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Spatiotemporal Analyses of Recycled Water Production

A thesis

presented to

the faculty of the Department of Geosciences

East Tennessee State University

In partial fulfillment

of the requirements for the degree

Master of Science in Geosciences

by

Jana E. Archer

May 2017

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Keywords: Recycled Water/Water Reuse/Reclaimed Water, Recycled Water Products, Florida, California, Geographic Information System (GIS), Geospatial Analysis, Kernel Density Estimation (KDE), Statistical Analysis

ABSTRACT

Spatiotemporal Analyses of Recycled Water Production

by

Jana E. Archer

Increased demands on water supplies caused by population expansion, saltwater intrusion, and drought have led to water shortages which may be addressed by use of recycled water as recycled water products. Study I investigated recycled water production in Florida and California during 2009 to detect gaps in distribution and identify areas for expansion. Gaps were detected along the panhandle and Miami, Florida, as well as the northern and southwestern regions in California. Study II examined gaps in distribution, identified temporal change, and located areas for expansion for Florida in 2009 and 2015. Production increased in the northern and southern regions of Florida but decreased in Southwest Florida. Recycled water is an essential component water management a broader adoption of recycled water will increase water conservation in water-stressed coastal communities by allocating recycled water for purposes that once used potable freshwater.

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DEDICATION

This thesis is dedicated to Jan Freeman, Tommy Cook, James and Carmel Freeman, Kenny and Gail Archer, Martha Archer, Phil and Janice Weaver, and Tim and Judy Harris.

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LIST OF ACRONYMS

ANOVA—Analysis of Variance

ASR—Aquifer Storage Recovery

BCE—Before Common Era

BMAPs—Basin Management Action Plans

BMPs—Best Management Practices

CDPH—California Department of Health

CDWR—California Department of Water Resources

CE—Common Era

CECs—Constituents of Emerging Concern or Chemicals of Emerging Concern

CPUC—California Public Utilities Commission

CWNS—Clean Water Needs Survey

FDEP—Florida Department of Environmental Protection

GIS—Geographic Information System

KDE—Kernel Density Estimation

NNC—Numeric Nutrient Criteria

NOAA—National Oceanic and Atmospheric Administration

NRC—National Research Council

NPDES—National Pollutant Discharge Elimination System

MGD—Millions of Gallons per Day

POTWs—Publicly Owned Treatment Works

RWBs—Regional Water Boards or Regional Water Quality Control Boards

SPSS—Statistical Package for the Social Sciences

SWB—State Water Board or State Water Resources Control Board

US—United States

USCB—United States Census Bureau

USEPA—United States Environmental Protection Agency

USGS—United States Geological Survey

WMDs—Water Management Districts

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CHAPTER 1

INTRODUCTION

Since the 1940s, human consumption of water has doubled in the United States (US), which has increased pressure on municipal water management systems (Montagna 2002). Problems with limited supplies or quality of freshwater have led municipalities to adopt the use of recycled water. Recycled water use is the reuse of highly treated wastewater in the form of products for irrigation, industrial reuse, groundwater recharge, and wetland reclamation, among others. These applications are important for water conservation which has intensified recently due to increased demands associated with population expansion, reduced availability, and drought which are exacerbated by climate change (Jenkins et al. 2004).

The National Research Council (NRC 2012) indicated that the use of recycled water could assist in water mitigation strategies, specifically water conservation measures. Approximately 12 billion gallons of effluent is discharged from wastewater treatment plants into streams and oceans daily. This effluent could be used to create recycled water products and in turn would increase available freshwater by up to 6% of the estimated total US freshwater use and by up to 27% for municipal supply of residential, commercial, and industrial uses (NRC 2012).

Scholarly research on recycled water use focuses on acceptance by the public and sound practices for adoption of water use. For example, several studies examined public perception of recycled water use acceptance (Po et al. 2003; Dolnicar 2006; Dolnicar and Schäfer 2009; Crampton and Ragusa 2016; and Rozin et al. 2015) reporting that global and national public perceptions of the “yuck factor” could be remedied by providing communities with educational information regarding the quality of water after the recycled water treatment process has

occurred (Dolinicar and Schäfer 2009; Qian and Leong 2016). Po et al. (2003) described the “yuck factor” as a psychological barrier of emotional discomfort because most people perceived recycled water as unclean with potential risk factors associated with the quality of recycled water. Participants of the study indicated they would rather recycled water be referred to as “repurified water” (Po et al. 2003). Qian and Leong (2016) found that the “yuck factor” is the only statistically significant variable that prevents implementation for direct potable reuse. A review of perception by Dolnicar (2006) indicated that proper branding of recycled water could increase trust and security among the general public. In 2002, Singapore became the first country to blend recycled water with raw water in a reservoir to be used as recycled drinking water, called NeWater (Qian and Leong 2016). Efforts similar to these have been conducted in California and Florida, but public perception, not water quality, have halted these projects (Rodriguez et al. 2009). Currently, the use of recycled water as direct potable reuse is constrained by policy in most regions (Qian and Leong 2016). According to Rozin et al. (2015), if recycled water were approved for direct potable reuse its use would become more commonplace and eventually become the norm. Others investigated best management practices (BMPs) for implementation and management of water reuse systems (such as Bixio et al. 2005; Wintgens et al. 2005; and Luo et al. 2016). Wintgens et al. (2005) suggested that dual systems (e.g. microfiltration and reverse osmosis) was better suited for large urban areas and a single system (e.g. membrane bioreactors) were more appropriate for small urban and rural regions.

The first spatial analysis of recycled water was an econometric analysis of Florida’s county-level water reuse capacity from 1996–2012 (Kuwayama and Kamen 2016). Water quality and scarcity were investigated in the study and water quality was determined to be one major reason Florida has become highly dedicated to recycling water. According to Kuwayama and

Kamen (2016), variability in precipitation also contributed to recycled water production. Regions with large urban population have increased industrial activity and industrial recycled water production. Kuwayama and Kamen (2016) suggested future research at the facility-level and this research fills that gap. This thesis includes research of Florida and California since they are the top ranked US producers of recycled water, ranked first and second respectively (FDEP 2015). The comparison of these two states includes facility-level analysis and the different drivers for production of recycled water.

Population

Human consumption of water has doubled in the US since the 1940's which has placed increased pressure on water management systems (Montagna 2002). According to the 2010 United States Census Bureau (USCB), Florida's population was 18.8 million people in 2010 and the current (2016) estimated population is 20.6 million people (USCB 2016). Florida's current water supplies will no longer be sustainable given the projected population increase to approximately 28 million by 2030 and 34 million by 2060 (Koch-Rose et al. 2011). This increase in population could cause a major depletion of the Floridian aquifer and other groundwater sources (Koch-Rose et al. 2011). Much of the state relies on groundwater for municipal water supply, which is vulnerable to extreme variability. As a result, recycled water has been adopted to improve water management and meet future demand. A 2010 United States Geological Survey (USGS) report on water use in the US indicated that Florida ranked fourth for total freshwater withdrawal (Maupin et al. 2014). In 2015, Florida ranked first in the US for recycled water distribution (FDEP 2016).

Comparatively, a 2010 USGS report on water use in the US indicated that California ranked first for total freshwater withdrawal (Maupin et al. 2014). In 2015, California ranked

second in the US for recycled water distribution (FDEP 2016). California's population in 2010 was 37.3 million people and the current (2016) estimated population is 39.3 million people (USCB 2016). California's population is projected to increase to approximately 44 million in 2030 and 52 million by 2060 (Department of Finance State of California 2014). As populations increase, water demands also increase throughout the state. Over 80% of California's municipal water is withdrawn from surface waters such as lakes, reservoirs, and rivers (Klausmeyer and Fitzgerald 2012).

Background

Global History of Recycled Water Use

Effluent irrigation reuse dates as far back as 5000 years to Minoan time (ca. 3200-1100 BCE) when the Harrapan Civilization in the Indus Valley used effluent for agricultural irrigation. (Angelakis and Gikas 2014; De Feo et al. 2014). With a rise of urbanism in Ancient Egypt (ca. 2000-500 BCE), efforts were made to separate organic and inorganic wastes as effluent was discharged into rivers (De Feo et al. 2014). The first documented wastewater treatment plant was constructed in Lingzi/Zibo City of Shandong Province along the Yellow and Yangtze Rivers (Angelakis and Gikas 2014; De Feo et al. 2014). A moat was constructed around Lingzi/Zibo City that cycled freshwater in and wastewater out of the Yellow and Yangtze Rivers (De Feo et al. 2014). During the Hellenistic Period (ca. 480-67 BCE) water quality became a priority when Alcmaeon of Croton in Greece associated the health of individuals to water quality and hygiene (De Feo et al. 2014). During the Roman Period (ca. 730 BCE-330 CE), Cloaca Maxima was built, a multifunctional hydraulic aqueduct infrastructure for wastewater, stormwater, and swamp drainage from the city (De Feo et al. 2014). Progress on sanitation, water quality, and wastewater drainage systems halted during and after the fall of the Roman Empire in the 3rd century CE (De

Feo et al. 2014). In the 5th century CE, Athens, Greece constructed a collection basin for wastewater outside of the city which was used to irrigate and naturally fertilize orchards and other crops (De Feo et al. 2014). In the 12th century CE in medieval Europe, human waste was used as compost and other organic waste was fed to pigs and other farm animals (De Feo et al. 2014).

From 14th century CE and into the 19th century CE great progress was made in Paris, France when legislation was enacted to prevent dumping of waste into covered sewage systems (De Feo et al. 2014). In 19th century CE Europe, sanitation was of great importance when an epidemic of cholera occurred in 1854 CE (De Feo et al. 2014). This epidemic was initially thought to have occurred from effluent within the sewage system, but after John Snow and Edmund Cooper (an engineer for the Metropolitan Commission of Sewers in London) mapped cases of cholera, a local water supply pump was identified as a probable source of infection (Brody et al. 2000). This work is the first known use of spatial analysis in epidemiology and led to water reforms throughout Europe. Throughout the 19th century CE most European countries (Europe 1859, Germany 1887, Italy 1899, Copenhagen 1903, and French-India 1930's) began to establish separate drainage systems for water supply and wastewater discharge as effluent into rivers (De Feo et al. 2014).

In the present time, at least 60 countries utilize wastewater as recycled water. China, Mexico, and the US have the highest annual total volume, but China and Mexico have not implemented as stringent regulations upon wastewater treatment as the US (Angelakis and Gikas 2014). Israel, Kuwait, and Singapore are ranked highest on per-capita volume of reuse (Angelakis and Gikas 2014). The best technological advancements (wastewater treatment

processes and superior recycled water quality implemented by policy regulation) in recycled water have been attributed to Japan, Singapore and California (Angelakis and Gikas 2014).

Recycled Water Use in Florida

Florida's recycled water program began in Tallahassee in the mid-1960s to produce recycled water for spray irrigation agricultural purposes for 120 acres at the Tallahassee Reclaimed Water Farm. By the mid-1970s, St. Petersburg had constructed a dual system that installed a separate pipe for recycled water for landscape irrigation (Toor and Rainey 2009). During the 1980s, Orange County developed the Water Conservation II project which eliminated wastewater discharge into creeks and lakes (Toor and Rainey 2009). Detailed history of Florida's recycled water is shown in Table 1.1. By 2009, Florida maintained 426 domestic wastewater treatment facilities that generated recycled water products (FDEP 2010).

Table 1.1: Timeline of Florida’s recycled water use (modified after Toor and Rainey 2009).

Year	City/Region	Application
1966	Tallahassee	Spray irrigation: crops
1973	Fiesta Village	Irrigation: golf course
1976	Vero Beach	Industrial: power plant cooling tower
1977	St. Petersburg	Dual water distribution begins: landscape irrigation
1977	Gainesville	Groundwater recharge: wastewater injection into Floridian aquifer
1978	Loxahatchee River Environmental Control District	Reuse program begins
1980	Tallahassee	Opens Southeast farm
1986	Orlando–Orange County	Water Conservation II starts: Irrigation of citrus groves and groundwater recharge thru rapid infiltration basins
1987	Orlando	Wetlands begins: 1640 acres in public park and nature preserve
1987-1989	Tampa	Tampa Water Resource Recovery Project
1991	Altamonte Springs	Project APRICOT (A Prototype Realistically Innovative Community of Today) begins: landscape irrigation
1992	Cape Coral	World's largest residential irrigation program
1998	West Palm Beach	Permit issued for indirect potable water reuse
2001	Hillsborough County	Testing of reclaimed water Aquifer Storage Recovery (ASR) well
2006	Lake County	Woodlea Road Reclamation Facility constructed for irrigation use

Distribution of recycled municipal wastewater in Florida is monitored by five Water Management Districts (WMDs) (Figure 1.1) under the oversight of the Florida Department of Environmental Protection (FDEP), which manages the quality and quantity of water distribution (FDEP 2016). WMDs administer flood protection and perform technical duties, which include the investigation of water resources, development of water management plans for water shortages due to drought, and regulatory oversight of recycled water use (FDEP 2016). WMDs classify recycled water products into five categories; public access areas, agricultural irrigation, groundwater recharge, industrial, and wetlands and other (toilet flushing, fire protection, and other) (Table 1.2).

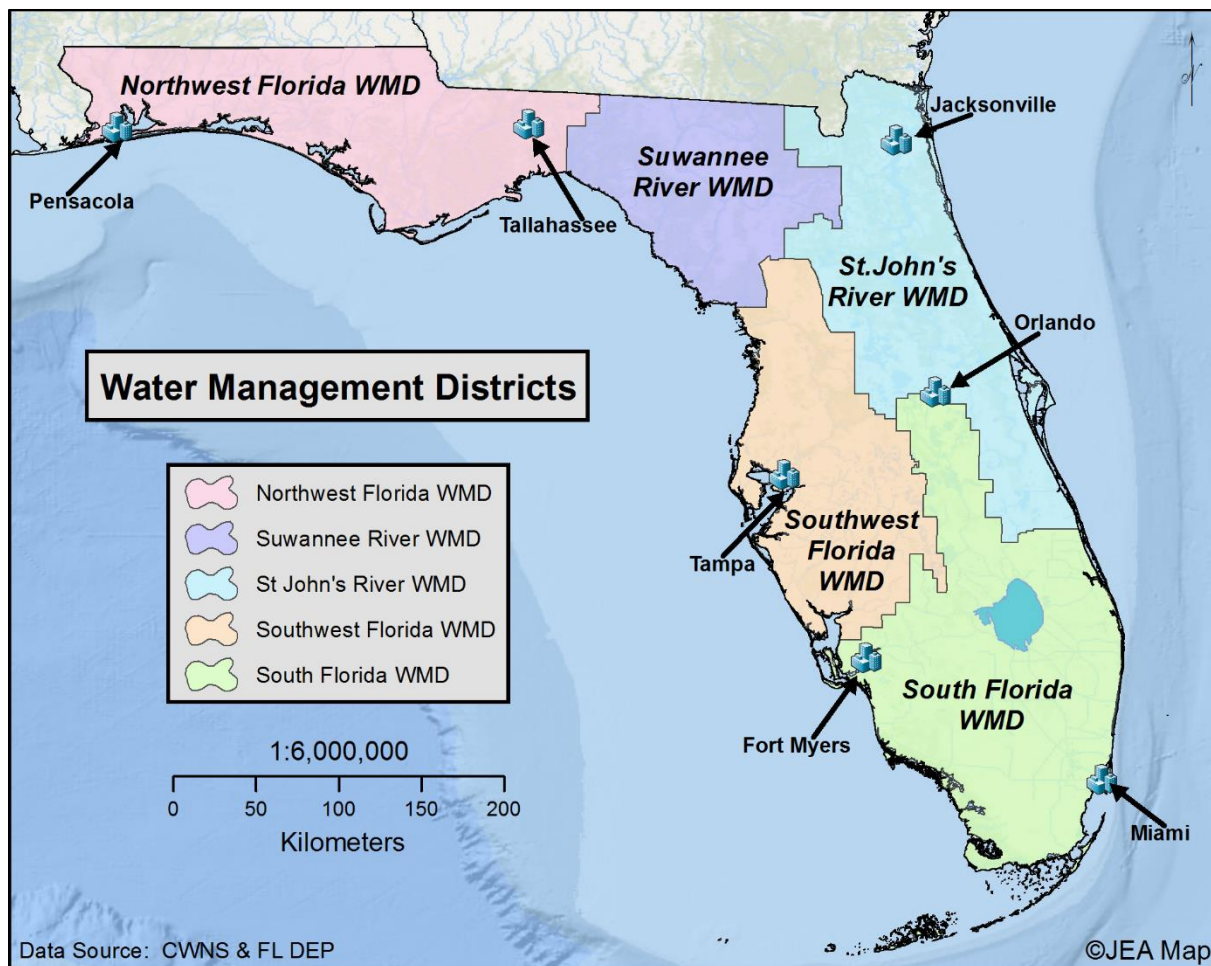


Figure 1.1: Florida Water Management Districts.

Table 1.2: Florida’s types of recycled water products (FDEP 2016).

Type	Explanation
Public Access Areas	Golf courses, cemeteries, parks, landscape areas, hotels, motels, private property, residential dwellings. and highway median irrigation
Agricultural Irrigation	Includes edible crops and crops used for feed and fodder
Groundwater Recharge	Groundwater injection and indirect potable reuse (withdrawn for drinking water)
Industrial	Manufacturing facilities, cooling towers
Wetlands and Other	
• Wetlands	Addition to wetlands
• Toilet Flushing	Reuse for toilet flushing
• Fire Protection	Reuse for fire protection
• Other	Permitted uses include--decorative fountains, commercial laundries, cleaning of roads and sidewalks, vehicle washing, concrete making, and other permitted uses

California Recycled Water Use

Water reuse has existed in California since the late 1800s when recycled water use was unregulated and used primarily for irrigation on farms (Newton et al. 2011). At this time, waterborne diseases were a major public health concern because farmers had acquired easements to access sewer mains which were used to pump untreated wastewater as fertilizer on crops (Newton et al. 2011). Recycled water use continued to expand and by 1910 at least 35 sites produced recycled water (Newton et al. 2011). To quell the concern of waterborne disease, the California State Board of Public Health implemented the first regulation on recycled water use in 1918, *Regulation Governing Use of Sewage for Irrigation Practices* (California State Board of Public Health 1918). By 1952, over 100 sites were in operation (Newton et al. 2011). The largest recycled water project was the Montebello Forebay Groundwater Replenishment System in 1962, which utilized recycled water for a seawater intrusion barrier (Newton et al. 2011). Detailed history of California’s recycled water is shown in Table 1.3. By 2009, California

maintained 228 Publicly Owned Treatment Works (POTWs) facilities that produced recycled water (Newton et al. 2011).

Table 1.3: Timeline of California’s recycled water use (modified after Metcalf and Eddy, Inc. 2003).

Year	Location	Application
1912-1985	Golden Gate Park, San Francisco, CA	Watering lawns and supplying ornamental lakes
1929	City of Pomona, CA	Irrigation of lawns and gardens
1961	Irvine Ranch Water District, CA	Irrigation and toilet flushing
1962	Montebello Forebay by County Sanitation District of Los Angeles County, CA	Groundwater recharge
1976	Orange County Water District, CA	Groundwater recharge (Water Factory 21)
1985-1989	San Diego Water Repurification Project	First use of reverse osmosis at an advanced water purification facility sent to San Vincent Reservoir
1987	Monterey Regional Water Pollution Central Agency, Monterey, CA	Irrigation of food crops eaten raw
1991	Palo Alto and Santa Clara, CA	Regional Water Quality Control Plant constructed for irrigation
1995	San Jose, Santa Clara, Milpitas, CA	South Bay Water Recycling Project Phase 1 construction began
1995	West Basin Municipal Water District Carson, CA	Industrial reuse and irrigation
2007	Orange County, CA Groundwater Replenishment System (GRS)	Upgrade of Water Factory 21
2008	Palo Alto, CA	Mountain View Recycled Water project used for irrigation and other non-potable use

Distribution of recycled municipal wastewater in California is ultimately controlled by nine Regional Water Quality Control Boards (Regional Water Boards, RWBs) assembled by the State Water Resources Control Board (State Water Board, SWB) (Figure 1.2). RWBs monitor standards for constituents of emerging concern (CECs) (or chemicals of emerging concern that may impact the quality of recycled water) and work in conjunction with the SWB, California Department of Health (CDPH), California Department of Water Resources (CDWR), and

California Public Utilities Commission (CPUC) to prioritize the extent of use and denote the type of treatment needed (California Environmental Protection Agency SWB 2013). RWBs produce recycled water products in eleven categories; agricultural irrigation, landscape irrigation, groundwater recharge, industrial uses, seawater intrusion barrier, golf course irrigation, natural system restoration and wetlands and wildlife habitat, recreational impoundment, geothermal energy production, commercial uses, and other (Table 1.4).

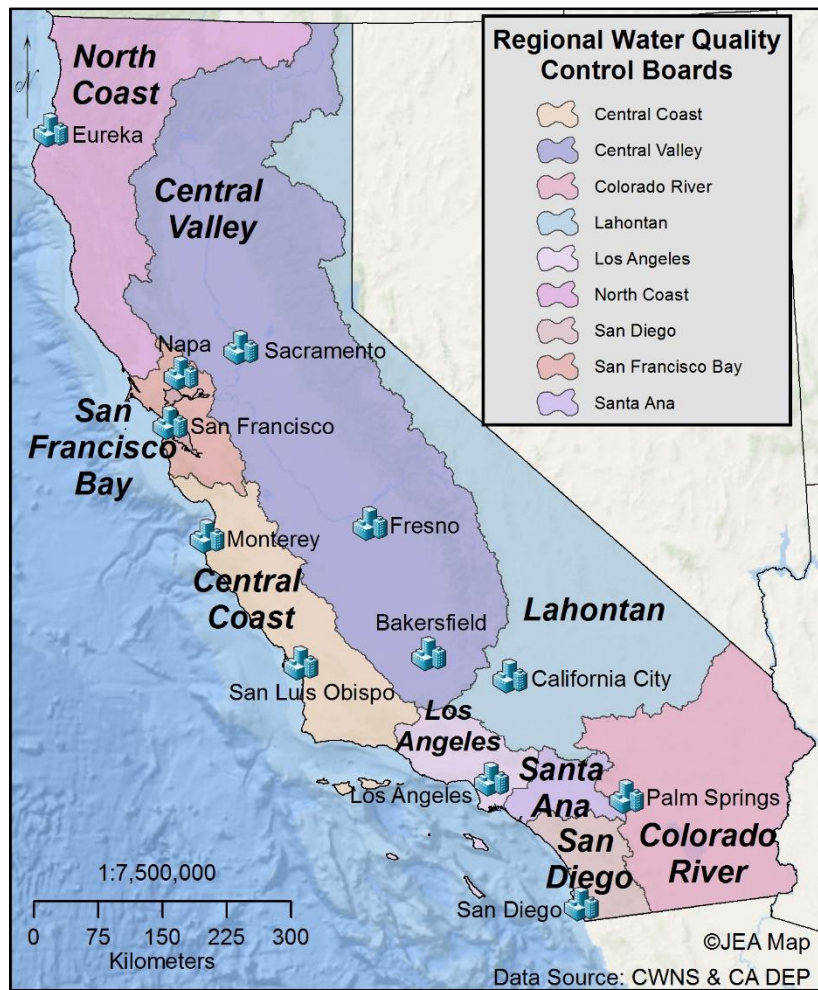


Figure 1.2: California Regional Water Boards.

Table 1.4: California’s types of recycled water products (Newton et al. 2011).

Type	Explanation
Agriculture Irrigation	Pasture and crop irrigation
Landscape Irrigation	Non-golf course—business, highways, schools, parks irrigation
Groundwater Recharge	Recharge basins to augment depleted groundwater aquifers injection
Industrial Uses	Manufacturing facilities, cooling towers
Seawater Intrusion Barrier	Groundwater injection to prevent or reduce seawater intrusion
Golf Course Irrigation	Private and public golf course irrigation
Natural System Restoration, Wetlands, and Wildlife Habitat	Addition to wetlands
Recreational Impoundment	Addition to recreational lakes
Geothermal Energy Production	Augmentation of geothermal fields
Commercial	Businesses—laundry services and office buildings
Other	Construction use, dust control, or unknown

Climate

Florida’s climate ranges from Humid Subtropical (Köppen Cfa) in the panhandle and northern areas to Tropical (Köppen Af, Am, and Aw) in the southern region (Cannon 2012) (Table 1.5 and Figure 1.3).

Table 1.5: Climate classification for Florida (Cannon 2012; NOAA 2016).

Climate Class	Annual Temperature Average	Annual Precipitation Average	Region(s)
Humid Subtropical (Cfa) <ul style="list-style-type: none"> • Warm and temperate 	21.5°C	1285 mm	Tampa, Jacksonville, St. Petersburg, Tallahassee
Tropical (Af) <ul style="list-style-type: none"> • Tropical rainforest 	23.5°C	1475 mm	Fort Lauderdale, Palm Beach, Lake Park, Tequesta, Juno Beach
Tropical (Am) <ul style="list-style-type: none"> • Tropical monsoon 	23.8°C	1509 mm	Pompano Beach, West Palm Beach, Boca Raton, Deerfield Beach, Boynton Beach
Tropical (Aw) <ul style="list-style-type: none"> • Tropical savannah 	23.9°C	1278 mm	Miami, Kendall, Miami Beach, Homestead, Key West

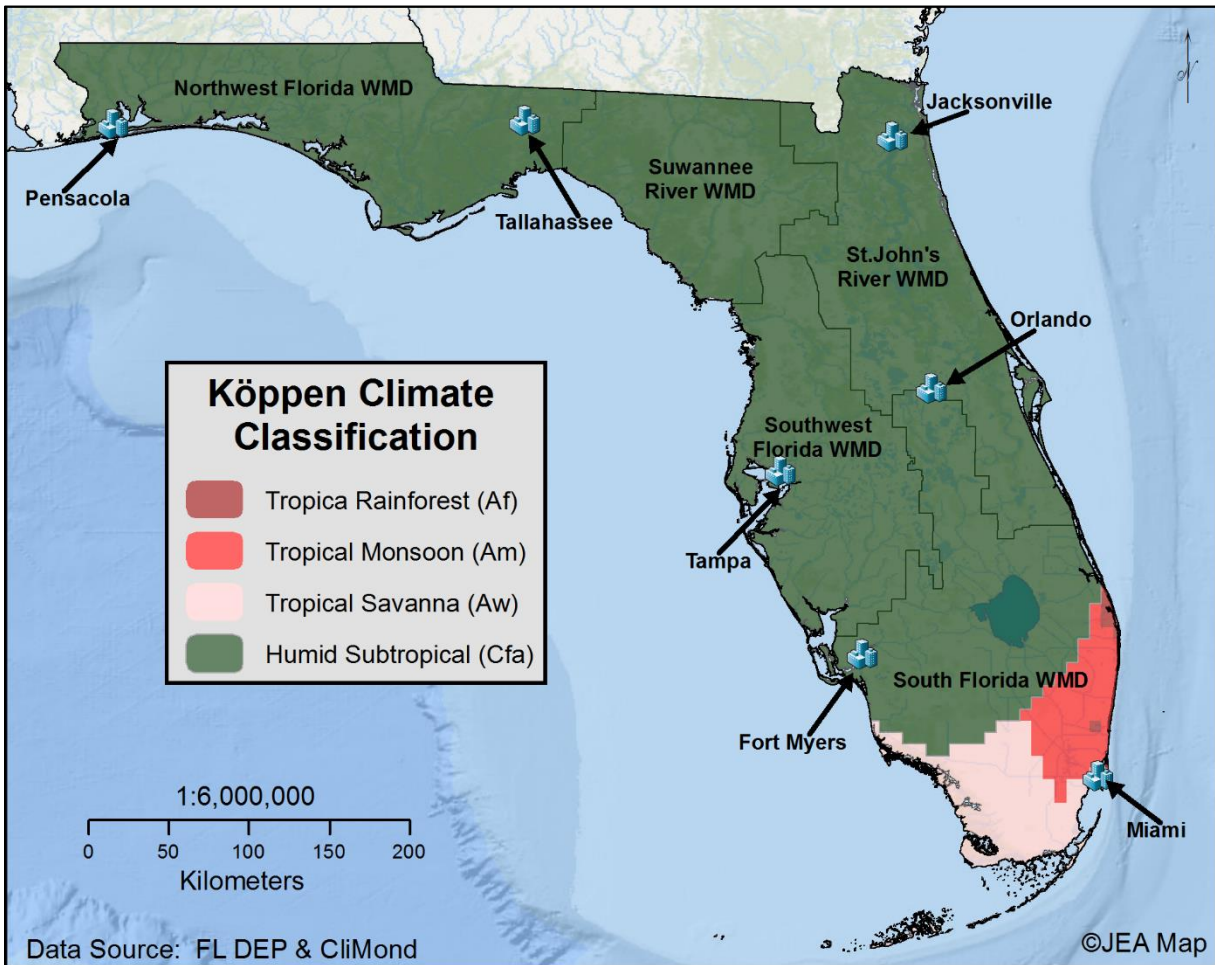


Figure 1.3: Florida’s Köppen climate classification.

According to the National Oceanic and Atmospheric Administration's (NOAA) (2016) Climatological Rankings, Florida had near average annual precipitation (20th century average 1488 mm) in 2009 with 1314 mm and 2015 with 1343 mm (Figure 1.4). Despite receiving adequate amount of rainfall, recycled water production was continued. Kuwayama and Kamen (2016) concluded that Florida has invested in recycled water for the dual benefit of water supply and water quality. Effluent that would normally be discharged to streams is highly treated and returned to the system as recycled water.

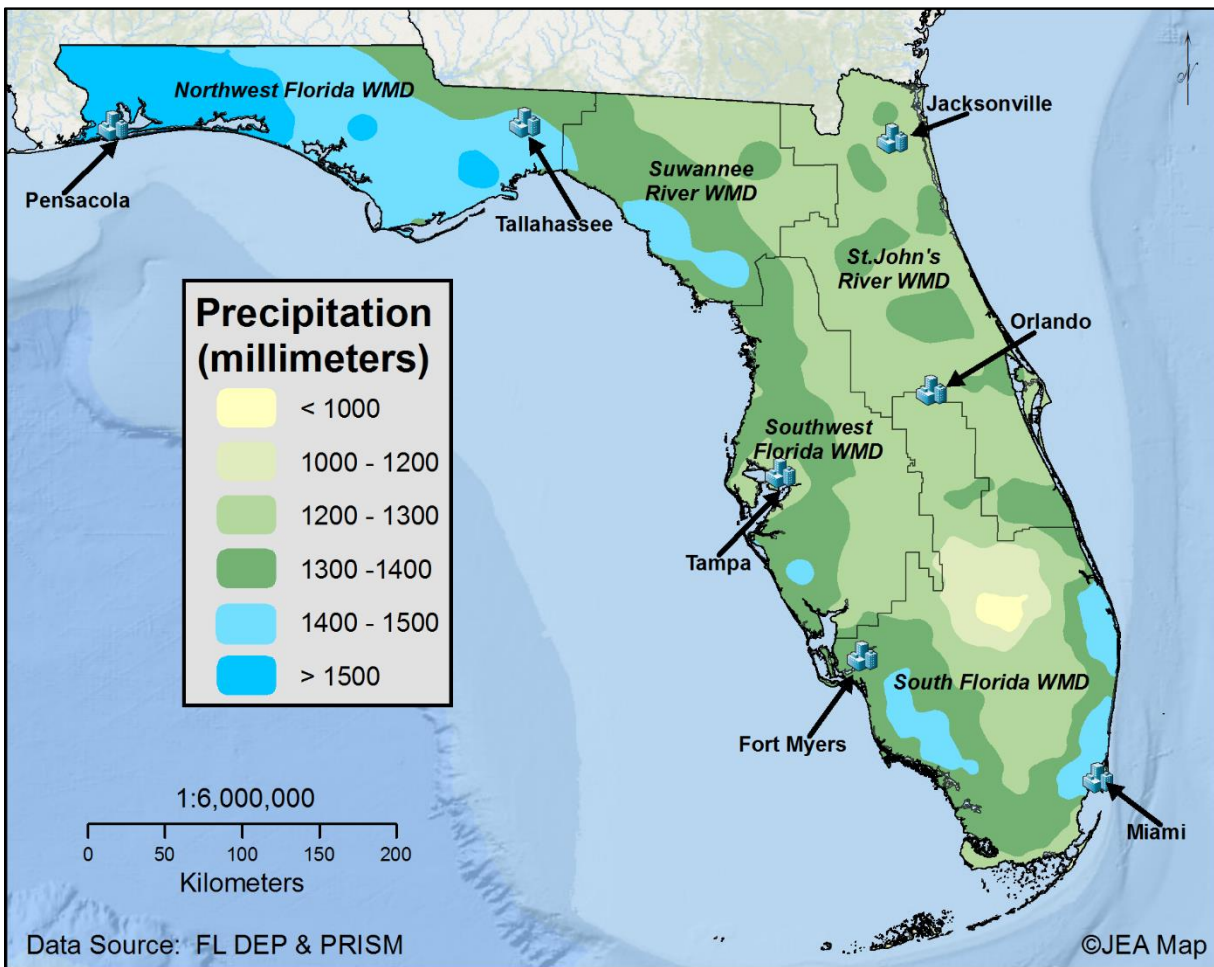


Figure 1.4: Florida's annual precipitation 30-year average (1981-2010).

In contrast to Florida, California’s climate includes Steppe (Köppen BSh and Köppen BSk), Desert (Köppen BWh and Köppen BWk), Mediterranean (Köppen Csa and Köppen Csb), Continental (Köppen Dsb and Köppen Dsc), and Polar (Köppen Ef) zones (Cannon 2012) (Table 1.6 and Figure 1.5).

Table 1.6: Climate classification for California (Cannon 2012; NOAA 2016).

Climate Class	Annual Temperature Average	Annual Precipitation Average	Region(s)
Steppe (BSh) • Hot semi-arid	18.1°C	318 mm	Riverside, San Bernardino, Downey, Compton, Lynwood
Steppe (BSk) • Cold semi-arid	17.4°C	294 mm	San Diego, Fresno, Long Beach, Anaheim, Santa Ana
Desert (BWh) • Hot desert	21.7°C	116 mm	Bakersfield, Indio, Cathedral City, Palm Desert, Palm Springs
Desert (BWk) • Cold desert	17.1°C	155 mm	Adelanto, Wasco, Shafter, California City, Huron
Mediterranean (Csa) • Dry and hot summers	17.2°C	403 mm	Los Angeles, Sacramento, Stockton, Fontana, Glendale
Mediterranean (Csb) • Warm temperate summers	15.0°C	448 mm	San Jose, San Francisco, Santa Barbara, Oakland, Fremont
Continental (Dsb) • Warm and humid	7.1°C	541 mm	South Lake Tahoe, Susanville Truckee, Mammoth Lakes, Alturas
Continental (Dsc) • Dry, cold, and humid	19.6°C	166 mm	Yosemite Valley
Polar (Ef)	10.7°C	114 mm	Mount Whitney

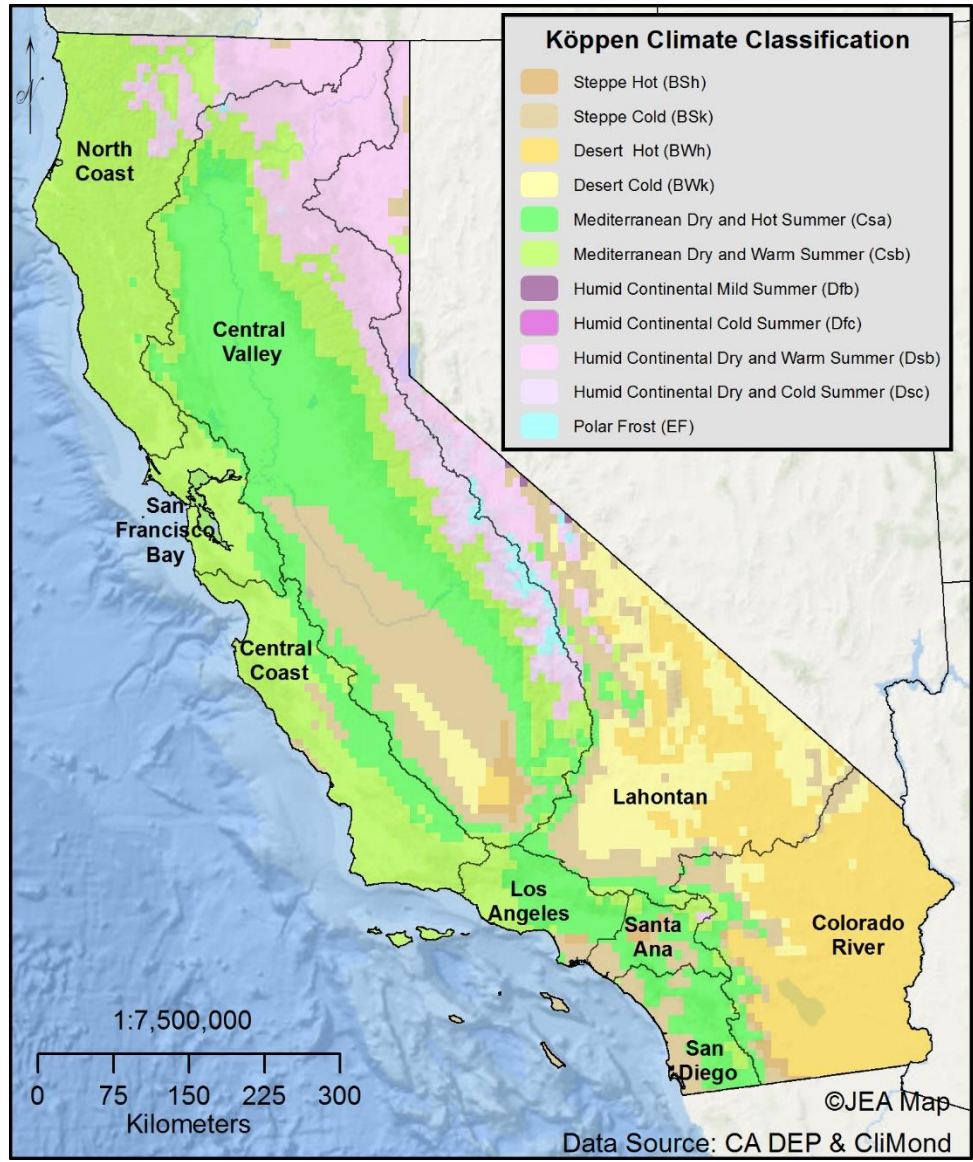


Figure 1.5: California’s Köppen climate classification.

According to NOAA’s (2016) Climatological Rankings, California had below average annual precipitation (20th century average 594 mm) in 2008 with 492 mm and in 2009 with 456 mm (Figure 1.6). California, overall, is a much more arid state with minimal annual rainfall. This has caused drought issues across the state leading to the use of recycled water as a mitigation method that complements water conservation measures.

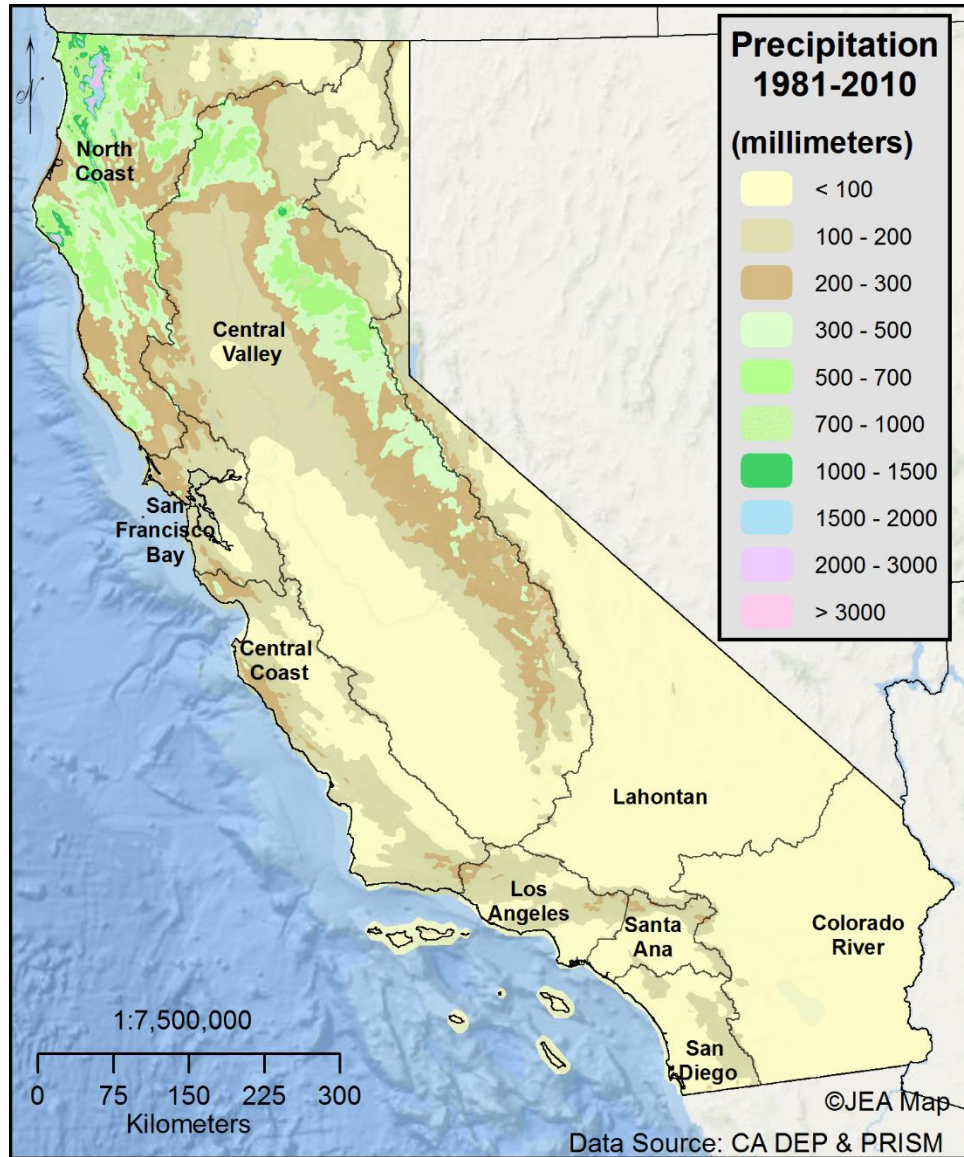


Figure 1.6: California’s annual precipitation 30-year average (1981-2010).

Geospatial, Statistical, and Temporal Analyses

Over the last few decades, geospatial, statistical, and temporal analyses have become integrated into science, specifically GISciences (James et al. 2012). Geospatial representation of empirical data was used to perform statistical analysis (analysis of variance (ANOVA) and paired t-tests) as well as Kernel Density Estimation (KDE), which represented temporal changes throughout this thesis. Hanna-Attisha et al. (2014) utilized ANOVA to assess demographics in

relation to the Flint, MI drinking water crisis in 2014. Isaak et al. (2014) used ANOVA techniques to evaluate relationships between fish, habitat conditions, and water quality. KDE has been used to study crime forecasting (Hart and Zandbergen 2014), location-based social network analysis (Zhang and Chow 2013), fire occurrence zoning in Greece (Koutsias et al 2014), identification of vulnerable marine ecosystem indicators (Kensington et al. 2014), among other topics. Additionally, spatio-temporal analysis has been used to examine semi-arid forest regions and their relationship to drought (Volcani et al. 2005). KDE has been widely used as spatial analysis for a number of different applications with point data, therefore it was selected for these studies.

Study Area, Research Questions, and Study Objectives

Study Areas:

The study areas include Florida's WMDs and California's RWBs.

Study I

Research Questions:

How many POTWs are producing recycled water products? Where are the gaps in production for each state? Are these areas appropriate locations to increase recycled water production?

Objective:

To examine the spatial patterns of recycled water production and use in Florida and California during 2009 to detect gaps in distribution and identify potential areas for expansion as a way to increase supply of freshwater.

This study compiled national (USEPA) and state (FDEP 2010; Newton et al. 2011) data into two databases (one for each state) for recycled water production in 2009. Descriptive

statistics were calculated, and ANOVA, Tukey *post hoc*, and Kruskal-Wallis tests were conducted using IBM SPSS Statistics Version 23 (IBM Corp. 2014). CrimeStat IV was used to generate hot spot spatial patterns with KDE (Levine 2015). All data were displayed in the geographic information systems (GIS), ArcGIS 10.4.1(ESRI 2016). These analytical methods are likely to identify underserved areas that indicate potential need for expansion.

These analyses produced:

- a. Visualization of the distribution for POTW's that recycle water in Florida and California.
- b. Descriptive statistics of recycled water flow volume in millions of gallons per day (mgd) for Florida Water Management Districts (WMDs) and California Regional Water Boards (RWBs).
- c. ANOVA and Tukey *post hoc* tests for comparison of recycled water flow volume (mgd) between Florida WMDs and California RWBs.
- d. Kernel Density Estimation (KDE) surfaces that identify clusters of recycled water production.
- e. Recommend actions of potential areas for increased recycled water production.

Study II

Research Question:

How many POTWs produce recycled water products in Florida during 2009 and 2015? Where are the gaps for each year? Are these areas potential locations to increase recycled water production? What is the temporal change from 2009 and 2015? Were gaps filled by 2015?

Objective:

To examine the spatial patterns of recycled water production in Florida during 2009 and 2015 to detect gaps in distribution, identify potential areas for expansion as a way to increase supply of freshwater, and to assess change over time.

This study compiled national (USEPA) and state (FDEP 2010; FDEP 2016) data into two databases (2009 and 2015) for recycled water production. Descriptive statistics were calculated, and ANOVA, Tukey *post hoc*, and paired-t tests were conducted using IBM SPSS Statistics Version 23 (IBM Corp. 2014). CrimeStat IV was used to generate hot spot spatial patterns with KDE (Levine 2015). All data were displayed in the geographic information systems (GIS), ArcGIS 10.4.1 and QGIS “Essen” 2.14.0 (QGIS 2016). These analytical methods are likely to identify underserved areas that indicate potential need for expansion as well as locate areas of growth from 2009 to 2015.

These analyses produced:

- a. Visualization of the distribution for POTW’s that recycle water in Florida.
- b. Descriptive statistics of recycled water flow volume (mgd) for Florida WMDs.
- c. ANOVA, Tukey *post hoc*, paired t-tests, and Wilcoxon signed-rank for comparison of recycled water flow volume (mgd) between Florida WMDs.
- d. Kernel Density Estimation (KDE) surfaces that identify clusters of hot spots of recycled water production.
- e. Recommend actions for potential areas for increased recycled water production.
- f. Identification of areas that increased recycled water production from 2009 to 2015.

CHAPTER 2

IDENTIFYING UNTAPPED POTENTIAL FOR RECYCLED WATER DISTRIBUTION USING GEOSPATIAL ANALYSIS: A COMPARATIVE STUDY OF FLORIDA AND CALIFORNIA IN 2009

Abstract

Increased demand on water supply can lead to water shortages which can be attributed to population expansion coupled with reduced freshwater availability caused by saltwater intrusion and drought. These water shortages may be addressed, in part, by use of recycled water. Coastal states are highly susceptible to these variables, therefore, this study examined spatial patterns of recycled water use in Florida and California, during 2009 to detect gaps in distribution and identify potential areas for expansion. Databases of recycled water products and distribution centers for Florida and California were developed by combining the 2009 Clean Water Needs Survey database with Florida's 2009 Reuse Inventory database and California's 2009 Recycling Survey database, respectively. Recycled water products are produced by both states; Florida had over twice the number of distribution centers ($n=426$) and produced 674.85 mgd, while California had fewer ($n=228$) yet produced 597.48 mgd. Within each state, water reuse is not balanced between Water Management Districts (Florida) or Regional Water Quality Control Boards (California). Kernel Density Estimation shows the majority of distribution in central Florida (Orlando and Tampa), California's Central Valley region (Fresno and Bakersfield), and around major cities in California. Areas for growth were identified in the panhandle and southern regions of Florida, and northern and southwestern California. Recycled water is an essential component of integrated water management and broader adoption of recycled water will increase water conservation in water-stressed coastal communities by allocating the recycled water for purposes that once used potable freshwater.

Introduction

Freshwater scarcity has incentivized mitigation measures that restrict water use, which in turn, have generated novel ideas and innovative technologies to improve water management. One innovation to increase public water supplies is to expand water reuse (the use of wastewater in the form of recycled water). As of 2006, Florida (663 mgd) was ranked first in the US followed by California (580 mgd), Texas (31.4 mgd), Virginia (11.2 mgd), Arizona (8.2 mgd), Colorado (5.2 mgd), Nevada (2.6 mgd), and Idaho (0.7 mgd) for recycled water distribution (Bryck et al. 2008). Florida and California were chosen to evaluate in this study because they ranked first and second in the US, respectively. The Florida Department of Environmental Protection (FDEP) defines recycled water as “water that has received at least secondary treatment and basic disinfection and is reused after flowing out of a domestic wastewater treatment facility” (FDEP 2010). Whereas, the California Water Code defined recycled water as the “result of treatment of waste, [which] is suitably considered a valuable resource” (State of California 1943).

Use of recycled water products can result in reduced demand on current freshwater supply and increased conservation of freshwater as storage (e.g. groundwater recharge) (Toor and Rainey 2009). Recycled water products may include water for irrigation (e.g. agriculture, parks, school, golf courses, etc.), industrial reuse, groundwater recharge, and as effluent discharge returned to streams. This study examines the spatial pattern of recycled water use in Florida and California during 2009 to find gaps in distribution and identify potential areas for expansion of recycled water production as a way to increase supply of freshwater. Florida and California were selected because they are the top US ranked producers of recycled water, ranking first and second respectively (FDEP 2016).

Background

Population Demands

Since the 1940s, US water use has doubled due to population growth resulting in added stress to water management systems (Montagna et al. 2002). Florida's current water supplies are at risk of depletion by 2025 due to groundwater withdrawal from the Floridian aquifer and other groundwater sources since much of the state relies overwhelmingly on aquifers for municipal water supply (Koch-Rose et al. 2011). Recycled water is one water management practice employed to meet this demand.

In 2010, the population in California was 37.3 million people and the current (2016) estimated population is 39.3 million (USCB 2016). As population increases, water demands also increase throughout the state. Over 80% of California's municipal water is withdrawn from surface waters such as lakes, reservoirs, and rivers (Klausmeyer and Fitzgerald 2012). Recycled water can be used to artificially recharge groundwater and as a barrier to saltwater intrusion as well as for irrigation, industrial reuse, and recreational impoundments which, in the past, have been supplied by fresh/surface waters that are at risk of depletion.

Recycled Water Use in Florida

Florida's recycled water production has increased since it was first introduced at the Tallahassee Reclaimed Water Farm in the 1960's as a means to irrigate agriculture (Toor and Rainey 2009). In 2010, Florida ranked fourth in the US for total freshwater withdrawal according to a 2010 United States Geological Survey (USGS) report on water use in the US (Maupin et al. 2014), and the state was ranked first in the U.S. during 2015 for recycled water distribution (FDEP 2016). More details about Florida's history can be found in Chapter 1.

Recycled Water Use in California

Since the late 1800's, California has recycled water primarily for agricultural irrigation (Newton et al. 2011). The Orange County Groundwater Replenishment System, built in 1962, was the largest recycled water project in California used for a seawater intrusion barrier. California ranked first in the US for total freshwater withdrawal according to a 2010 USGS report on water use in the US (Maupin et al. 2014), and the state was ranked second in the US during 2015 for recycled water distribution (FDEP 2016). More details about California's recycled water history can be found in Chapter 1.

Data and Methods

Databases of recycled water products for Florida and California were developed for 2009, the most recent years for which data were available for both states. Florida's POTWs locations, population total, and National Pollutant Discharge Elimination System (NPDES) were extracted from the Florida 2008 Clean Water Needs Survey (CWNS) database (USEPA 2008) and combined with Florida's 2009 Reuse Inventory database (FDEP 2010) using NPDES permit numbers as the key (Figure 2.1). Similarly, California's data were extracted from the California 2008 CWNS database (USEPA 2008) and combined with California's 2009 Recycling Survey database (Newton et al. 2011) using POTW name as the key (Figure 2.1).

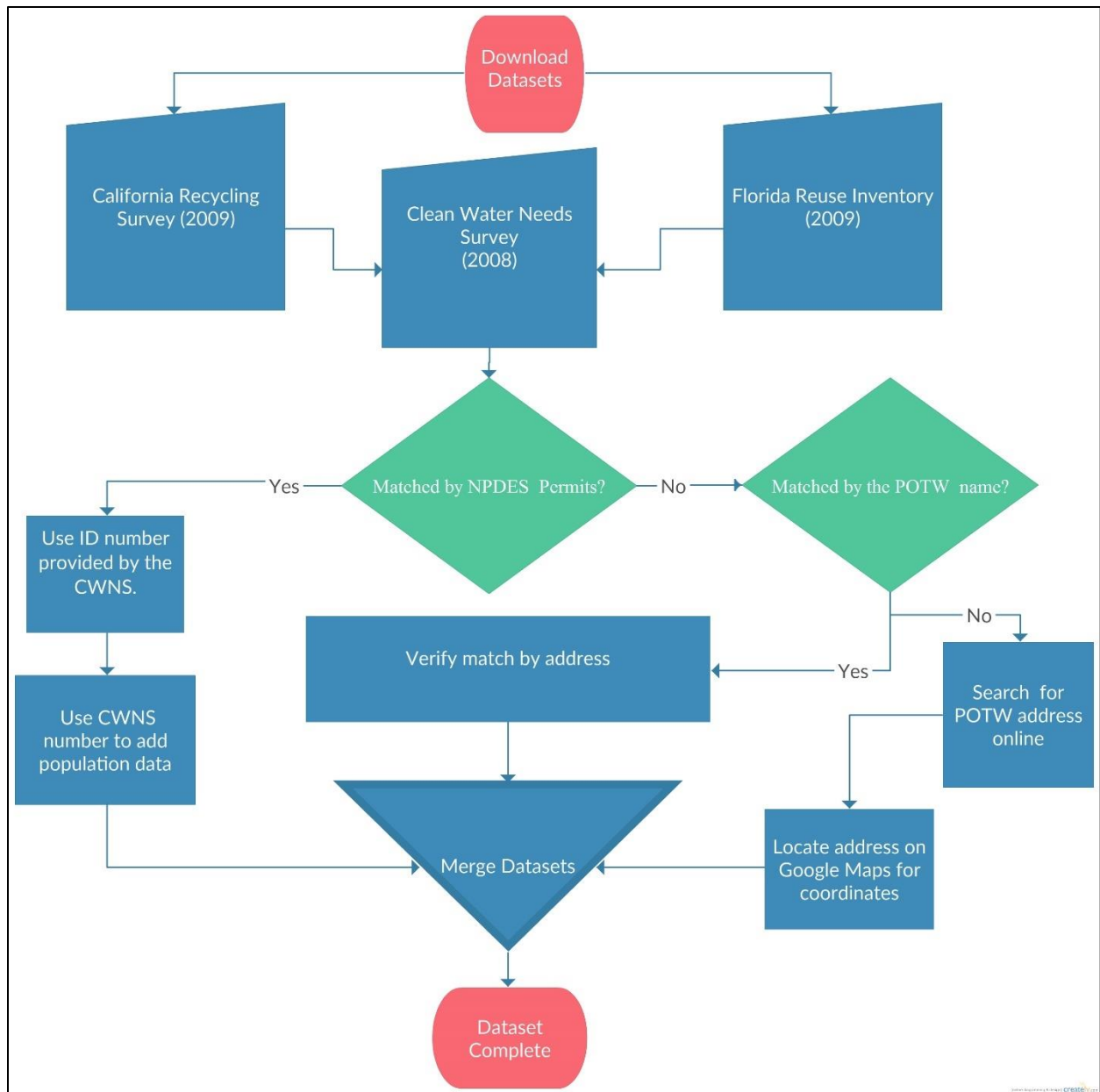


Figure 2.1: Flowchart for dataset organization procedures.

Description of Datasets

The United States Environmental Protection Agency (USEPA) produce the CWNS Microsoft Access database from information gathered from states and territories throughout the United States every four years. The information extracted from CWNS included summaries of facilities, NPDES permits, and population. The summary of facilities included: CWNS number for each POTW, the name of POTWs, county of origin, coordinates for location, and NPDES permit number. The summary of permits included: CWNS number for each POTW with a permit, NPDES permit number, and permit type. The summary of population included: CWNS number for each POTW and the present residents connected to public sewer lines. The CWNS number was used to extract data for POTWs that recycled water.

Florida's 2009 Reuse Inventory was a Microsoft Excel database obtained from the Florida Department of Environmental Protection (FDEP). It contained information for the distribution of recycled water, which included: name of POTWs, the Water Management District (WMD) location, type of recycled water product, volume of flow in millions of gallons per day (mgd), NPDES permit number, and acres served. Nearly all (414 of 426; 97%) POTWs in Florida's Reuse Inventory database were matched by NPDES permit numbers to entries in the CWNS database to obtain geographic coordinates for each. Wastewater treatment facilities with unmatched permits (N=15) were located using Google Maps and manually geocoded. The geocoded dataset was displayed using ArcGIS 10.4.1 (ESRI 2016) (Figure 2.2).

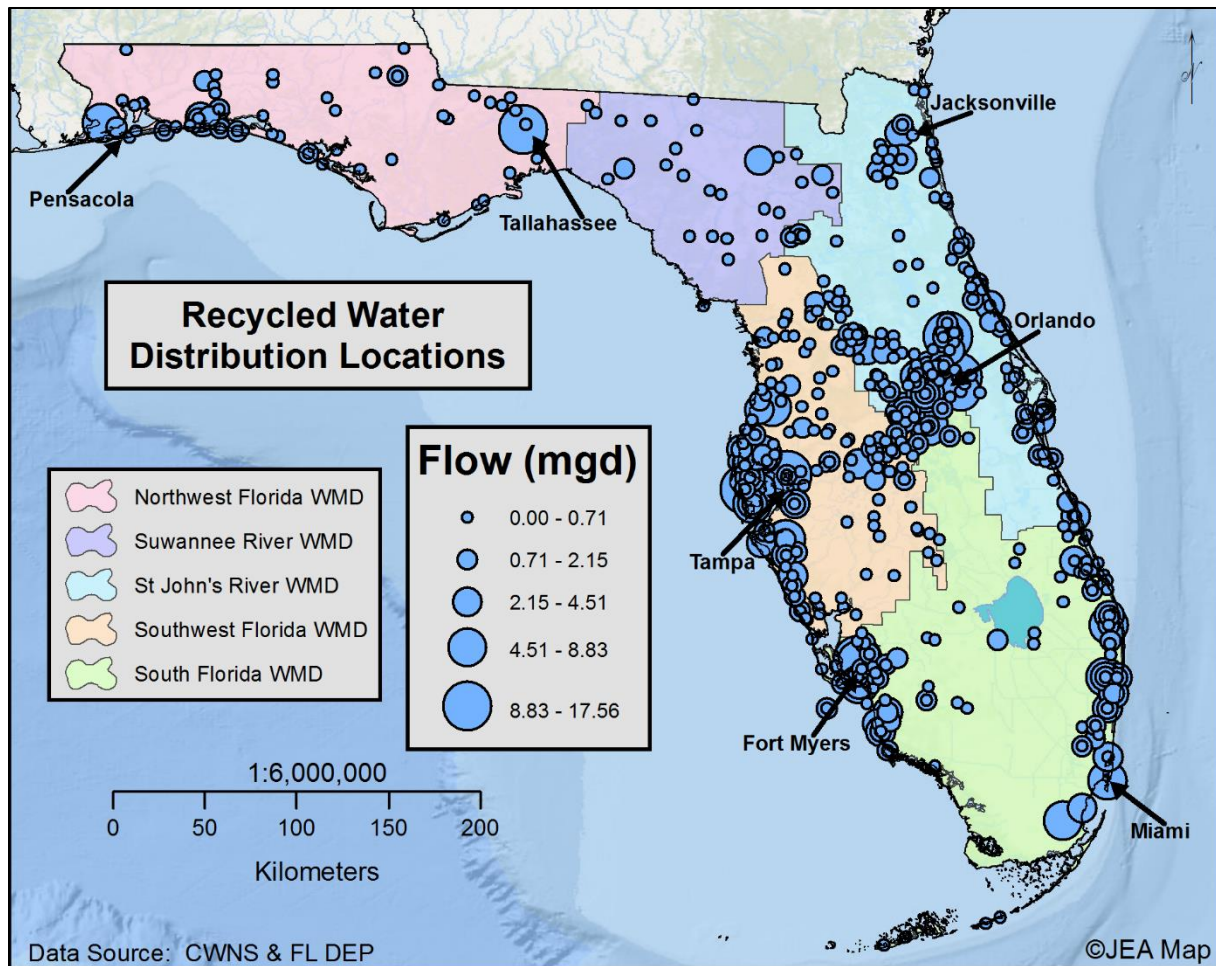


Figure 2.2: Florida recycled water distribution.

California’s 2009 Municipal Wastewater Recycling Survey was downloaded as a Microsoft Excel database from California Environmental Protection Agency’s department of State Water Resources Control Board (California State Water Resources Control Board, 2012). contained information for the distribution of recycled water, which included: name of POTWs, county, RWB district number, type of recycled water product, and volume of recycled water. Of 228 POTWs in California’s Recycling Survey database, 174 (83%) were matched by name and county to entries in the CWNS database to obtain geographic coordinates for each. The National Water Reuse Database (NWRD) was used to verify locations of POTWs (NWRD 2016). Wastewater treatment facilities with unmatched permits (N=36) were located using the NWRD

and Google Maps and manually geocoded. The geocoded dataset was displayed using ArcGIS 10.4.1(ESRI 2016) (Figure 2.3).

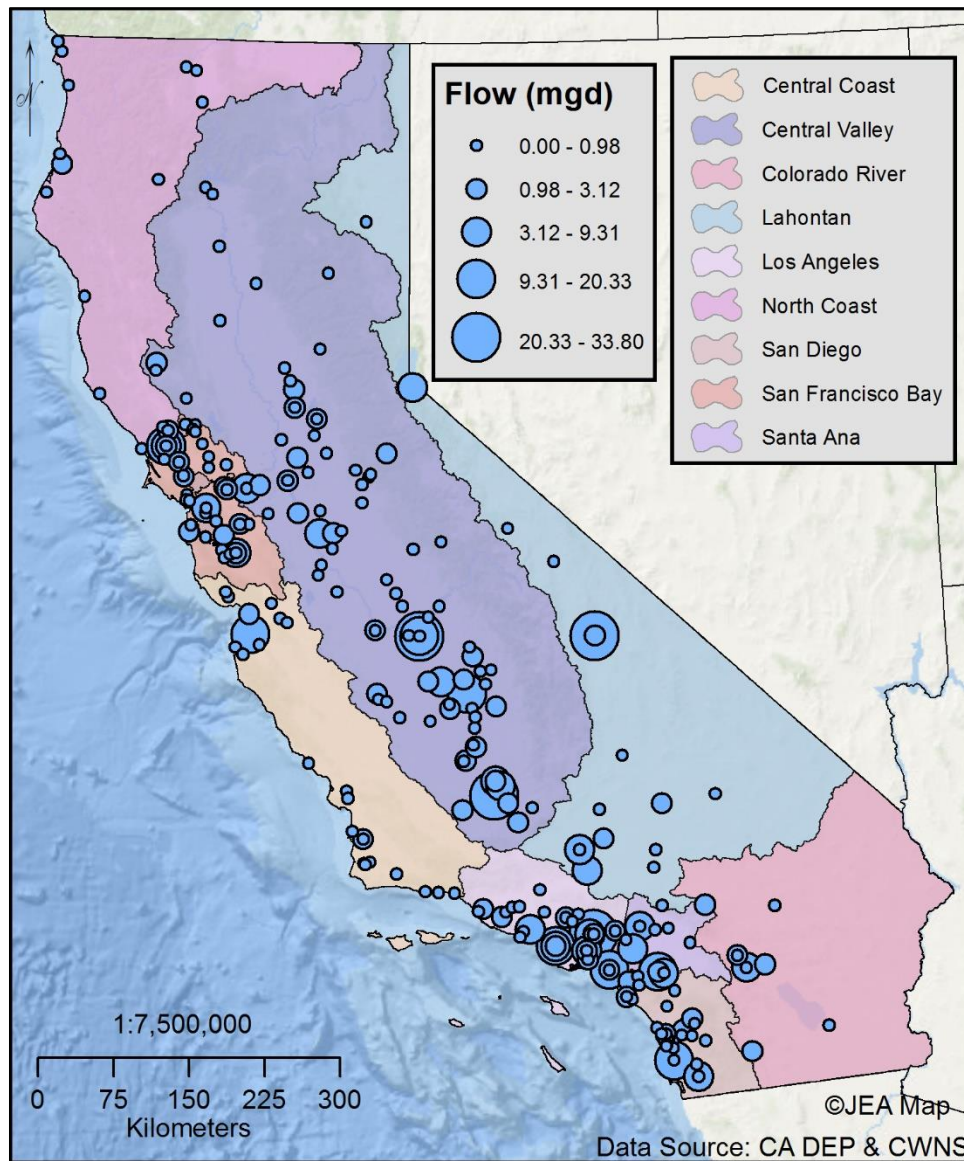


Figure 2.3: California recycled water distribution.

Statistical Analysis

Descriptive Statistics

Descriptive statistics were calculated to summarize the mean and variance for volume of flow at Florida's WMDs and California's RWBs.

Analysis of Variance

A one-way Analysis of Variance (ANOVA) was used to compare volume of recycled water products produced by Florida's WMDs and California's RWBs. Tukey *post hoc* tests were conducted to determine which pairs of locations were statistically different. All bivariate data were analyzed with Statistical Package for the Social Sciences (SPSS) Version 23 (IBM Corp 2014).

Kernel Density Estimation

Kernel Density Estimation (KDE) was used to identify hotspots of water reuse. The Quartic Kernel method was selected because it has a spherical shaped curve but is more gradual and stops at the defined radius limit rather than extending to infinity, therefore, the area is limited around the point of incidence (Levine 2015). KDE was performed on flow, flow normalized by population served, and flow normalized by acres served using fifteen points per cluster. All data were analyzed with CrimeStat IV (Levine 2015).

Results

Florida Recycled Water Products

Of 548 POTWs in Florida, 426 (78%) distribute recycled water (FDEP 2010). Most of these are located along the coast and in central Florida, concentrated in the major metropolitan areas around the cities of Orlando, Tampa, Fort Myers, and Miami. The highest mean production in 2009 was 1.13 mgd in South Florida WMD, whereas the lowest mean was 0.34 mgd in

Suwannee River WMD (Table 2.1). In 2009, Florida’s POTWs produced a total flow of 674.26 mgd, distributed as multiple recycled water products (Figure 2.4).

Table 2.1: Florida’s 2009 Descriptive Statistics with number of POTWs and flow (mgd) per WMD.

WMD	# POTW	Mean	Variance	Minimum	Maximum	Median	Flow
Northwest Florida	58	0.64	3.63	0.002	17.14	0.22	59.91
South Florida	97	1.13	3.99	0.00036	17.56	0.34	238.60
St. John’s River	129	0.57	1.53	0.00005	13.73	0.22	167.92
Southwest Florida	119	0.80	2.64	0.0001	11.99	0.24	198.45
Suwannee River	23	0.34	0.22	0.007	2.30	0.14	9.39
Average Total	426	0.69	2.40	0.0005	12.08	0.20	674.26

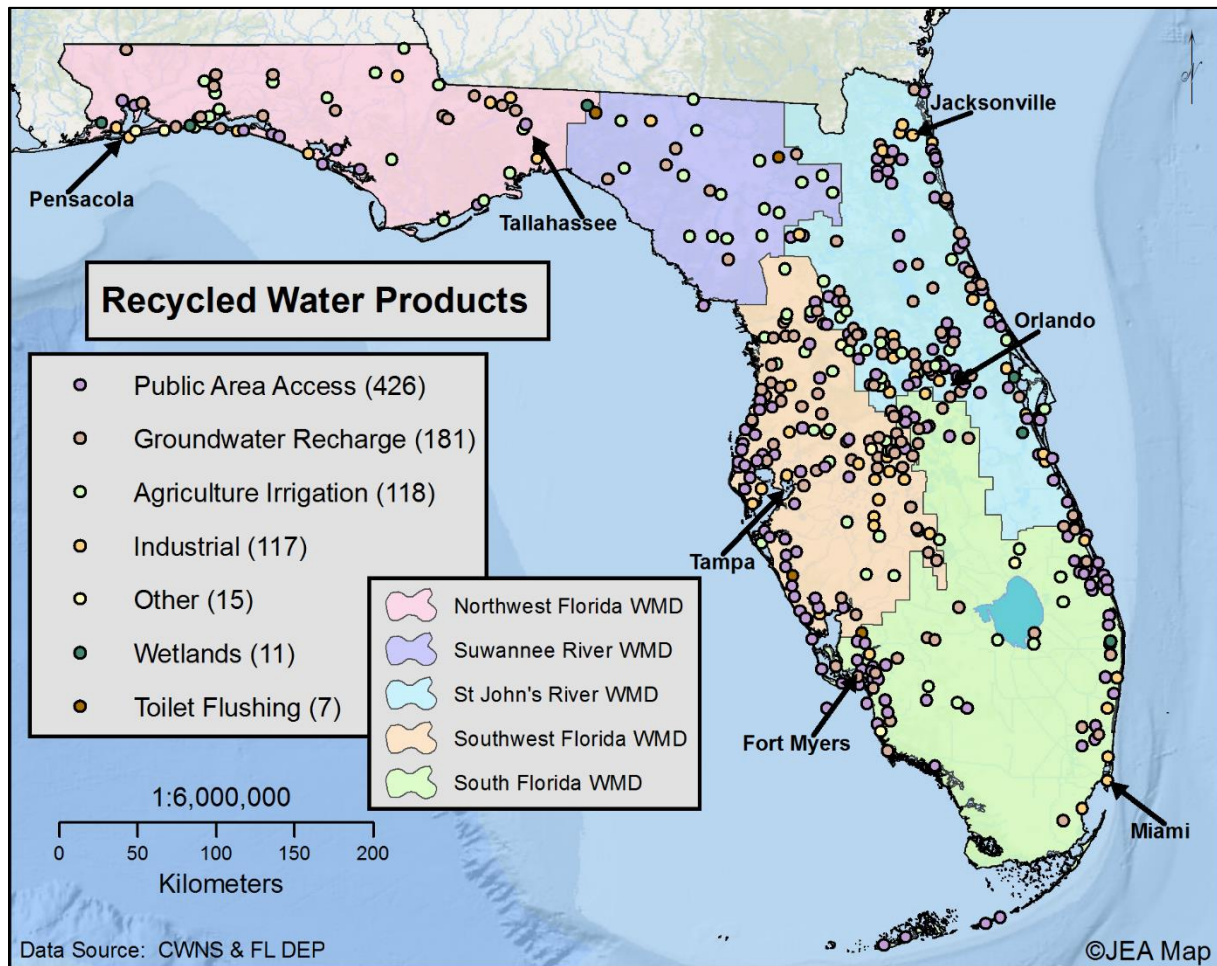


Figure 2.4: Recycled water products in Florida.

Descriptive Statistics

The most common product associated with recycled water was public access area irrigation with a total distribution of 381.38 mgd (56% of the state total). Nearly 41% (154.56 mgd) of recycled irrigation water was supplied by POTWs to the South Florida WMD (Figure 2.5A). Groundwater recharge was the next largest recycled water product in the state, with a total of 88.72 mgd (13% of the state total) with the largest portion distributed by POTWs to users in the South Florida WMD at 43.29 mgd (50%) (Figure 2.5B). Industrial reuse had a total state production of 91.64 mgd (14% of the state total). Nearly 47% (43.01 mgd) of industrial reuse was distributed by POTWs to users in the Southwest Florida WMD (Figure 2.5C). At the state level, recycled water used for agricultural irrigation totaled 75.56 mgd (11% of the state total), with the largest portion distributed by POTWs to users in the Northwest Florida WMD at 32.09 mgd (42%) (Figure 2.5D). Last, at the state level, wetlands and other recharge totaled 38.96 mgd (6% of the state total), two-thirds (27.72 mgd) of which was distributed by POTWs to users in the St. John's River WMD (Figure 2.5E).

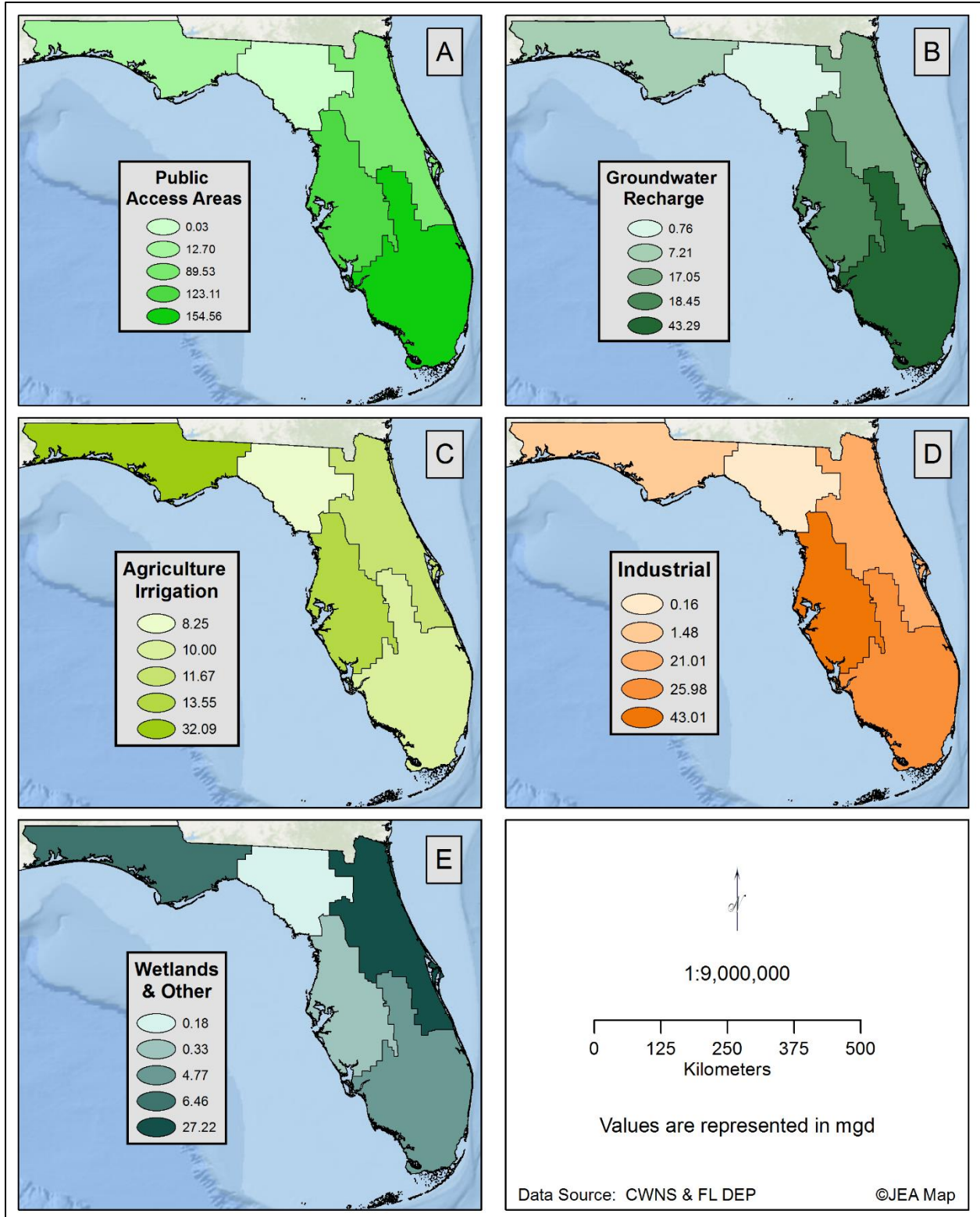


Figure 2.5: A) public access areas, B) groundwater recharge, C) agricultural irrigation, D) industrial uses E) wetlands recharge and other.

Analysis of Variance

Each district produced recycled water for each category of discharge method. The Suwannee River WMD was the lowest-producing district overall with a total production of 9.39 mgd (1.4% of the state total) and the lowest mean production at 0.34 mgd (per POTW), but was not significantly different from the other WMDs (Figure 2.6). ANOVA results indicated significant differences in recycled water production between WMDs overall and Tukey *post-hoc* tests further indicated significant differences ($p < 0.05$) between South Florida and St. John's River WMDs.

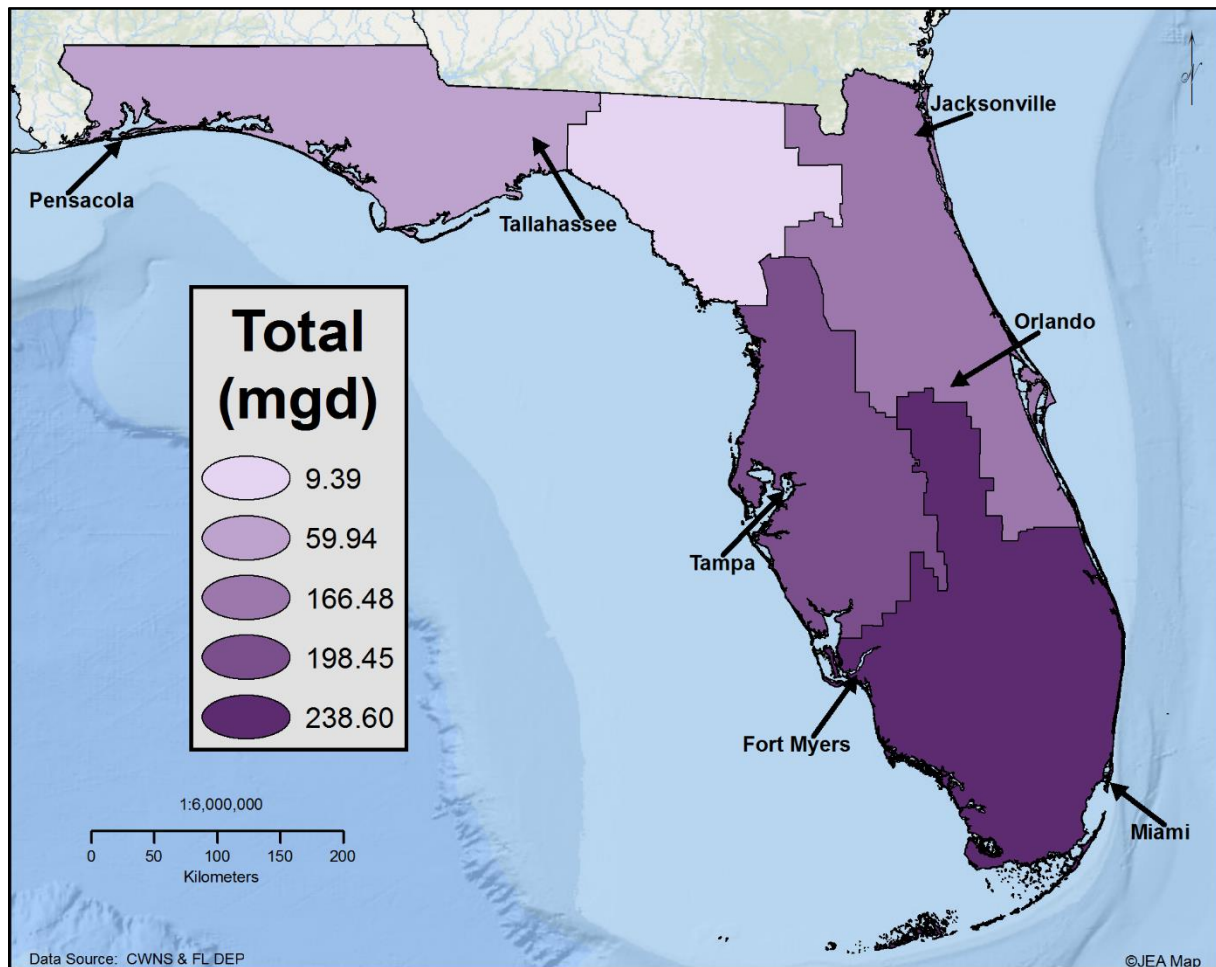


Figure 2.6: Florida total flow (mgd) per district.

Kernel Density Estimation

Hot spots for flow (mgd) were located around major cities in Florida (Figure 2.7A). The dark areas have the greatest production, whereas light ones are areas of lower production which may be areas for increased production. When flow data were normalized by area served central Florida had the highest production, followed by Fort Myers and Miami (Figure 2.7B). When flow data were normalized by population served, there is a large area of production in Suwannee River WMD, followed by Orlando, Tampa, and Fort Myers (Figure 2.7C). Normalization was performed to remove the effect of land area size and population size.

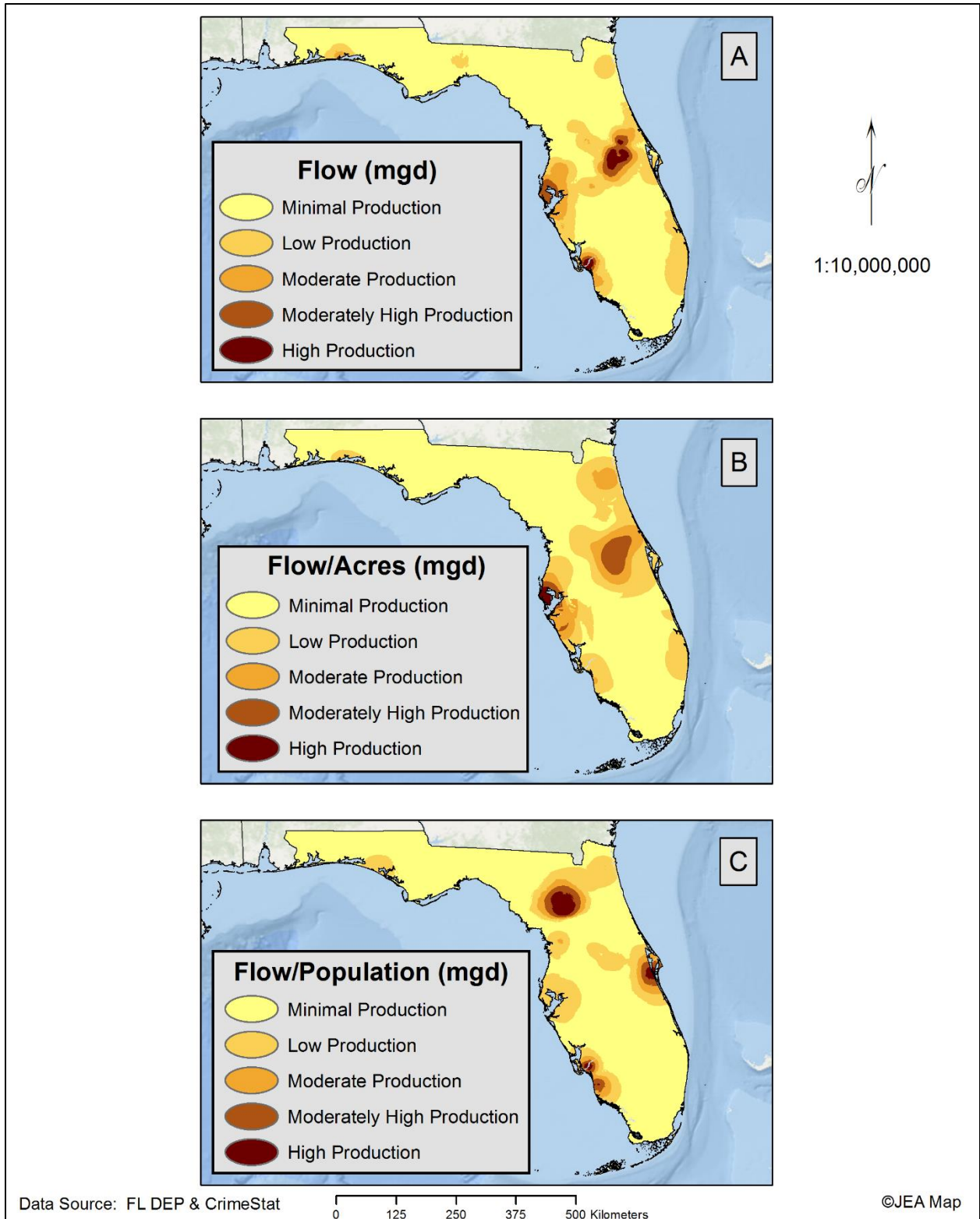


Figure 2.7: Florida kernel density estimation for A) flow (mgd), B) flow/acre served (mgd), and C) flow/population served (mgd).

California Recycled Water Products

Of 1,155 POTWs in California, 228 (20%) distribute recycled water (Newton et al. 2011). Most of these are located along the coast and in the Central Valley region of California, concentrated in the major metropolitan areas around the cities of San Francisco, Los Angeles, Fresno, Bakersfield, Santa Ana, and San Diego. The highest mean in 2009 was 4.31 (mgd) in Santa Ana RWB, whereas the lowest mean was 0.64 (mgd) in Central Coast RWB (Table 2.2). In 2009, California's POTWs produced a total flow of 597.48 mgd, distributed as multiple recycled water products (Figure 2.8).

Table 2.2: California's 2009 Descriptive Statistics with number of POTWs for flow (mgd) per RWB.

RWB	# POTW	Mean	Variance	Minimum	Maximum	Median	Flow
North Coast	14	1.05	6.38	0.003	11.31	0.12	23.02
San Francisco Bay	33	0.72	1.58	0.0009	6.47	0.23	43.23
Central Coast	21	0.64	3.33	0.003	10.55	0.20	20.98
Los Angeles	23	2.93	34.20	0.005	33.80	0.73	149.65
Central Valley	83	1.65	18.75	0.0009	30.80	0.45	153.65
Lahontan	16	0.65	1.08	0.003	4.29	0.33	11.07
Colorado River	6	1.38	3.61	0.006	6.24	0.73	13.26
Santa Ana	11	4.31	61.60	0.003	33.70	1.30	135.84
San Diego	21	0.94	3.52	0.0009	11.10	0.34	46.28
Average Total	228	1.59	14.89	0.0028	16.47	0.49	597.48

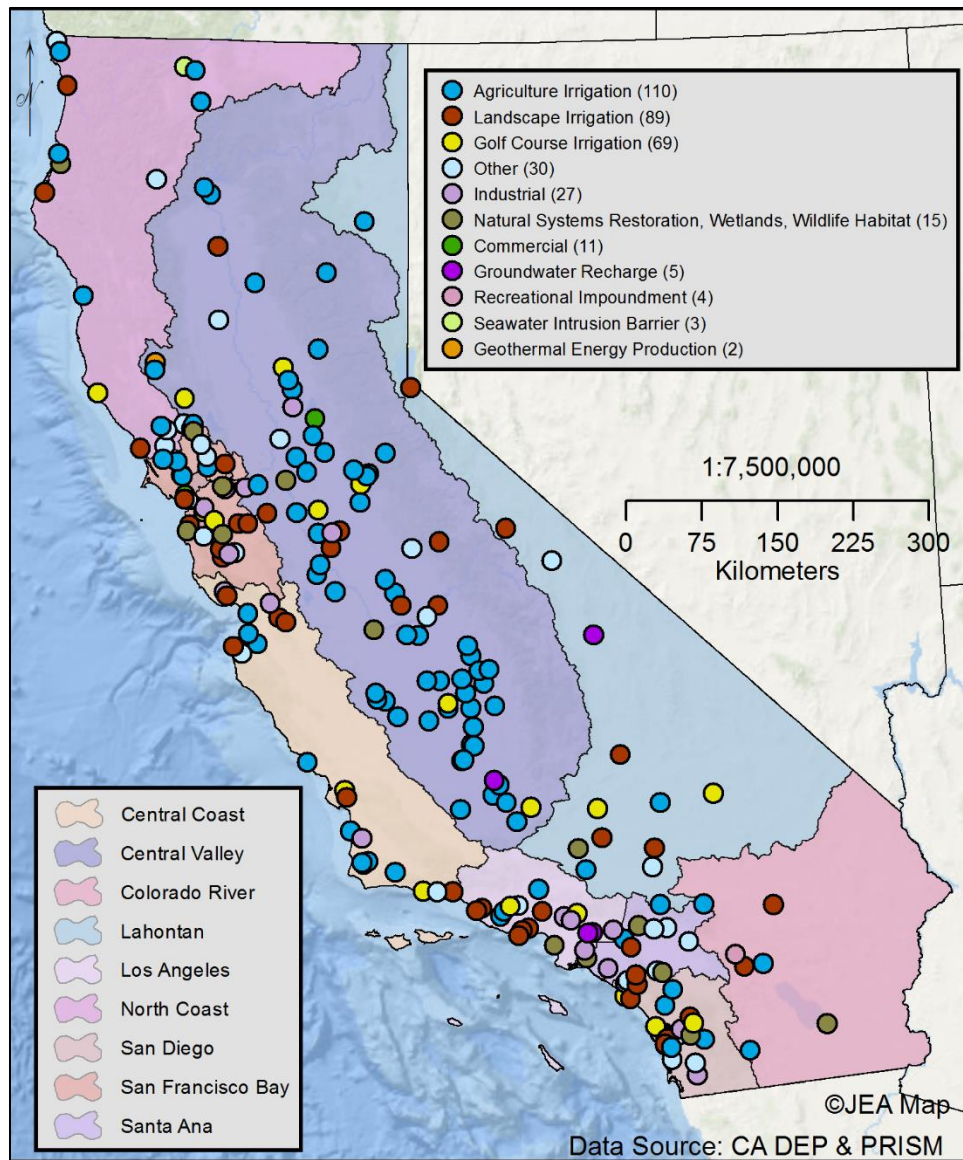


Figure 2.8: Recycled water products in California.

Descriptive Statistics

The most common discharge method associated with recycled water was agricultural irrigation with a total distribution of 218.33 mgd (37% of the state total). Nearly 62% (136.07 mgd) of recycled agriculture irrigation water was supplied by POTWs to the Central Valley RWB (Figure 2.9A). Landscape irrigation was the next largest recycled water product in the state, with a total of 100.86 mgd (17% of the state total). Nearly 28% (29.05 mgd) of landscape

irrigation water reuse was distributed by POTWs to users in the San Diego RWB (Figure 2.9B). Groundwater recharge had a total state production of 71.16 mgd (12% of the state total) with the largest portion distributed by POTWs to users in the Los Angeles RWB at 38.05 mgd (53%) (Figure 2.9C). Recycled water used for industrial purposes totaled 45.01 mgd (11% of the state total), with the largest portion distributed by POTWs to users in the Los Angeles RWB at 22.01 mgd (49%) (Figure 2.9D). Furthermore, recycled water used for seawater intrusion barriers totaled 41.85 mgd (7% of the state total), with the largest portion distributed by POTWs to users in the Santa Ana RWB at 33.70 mgd (81%) (Figure 2.9E). Additionally, recycled water used for golf course irrigation totaled 39.12 mgd (7% of the state total), with the largest portion distributed by POTWs to users in the Colorado River RWB at 9.01 mgd (23%) (Figure 2.9F). At the state level, recycled water used for natural systems restoration, wetlands, and wildlife habitat totaled 28.18 mgd (5% of the state total), with the largest portion distributed by POTWs to users in the Los Angeles RWB at 12.91 mgd (46%) (Figure 2.9G). Moreover, recycled water used for recreational impoundment totaled 23.07 mgd (4% of the state total), with the largest portion distributed by POTWs to users in the Los Angeles RWB at 17.79 mgd (77%) (Figure 2.9H). Also, recycled water used for geothermal energy production totaled 13.34 mgd (2% of the state total), with the largest portion distributed by POTWs to users in the North Coast RWB 11.31 mgd (85%) (Figure 2.9I). Similarly, recycled water used for other purposes totaled 10.84 mgd (2% of the state total), with the largest portion distributed by POTWs to users in the San Diego RWB at 4.07 mgd (38%) (Figure 2.9J). Last, at the state level, commercial use totaled 5.70 mgd (1% of the state total), with the largest portion distributed by POTWs to users in the Los Angeles RWB at 4.07 mgd (83%) (Figure 2.9K).

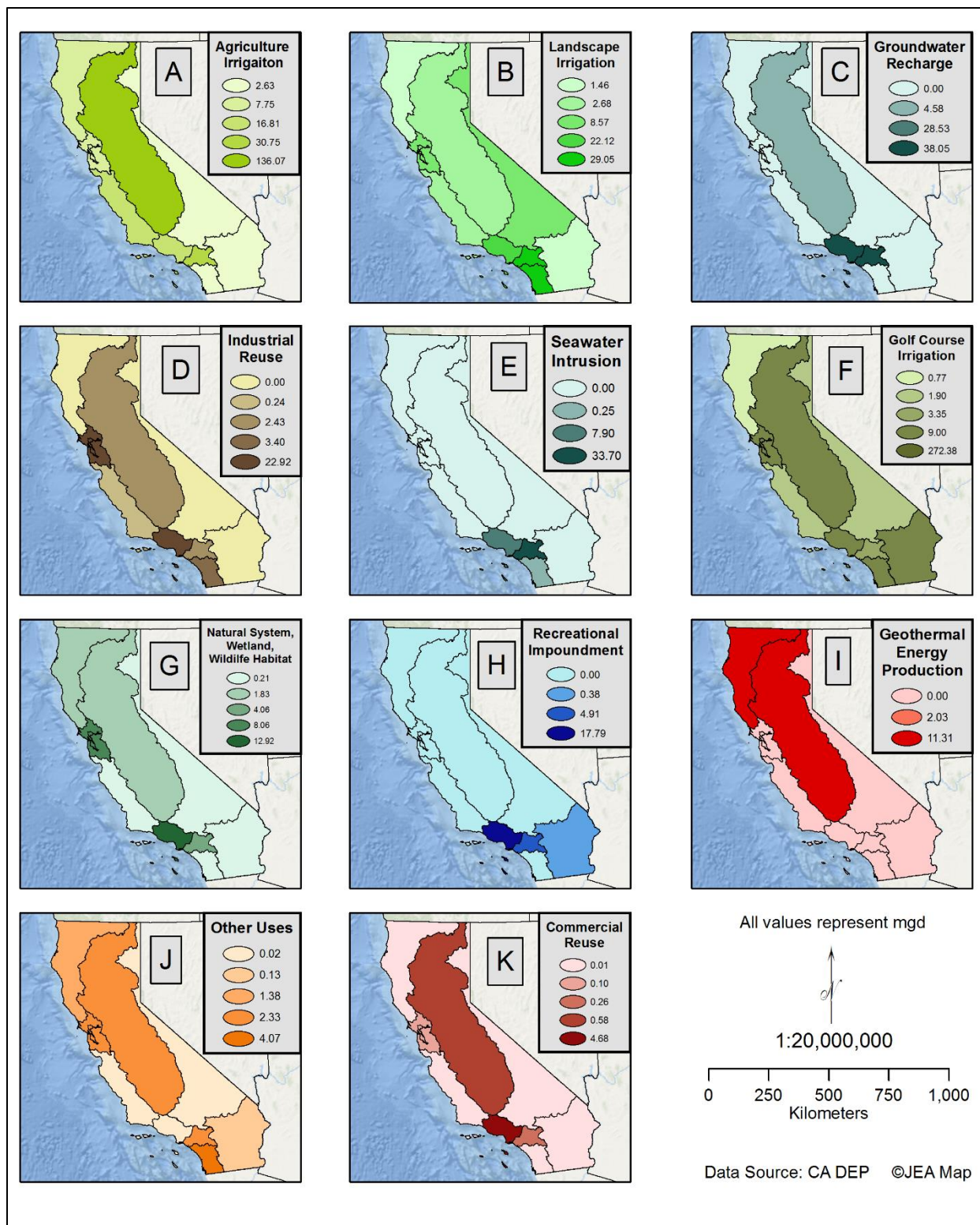


Figure 2.9: A) agricultural irrigation, B) landscape irrigation C) groundwater recharge, D) industrial reuse, E) seawater intrusion barrier, F) golf course irrigation, G) natural system restoration, wetlands, and wildlife habitat, H) recreational impoundment, I) geothermal energy production, J) other uses, K) commercial reuse.

Analysis of Variance

While each district produces recycled water for each category of discharge method, Lahontan was the lowest-producing district overall with a total production of 11.07 mgd (1.9% of the state total) (Figure 2.10). ANOVA results indicated significant differences in recycled water production between RWBs. Tukey *post-hoc* tests further show significant differences ($p < 0.05$) between Santa Ana RWB and San Francisco Bay, Central Coast, Central Valley, and Lahontan RWBs. The Central Coast RWB had the lowest mean production at 0.64 mgd (per POTW).

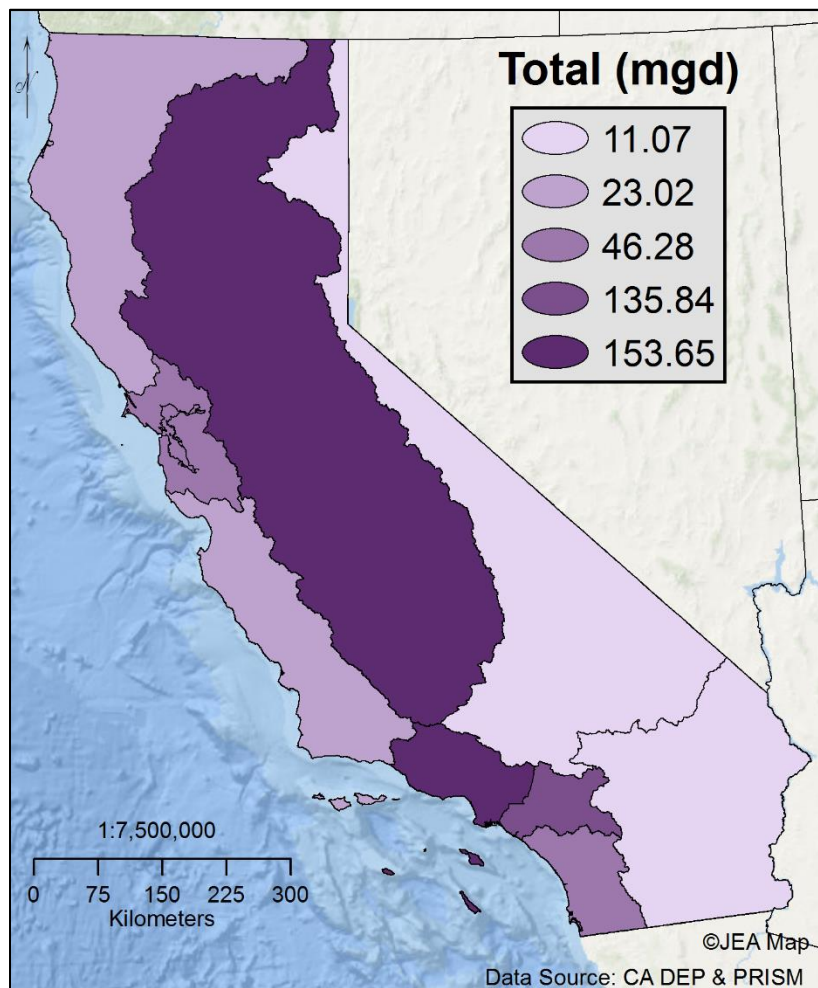


Figure 2.10: California total flow (mgd) per district.

Kernel Density Estimation

Hot spots for flow (mgd) are located throughout the Central Valley region and around major cities in California (Figure 2.11A). The dark areas have the greatest production, whereas light areas are targeted for increased production. The flow data were normalized by population served (Figure 2.11B) and showed a similar pattern. The majority of distribution occurs in the highly agricultural center of Central Valley (Fresno and Bakersfield) region; the areas for potential expansion are the northern and southeastern regions.

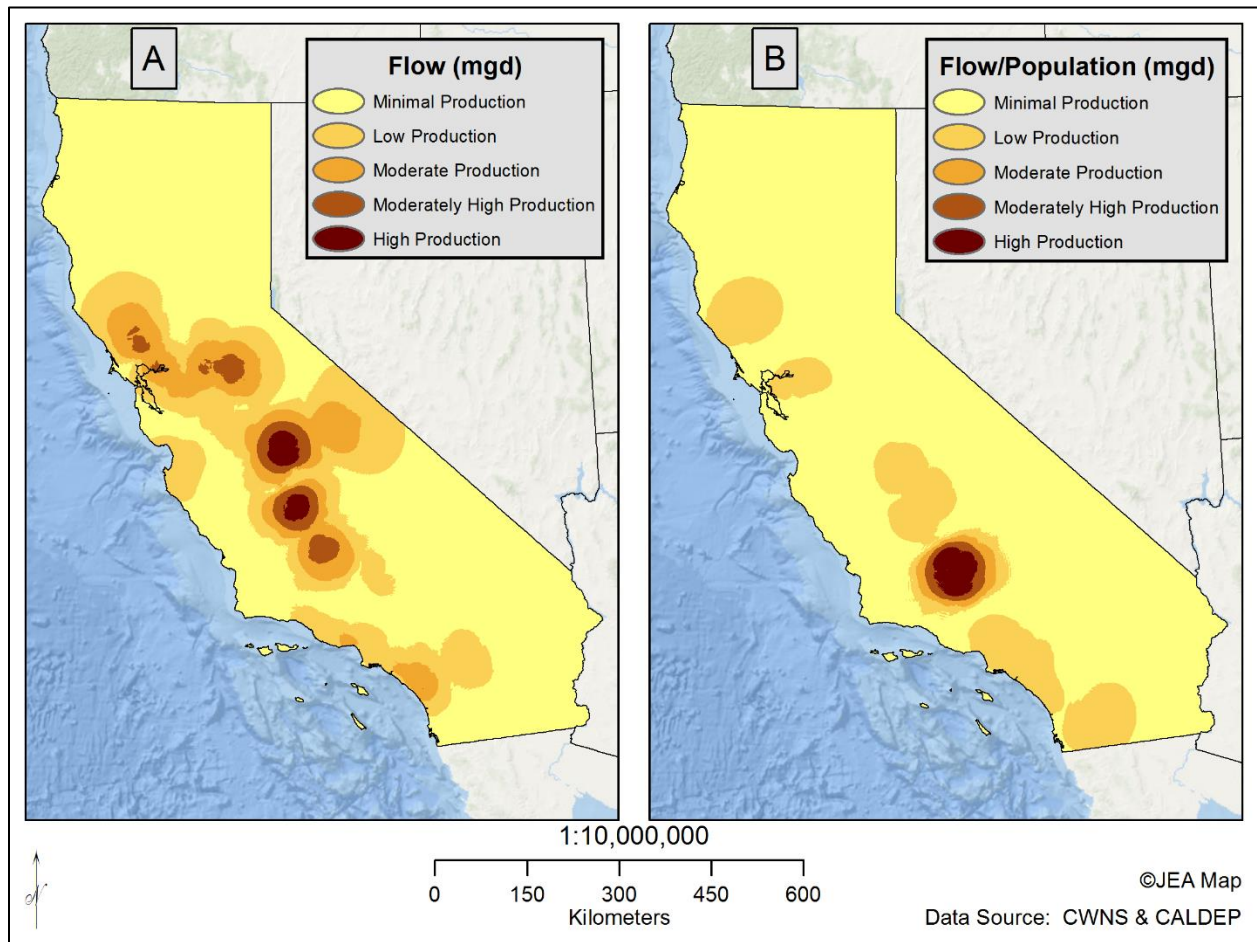


Figure 2.11: California kernel density estimation for A) flow (mgd), B) flow/population served (mgd).

Discussion

Florida

This analysis showed very minimal distribution of recycled water production in Suwannee River WMD. This lack of distribution could be attributed to land use in the Suwannee River WMD, which is primarily agricultural and includes a natural preserve. Given that Suwannee River WMD along with Northwest Florida WMD receive the bulk of Florida's precipitation, demand for water reuse products may be reduced. Tukey *post-hoc* tests indicated statistical difference between South Florida WMD was significantly greater than St. John's River WMD recycled water production.

KDE results indicated that hot spots for water reuse typically coincide with major cities, with one notable exception in Miami. Normalizing by population and acres served showed a similar overall pattern indicating that high population areas tend to utilize more recycled water products, even when accounting for population. The majority of distribution occurs in central Florida (Orlando and Tampa); one area for potential expansion is Miami. Miami receives more precipitation than areas in the northeast due to the tropical monsoon climate, yet Miami is vulnerable to saltwater intrusion due to rising sea level and groundwater withdrawal. Replacing even a small portion of this water with recycled water for applications such as saltwater intrusion barriers, wetland restoration, and groundwater recharge could reduce freshwater demands.

California

Analysis showed very minimal distribution to Lahontan RWB. This may be attributed to land use in Lahontan RWB, which is primarily desert and includes federal lands, such as Death Valley and Mojave National Preserve, so there is less demand for water from the rural

population. Tukey *post-hoc* tests indicated statistical differences between Santa Ana RWB was significantly greater than San Francisco Bay, Central Coast, Central Valley, and Lahontan RWB

Central Coast is another RWB region that could increase recycled water production. Land use in the Central Coast RWB is primarily mixed conifer forests with some agricultural applications (e.g. vineyards). In addition, Central Coast RWB receives moderate precipitation, further reducing demand for water reuse products.

Furthermore, Santa Ana RWB indicated a significant difference between San Francisco Bay, Central Coast, Central Valley, and Lahontan RWBs. This can be attributed to a large mean value (4.31 mgd), which resulted from as a small number of POTWs producing a high volume of recycled water products. Santa Ana RWB had the highest recycled water production of California RWBs.

KDE showed hot spots for water reuse are typically located at major cities and throughout the Central Valley, which is California's primary agricultural region. Normalizing by population showed a similar overall pattern with the highest water use per person in Bakersfield. Hot spots for recycled water use occur predominantly along coastal cities (Napa, San Francisco, Monterey, Los Angeles, and Santa Ana) and the agricultural hub of the Central Valley (Sacramento, Fresno, Bakersfield, and California City). Areas for potential expansion are the North Coast RWB (highest production of geothermal energy production and seawater intrusion), Central Coast RWB (along the coast which could use recycled water for seawater intrusion barriers and irrigation), Colorado River RWB (used recycled water for golf course irrigation), and Lahontan RWB (use of recycled water for landscape irrigation).

Comparison

California receives much less precipitation than Florida, which should encourage more recycled water production, but the state is somehow falling short. Similar patterns of use exist between both states with recycled water produced near most major cities, even when accounting for population. California used recycled water products primarily for agricultural and landscape irrigation, whereas Florida used recycled water products primarily for irrigation of public access areas and groundwater recharge. California has a large agricultural hub for the US, while Florida has a large amount of tourism which could explain the aesthetic need for public access areas irrigation.

Recycled water products are produced by both states but Florida had more POTWs (426; 78%) producing recycled water at 674.85 mgd, whereas, California had fewer POTWs (228; 20%) producing recycled water at 597.48 mgd. Most recycled water products are found throughout major cities in Florida and California. Agriculture, golf course, and other irrigation purposes are the most common recycled water products used in both states.

Limitations and Future Research

One major limitation to this study was the inability to acquire more recent recycled water data than 2009 for California. Once those California data are obtainable, it would be warranted to examine California's increase or decrease over time, especially considering the recent drought. Florida data are available through 2015 and a future study will analyze temporal changes from 2009 to 2015.

Conclusion

A spatial examination of recycled water use in Florida and California is a first step toward addressing water shortages through expansion of recycled water use. Water reuse is not balanced between Florida Water Management Districts nor California Regional Water Quality Control Boards even after accounting for the number of POTWs per district. Recycled water production is significantly less in Miami and the Suwannee River WMD of Florida and the Central Coast RWB of California than in the other locations; this may present an opportunity for expansion. Kernel Density Estimation indicated the majority of distribution occurs in central Florida (Orlando and Tampa) and California's Central Valley region (Fresno and Bakersfield) and around major cities in California. KDE indicated potential areas of growth for the panhandle and southern regions of Florida, as well as northern and southeastern regions in California.

Implementation of a recycled water program can enhance ecosystem health by reducing water withdrawal in coastal aquifers, slowing saltwater intrusion, and decreasing nutrient (mainly nitrogen and phosphorous) loading in surface streams (USEPA 2012). Consequently, recycled water use is an essential component of water conservation plans in water-stressed coastal communities. Water conservation may be increased if the use of recycled water products were considered for public water supply distribution in municipalities across Florida, California and other coastal or drought-stricken states.

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CHAPTER 3

FLORIDA'S RECYCLED WATER FOOTPRINT: A GEOSPATIAL ANALYSIS FOR DISTRIBUTION OF FLOW FROM 2009-2015

Abstract

Population expansion, resulting in increased water supply demands, coupled with reduced freshwater availability caused by saltwater intrusion and drought have led to chronic and persistent water shortages in many areas. These water shortages may be addressed, in part, by recycled water used for irrigation, industrial reuse, groundwater recharge, and as effluent discharge returned to streams. Recycled water is an essential component of integrated water management and broader adoption of recycled water will increase water conservation in water-stressed coastal communities. This study examined spatial patterns of recycled water use in Florida in 2009 and 2015 to detect gaps in distribution, quantify temporal change, and identify potential areas for expansion. Databases of recycled water products and distribution centers for Florida in 2009 and 2015 which were developed by combining the 2008 Clean Water Needs Survey database with Florida's 2009 Reuse Inventory database and combining the 2012 Clean Water Needs Survey database with Florida's 2015 Reuse Inventory database, respectively. Florida increased recycled water production from 674.85 mgd in 2009 to 738.15 mgd in 2015. South Florida Water Management District had the largest increase in production of 44.38 mgd (69%) while Southwest Florida Water Management District had a decrease in production of 1.68 mgd or 3%. Water reuse is not balanced between Florida Water Management Districts. Kernel Density Estimation shows the majority of distribution in central Florida (Orlando and Tampa), attributed to high population in those regions.

Introduction

Recycled water use is the reuse of highly treated wastewater for irrigation, industrial reuse, groundwater recharge, and wetland reclamation, among other uses. These applications are important for water conservation, the need for which has been intensified by climate change, population growth, groundwater withdrawal, and saltwater intrusion (Koch-Rose et al. 2011). The National Research Council (2012) indicated that the use of recycled water could assist in water mitigation strategies, specifically water conservation measures. The approximately 12 billion gallons of effluent discharged from wastewater treatment plants into streams and oceans daily could be recycled to increase available freshwater resources, supplying up to 6% of the estimated total United States (US) freshwater demand and up to 27% for municipal supply of residential, commercial, and industrial uses (NRC 2012).

Recycled water use dates back 5000 years to Minoan time (ca. 3200-1100 BC) when the Harrapan Civilization in the Indus Valley used effluent for agricultural irrigation, water for domesticated farm animals, and proto-industries for silk (Angelakis and Gikas 2014; De Feo et al. 2014). More recently, Florida began recycling water in the mid-1960's to produce recycled water for agricultural spray irrigation for 120 acres at the Tallahassee Reclaimed Water Farm (Toor and Rainey 2009). By 2015, Florida maintained 418 domestic wastewater treatment facilities that produced a variety of recycled water products (FDEP 2016).

A thorough literature review indicated there was a lack of geospatial and statistical evaluation of recycled water use. Public perception of recycled water acceptance was examined (such as Po et al. 2003; Dolnicar 2006; Dolnicar and Schäfer 2009; and Crampton and Ragusa 2016) and found that there is a “yuck factor” from the general public, but further education of communities about the recycled water treatment process could change that perception (Dolnicar

and Schäfer 2009; Qian and Leong 2016). Po et al. (2003) described the “yuck factor” as a psychological barrier of emotional discomfort because most people perceived recycled water as unclean with potential risk factors associated with the quality of recycle water. Participants of the study indicated they would rather recycled water be referred to as repurified water (Po et al. 2003). Qian and Leong (2016) found that the “yuck factor” is the only statistically significant variable that prevents implementation for direct potable reuse. The best management practices and water quality of wastewater treatment plant’s discharge were also investigated (such as Wang et al. 1999; Bixio et al. 2005; Wintgens et al. 2005; and Luo et al. 2016). Wintgens et al. 2005 concluded that a single system (e.g. membrane bioreactors) were suitable for small urban and rural areas and dual systems (e.g. microfiltration and reverse osmosis) were better suited for large urban areas. Kuwayama and Kamen (2016) conducted the first econometric analysis of Florida’s county level water reuse capacity from 1996–2012. This study investigated water quality and scarcity of which water quality was a major factor that Florida has been extremely dedicated to recycled water distribution.

Florida’s recycled water production is managed from five Water Management Districts (WMDs) (Figure 3.1). These WMDs are the “general supervisory authority” which delegate water resource programs (such as flood protection, technical duties, development of water management plans, and procedures for recycled water use) intended to manage the quality and quantity of water mitigation techniques between city, county, and state level government under the oversight of the U.S. Environmental Protection Agency (USEPA) (Olexa et al. 2002).

The present spatial and temporal study is an empirical analysis of recycled water use in Florida in 2009 and 2015. This investigation provides the most recent analysis of recycled water use in Florida which contributes to the existing literature about recycled water. The purpose of

this study is to examine the spatial distribution among five WMDs in 2009 and 2015 to identify gaps in distribution, temporal changes, and potential areas for expansion. As population continues to rise, supply of freshwater typically decreases and recycled water has become an important and essential water mitigation strategy for Florida.

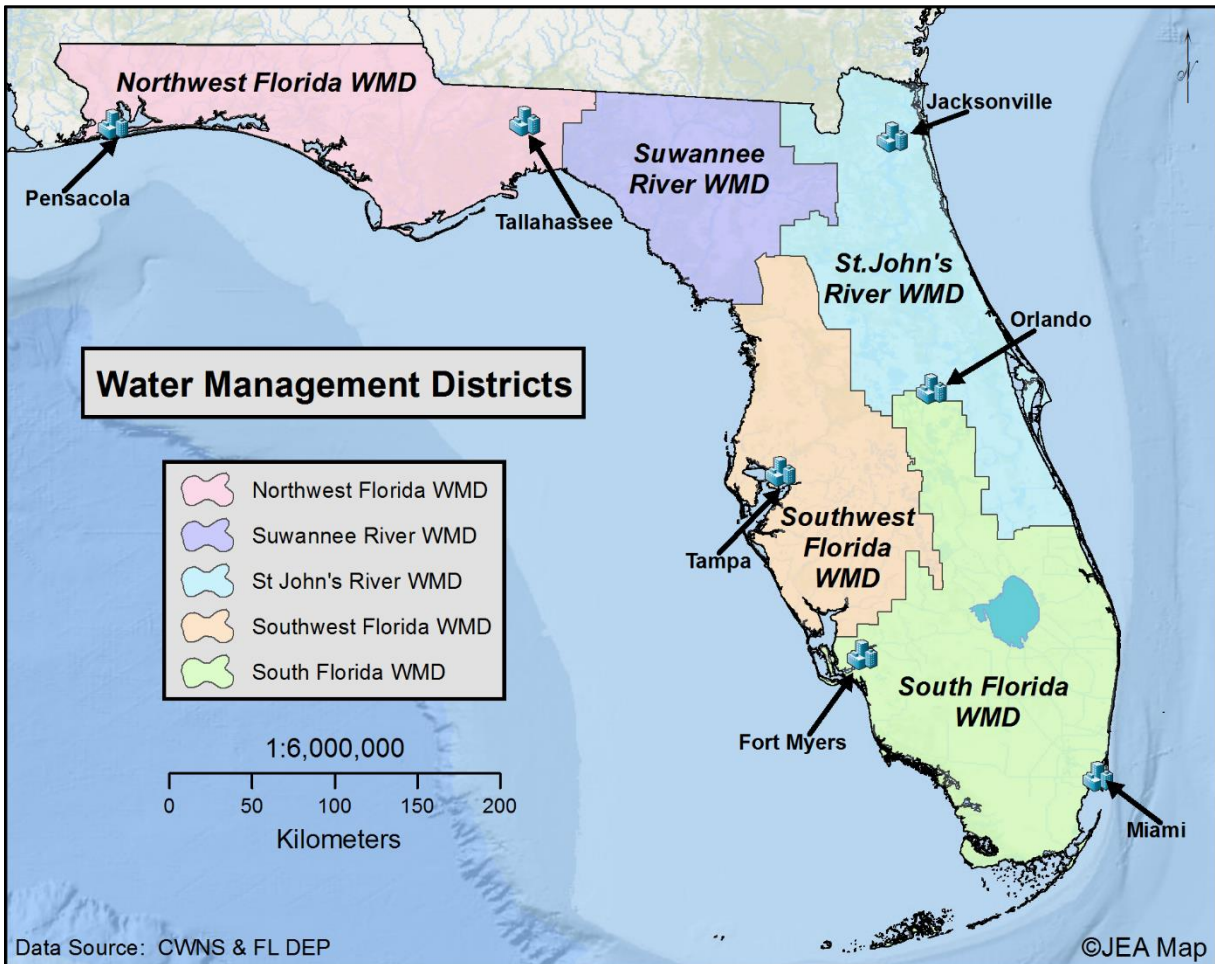


Figure 3.1: Florida Water Management Districts.

Background

Since the 1940s, water use in the US has doubled due to population growth which caused added stress to water management systems (Montagna et al. 2002). Florida's current water supplies are at risk of depletion by 2025 due to groundwater withdrawal from the Floridian

aquifer and other groundwater sources since much of the state relies overwhelmingly on aquifers for municipal water supply (Koch-Rose et al. 2011). Recycled water is one water management practice implemented to meet this demand, serving a dual purpose as a water conservation measure (especially in relation to groundwater recharge). Florida's recycled water program began in Tallahassee in the mid-1960s to produce recycled water for spray irrigation agricultural purposes for 120 acres at the Tallahassee Reclaimed Water Farm. Florida ranked fourth in the US for total freshwater withdrawal according to a 2010 United States Geological Survey (USGS) report on water use in the U.S. (Maupin et al. 2014). Bryck et al. 2008 reported that as of 2006 Florida (663 mgd) was ranked first in the US followed by California (580 mgd), Texas (31.4 mgd), Virginia (11.2 mgd), Arizona (8.2 mgd), Colorado (5.2 mgd), Nevada (2.6 mgd), and Idaho (0.7 mgd) for recycled water distribution.

Florida's WMDs produce recycled water for five use categories: public access areas, agricultural irrigation, groundwater recharge, industrial, and wetlands and other (toilet flushing, fire protection, and other) (Table 3.1). These recycled water products are distributed across the state and are regulated by consumptive use permits that identify the level of treatment at wastewater facilities, limit withdrawal based upon the need of recycled water (e.g. agricultural and industrial), and prevent saltwater intrusion (e.g. groundwater recharge injection well locations near estuaries) (NRC 2012).

Table 3.1: Florida's types of recycled water products (FDEP 2016).

Type	Explanation
Public Access Areas	Golf courses, cemeteries, parks, landscape areas, hotels, motels, private property, residential dwellings and highway medians irrigation
Agricultural Irrigation	Includes edible crops and crops used for feed and fodder
Groundwater Recharge	Groundwater injection and indirect potable reuse (withdrawn for drinking water)
Industrial	Manufacturing facilities, cooling towers
Wetlands and Other	
• Wetlands	Addition to wetlands
• Toilet Flushing	Reuse for toilet flushing
• Fire Protection	Reuse for fire protection
• Other	Permitted uses include--decorative fountains, commercial laundries, cleaning of roads and sidewalks, vehicle washing, concrete making, and other permitted uses

Data and Methods

Databases of recycled water products for Florida were developed for 2009 and 2015. Publicly Owned Treatment Works (POTWs) locations, population total, and volume of production were extracted from the Florida 2008 and 2012 Clean Water Needs Survey (CWNS) database (USEPA 2008; USEPA 2012) and combined with Florida's 2009 and 2015 Reuse Inventory database using permit numbers as the key (FDEP 2010; FDEP 2016) (Figure 3.2). The databases created for 2009 and 2015 were also combined to examine spatial change over time.

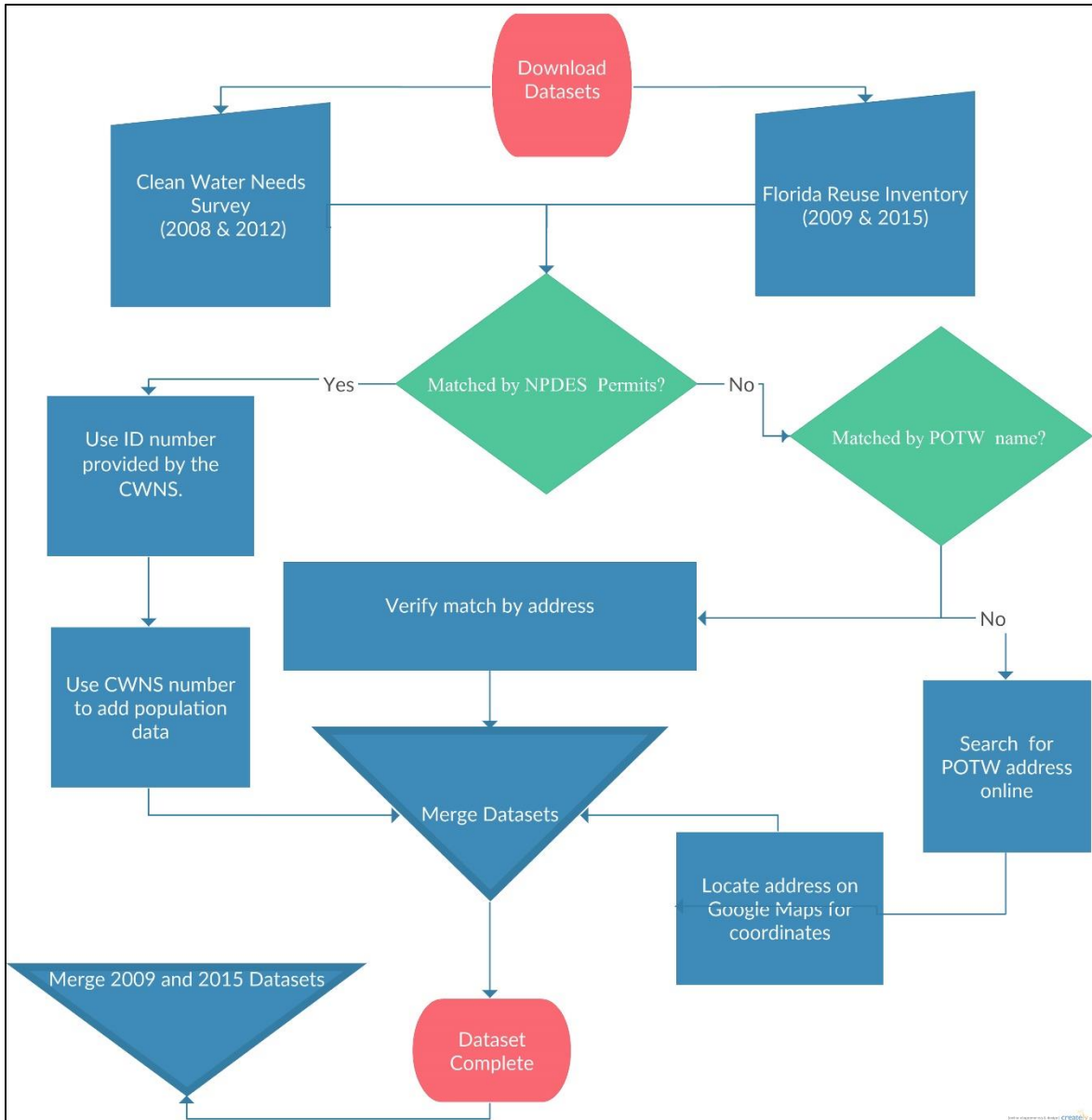


Figure 3.2: Flowchart for dataset organization procedures.

Dataset Assembly

The EPA’s CWNS database was downloaded from <https://www.epa.gov/cwms> and summary of facility, permit, and population data were extracted. Summary of facilities included: CWNS number for each POTW, the name of POTWs, county of origin, geographic coordinates for location, and permit number. Summary of permits included: CWNS number for each POTW

with a permit, permit number, and permit type. Summary of population included: CWNS number for each POTW and the present residents connected to public sewer lines. The CWNS number was used to extract data for all POTWs that recycle water.

Florida's 2009 and 2015 Reuse Inventories were obtained from the Florida Department of Environmental Protection (FDEP). This database included information on the distribution of recycled water: name of POTWs, the water management district location, type of recycled water product, use in millions of gallons per day (mgd) of recycled water, and acres served. In 2009, 414 of 426 (97%) and in 2015, 407 of 418 (97%) POTWs in Florida's Reuse Inventory database were matched by permit numbers to entries in the CWNS database which contained geographic coordinates for each in 2009 and 2015, respectively. Wastewater treatment facilities with unmatched permits (2009 N=15; 2015 N=11) were located using Google Maps and manually geocoded. The geocoded datasets were mapped using ArcGIS 10.4.1(ESRI 2016) (Figure 3.3 and 3.4).

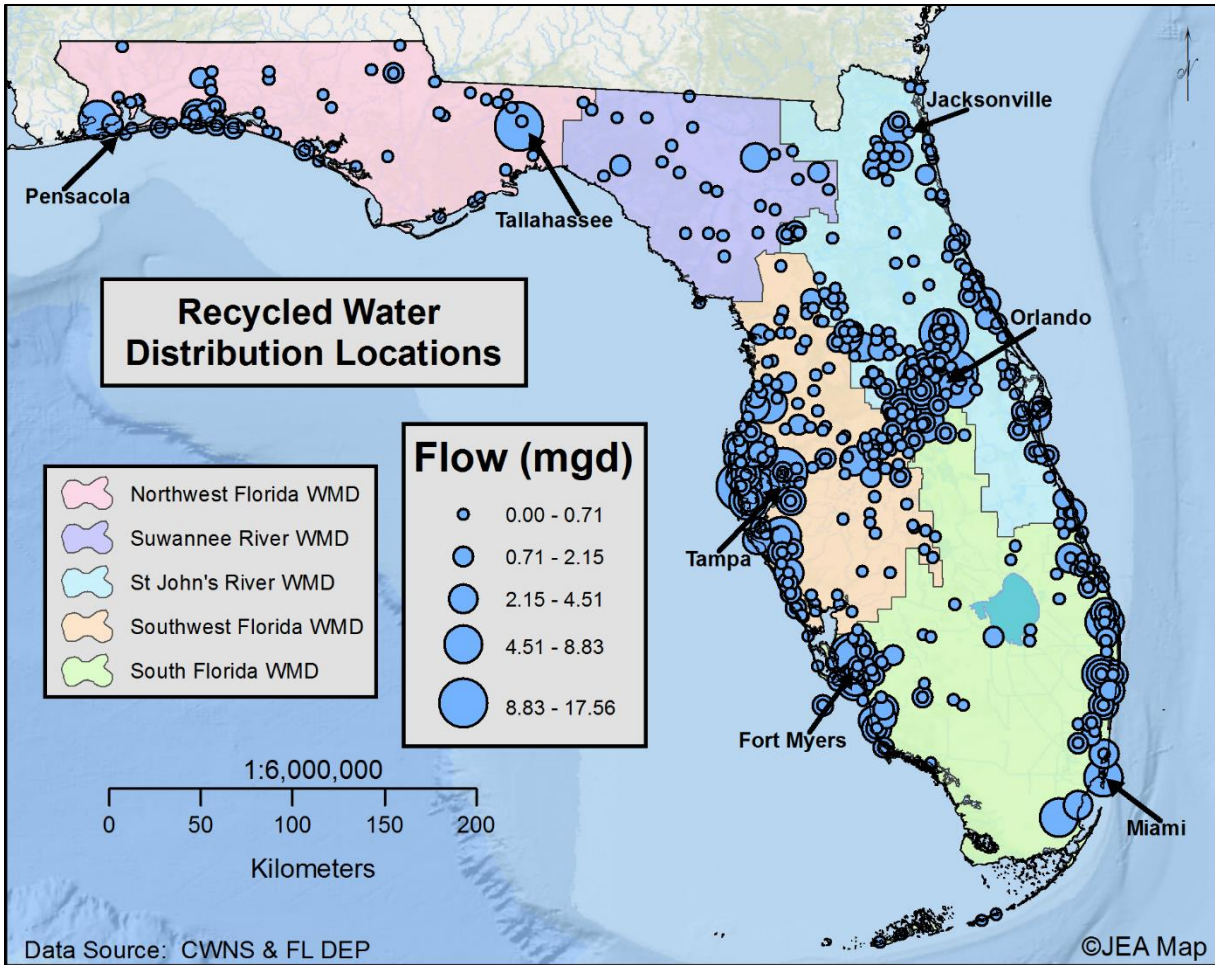


Figure 3.3: 2009 Florida Recycled water distribution locations.

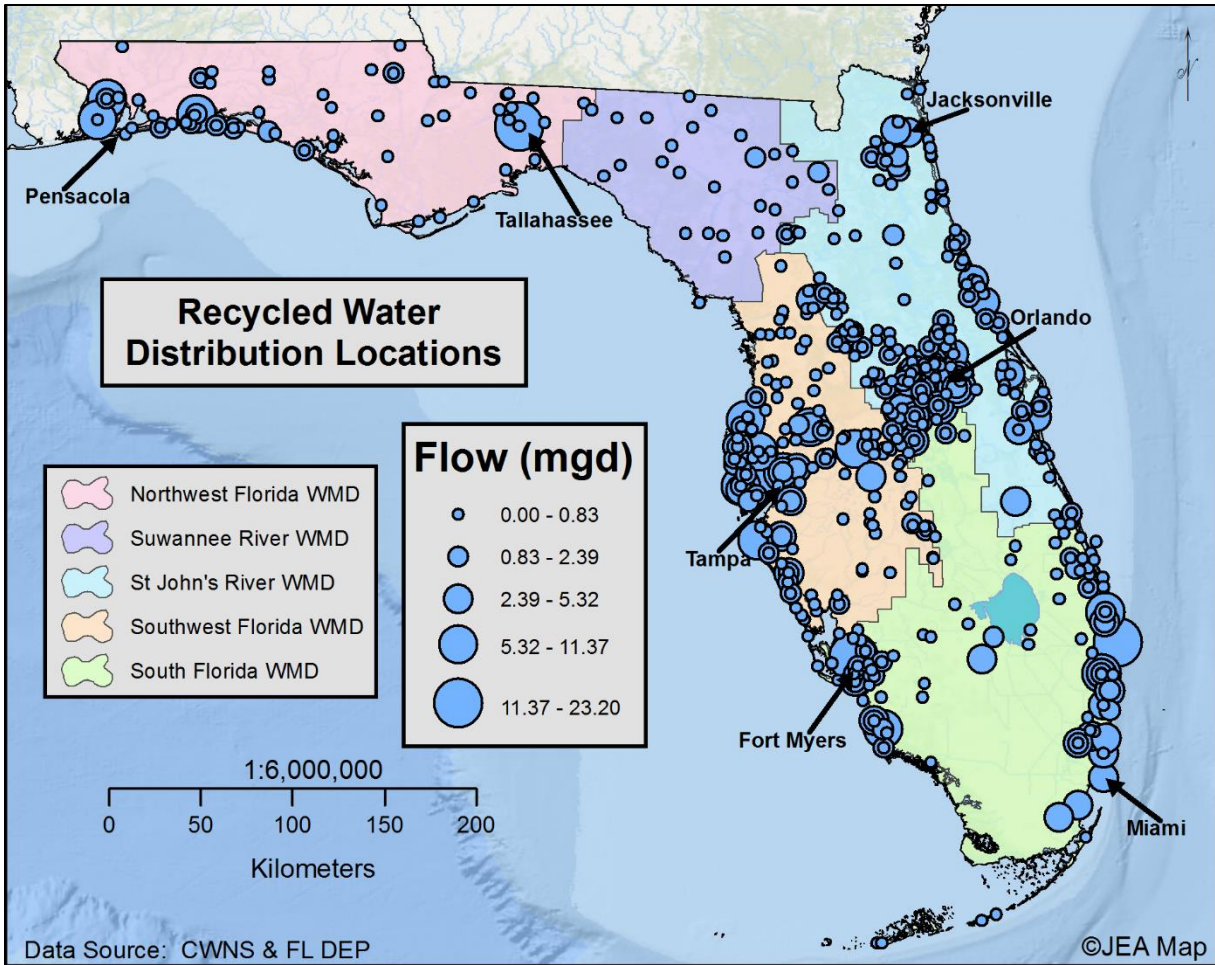


Figure 3.4: 2015 Florida Recycled water distribution locations.

Next, a third database was created which combined 2009 and 2015 water reuse data to investigate differences over the 6-year period. These data included POTW name, geographic coordinates, 2009 and 2015 flow (mgd), 2009 and 2015 acres served, and average population served by the POTWs. Population data were provided only in the CWNS published every four years, and because of missing values in 2008 and 2012, averages were used.

Statistical Analysis

Descriptive Statistics

Descriptive statistics were calculated for volume of flow at Florida's WMDs for 2009, 2015, and the changes from 2009 to 2015.

Analysis of Variance

Flow volume of recycled water products in 2009 and 2015 were compared between Florida's WMDs with a one-way Analysis of Variance (ANOVA). Tukey *post hoc* tests were conducted to determine statistical significance between flow volume (mgd) for WMDs in 2009 and 2015.

Paired t-tests were performed to identify statistically significant differences between the 2009 and 2015 flow volume of recycled water products for each WMD. A Wilcoxon signed-rank test was used to assess differences between 2009 and 2015 flow volume of recycled water products. All bivariate data were analyzed with Statistical Package for the Social Sciences Version 23 (SPSS) (IBM Corp 2014).

Kernel Density Estimation

Hotspots for recycled water production were identified with Kernel Density Estimation (KDE). Quartic Kernel was selected because it has a gradual, spherical-shaped curve which halts at a defined radius limit. This prevents the kernel from extending to infinity and limits the area of influence (Levine 2015). Bandwidth was set as adaptive to find the minimum number of points which was set as fifteen points per cluster. KDE was performed on flow, flow normalized by acres served, and flow normalized for average population served. CrimeStat IV was used to analyze all data (Levine 2015).

Results

In 2009, 426 of 548 (78%) POTWs distributed recycled water products with a total flow of 674.26 mgd (FDEP 2010), whereas in 2015, 418 of 524 (87%) POTWs distributed recycled water products with a total flow of 738.15 mgd (FDEP 2016). Major metropolitan areas (Orlando, Tampa, Fort Myers, and Miami) had higher recycled water production. The highest mean production in 2009 was 1.13 mgd in South Florida WMD, whereas the lowest mean production was 0.34 mgd in Suwannee River WMD (Table 3.3). In 2015, the highest mean production was 1.32 mgd in South Florida WMD, whereas the lowest mean production was 0.28 mgd in Suwannee River WMD (Table 3.4).

Table 3.2: 2009 Florida Descriptive Statistics with number of POTWs for flow (mgd) per WMD.

WMD	# POTW	Mean	Variance	Minimum	Maximum	Median	Flow
Northwest Florida	58	0.64	3.63	0.002	17.14	0.22	59.91
South Florida	97	1.13	3.99	0.00036	17.56	0.34	238.60
St. John's River	129	0.57	1.53	0.00005	13.73	0.22	167.92
Southwest Florida	119	0.80	2.64	0.0001	11.99	0.24	198.45
Suwannee River	23	0.34	0.22	0.007	2.30	0.14	9.39
Average Total	426	0.69	2.40	0.0005	12.08	0.20	674.26

Table 3.3: 2015 Florida Descriptive Statistics with number of POTWs for flow (mgd) per WMD.

WMD	# POTW	Mean	Variance	Minimum	Maximum	Median	Flow
Northwest Florida	59	0.69	4.39	0.0003	17.10	0.20	70.11
South Florida	97	1.32	7.82	0.001	23.20	0.32	282.98
St. John's River	124	0.61	1.43	0.001	11.37	0.20	178.62
Southwest Florida	112	0.73	1.92	0.001	7.90	0.23	196.77
Suwannee River	26	0.28	0.16	0.005	2.18	0.16	9.68
Average Total	418	0.73	3.14	0.002	12.35	0.22	738.15

2009 Descriptive Statistics

Public access area irrigation was the most common recycled water product associated with recycled water accounting for a total distribution of 381.38 mgd (57% of state total), mostly distributed by South Florida WMD (41% 154.56 mgd) (Figure 3.5A). The next largest recycled water product was industrial reuse with a production of 91.64 mgd (14% of state total), with the largest distributed by Southwest Florida WMD at 43.01 mgd (47%) (Figure 3.5B). Groundwater recharge followed next with a total of 86.72 mgd (13% of state total), with the largest distributed by South Florida WMD at 43.29 mgd (50%) (Figure 3.5C). Recycled water used for agricultural irrigation totaled 75.57 mgd (11% of state total), with the largest portion distributed by Northwest Florida WMD at 32.09 mgd (42%) (Figure 3.5D). Wetlands and other (which include toilet flushing and fire protection) totaled 38.96 mgd (6% of state total), with a majority (69% at 27.72 mgd) distributed by St. John's River WMD (Figure 3.5E).

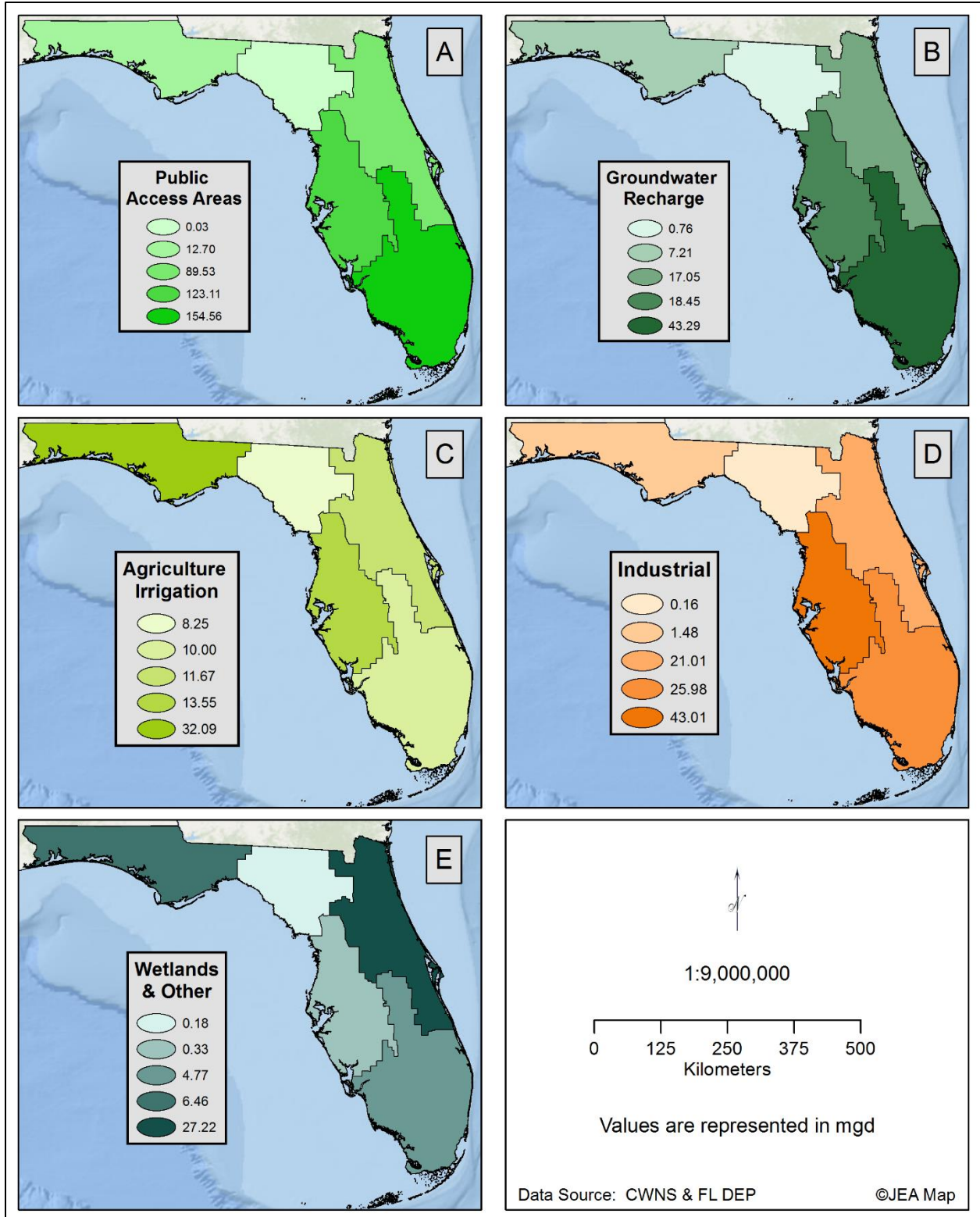


Figure 3.5: 2009 A) Public access areas, B) groundwater recharge, C) agricultural irrigation, D) industrial reuse, E) wetlands recharge and other.

2015 Descriptive Statistics

The most common recycled water product in 2015 was public access area irrigation accounting for a total distribution of 419.82 mgd (57% of state total), mostly distributed by South Florida WMD (43% at 179.48 mgd) (Figure 3.6A). Industrial reuse was the next largest recycled water product with a production of 123.84 mgd (17% of state total) and the largest distributed by South Florida WMD at 46.15 mgd (37%) (Figure 3.6B). Next was groundwater recharge with a total of 94.68 mgd (13% of state total), distributed most widely by South Florida WMD at 48.79 mgd (52%) (Figure 3.6C). Agricultural irrigation reuse totaled 64.69 mgd (9% of state total), with the largest proportion distributed by Northwest Florida WMD at 28.50 mgd (44%) (Figure 3.6D). Finally, wetlands and other (which include toilet flushing and fire protection) totaled 35.12 mgd (5% of state total), with a majority (69% at 24.24 mgd) distributed by St. John's River WMD (Figure 3.6E).

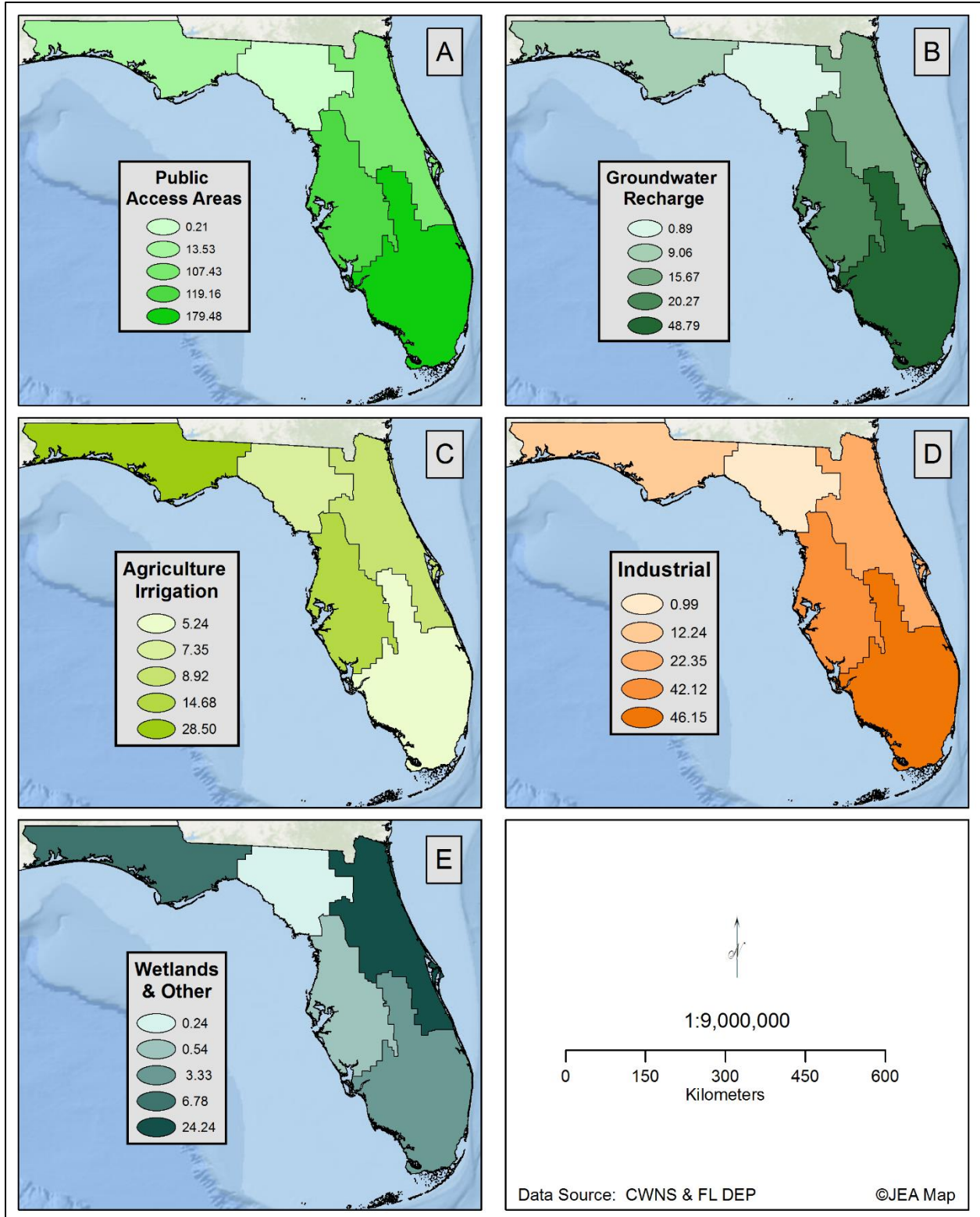


Figure 3.6: 2015 A) Public access areas, B) groundwater recharge, C) agricultural irrigation, D) industrial reuse, E) wetlands recharge and other.

Analysis of Variance

In both 2009 and 2015, Suwanee River WMD was the lowest-producing district with a total production of 9.39 (1.4%) and 9.68 (1.3%), respectively (Figure 3.7 and Figure 3.8). ANOVA results for 2009 indicated significant differences ($p < 0.05$) in recycled water production between WMDs. Additional assessment with Tukey *post-hoc* tests indicated significant differences ($p < 0.05$) between South Florida and St. Johns River WMDs in 2009. While Suwanee River WMD had the lowest mean production at 0.34 mgd (per POTW) in 2009, it was not significantly different from the other WMDs.

In 2015, ANOVA results again indicated significant differences ($p < 0.05$) in recycled water production between WMDs. Tukey *post-hoc* tests indicated significant differences ($p < 0.05$) between South Florida and St. Johns River, Southwest Florida, Northwest Florida, and Suwanee River, WMDs.

Paired t-tests showed 2009 and 2015 volume of recycled water flow and WMDs were highly and positively correlated, $r = 0.94$, $p = 0.05$. Flow volume in 2015 increased significantly over 2009, $t_{372} = 1.939$, $p = 0.05$, $d = 0.1$.

The 373 POTWs that generated recycled water production in both 2009 and 2015 were assessed with a Wilcoxon signed-rank test which showed symmetrical distribution, as assessed by a histogram. Volume of flow for 2015 indicated a statistically significant median increase (0.475 mgd) compared to the median volume of flow in 2009 (0.395 mgd), $z = -1.973$, $p < 0.009$.

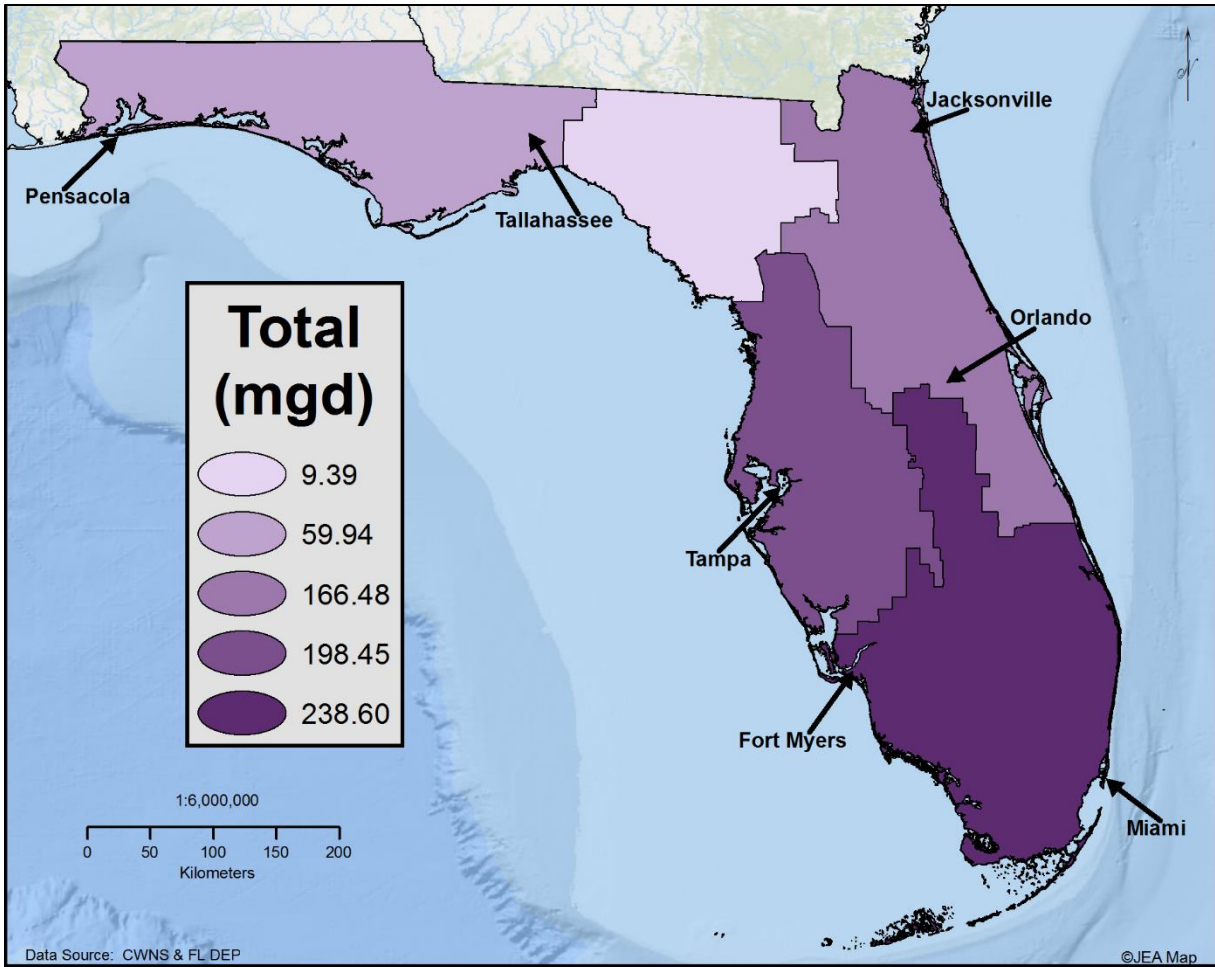


Figure 3.7: 2009 Florida total flow (mgd) per district.

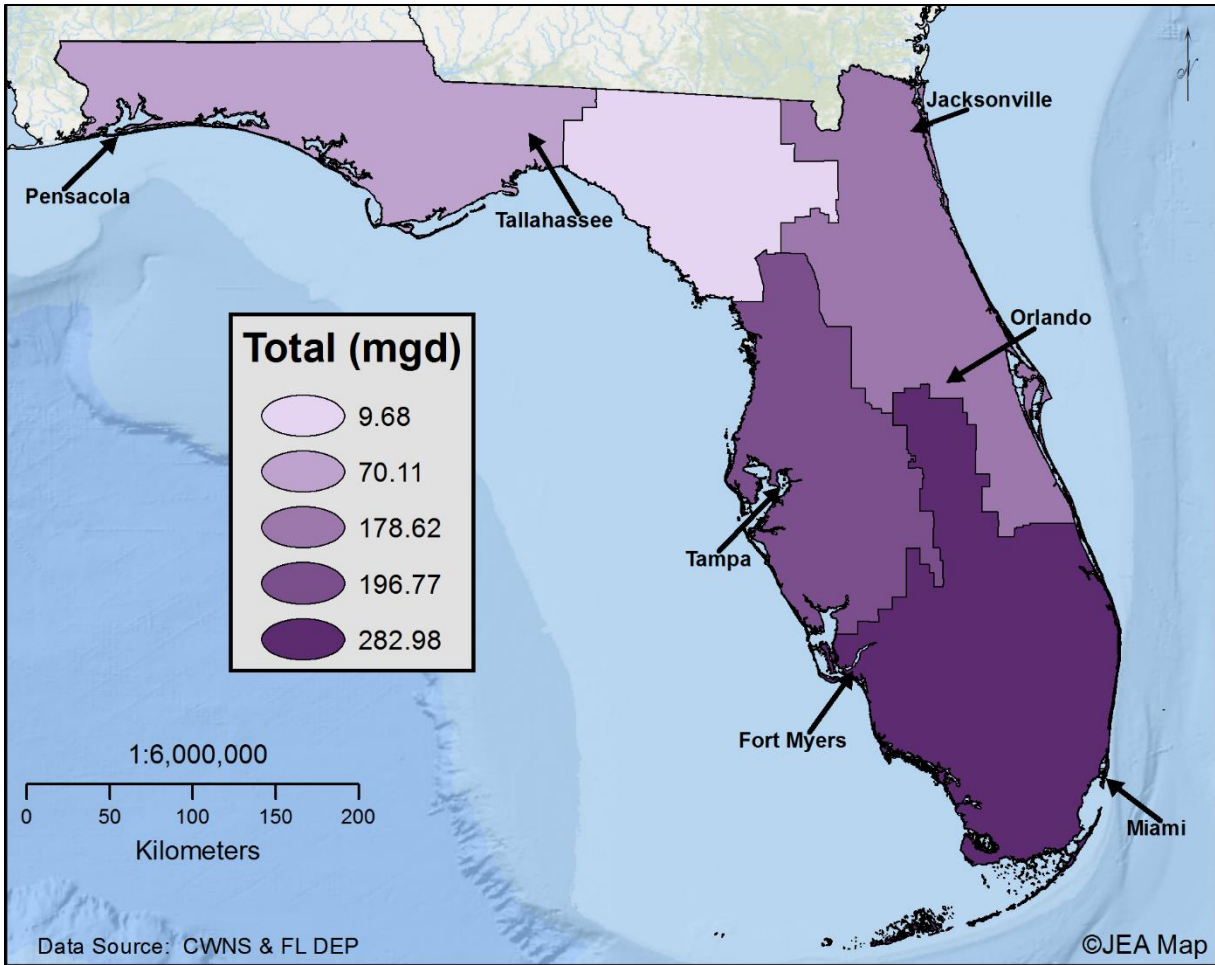


Figure 3.8: 2015 Florida total flow (mgd) per district.

Kernel Density Estimation

KDE of flow volume identified hot spots near most major cities (Figure 3.9A and Figure 3.10A). The dark areas have greatest production, whereas light areas could be considered potential areas for increased production. Flow data were normalized by area served (Figure 3.9B and Figure 3.10B) and average population served (Figure 3.9C and Figure 3.10C).

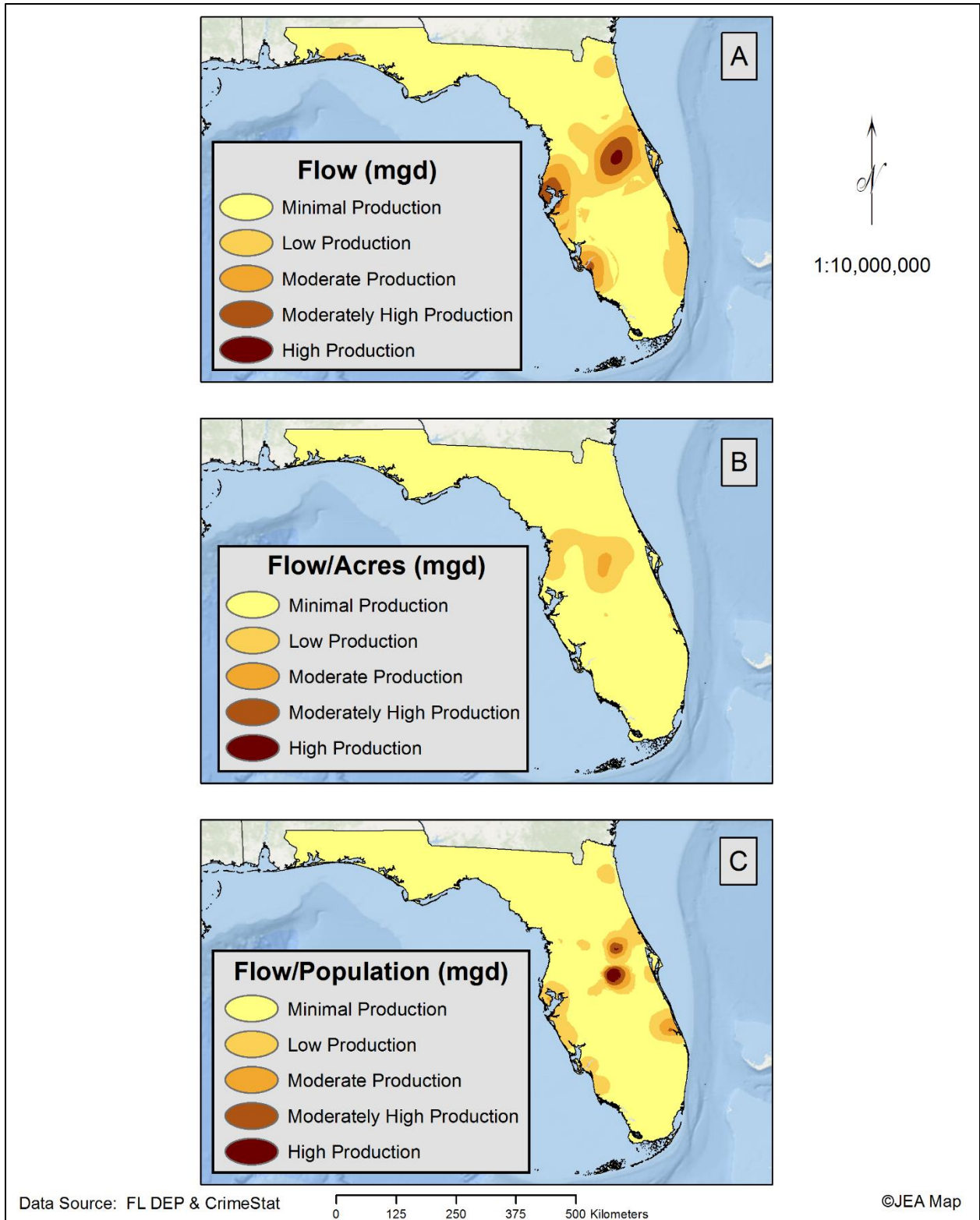


Figure 3.9: 2009 Florida kernel density estimation for A) flow (mgd), B) flow/acres served (mgd), and C) flow/average population served (mgd).

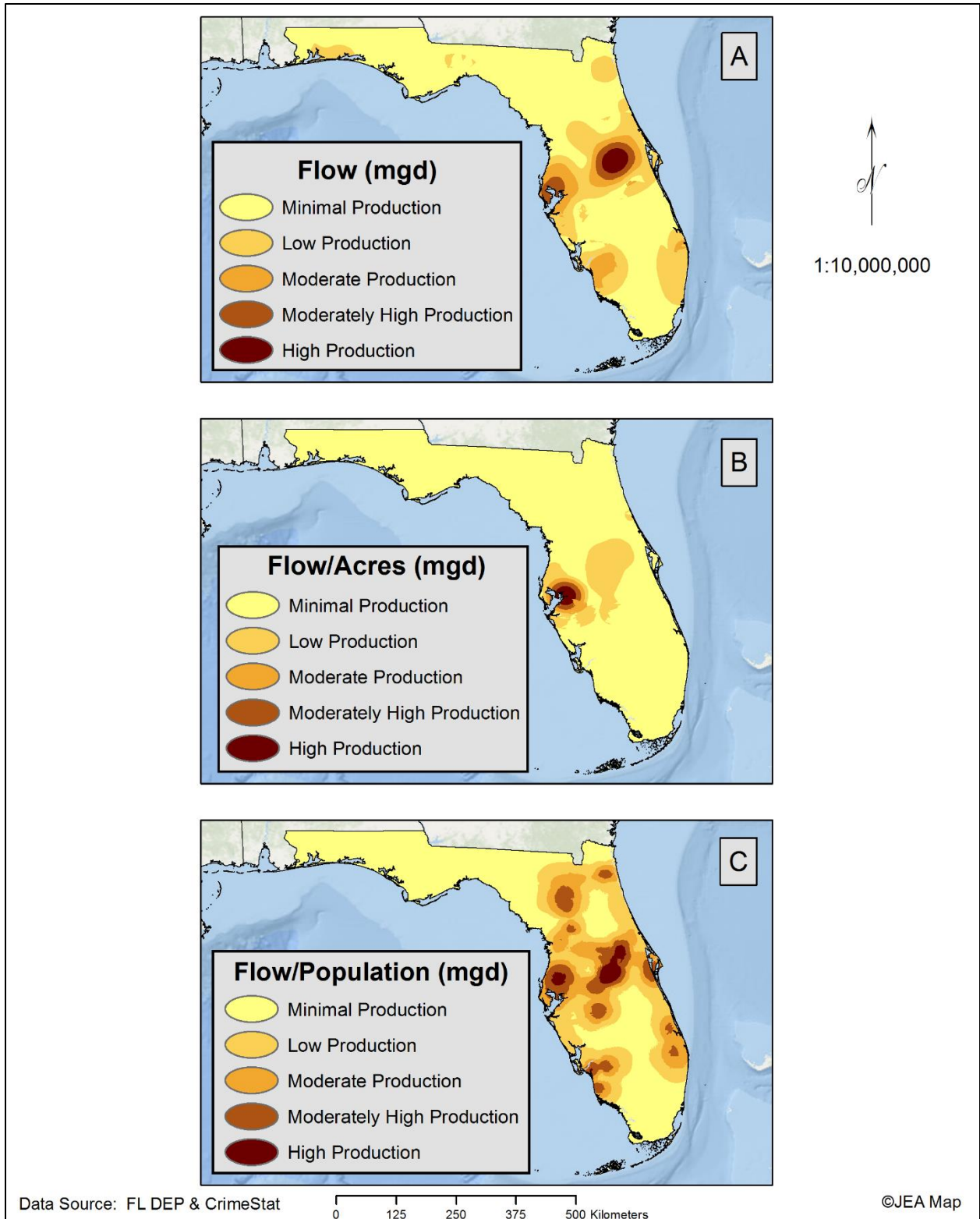


Figure 3.10: 2015 Florida kernel density estimation for A) flow (mgd), B) flow/acres served (mgd), and C) flow/average population served (mgd).

Discussion

Production of recycled water increased by a total of 63.88 mgd from 2009 to 2015. This increase was seen in public access areas (38.44 mgd) (Figure 3.11A), groundwater recharge (7.96 mgd) (Figure 3.11B), and industrial reuse (32.21 mgd) (Figure 3.11D), all of which can be attributed to South Florida WMD. Decreases in agricultural irrigation (10.87 mgd) occurred in South Florida WMD (Figure 3.11C) and wetlands reclamation (3.84 mgd) in St. Johns River WMD (Figure 3.11E). Increase in distribution was most apparent in South Florida WMD which totaled 44.38 mgd (69%). This overall increase in South Florida results from increases in recycled water for public access area irrigation (24.92 mgd) (Figure 3.11A), industrial reuse (20.17 mgd) (Figure 3.11D), and groundwater recharge (5.50 mgd) (Figure 3.11B). Decrease in distribution was most notable in Southwest Florida WMD which totaled a loss of 1.68 mgd (3%). The analysis showed a slight increase in Suwannee River WMD (0.29 or 0.5%), which was a region identified for potential increase in study one (Chapter 2). Tukey *post-hoc* tests indicated statistical differences between South Florida WMD was significantly greater than St. Johns River, Southwest Florida, Northwest Florida, and Suwannee River, WMDs recycled water production.

Increase may be attributed to population and urban growth to meet water supply demand (USEPA 2012). For example, in 2010 the City of Pompano in South Florida WMD began an “I Can Water” campaign to connect single family homes to recycled water lines which would be used for public access area irrigation of lawns (USEPA 2012). This campaign did not target commercial and multi-family dwellings because they were already mandated for connection to recycled water lines (USEPA 2012). In 2008, the FDEP, WMD officers, utilities, and local governments met to discuss regulatory authorization to discuss jurisdictional regulation of

recycled water for consumptive use to optimize the use of recycled water (FDEP, 2009). In 2014, Senate Bill 536 passed which covered “expansion of beneficial use of reclaimed water, stormwater, and excess surface water” (FDEP 2015). These meetings continued throughout 2016 and have impacted regulation and increased recycled water use (FDEP 2016).

KDE results indicated growth in recycled water production was experienced in major cities (Figure 3.12). Miami was a low production area in 2009 given its population but an increase of flow (mgd) was noticed in 2015 (Figure 3.12A). Miami was identified in Chapter 2 as an area for expansion. The increase did fill the gap in Miami, but as populations continue to grow and saltwater intrudes more recycled water will be necessary in the future. Normalizing by acres (Figure 3.12B) indicated an increase in Tampa, Orlando, Fort Myers, and Jacksonville. Normalizing by average population (Figure 3.12C) showed a large increase in Orlando and minor increases in Tampa and Fort Myers. Normalizing by population is most representative of persons served by recycled water. The majority of change occurred in central Florida (Orlando and Tampa).

Florida has become the pioneer state for recycled water production and distribution. There has been an increase of recycled water production since Florida began this innovative water mitigation strategy as a means of freshwater conservation. Florida’s success in recycled water production could be used as a model to integrate recycled water mitigation strategies within any municipality, county, or state. Florida has an abundance of precipitation and surface waters, therefore the principal driver for recycled water production increases was water quality (Kuwayama and Kamen 2016). Many states experience water quality issues due to pollutants in surface water and groundwater and release of recycled water to streams can mitigate surface water pollution. Florida waters in particular are targeted for improvement through Basin

Management Action Plans (BMAPs) (FDEP 2015). Wastewater effluent has been identified by the BMAPs as a significant source of increased nutrient load in already impaired waters (FDEP 2015). This could be eliminated with advanced treatment of wastewater so that it meets standards of recycled water to assist in management of waterbody nutrient budgets (FDEP 2015). In 1998, Florida adopted the Numeric Nutrient Criteria (NNC) which calculates nutrient load as a water quality standard across the state (USEPA 2012). Coastal areas that experience saltwater intrusion, water-stressed regions, low water quality conditions, and low precipitation locations should consider recycled water as a valuable component of future water conservation plans.

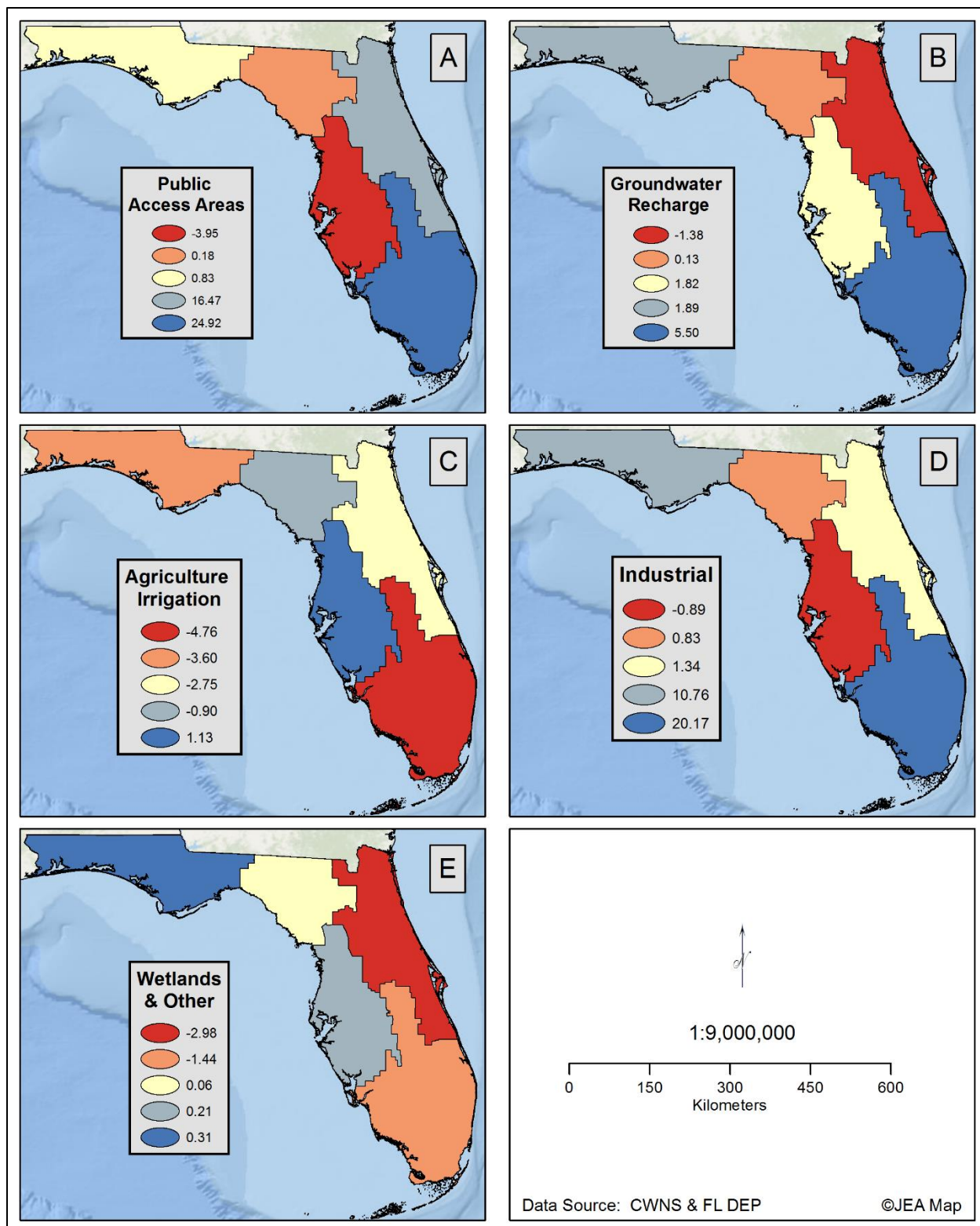


Figure 3.11: 2015-2009 intervals based on classification type for A) Public access areas, B) groundwater recharge, C) agricultural irrigation, D) industrial uses, E) wetlands recharge and other.

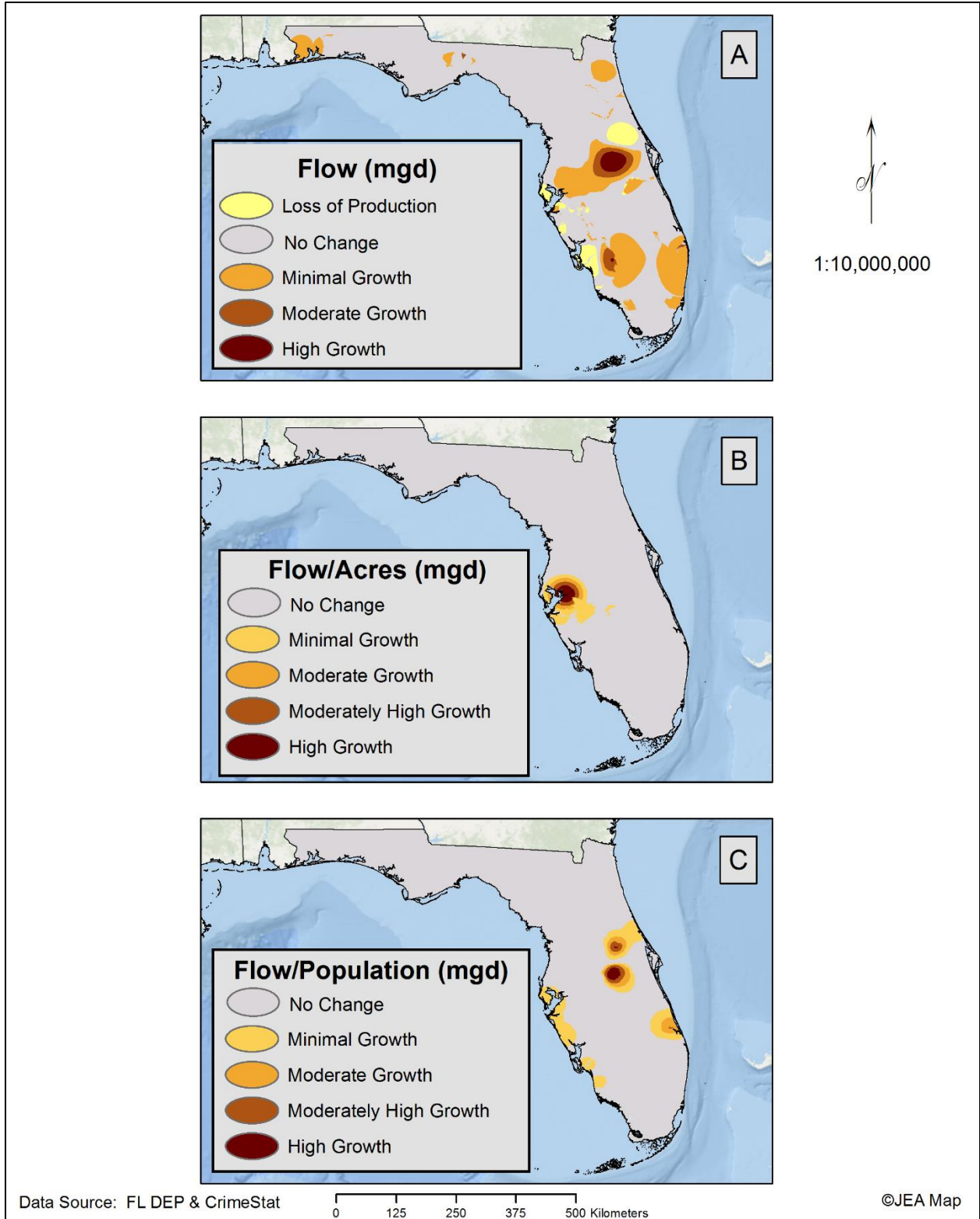


Figure 3.12: 2015-2009 Florida kernel density estimation for A) flow (mgd), B) flow/acre served (mgd), and C) flow/average population served (mgd).

Limitations and Future Research

The one major limitation to this study was the inconsistency in population data provided by CWNS which is why average population was used for KDE analysis. Future work would continue analyzing the increase in Florida's recycled water production as annual FDEP data are released. Future studies can indicate where growth has occurred and where it may need to be implemented further and how regulations have been implemented. Also, recycled water has become freshwater supply where there is demand due to climate change issues.

Conclusion

Spatial examination of Florida's recycled water production based on the five Water Management Districts from 2009 to 2015 indicated there was an increase in production for Suwanee River WMD and Miami in South Florida WMD and a decrease of production in Southwest Florida WMD. Water reuse is not balanced between each WMD even after accounting for the uneven spatial distribution of service areas and populations. KDE indicated most growth occurred in Orlando which indicates potential for growth throughout the state, especially in major cities.

Recycled water production has been on the rise in Florida for decades, and will continue to rise in the future. Florida could be used as a model location to integrate recycled water into municipal water systems. Recycled water use is a valuable resource for water conservation plans, especially in water-stressed states and coastal communities which have saltwater intrusion problems. NRC research has indicated recycled water use could decrease the amount of freshwater used up to 6% and as high as 27%. All the while, ecosystem health is maintained by reduction of withdrawal in aquifers, preventing saltwater intrusion, and decreasing nutrient load in surface waters.

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CHAPTER 4

CONCLUSIONS

The materials presented in this thesis integrated advanced geospatial, statistical, and temporal analysis for recycled water production in Florida (2009 and 2015) and California (2009). This conclusion summarizes the findings from both studies, answers the research questions, discusses the limitations, and suggests future work with recycled water production data.

Overview of Research Questions

The introductory chapter identified the following research question for both studies:

Study I

How many POTWs are producing recycled water products? Where are the gaps throughout each state? Are these areas potential locations to increase recycled water production?

Study II

How many POTWs produced recycled water products in 2009 and 2015? Where are the gaps for each year? Are these areas potential locations to increase recycled water production? What is the temporal change from 2009 and 2015?

Summary of Study I Methods and Findings

In 2009, Florida had 426 of 484 (88%) POTWs that produced 674.26 mgd (FDEP 2010), whereas California had 228 of 1155 (20%) POTWs that produced 578.48 mgd (Newton et al. 2011). These data indicated that Florida utilized more of their POTWs for recycled water production which showed a huge gap in production for California POTWs although there was a high volume of production for those POTWs that produced recycled water. Recycled water production in both states were shown to be within major cities in Florida: Jacksonville, Orlando,

Tampa, Fort Myers, and Miami and in California: San Francisco, Los Angeles, Fresno, Bakersfield, Santa Ana, and San Diego.

Descriptive statistics indicated minimal distribution in Suwanee River WMD in Florida, but this was one of the most rural regions, it received adequate amounts of rainfall, and it includes a natural preserve; therefore, this area was determined to not be a priority for an increase of recycled water production. Florida's KDE results indicated minimal production, especially when normalized by population, in Miami. Miami received more than adequate rainfall, and so as a coastal city susceptible to saltwater intrusion, recycled water production can assist in combating this issue (USEPA 2012). Overall suggestions for increased production in Florida were the panhandle and southern regions of Florida, specifically Miami.

California descriptive statistics showed minimal distributions to Lahontan RWB, but this region is rural, primarily desert, and includes federal lands; therefore, there is less demand for recycled water and this district was not a priority. Central Coast RWB was the most notable region which could increase recycled water production since the area received only moderate precipitation, was mixed conifer forest, had agricultural production (e.g., vineyards), and was vulnerable to saltwater intrusion. California's KDE results indicated areas for potential increase in production are the North Coast RWB, which produced the highest geothermal energy with recycled water and could expand use of recycled water to combat saltwater intrusion, Central Coast RWB which are susceptible to saltwater intrusion, Colorado River RWB could increase the use of recycled water for golf course irrigation, and Lahontan RWB could increase production for landscape irrigation. The overall suggestions for increase for recycled water production in California are the northern and southeastern regions.

Summary of Study II Methods and Findings

In 2009, Florida had 426 of 484 (88%) POTWs that produced 674.26 mgd (FDEP 2010), whereas in 2015 Florida had 418 of 478 (87%) POTWs that produced 738.15 mgd (FDEP 2016). Recycled water production increased 63.89 mgd in 2015 even though there were fewer POTWs (8) than there were in 2009.

As noted in study I, there was a major gap in distribution in the panhandle and southern regions of Florida with specific potential for an increase in Miami. Descriptive statistics for 2015 indicated Miami had increased tremendously (44.38 mgd of 63.89 mgd; 69% of 2015's increase). This increase was most notable in public access area irrigation (24.93 mgd), industrial reuse (20.17 mgd), and groundwater recharge (5.50 mgd). A slight increase was noticed in Suwannee River WMD (0.29 mgd of 63.89 mgd; 5%). A decrease in production was identified in Southwest Florida WMD in 2015 which was attributed to a loss in public access areas (3.95 mgd), industrial reuse (0.89 mgd); therefore, this WMD has become an area of potential increase for recycled water production. KDE results showed the majority of growth in central Florida, specifically Orlando.

Final Thoughts

Florida and California are leaders in recycled water production, yet Florida has regulated more wastewater treatment plants to produce recycled water products which in turn produced more total volume. Florida is a good model for any state to follow recycled water production. California has been a great resource to study, but data are limited and dated. Access to more recent data would assist in reviewing temporal changes associated with recycled water production. Recycled water use is a valuable practice for implementation of water conservation plans. This research may have methodological implications upon the future of recycled water

production as a means for integration into all states across the US. Future recycled water use in the US may depend upon whether water-stressed states follow Florida and California in the use of wastewater as a water conservation and water quality improvement measure, which can reduce the use of drinking water for such purposes as irrigation, industrial reuse, groundwater recharge, saltwater intrusion barriers, and geothermal energy production.

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