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Spatial Analysis of Water Use in Oregon, USA, 1985–2005

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Abstract Water use patterns are not distributed evenly over space and time. Determining the amount of water used within a region, as well as the various ways in which water is used is important for making adequate and sustainable water management policies and determining future water availability. We examined differences in spatial trends in Oregon freshwater use (total, municipal, and agricultural water withdrawals), by county, between the years 1985 and 2005. We also explored biophysical and socioeconomic factors that explain spatial patterns using Moran's I, local index of spatial autocorrelation (LISA), and spatial regression models. There was a moderate positive spatial autocorrelation among counties that had similar total and irrigation withdrawals. LISA analysis identified hot spots between certain arid agricultural counties in the southeastern Oregon and cold spots between certain humid northwestern counties, including within the Portland metro area. Annual precipitation and income are negatively associated with total water withdrawals. Summer temperature and farm size is positively associated with irrigation water withdrawals, while net cash return and income are negatively associated with irrigation water withdrawals. When compared to ordinary least square regression models, spatial error models that take into account spatial dependence provide a more comprehensive explanation of the variations of water use, suggesting that water resource planning and management should incorporate spatial and neighborhood effects to effective manage limited natural resources.

Keywords Water use · Oregon · Municipal supply · Irrigation · Spatial autocorrelation · Spatial regression

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1 Introduction

Water is a finite resource and is fundamentally linked to economic and societal growth and well-being. Drinking, irrigation, industrial use, hydroelectric power production, transportation, and recreation are all major uses that depend on sufficient amounts of water availability. Changing demographics, growing water-intensive crops, the surrounding climate, and the efficiency of irrigation practices all can have an effect on the amount of water demand. Water use patterns are not only dependent upon these socioeconomic and biophysical factors, but also rely on the geographical location of a region and its interactions with other adjacent regions. In order to create successful water policies, managers must assess these attributes and geographic factors affecting the present and future supply and demand. One part of meeting this challenge is to determine the past water withdrawals patterns over space. Understanding historic–geographic patterns of water withdrawals help guide the development of spatially-oriented future water management and policy.

The term "water withdrawal" is defined as water that is removed for human use and eventually returned to the source, with possible changes in quantity and quality. It can also include water that is removed and used consumptively, or not returned to the source (Gleick 2003). The regional characteristics of water withdrawals can be influenced by many environmental and socioeconomic variables, such as climate, economic development, and resource availability. It follows that areas with similar environmental and socioeconomic variables influencing water use might exhibit similar degrees of water withdrawal (Dziegielewski 2006; Weiskel et al. 2007). However, there is no previous study linking the spatial trends of water use to changing economy and environment.

Both population growth and climate change are predicted to increase stress on freshwater systems around the world (Vörösmarty et al. 2005; Oki and Kanae 2006; Iglesias et al. 2007; Ruth et al. 2007). Oregon's water management systems are not the exception. In the Willamette River basin, which encompasses the Portland metropolitan area, Salem, and Eugene, population is projected to double between 1990 and 2050 (Baker et al. 2004). Graves and Chang (2007) determined that as temperatures increase in the Pacific Northwest of USA, reduced winter snow pack and warmer, longer summers will significantly impact the timing and volume of runoff throughout the year. A similar study by Hamlet and Lettenmaier (1999) showed that reductions in summer and spring runoff would have a negative impact on irrigation, non-firm energy, recreation, and in-stream flow. Anticipating these changes and incorporating them into management policies will be essential for providing a reliable water supply to a growing demand.

This paper answers the following research questions: (1) What are the determinants of county water use in Oregon? (2) Have the relative importance of factors changed over time? and (3) Do water use patterns show spatial trends and have the trends changed over time? To answer these questions, we analyzed freshwater use data for 1985–2005 compiled by the USGS for the 36 Oregon counties. We hypothesize that the Oregon counties that exhibit similar water withdrawal patterns will be located in a clustered pattern throughout the state rather than completed dispersed or random. This association among counties is supported by the idea that, although each county is unique to some degree, counties in closer proximity to each other display more similarity in water availability and uses than ones more distant

(Miller 2004). Understanding the spatial structure and potential factors affecting the withdrawal patterns are thus important to unravel the complex relationship among water use, economy, and environment. This paper focuses on Oregon's total, irrigation, and municipal freshwater withdrawals. This assessment is important to water management organizations because understanding the spatial relationships of water use determinants helps to provide a base line that can be used in predicting future water use in relation to changing environment (e.g., climate change) and economy (population growth). It can also assist in future water resource planning by determining whether water can be reallocated from counties with greater surplus to those with higher requirements.

2 Literature Review

This study focuses on the 20-year time period after mean water use per capita in the United States had peaked (1980) and then remained unchanged, despite a continuing rise in population (National Research Council 2002). This phenomenon challenged a primary assumption made by water managers; that population and economic growth typically leads to increases in water withdrawals and supply infrastructure expansion (Gleick 2003; Shiklomanov and Rodda 2004). Additionally, because water use patterns cannot solely be explained by population and economic growth, we need to introduce other biophysical and socioeconomic factors influencing water usage. As these factors often exhibit spatial dependence, spatial effects also need to be taken into account in understanding water use patterns.

There has been much written about the relationship between water and economy over long periods of time. Rock (1998) stated that each region goes through similar phases in their use of water resources as a function of their socio-economic growth. The predevelopment phase is characterized by a general lack of necessity for managing water supply, but as regional population and economic growth increases, the use and development of available water resources rise dramatically. The final phase, characterized by increased conservation replacing continued development of water resources, occurs because of the rising cost of infrastructure expansion and the rising price of supply (Rock 1998). Rock (1998) demonstrated this nonlinear relationship of water and economic growth by analyzing GDP and per capita water withdrawals for 68 countries. He found that water withdrawals peak occurred around $20,000 GDP. Beyond this peak, water withdrawals start to decline even as economic growth continues. The shape of the curve is comparable to an inverted U curve and resembles a response that in environmental science is labeled the environmental Kuznets curve. The implication of these findings is that it is possible to "grow" out of natural resource limitations through developmental expansion (Rothman 1998). This research could explain the peak in water use reached by the United States in the early 1990s (Dziegielewski 2006).

Further research by Rock (2000) indicates that rising income per capita always leads to eventual reductions in water-use intensity. The structure of the economy, the regional water availability, and environmental regulations concerning water can all have an effect on this reduction of water use per capita. He states that the importance irrigated agriculture has to an economy also has a great influence on the intensity of freshwater-use. Unlike the average water use for the rest of the country, between

1985 and 2000 the state of Oregon has maintained a significant portion of its water withdrawals for agriculture. Irrigation water withdrawal accounts for 88% of total water withdrawals in Oregon in the year 2000, while it accounts for only 34% of total water withdrawals in the U.S.

Other studies, however, have questioned the relationship between the measure of a country's well being and its intensity of water use (Gleick 2003; Hoekstra and Hung 2005). Gleick (2003) found almost no discernable correlation between the water use and GDP in representative countries. He states that high GDP or income does not necessarily mean low water withdrawals, or visa versa. There are many countries that have a very high standard of living and yet withdraw low amounts of water, such as Austria, Norway, and Singapore. These findings can be determined by several factors, including whether a country produces or imports water intensive products, such as grain. This can have a major impact on the water use of the county or region (Gleick 2003). For example, South Korea's economic growth throughout the mid-to-late twentieth century was not accompanied by increases in total water use as the country focused on manufacturing sectors that consume less water. It imported agricultural products that require a large amount of water to produce (so called virtual water), essentially "saving" water for other purposes (Rock 1998; Hoekstra and Hung 2005; Hoekstra and Chapagain 2007).

As shown in aforementioned studies, water uses are not distributed evenly over space and the relationship between water and economy is not linear at the national scale, but it is less well known whether water use is also a function of economic development at the regional and local scales. In addition, while the geographical patterns of water use at a large scale has been suggested in the literature (Dziegielewski 2006), the importance of geographical location and potential linkages in water use at the country or state or county level has not been addressed in previous studies. An exceptional study was conducted by Wentz and Gober (2007) who explicitly modeled the spatial effects on residential water use consumption by census block group in Phoenix, Arizona using geographically-weighted regression (GWR). Their research showed an improvement of the GWR model results over those of the OLS models. Among the four factors that affect water consumption (household size, the presence of a pool, landscaping practices, and lot size), there was a strong neighboring effect of household size and pools, which then affected the geographical patterns of water consumption. These findings are important as water resource planners can use the model parameters to guide planning newly developed areas by regulating lot size, pool construction, and landscape practices.

3 Study Area Description

The physical geography of Oregon is characterized by profound spatial differences in average temperatures, annual precipitation amounts, and types of eco-regions (Fig. 1). The natural distribution of water in the state of Oregon is primarily dependant on seasonal variations and the influence of the Cascade Mountain Range. Precipitation levels west of the Cascades are between 1,000 to 5,000 mm annually, whereas east of the Cascades, levels only reach between 250 to 500 mm annually (Broad and Collins 1996). The largest rivers in the state are located west of the Cascade Range, while the rivers east of the mountains experience much lower flows

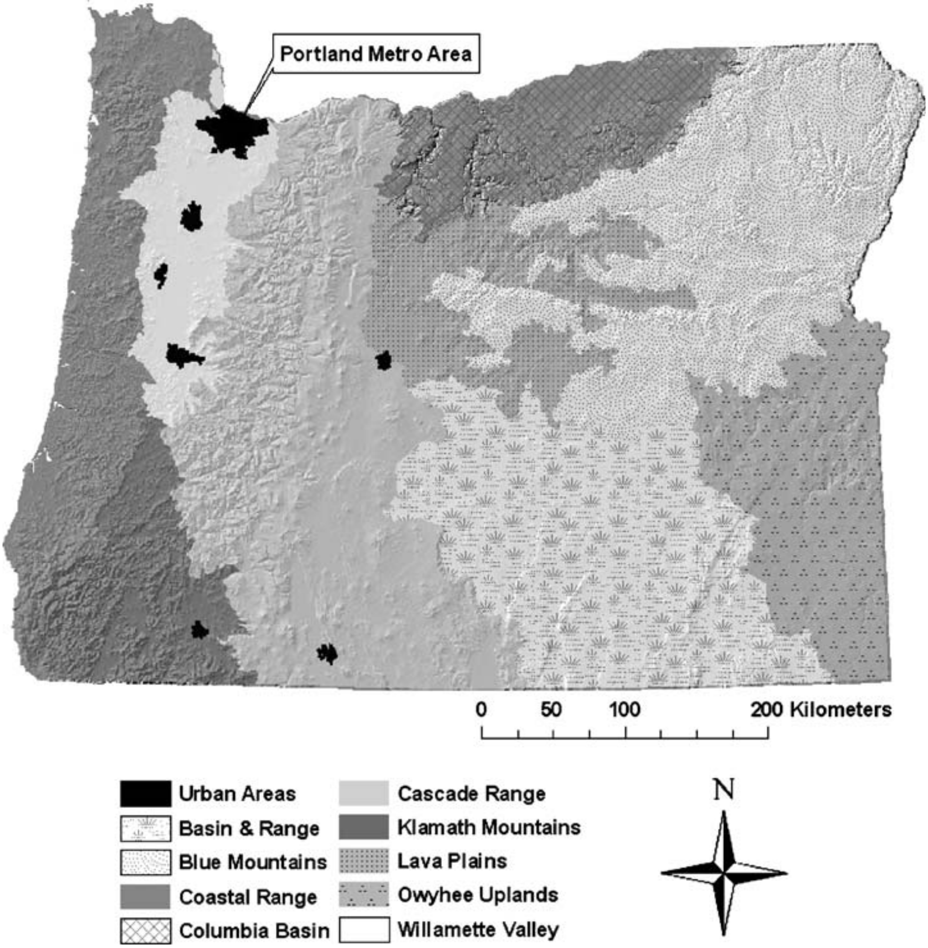
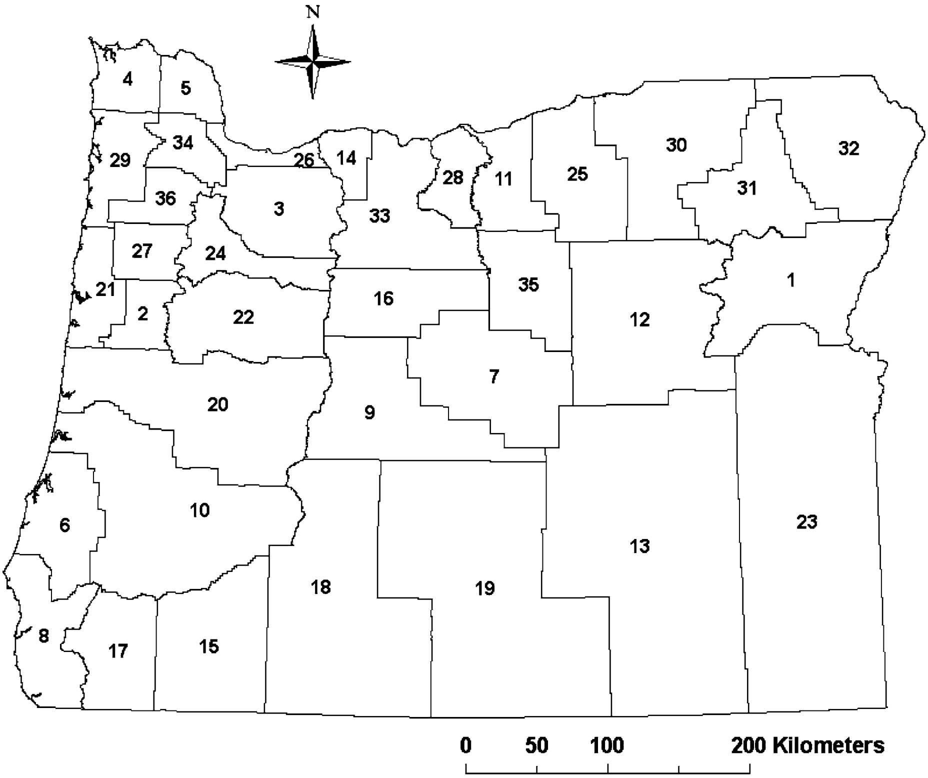


Fig. 1 Topographical map of Oregon showing major physiographic regions (source: Oregon. Gov)

and are more widely spaced (Allan et al. 2001). This difference in precipitation and river distribution significantly affects the availability and use of water across the state (Broad and Collins 1996). Because of the drier climate and increased human demand, surface water in the state is essentially fully appropriated during the summer months. As a result, groundwater is utilized to a greater extent, especially in the eastern portion of the state (Allan et al. 2001).

Between 1985 and 2000, Oregon's population grew by 24% (U.S. Bureau of the Census 2006), while the strength of its economy was mixed. The unemployment rate during the 1980s dropped, from 8.3% at the beginning of the decade, to 5.5% in 1990. During the same time period, the per capita personal income dropped from equal to the average of the U.S. to only 93% of the country's average. This trend continued into the 1990s and per capita personal income never reached the national average in the next ten years, ending the decade at 95%. However, the state's unemployment rate ended up equal to the national average in 2000 (Oregon Progress Board 2005). Population in Oregon increased by 20.4% from 1990 to 2000 (Fisher 2005).

Oregon is divided into 36 counties, each with their own unique water resources and demands (Fig. 2). The largest population centers as well as the areas of greatest agricultural production are in the Willamette Valley, which is located in the western portion of the state. The Portland Metropolitan Area, and particularly Multnomah and Washington Counties, is the most populated region of Oregon, accounting for approximately one-third of the total. Irrigated crop production is one of the most



COUNTY	NUMBER	COUNTY	NUMBER	COUNTY	NUMBER
BAKER	1	HARNEY	13	MORROW	25
BENTON	2	HOOD RIVER	14	MULTNOMAH	26
CLACKAMAS	3	JACKSON	15	POLK	27
CLATSOP	4	JEFFERSON	16	SHERMAN	28
COLUMBIA	5	JOSEPHINE	17	TILLAMOOK	29
COOS	6	KLAMATH	18	UMATILLA	30
CROOK	7	LAKE	19	UNION	31
CURRY	8	LANE	20	WALLOWA	32
DESCHUTES	9	LINCOLN	21	WASCO	33
DOUGLAS	10	LINN	22	WASHINGTON	34
GILLIAM	11	MALHEUR	23	WHEELER	35
GRANT	12	MARION	24	YAMHILL	36

Fig. 2 Map showing the names and locations of the 36 Oregon counties (source: Oregon. Gov)

important parts of Oregon's economy, making up 75% of farm sales receipts, while only using 30% of total farm acreage. Although the eastern region of the state also produces considerable numbers of crops, their primary agricultural product is livestock (Allan et al. 2001).

4 Data and Methods

We used the county surface and groundwater withdrawal data compiled by the USGS Oregon Water Science Center Water Use Program (Fisher 2005). The USGS has been collecting county water-use data in Oregon since 1950, but increased the data accuracy in 1985 by introducing more detailed collection methods. Therefore, our analysis focused on county-level water use since 1985. The analysis of water withdrawals by county instead of hydrologic unit (drainage basin) is significant because water use, agricultural and income data are more readily available at this scale. The county is also a political unit commonly used for water resources planning and management, which has wider implications for water resource planning in other regions.

The surface and groundwater data were reported by the USGS separately for each use category, by county, in million gallons per day (Mgal/d). For the purposes of our research, surface and groundwater data were aggregated for each county to generate total freshwater withdrawals for each water use category for each year in the study period. Data for the two water use sectors, irrigation and municipal supply, and totals for each county were included in the analysis. Industry and hydropower were not included for two reasons: (1) both contributed an insignificant amount to the total and (2) many counties did not report any water use for these sectors (Fisher 2005). At the time of this study, water use data for 2005 was incomplete; therefore, analysis for this year only included withdrawals for irrigation and municipal uses.

As climate is the major driver of water availability (precipitation) and consumption (temperature), we obtained annual precipitation and summer maximum temperature (June to August) data between 1985 and 2005 from Oregon Climate Service (2006) in the form of Parameter-elevation Regressions on Independent Slopes Model (PRISM) datasets. PRISM datasets provide precipitation and daily maximum temperature data averaged over a monthly time scale as 4 km by 4 km grids across the entire country. The climate grids are intersected with the county boundaries to determine each county's area-weighted average for each variable. Annual precipitation data was selected because it determines regional water availability. Summer month maximum temperatures (June, July, August) were chosen because research has determined that municipal and agricultural water demands in mid-latitude regions are temperature sensitive (Akuoko-Asibey et al. 1993; Chen et al. 2006).

Data for county population, population in urban areas, income, and family size were obtained from the U.S. Bureau of the Census (2006). Traditionally, a country or state's gross domestic product (GDP) is used to measure economic strength; however, because there is not a corresponding measure of economic strength at the county level, we used county income data as a surrogate. Agricultural census data, including irrigated land, farm size, and farm income, which presumably affect irrigation water withdrawals, were obtained from U.S. Department of Agriculture

(2006). Agricultural census data were based on years 1987, 1992, 1997, 2002, so there is two years of time lag between the U.S. Census Bureau and USGS water use data and agricultural census data.

We used GIS and statistical methods in order to analyze the characteristics of Oregon's municipal supply, irrigation, and total county water withdrawals as well as the relationship between water use and other physical and socioeconomic variables. For visually displaying the spatial distribution of county level withdrawals throughout the state, an Oregon county map shapefile (Oregon.gov 2006) was joined with the appropriate USGS data and manipulated in ArcGIS. In this way, we could exhibit statewide temporal distribution changes throughout the study period.

In order to measure the relationship between water use and economic well-being, the correlation between water use and annual income was measured using a bivariate regression model. In order to determine the degree of spatial interdependence among counties based on their water withdrawals, we used the spatial analysis software, GeoDa (Anselin et al. 2006). The Global Moran's Index and Local Indicator of Spatial Autocorrelation Index (LISA) determined the degree of spatial autocorrelation among counties. In this way, we can determine if counties with similar amounts of total, irrigation, or municipal water use occur in clusters or are randomly distributed throughout the state. While the Moran's index describes the extent to which the overall configuration of counties is autocorrelated, LISA analysis calculates a spatial autocorrelation value for each unit (i.e. county) by explaining the extent to which individual counties resemble their neighboring counties. This provides an evaluation of where unusual interactions occur, isolating either "hot" spots (areas of high local autocorrelation) or "cold" spots (areas of low local autocorrelation) (Anselin 1995). This will provide more detail on the regional water use around the state and further identify county groups, based on their water withdrawal similarities or differences.

Ordinary least squares (OLS) and spatial regression models were used to determine the relationship between water use and explanatory variables. Table 1 lists the modeled variables used in this study. OLS regression models are aspatial in nature, so

Table 1 Biophysical and socioeconomic variables used in the regression models

Variable description	Units	Source
Dependent variable		
Total water withdrawal per capita	1,000 m^3 $person^{-1}$ $year^{-1}$	USGS
Public water withdrawal per capita	M^3 $person^{-1}$ $year^{-1}$	USGS
Irrigated water withdrawal per irrigated land	1,000 m^3 ha^{-1} $year^{-1}$	USGS & USDA
Independent variable		
Annual precipitation	mm	OCS
Summer maximum temperature	°C	OCS
Mean income	$	USCB
Average family size	Person	USCB
Percent of urban population	%	USCB
Average farm size	ha	USDA
Net cash return from agricultural sales	$	USDA

USGS U.S. Geological Survey, *USDA* U.S. Department of Agriculture, *OCS* Oregon Climate Service, *USCB* U.S. Census Bureau they are not considered adequate for modeling spatial processes (Fotheringham et al. 2000). The results from the OLS regression models and spatial regression models were compared in order to investigate which modeling method provided a more comprehensive explanation of water use patterns. The general assumptions (e.g., multicollinearity, normality, homoskedasticity and spatial independence of errors) of OLS models were tested in GeoDa. Spatial regression models, by accounting for spatial lags and errors, provide an alternative to OLS regression models by considering the spatial component of water use data throughout the state. This method was used in this study to explain possible causes of changes in water consumption over time and to isolate and characterize significant outlier counties. The general form of the spatial regression models is as follows:

$$Y = Xi\beta i + \varepsilon$$
$$\varepsilon = \lambda W\varepsilon + \xi$$

where, Y is the dependent variable, Xi is the explanatory variables, βi is parameter estimates, ε is the error terms, λ is the autoregressive coefficients of the spatial error model, $W\varepsilon$ is the spatially lagged error term, and ξ is a homoskedastic and independent error term. The higher the λ value, the greater the improvement of the spatial model over the OLS model. Recently (Ward and Gleditsch 2008), spatial regression models have been used for a variety of applications in the literature, including jobs and homes (Curry 2007), population density (Griffith and Wong 2007), water quality (Chang 2008), and land use change (Gellrich and Zimmermann 2007).

5 Results and Discussion

5.1 Total Water Withdrawals

Between 1985 and 2000, there was no significant upward or downward trend in Oregon's total water withdrawals (Fig. 3) even as the population grew at a steady, gradual rate. The results were similar to the rest of the U.S., which was experiencing a level trend in water use during the same time period (USGS 2006). The causes for this nation-wide level trend were attributed to improved water-use efficiency and less production of water-intensive goods (Gleick 2003). There was a significant decrease in Oregon's water withdrawals between 1990 and 1995, which could be attributed to some of the factors affecting the national use. In 2000, Oregon's total water withdrawals per capita (7.7 m^3 day^{-1}) were much higher than US average withdrawals (5.4 m^3 day^{-1}), which may be the result of Oregon's agriculture based economy. In other words, Oregon is a net exporter of virtual water to other parts of US or world.

Indeed, irrigation made up the largest percentage of total water used in Oregon (88% in 2000) and virtually mirrored the overall trend variations. This is not unexpected, considering that the agricultural sector is an important contributor to the state's economy (Oregon Department of Agriculture 2007). Municipal water withdrawals accounted for approximately 6–8% of total water withdrawals, followed by industrial water withdrawals (3–5%). It was also found that, with the exception

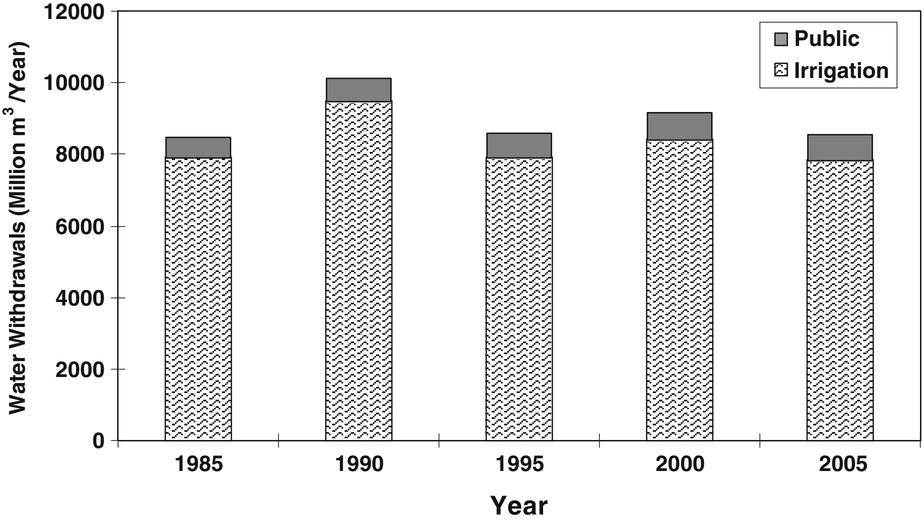


Fig. 3 Oregon's water withdrawals for irrigation and public supply from 1985 to 2005

of the southwest region, counties with higher water withdrawals generally remained similarly distributed throughout the state between 1985 and 2000, when compared to their neighbors (see Fig. 4a).

As shown in Fig. 4a, the pattern of total water withdrawals in Oregon differs greatly from east to west. The range of total per capita water withdrawals in 2000 is between 86 m^3 (Multnomah County) and 12,361 m^3 (Lake County). Through the use of the global Moran's index statistical test, it was determined that, the counties of Oregon exhibit moderately positive spatial autocorrelation (I-value = 0.39) (Table 2). The strength of this relationship has diminished slightly from 1985 (I-value = 0.47), suggesting a slightly more scattered pattern of water use overall (Fig. 5). Local Moran's analysis showed that there were changes in "hot" and "cold" spot clustering between 1985 and 2000 (Fig. 4b). In 1985, there was a cluster of counties (eight) that displayed a minimal measure of spatial autocorrelation (i.e. a "cold" spot) in the northwestern corner of the state. This indicated that their total water use patterns were considerably different. By 2005, the "cold" cluster had expanded to nine counties, and remained in the same area of the state. In 1985, a cluster of highly autocorrelated counties (three) appeared in the eastern region of the state. This indicated that their total water use patterns were similar, when compared to the neighboring counties. By 2000 this grouping had expanded slightly to four counties and encompassed the southeastern region.

In all years, there is a positive spatial autocorrelation (as measured by λ) with differing degrees of spatial dependence (Fig. 6). The clustering was generally in the eastern portion of the state, suggesting that the low populations and high irrigation withdrawal (over 90% of total water withdrawals in those regions) are responsible for explaining the clustered pattern. These results provide moderate support to the alternate hypothesis (clustered distribution).

The spatial variations of total water withdrawals are mostly explained by climate variability for all study years (see Table 3). Annual precipitation is mostly negatively

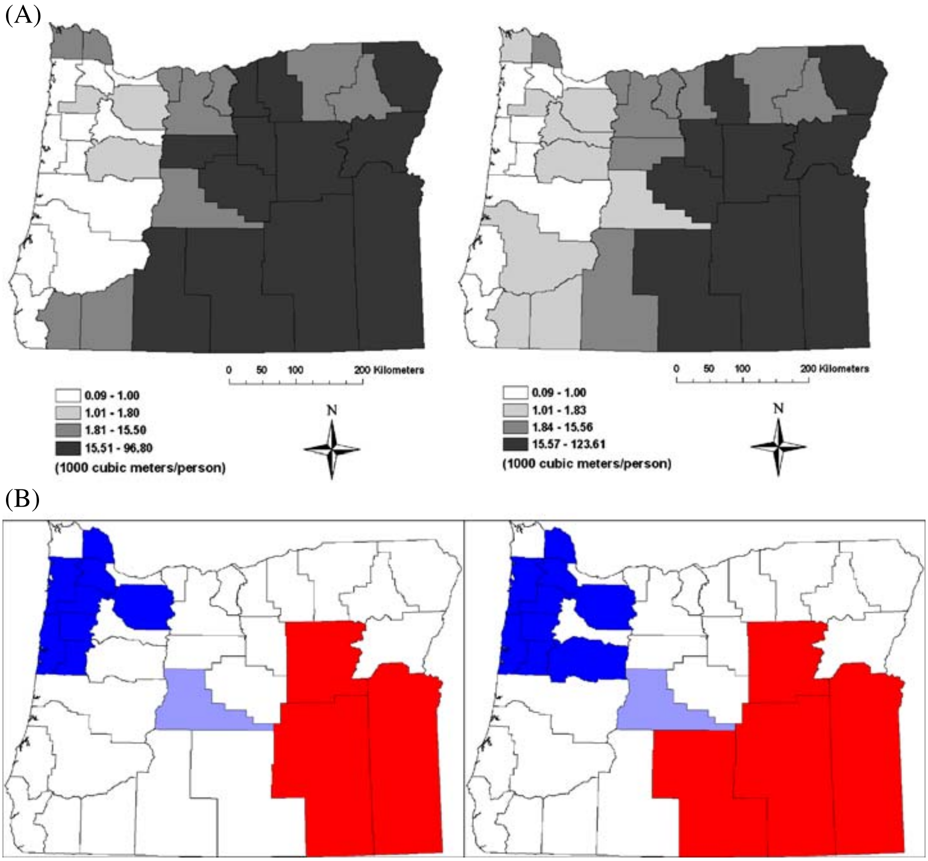


Fig. 4 The distribution of total water withdrawals per capita **a** by Oregon counties for the years 1985 (*left*) and 2005 (*right*) and **b** using LISA cluster maps showing hot (*red*) and cold (*blue*) spots

associated with total water withdrawals and explains about a quarter of variations in total water use. Summer maximum temperature is excluded in the model because it is strongly correlated with annual precipitation ($r > 0.7$). While income is also negatively associated with total water withdrawals, it is only significant in 1995 and 2000. In both years, income additionally explains 13% and 7% of variations in water withdrawals, respectively. In all models, the multicollinearity condition numbers reported in GeoDa are less than 30, indicating that there is no significant multicollinearity among variables. These results suggest that climate variability is the

Table 2 A summary of global Moran's index results for total water use in Oregon for 1985 and 2000, and municipal supply and irrigation water use in Oregon for 1985 and 2005

	Total		Municipal		Irrigation	
Year	1985	2000	1985	2005	1985	2005
Moran's *I*	0.4661	0.3934	0.0144	0.1155	0.2702	0.4465

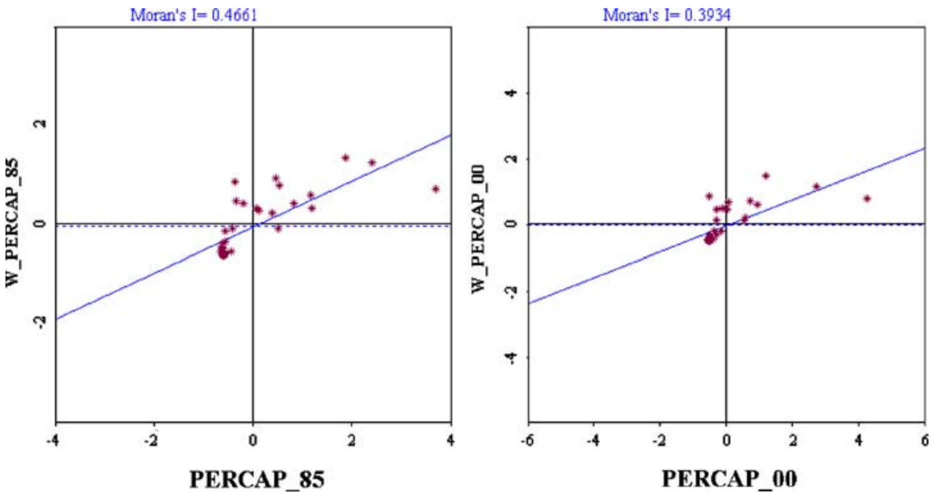


Fig. 5 The measure of spatial autocorrelation between total water withdrawals per capita and Oregon counties for the years 1985 (*above*) and 2000 (*below*), using Moran's index

major driving force of per capita total water withdrawals in Oregon. However, it is also possible that climate variability could influence the types of crops grown or other decisions related to agricultural production.

The spatial error models fit the data better than the non-spatial models. In all cases, as demonstrated by higher R^2 values, the spatial error model better explains variations of total water use than OLS models (see Table 3). Notice that when there is less spatial autocorrelation (i.e. for the year 1990), the improvement is minimal. While the direction of the coefficients of the explanatory variables (annual precipitation and income) remains negative (see Table 3), the significance and magnitude of the coefficients changes over time. For example, once spatial correlation is taken into account, neither annual precipitation nor income is significant variables for explaining the variations in water use patterns in 2000. These findings suggest, when we take into account spatial correlation among the residuals, that OLS analysis that treats individual county as an independent sample introduces overconfidence in estimates and thus may be less robust than the results of spatial regression models.

5.2 Municipal Water Withdrawals

Because the USGS municipal water withdrawal results for Multnomah and Clackamas counties were inaccurate for 1995 (Fisher 2006), information for this year was excluded in this portion of the analysis. While this may affect long-term trend analysis, it was not detrimental to our study results. Our research revealed virtually no spatial autocorrelation between counties of similar per capita municipal water use, for either the year 1985 or 2005 (I-values = 0.014 and 0.116 respectively). Visually, this is represented in the scattered patterns for both 1985 and 2005 illustrated in Fig. 6a. It also showed no significant change in this trend for any of the years

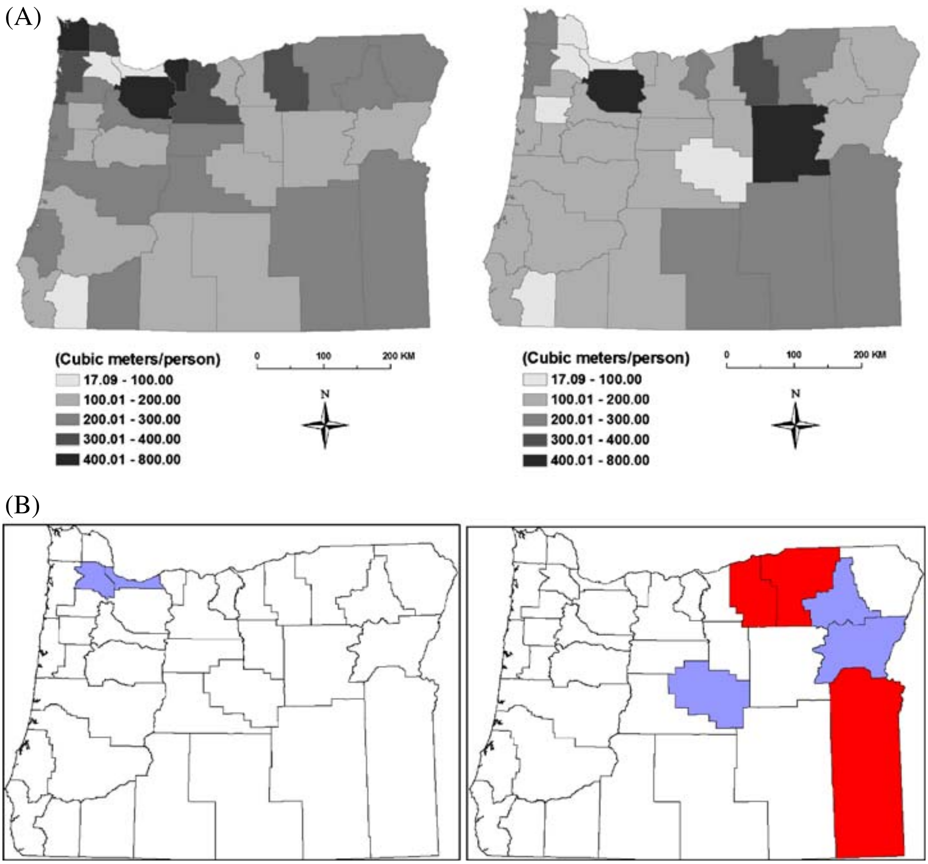


Fig. 6 The distribution of public supply withdrawals per capita **a** by Oregon counties for the years 1985 (*left*) and 2005 (*right*) and **b** using LISA cluster maps showing hot (*red*) and cold (*blue*) spots

in between. A local Moran's *I* analysis revealed only slight changes in "hot" and "cold" spot clustering between 1985 and 2005 (Fig. 6b). In 1985, there were no hot or cold spots found throughout the state. Spatial outlier counties were clustered in and around the Portland Metro Area. By 2005, a small hot spot had appeared in the state's southern region and the cluster of outlier counties had disappeared. Two highly urbanized counties, Multnomah and Washington, both had what could be considered low per capita use for both years; however, Clackamas County, with a rapidly growing urban population, had high per capita use for both years. Because different forms of urban development (compact versus sprawl) could affect residential water consumption patterns in urban areas (Wentz and Gober 2007), a scale finer than the county level should be used, which is beyond the scope of this study. In addition, per capita municipal water withdrawals may be low as a result of the extensive water infrastructure and the efficient use of water in these counties.

There was very weak positive correlation between the per capita municipal water withdrawals and annual incomes for both years 1990 and 2000 (only the year

Table 3 A summary of ordinary least square models (OLSM) and spatial error models (SEM) for per capita total water withdrawals in Oregon (1985–2000)

Unstandardized coefficients	1985		1990		1995		2000	
(*p*-value)	OLSM	SEM	OLSM	SEM	OLSM	SEM	OLSM	SEM
Annual precipitation	−0.025	−0.0167	−0.024	−0.0227	−0.013	−0.0115	−0.018	−0.014
	(< 0.001)	(0.037)	(0.002)	(0.002)	(0.008)	(0.029)	(0.005)	(0.056)
Income	−0.003	−0.00014	−0.001	−0.00158	−0.002	−0.00285	−0.001	−0.0013
	(0.274)	(0.954)	(0.342)	(0.287)	(0.006)	(0.0007)	(0.079)	(0.064)
Lambda		0.575		0.14		0.383		0.487
		(0.0002)		(0.54)		(0.049)		(0.005)
R^2	0.352	0.475	0.316	0.323	0.454	0.505	0.310	0.414

2000 is shown in Fig. 7). Further analysis on the outliers revealed several atypical counties. The highest annual mean income, coupled with the lowest municipal water withdrawals, was in Washington County. Clackamas County had the highest water withdrawals and annual mean income of all the Oregon counties, while Morrow County showed a significant drop in per capita use over the 10-year study period. Annual precipitation and percentage of urban population showed a weak negative association with municipal water withdrawals in 2000 ($r = -0.2$, and -0.15 respectively), and the relationship was not statistically significant (see Table 4). According to the Oregon Progress Board (2005), per capita income is considered a very good signifier of overall economic health. However, our results indicate that there are other determinants, besides income or climate, that influence municipal water use. Results also suggest the complexity of understanding the determinants of municipal water withdrawals at the county scale. Census track or block or parcel level analysis might reveal the factors affecting municipal water use.

5.3 Irrigation Water Withdrawals

Irrigation withdrawals make up the largest percentage of water use in the state, at 88% during the year 2000. This is similar to the rest of the world, where approx-

Fig. 7 Regression model of the correlation between municipal water withdrawals (cubic meter per year) and annual mean income ($) for the year 2000. The outlier counties are Wheeler County, Morrow County, Multnomah County, Clackamas County, and Washington County

Table 4 A summary of correlation for municipal water withdrawals per capita in Oregon, 1990 and 2000

Year	Income	Urban population	Annual precipitation	Maximum temperature
1990	−0.227	−0.27	0.013	−0.192
2000	0.019	−0.15	−0.201	0.054

imately 85% of the total water consumption is by irrigated agriculture (Gleick 2003). However, these figures are more than two times higher than the US national average irrigation water withdrawal rate of 38% (Fisher 2005). In addition, Oregon's irrigation water application (9.68 km^3/ha) is higher than the US national average (7.65 km^3/ha), suggesting that Oregon's agricultural sector uses water much more intensively. This is particularly true for the eastern and southeastern counties, which produced large volumes of water intensive crops in a dry climate.

There is an increase in spatial autocorrelation between counties of similar irrigation water use between the years 1985 and 2005 from a low to a moderate relationship

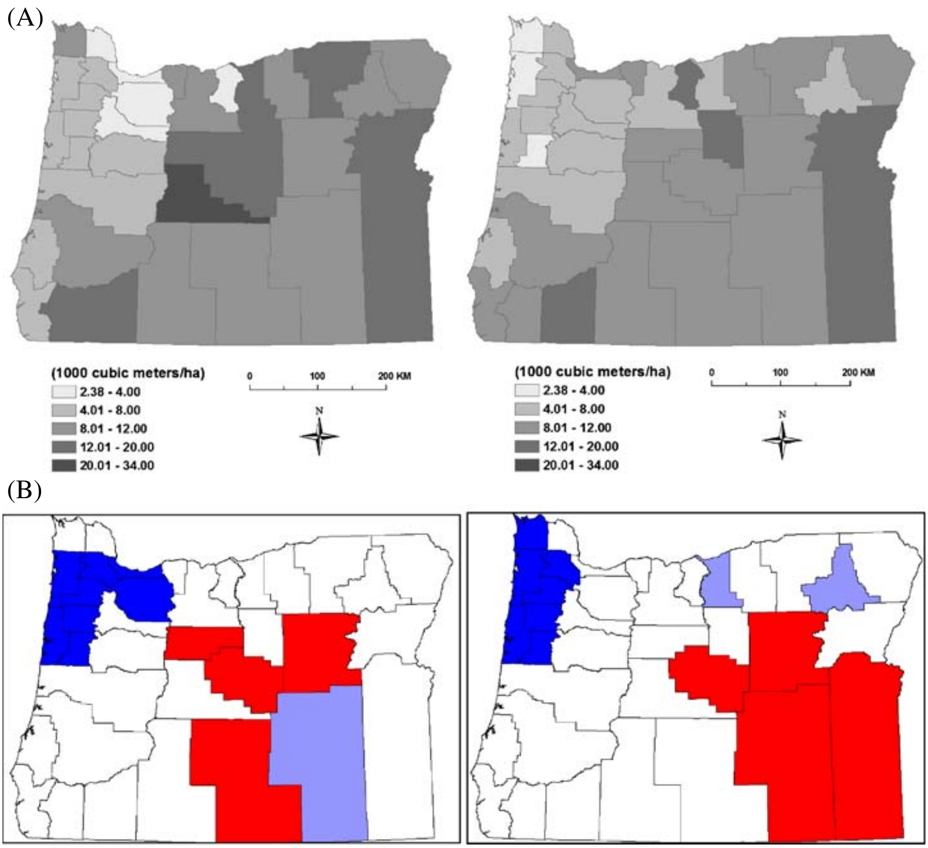


Fig. 8 The distribution of irrigation water withdrawals per land **a** by Oregon counties for the years 1985 (*left*) and 2005 (*right*) and **b** using LISA cluster maps showing hot (*red*) and cold (*blue*) spots

(global I-values = 0.27 and 0.45 respectively) (Fig. 8a and Table 2). A local Moran's I analysis revealed moderate changes in "hot" and "cold" spot clustering between 1985 and 2005 (Fig. 8b). In 1985, there was a small "hot" cluster of counties (four) in the southeastern corner of the state, indicating high spatial autocorrelation between these counties at this time. By 2005, this cluster had shifted eastward slightly. Analysis for 1985 showed a large "cold" cluster of counties (seven) in and around the Portland Metro Area and west to the coast. By 2005, this "cold" cluster remained as seven counties, but had shifted more toward the coastal region. These results reasonably support the alternate hypothesis (clustered distribution). Generally, counties with higher amounts of irrigated withdrawals are located in the eastern portion of the state, which corresponds with the drier climate. Irrigation water use declined slightly during the study period.

The slight changes in hot and cold spots between the study period suggest that changes in regional socioeconomic characteristics and associated agricultural practices (types of crops grown) will continue to play an important role in determining irrigation water withdrawals. In 1990, farm size had the most significant correlation to irrigation water withdrawals (Table 5). More recently, net cash return has become more important to the use of irrigation water, possibly reflecting the production of higher dollar crops. Income showed a significant negative correlation to irrigation at the beginning and end of the study period, suggesting that affluent farms could use irrigation water more efficiently. The negative relationship between these economic variables and irrigated water use per land suggests that higher profit could be achieved by using growing less water intensive crops. For example, the area of the state that had only moderate irrigation water withdrawals while producing the highest crop sales was the Willamette Valley. Four of the five most agriculturally profitable counties in Oregon were located in this region. Their primary plant production is in greenhouse and nursery crops, such as flowers, landscape plants, and Christmas trees that are less water intensive than hay and forage corps but highly profitable (Oregon State University Extension Service 2000).

Like the case of total water withdrawals, the spatial error models better explained data than the OLS regression models. The improvement over the OLS models, however, was not great compared to the results of total water withdrawals. This is due to the fact that spatial autocorrelation, which is demonstrated by the significance value of lambda, was only significant in 1990. OLS models overestimate the influence of summer temperature and income on irrigation water use as these explanatory variables become less significant once spatial correlation has been taken into account.

One factor affecting irrigation withdrawals in eastern Oregon is that counties such as Malheur, Lake, and Klamath produce vegetable crops, as well as hay and forage crops, all of which require significant amounts of water (Oregon State University Extension Service 2000). It should be noted that while the crop acreage used by these counties was similar to the counties in the Willamette Valley, their amount of water withdrawn was significantly higher. Any decline in future water availability in this part of the state could result in decreased production of these water intensive crops. Umatilla County in northeastern Oregon, a county not located in either the Willamette Valley or the southeastern region, used the largest amount of crop acreage. However, it was below the majority of southeastern counties in water withdrawals while maintaining high crop sales (Oregon State University Extension Service 2000).

Table 5 A summary of ordinary least square models (OLSM) and spatial error models (SEM) for irrigation water withdrawals per irrigated land in Oregon (1985–2005)

Unstandardized coefficients	1985		1990		1995		2000		2005	
(*p*-value)	OLSM	SRM	OLSM	SRM	OLSM	SRM	OLSM	SRM	OLSM	SRM
Summer temperature	1.389 (0.055)	1.169 (0.869)							2.03 (0.001)	1.825 (0.001)
Farm size			0.021 (0.001)	0.021 (0.001)						
Net cash return					−0.00015 (0.22)	−0.00021 (0.06)	−0.00008 (0.038)	−0.00005 (0.11)		
Income	−0.0018 (0.018)	−0.0017 (0.022)							−0.0001 (0.034)	−0.00028 (0.085)
Lambda		0.289 (0.167)		−0.67 (0.004)		0.404 (0.034)		0.30 (0.15)		0.267 (0.21)
R^2	0.226	0.276	0.295	0.469	0.044	0.152	0.120	0.184	0.404	0.434

6 Conclusions

Between 1985 and 2005, water withdrawal estimates in the state of Oregon have exhibited a general level trend. This trend was similar to estimates for the rest of the country, where water use flattened out during the two decades. The study period coincides with drier and warmer climate and increases in population in Oregon. While the importance of agriculture and subsequently irrigation water use diminished throughout the U.S., agriculture still remains one of the primary industries within Oregon. Irrigation was the largest user of freshwater in Oregon, followed by municipal water withdrawals, industry and hydropower.

The spatial patterns of total water withdrawals in Oregon are largely determined by climate variability, due to a wide range of precipitation variability. While income accounts for small variations in total water withdrawals, its significance is only apparent toward the end of the study period. This study also suggests the importance of spatial approach in determining water use patterns. The presence of spatial dependence in error measurements, as revealed by the Moran's *I* values, suggests that the spatial error model results are more revealing than those of the OLS regression models. This suggests that water resource planning and management should incorporate spatial and neighborhood effects, which provides an appropriate management unit. Such a geographically-based management unit could provide a guideline for water (re)allocation under projected climate change and population growth.

More extensive analysis is needed for determining the relationship between municipal water withdrawals and other explanatory variables. Using long-term data with a finer spatial scale (e.g., metropolitan scale) might also help in exploring the factors that affect municipal water withdrawals. Future studies might also include how interstate and international trades might affect regional water use at multiple scales. While this study has a limited scope, it is the first attempt to investigate the determinants of the spatial variations of water withdrawals in Oregon and provides baseline information on regional water demand under the changing environment. The study demonstrates that the complex patterns of water use cannot be solely explained by economic development but other biophysical factors as well as spatial effects. The spatial modeling used in this study could serve as a useful guideline for coordinating water resource management in other regions experiencing potential water stresses.

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