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Management implications of spatiotemporal non-stationarity in municipal water consumption patterns and drivers

Matthew H. Connolly[a,*], Ronald R. Hagelman III[b]

[a] Department of Geography, University of Central Arkansas, 201 Donaghey Avenue, Conway, AR 72035, USA
[b] Department of Geography, Texas State University, 601 University Drive, San Marcos, TX 78666, USA

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ABSTRACT

This study analyzed the individual and joint influences of social, urban, and physical drivers on patterns of county-scale municipal water consumption (MWC) the for the state of Texas using a cross-sectional research design on three distinct temporal slices (1990, 2000, and 2010). Global multiple linear regression models and measures of global and local spatial association were combined to determine which drivers significantly influenced county-scale per capita MWC, whether or not the statistically significant drivers varied over time, and to assess the degree to which the patterns and drivers of MWC exhibited spatial stationarity. Overall results suggested the social, urbanized, and physical environments contributed significantly to the patterns of per capita MWC to varying degrees in each year. The social and urbanized environments consistently exerted the strongest influences on per capita MWC, while the physical environment was generally less important. The social environment had the greatest cumulative influence in all three years, and the urbanized environment singly accounted for the majority of the variation in per capita MWC when the joint influences of the other significant drivers were considered. Spatial analysis of MWC patterns and drivers suggested that they both exhibited weak to moderate degrees of spatial non-stationarity in each year, as well as that MWC patterns and drivers may be sensitive to regional and climatic boundaries. Identification of temporally consistent MWC drivers merged with longitudinal and cross-sectional research designs can improve water management strategies by offering managers greater insight into the relationships between landscape change and water consumption patterns.

1. Introduction

Sociopolitical disputes over fresh water resource access are common and reflect the degree to which demand often outstrips supply (Arbues, Garcia-Valinas, & Martinez-Espineira, 2003). This mismatch is exacerbated by spatial and temporal variability in freshwater resources and by the fact that, in general, municipal water consumption (MWC) is not easily reduced through conservation initiatives (Arbues et al., 2003; Dingman, 2015; Martinez-Espineira & Naughes, 2004; Petersen, Sack, & Gabler, 2012). Research also indicates climate change, along with population growth (Cooley & Gleick, 2009) and urbanization, will continue to alter the quantity, quality, and spatial distribution of global fresh water resources (Bednarek, 2001; Dallman & Spongberg, 2012; Kundzewicz et al., 2008; Ward, 2011), thus further complicating management of this precious resource.

The goal of this research is to discover the degree to which human and physical drivers significantly influence MWC in support of more informed freshwater management decisions. In this study, MWC is a combination of both residential and commercial water use. Municipal water use managers will benefit from an improved understanding of significant landscape drivers for water consumption, while analytical research into water resource patterns will benefit from further exploration of relevant landscape drivers for municipal water use in an ever changing, rapidly urbanizing world.

Although simple population growth would seem to be the main contributor to increased water use, previous studies have demonstrated MWC is a function of both human and physical landscape factors (Ahmad & Prashar, 2010; House-Peters, Pratt, & Chang, 2010; Kenney, Goemans, Klein, Lowery, & Reidy, 2008;

* Corresponding author.
E-mail addresses: mconnolly@uca.edu (M.H. Connolly), rhagelman@txstate.edu (R.R. Hagelman III).

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Ouyang, Wentz, Ruddell, & Harlan, 2014). Furthermore, local differences within human and physical factors may produce inequalities in MWC that disrupt delicate supply and demand relationships between neighboring communities (Murray et al., 2012). This interaction between the municipal consumption of one community and municipal supply of another could potentially trigger political conflict or regional emigration with deleterious economic and environmental consequences (Ward, 2011). In addition to influences of natural and anthropogenic drivers, changing management goals can also influence water use. Water conservation remains unpopular in many communities (Chang, in press; Saurí, 2013) and further complicates municipal water management. More often than not, increasing demand results in costly engineering solutions rather than conservation methods (Graf, 2005), which may trigger physical environmental changes such as degradation of water quality and loss of aquatic habitat (Bednarek, 2001).

Understanding MWC drivers is especially important in arid and semi-arid climatic regions with highly variable precipitation patterns and rapid population growth such as those found throughout the American Southwest. Texas is no exception, with its mosaic of arid, semi-arid, and sub-tropical humid climates (Dixon & Moore, 2011; Petersen et al., 2012) and booming urban populations. According to the Texas Water Development Board (TWDB), the population of Texas is expected to grow 80% between 2010 and 2060, and require an additional 8.4 million acre feet of water per year from a variety of sources throughout the state including construction of new reservoirs, increased surface water withdrawals, water re-use, irrigation conservation, and municipal conservation (TWDB, 2012a) to meet projected demands for all water using groups (e.g. municipal, agriculture, industry, etc.).

Potential mismatches between MWC, and available water supply may be especially important in North Central and East Texas as they are home TWDB Planning Regions C, D, H, and I (Fig. 1) that are expected to show a collective 68% increase in water consumption, and an 86% increase in population between 2010 and 2060 (Table 1). Research has shown MWC, like freshwater location, is also spatially variable (Franczyk & Chang, 2009; House-Peters & Chang, 2011; March & Saurí, 2010; Ouyang et al., 2014; Wentz & Gober, 2007), and that MWC is a function of human and geophysical factors (Carver & Boland, 1980; Cochran & Cotton, 1985; Kenney et al., 2008). Spatial variability in MWC is further confounded by the fact that meeting freshwater demands is often accomplished through expansion of existing water supplies, which has far-reaching environmental consequences. For example, new reservoir constructions may trigger bank erosion and degradation of water quality a considerable distance downstream from new impoundments (Bednarek, 2001; Wellmeyer, Slattery, & Phillips, 2005).

The purpose of this research is to improve our understanding of quantitative synergies among social and physical environmental drivers relative to MWC, to characterize spatiotemporal changes among those characteristics, and to assess the degree to which MWC can be explained by a spatially stationary model. These purposes were operationalized using spatiotemporal analysis of MWC patterns in Texas counties in comparison to social, urban, and physical drivers at three temporal slices over a twenty-year period. Specifically, this study addresses three research questions: 1) Which social, urban, and physical drivers contribute significantly to county-scale MWC patterns?; 2) Do these drivers vary over time?; and 3) To what degree do MWC patterns exhibit spatial stationarity?

This analysis also addresses the larger question regarding the degree to which quantitative measures of human environments, physical environments, and synergies between the two explain MWC patterns. This study explicitly considers time, identifying consistently significant MWC drivers over multiple cross-sections of a period of record using multiple temporal slices. Simultaneously analyzing time and spatial stationarity adds to previous quantitative water consumption research that focused largely on a small number of demand drivers (Carver & Boland, 1980; Cochran & Cotton, 1985; Franczyk & Chang, 2009; Gutzer & Nims, 2005; House-Peters et al., 2010; Kenney et al., 2008; Wentz & Gober, 2007; Zhou, McMahon, Walton, & Lewis, 2000). Understanding the role of spatial stationarity and time in the evolution of municipal water demand will also aid current management and future planning for water resource development and conservation. Additionally, an awareness of temporally consistent significant MWC influences could help water managers anticipate future needs, and improve targeting of use-reduction campaigns.

2. Background

2.1. Human environment

Increasing population size and expanding urbanization increase human use of water, as well as, altering its quantity, quality, and spatial distribution (Dallman & Spongberg, 2012). These expansion processes typically reduce water resource availability by increasing demands for municipal water and electricity (Hitchcock, 2011; Murdoch, Baron, & Miller, 2000). TWDB Planning Region C's (Dallas, Tarrant, and Denton Counties among others) population alone, is projected to increase by 96% between 2010 and 2060, and will result in an 86% increase in MWC (Table 1), and a corresponding stress on existing water supplies. Growth of electricity demand is especially important due to the amount of water consumed by the average thermoelectric power plant, and the amount of energy consumed by water purification in treatment plants (Stillwell, King, Webber, Duncan, & Hardberger, 2011). In this way, an increase in MWC could create a positive feedback loop. Increasing MWC requires additional electricity that in turn requires additional water consumption.

Addressing these potential shortages created by population growth and urbanization will be complicated by structural solutions such as new reservoir construction and inter-basin transfers that are much more difficult to implement than in the past. For example, nearly all amenable reservoir construction sites in Texas are already in service (Schmandt, 1995), and the strong influences of population and urbanization on fresh water demand, as well as the state's heavy reliance on surface water are likely to alter freshwater characteristics and other aspects of the physical environment. Additionally, existing municipal water supply reservoirs may be compromised by Texas' natural inter-annual climate variability, and potential climate warming.

2.2. Physical environment

Texas is home to four primary Köppen–Geiger climate types including humid subtropical (Cfa), cold mid-latitude desert (BSk), cold mid-latitude steppe (BWk), and hot subtropical steppe (Bsh) (Dixon & Moore, 2011). Temperature and precipitation patterns follow north-south and east to west gradients respectively, with temperature increasing from north to south, and precipitation increasing from west to east. In addition to regional climatic differences, Texas climates also experience high inter-annual variability in temperature and precipitation which complicate water planning efforts (North, 1995). Given the water management difficulties under current climatic conditions, climate warming would only exacerbate Texas' municipal water predicament.

The Intergovernmental Panel on Climate Change has demonstrated atmospheric concentrations of greenhouse gasses such as