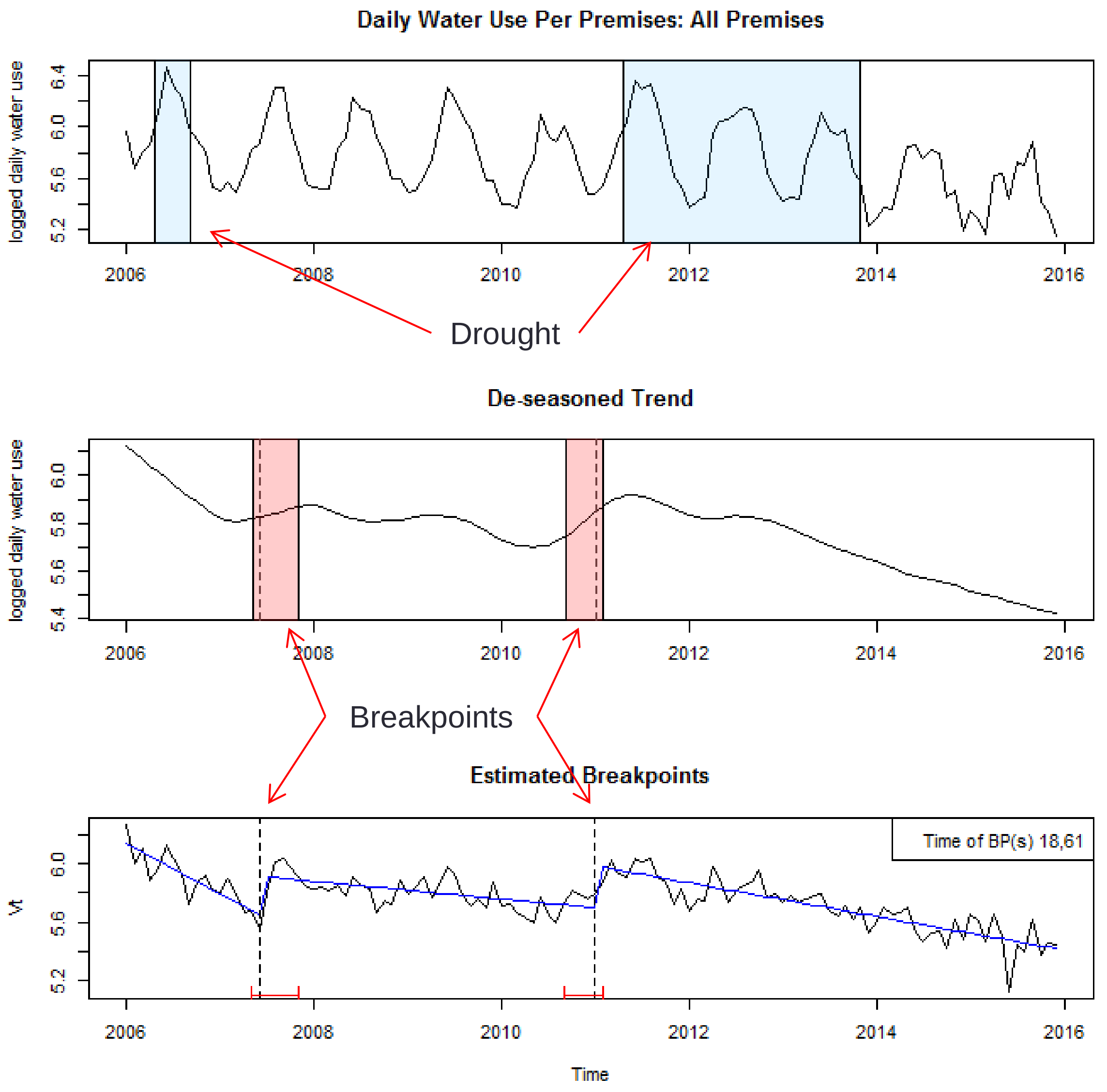
Year	Without rebate			With rebate		
	Mean	Std. Dev.	Median	Mean	Std. Dev.	Median
2006	235	67	232	271	84	266
2007	208	58	197	239	78	228
2008	210	57	210	247	82	235
2009	212	55	209	254	76	236
2010	201	54	198	230	70	220
2011	205	63	205	244	90	235
2012	205	55	203	244	79	228
2013	182	51	184	213	70	201
2014	175	44	180	202	60	195
2015	169	46	154	189	60	181
Total	199	58	192	232	79	221

Note: Without rebate subset excludes all premises that did not receive a rebate at any point. With rebate subset includes all premises that received a rebate.

Seasonal trend & breakpoints

Use per premises: all users

- De-seasoned trend show two break-points: late-2007 and in 2011.
- Overall trends are downward; greatest downward trends in 2011 to 2015.



Trend and breakpoint analysis

- Trend analysis: Used to identify trends in the data – in this case, while controlling for seasonality.
  - Highlights declining trend in water use in the area
- Breakpoint analysis: used to show structural breaks in water use through time
  - Some breaks are interesting; however, still highlights generally declining trends
- Looking at total water use and mean water use per premises.
  - In this case, dependent variable is one observation per month from January 2006 to December 2015 for Clovis.

Trend and break point empirical models

- Seasonal trend decomposition model

$$WU_t = T_t + S_t + u_t$$
$$t = 1, \ldots\ldots, n$$

Where T is the unobserved trend; S is the known seasonal element; u is residual

- Breakpoint analysis model

$$WU_t = \alpha_j + \beta_j t + \sum_{i=1}^{s-1} \delta_{i,j} D_{i,t} + u_t$$
$$t = t_{j-1}^{*} + 1, \ldots\ldots, t_{,}^{*}$$

Where

- strucchange and Bfast packages in R are used

Spatial econometrics

Empirical model (matrix form)

$$\ln\mathrm{WU} = (\iota_T \otimes I_N)\alpha + X\beta + lnAvgPrice\varphi + \varepsilon$$

$$\iota_T \otimes I_N \rightarrow \begin{bmatrix} 1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 1 \end{bmatrix}_{TxT} \otimes \begin{bmatrix} 1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 1 \end{bmatrix}_{NxN} \rightarrow \begin{bmatrix} 1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 1 \end{bmatrix}_{NTxNT} \equiv \iota_{NT}$$

Subscript T accounts for period and N accounts for observation/location.

Next, account for IV

$$\ln\mathrm{WU} = \iota_{NT}\alpha + Z\delta + \varepsilon$$

Spatial lag model

$$\ln \mathrm{WU} = \lambda W_{NT}\mathrm{WU} + \iota_{NT}\alpha + Z\delta + \varepsilon$$

$$W_{NT} = W_N \otimes \iota_T \rightarrow \begin{bmatrix} w_{1,1} & \cdots & w_{1,N} \\ \vdots & \ddots & \vdots \\ w_{N,1} & \cdots & w_{N,N} \end{bmatrix}_{N\mathrm{x}N} \otimes \begin{bmatrix} 1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 1 \end{bmatrix}_{T\mathrm{x}T}$$

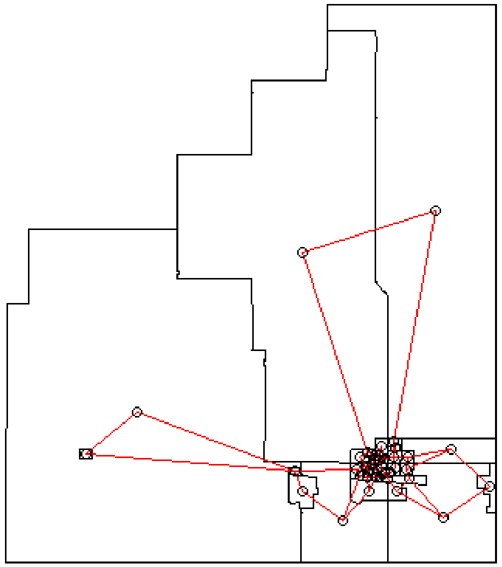
$$\rightarrow \begin{bmatrix} \begin{bmatrix} w_{1,1} & \cdots & w_{1,N} \\ \vdots & \ddots & \vdots \\ w_{N,1} & \cdots & w_{N,N} \end{bmatrix}_{N\mathrm{x}N} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \begin{bmatrix} w_{1,1} & \cdots & w_{1,N} \\ \vdots & \ddots & \vdots \\ w_{N,1} & \cdots & w_{N,N} \end{bmatrix}_{N\mathrm{x}N} \end{bmatrix}_{NT\mathrm{x}NT}$$

Spatial error model

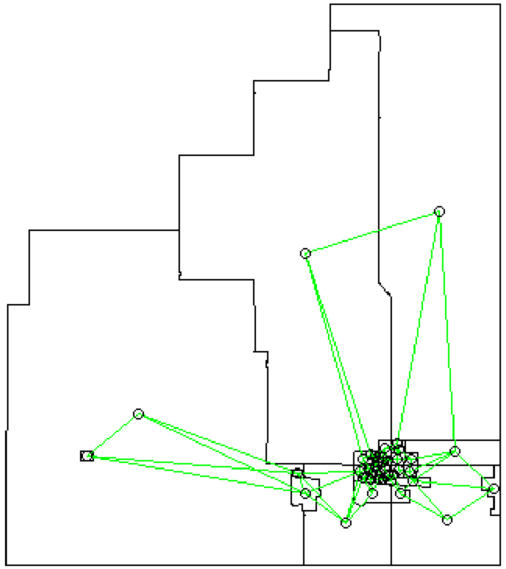
$$\mathrm{lnWU} = \iota_{NT}\alpha + Z\delta + \varepsilon$$
$$\varepsilon = \rho W_{NT}\varepsilon + u$$

Spatial models

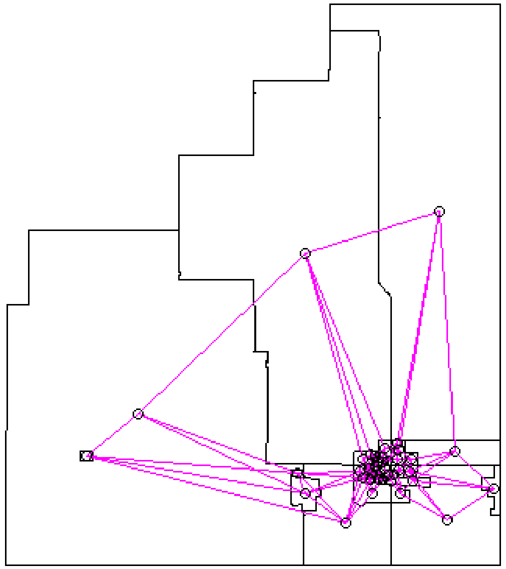
- Number of periods: 120 months (T)
- Number of premises/locations: 33 block groups (N)
- Matrix size: $(120\text{x}33)\text{x}(120\text{x}33) = 3{,}960\text{x}3{,}960$
- Built based on chosen number of closest neighbors k, where $k = 2, 3$ or 4



$k = 2$

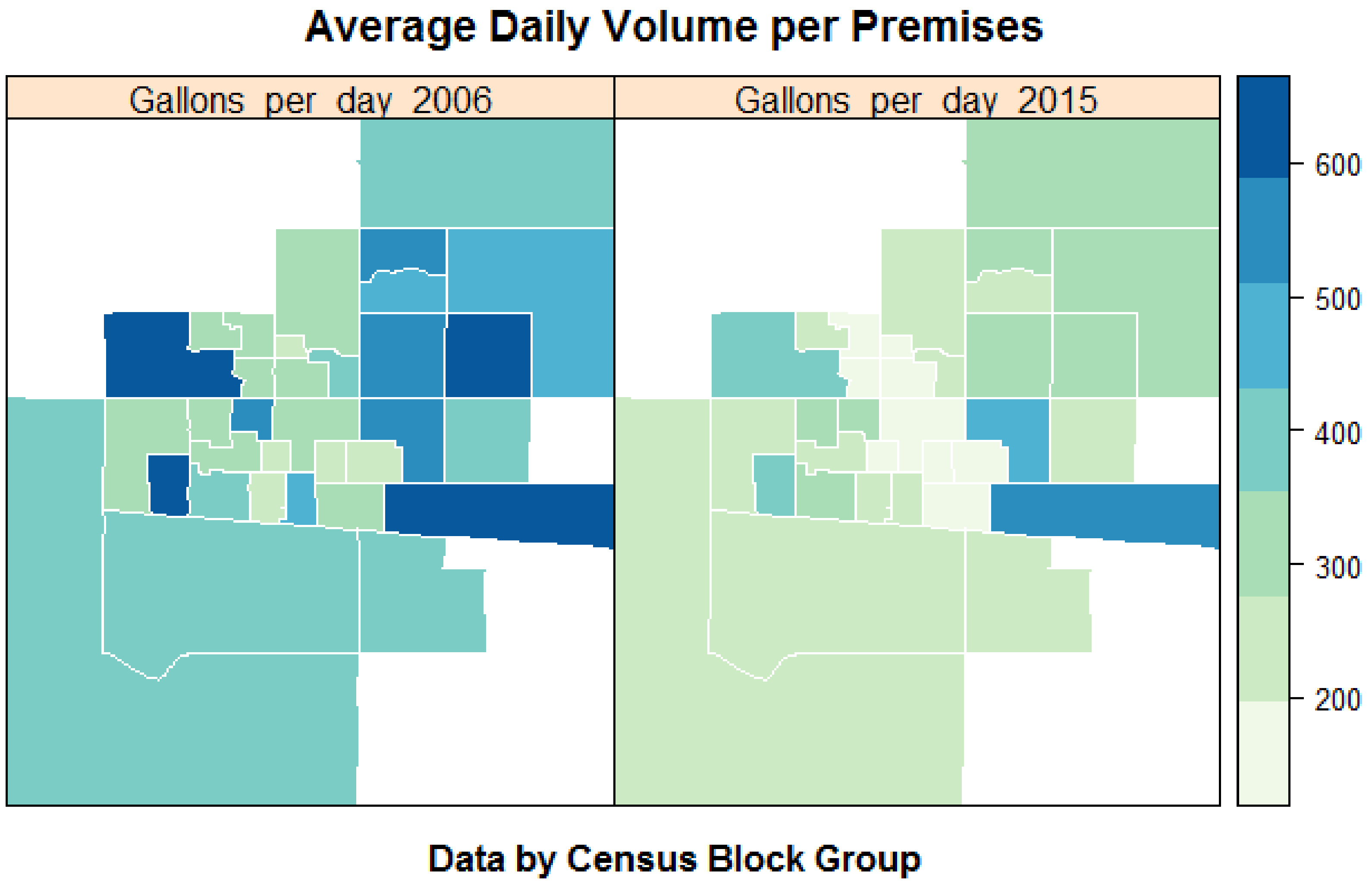


$k = 3$

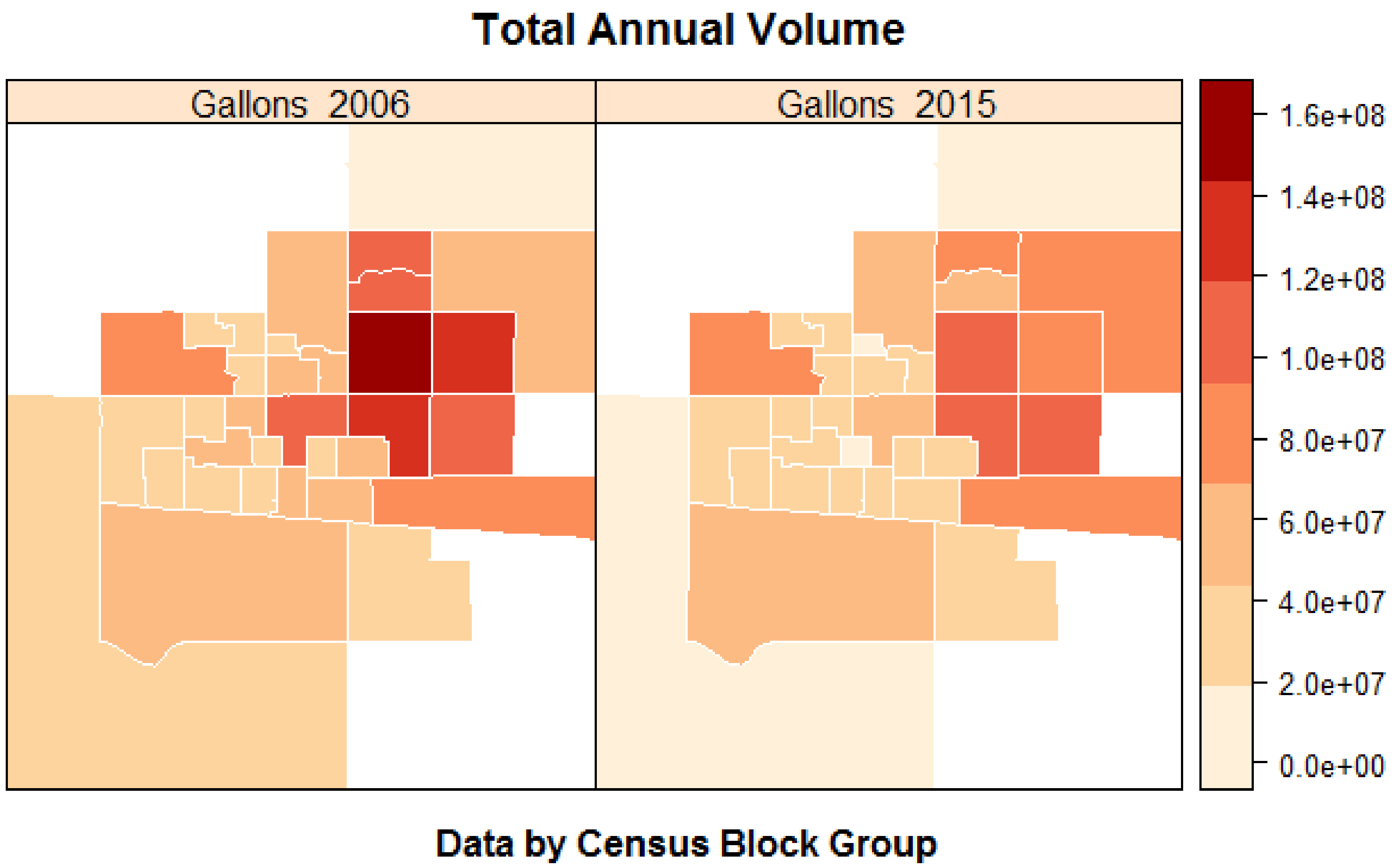


$k = 4$

Spatial map (premises-level)



Spatial map (aggregate)



Spatial diagnostics

- Discuss spatial diagnostics
- Lagrange multiplier test, etc.

Spatial econometric results

Table 5. FEIV and Spatial Models

Variable	Model 1 FEIV Premises-Level	Model 2 FEIV Block Group	Model 3 Spatial Lag	Model 4 Spatial Error	Model 5 Spatial Lag	Model 6 Spatial Error	Model 7 Spatial Lag	Model 8 Spatial Error
			$k = 2$		$k = 3$		$k = 4$	
lnAvgPrice	-0.534***	-0.406***	-0.407***	-0.392***	-0.285***	-0.389***	0.0358	-0.383***
	(0.0076)	(0.0386)	(0.0967)	(0.0423)	(0.0823)	(0.0445)	(0.0924)	(0.0471)
ToiletPrem	-0.083***	-0.123	-0.107	-0.156	-0.152	-0.148	-0.268**	-0.176*
	(0.0042)	(0.1061)	(0.1140)	(0.1047)	(0.1112)	(0.1046)	(0.1215)	(0.1031)
Washer	-0.060***	-0.613***	-0.595***	-0.683***	-0.659***	-0.769***	-0.836***	-0.738***
	(0.0059)	(0.1567)	(0.1601)	(0.1570)	(0.1628)	(0.1531)	(0.1794)	(0.1490)
Landscape	-0.100***	-0.937***	-0.921***	-0.864***	-0.856***	-0.814***	-0.670***	-0.722***
	(0.0071)	(0.1697)	(0.1698)	(0.1688)	(0.1739)	(0.1700)	(0.1933)	(0.1650)
lnIncome	0.568***	0.829***	0.806***	0.829***	0.635***	0.821***	0.229	0.826***
	(0.0268)	(0.1415)	(0.1744)	(0.1704)	(0.1705)	(0.1838)	(0.1888)	(0.2004)
Temp	0.010***	0.011***	0.010***	0.011***	0.008***	0.011***	0.003**	0.011***
	(0.0001)	(0.0009)	(0.0016)	(0.0011)	(0.0015)	(0.0012)	(0.0016)	(0.0013)
Precip	-0.012***	-0.012***	-0.011***	-0.012***	-0.010***	-0.012***	-0.001	-0.011**
	(0.0004)	(0.0028)	(0.0034)	(0.0034)	(0.0032)	(0.0036)	(0.0036)	(0.0039)
λ			0.021		0.227**		0.738***	
			(0.1337)		(0.1146)		(0.1309)	
ρ				0.183		0.246		0.321
N	1,575,980	3,960	3,960	3,960	3,960	3,960	3,960	3,960
R^2 (FEIV)	0.280	0.581						
R^2 (Spatial)			0.652	0.631	0.776	0.630	0.963	0.630

Standard errors reported in parentheses
*Significant at 10%; **significant at 5%; *** significant at 1%

Spatial modeling conclusions

- Likely spatial effect; however, some of the effect accounted-for by facing similar factors
- Spatial lag model goes haywire as number of neighbors increases
- Spatial error model appears to manage spatial hetroscedascity
- Data analysis at the spatial level may not make sense when individual records are available