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Identifying untapped potential: a geospatial analysis of Florida and California's 2009 recycled water production

Jana E. Archer, Ingrid Luffman, T. Andrew Joyner and A. Nandi

ABSTRACT

Increased water demand attributed to population expansion and reduced freshwater availability caused by saltwater intrusion and drought, may lead to water shortages. These may be addressed, in part, by use of recycled water. Spatial patterns of recycled water use in Florida and California during 2009 were analyzed to detect gaps in distribution and identify potential areas for expansion. Databases of recycled water products and distribution centers for both states were developed by combining the 2008 Clean Water Needs Survey database with Florida's 2009 Reuse Inventory and California's 2009 Recycling Survey, respectively. Florida had over twice the number of distribution centers ($n = 426$) than California ($n = 228$) and produced a larger volume of recycled water (674.85 vs. 597.48 mgd (3.78 mL/d = 1 mgd), respectively). 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, southwestern, and coastal 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.

Key words | California water supply, Florida water supply, kernel density estimation, recycled water products, water resources, water reuse

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INTRODUCTION

Freshwater scarcity has incentivized mitigation measures that restrict water use, generating novel ideas and innovative technologies to improve water management. One innovation to increase public water supplies is expansion of water reuse, which may assist in water mitigation strategies, specifically water conservation measures (National Research Council (NRC) 2012). Approximately 45 billion liters (12 billion gallons) of effluent is discharged from wastewater treatment plants into streams and oceans daily. This effluent, if reused as recycled water products, could supply up to 6% of the estimated total United States (US) freshwater use and up to 27% of municipal supply for residential, commercial, and industrial uses (NRC 2012). Case studies performed by Gude (2017) and Tran *et al.* (2017) suggest best management practices could include demand mitigation and supply enhancement. Demand mitigation refers to implementation of water conservation practices which may involve utility rate increases, pay-by-volume recycled water fill-up stations, low flush toilets, low flow shower heads, and other user-responsible behavior. Supply enhancement can be achieved by the creation of recycled water production for use within communities (Gude 2017; Tran *et al.* 2017). Demand management can become a significant factor for lowering potable water use per capita while increasing

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supply via recycled water supply enhancement techniques (Tran *et al.* 2017).

In 1943, 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). In June 2014, California amended the California Code of Regulations to include Title 22, Water Recycling Criteria. Title 22 would increase development of recycled water, provide statewide consistency for permits, minimize direct effluent discharge, and report recycled water production annually (California Department of Public Health (CDEP) 2014). In November 2014, Proposition 1 (Water Quality, Supply, and Infrastructure Improvement Act of 2014) replaced Proposition 43 (Water Bond). Proposition 1 developed a general fund budget of $7.12 billion, of which $725 million was allocated to water recycling and advanced water treatment projects. These projects would support and expand water management planning, instill more stringent guidelines for recycled water and the use on food crops, enhance reliable water supplies, prepare for droughts, create sustainable groundwater management, improve water quality, restore ecosystem diversity, better manage disruptions to the overall water system, and ensure proper management of water quality and quantity in terms of population growth and climate change (CalEPA (California Environmental Protection Agency), CDFA (California Department of Food and Agriculture), CNRA (California Natural Resources Agency) 2016). A case study from the Water Reuse Foundation found that better program management of recycled water systems was needed, which is addressed by Title 22 and Proposition 1 (Cushing *et al.* 2014).

Currently, the Florida Department of Environmental Protection 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' (Florida Department of Environmental Protection (FDEP) 2010). Like California, Florida has developed policies for water reuse. In 2008, the Ocean Outfall Legislation was passed to reduce wastewater ocean outfalls and provide funding to support water reuse projects that assist in eliminating ocean outfalls. A direct result of this legislation was an increase in water reuse projects in South Florida (WaterReuse Foundation 2018). Chapter 62-610 of the Florida Administrative Code, Statutory Directive 403.0653 describes policies for reclaimed water use at state facilities, directing these facilities to take a leadership role in substituting reclaimed water for other water sources to both conserve water and educate the public. Approved uses include landscape irrigation, toilet flushing, ponds/fountains, and water for thermoelectric cooling (Florida Statues § 403.0645 2017). In addition to policy development, Florida Water Management Districts have produced water reuse fact sheets targeted to the community to improve public perception of recycled water use.

Use of recycled water products can reduce demand on current freshwater supply and increase conservation of freshwater as storage (e.g. groundwater recharge) (Toor & Rainey 2009). In the United States, recycled water is not typically used for drinking water supply. Instead, 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.

Globally, at least 60 countries reuse wastewater as recycled water. China, Mexico, and the USA have the highest annual total volume (Angelakis & Gikas 2014). US recycled water production in 2006 was led by Florida (663 mgd), 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) (Bryck *et al.* 2008). The present study examines the spatial pattern of recycled water use in Florida and California during 2009, the most recent year for which data were available for both states. Florida and California were selected because they are the top US ranked producers of recycled water, ranking first and second, respectively (FDEP 2016).

Until recently, scholarly research on recycled water use has focused on acceptance by the public and sound practices for adoption. For example, several studies have examined public acceptance of recycled water use (Po *et al.* 2003; Dolnicar & Saunders 2006; Dolnicar & Schäfer 2009; Rozin *et al.* 2015; Crampton & Ragusa 2016), 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 (Dolnicar & Schäfer 2009; Qian & Leong 2016; Fu & Liu 2017). Beyond education in recycled water treatment, public understanding of conventional water treatment

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systems is lacking. Of $n = 457$ students asked to diagram the path water takes from the source to the tap and back to the natural environment, nearly one-third omitted the water treatment plant and nearly two-thirds omitted the water treatment plant (Attari *et al.* 2017).

Principles of epidemiology such as the dose-response assessment may be employed to assess the health risk associated with water reuse, as detection of a contaminant may not pose a significant health risk. Acceptance among the public has been found in early studies to be positively correlated with education, knowledge of the recycling process, and pro-environmental attitudes (Hui & Cain 2018). However, whether or not decision-makers support supplementing public water supplies with recycled water depends on several factors including cost, availability of alternative water sources, social and legal factors, in addition to public sentiment (NRC 2012). 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); the phrase 'toilet to tap' creates fear and revulsion that pathogens may remain in the water after processing (Hui & Cain 2018). Qian & 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 & Saunders (2006) indicated that proper branding of recycled water could increase trust and security among the general public. To test how branding may influence acceptance, Hui & Cain (2018) conducted a survey of willingness to use recycled water for ten applications ranging from lawn watering to clothes washing to drinking. They found that presenting recycled water use in a positive framework increased willingness to use. Interestingly, political affiliation was an important factor; Democrats were more willing than Republicans to use recycled water. In contrast to prior research, education was not a factor in how willing Californians were to use recycled water. A recent review of public responses to water reuse concluded that education on its own is not sufficient to change attitudes. Rather, multidisciplinary efforts to address the 'yuck factor' from scientific, technological, and behavioral psychology perspectives, including risk perception, are needed (Smith *et al.* 2018).

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 & Leong 2016). Similar efforts have been proposed 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 US regions (Qian & Leong 2016), however the Groundwater Replenishment System, a potable water reuse project in Orange County, California that injects recycled water directly into aquifers that supply local drinking water, has had wide public acceptance. From initial production of 70 mgd in 2007, expansion to 100 mgd in 2015, and future expansion to 130 mgd, the project invested heavily in public education and outreach. Newspaper coverage of the project from 2000 to 2016 was neutral or positive, with no negative articles (Ormerod & Silvia 2017).

Spatial analysis of recycled water products is not well represented in the literature. In Los Angeles, California, spatial modeling was used to optimize distribution of recycled water for groundwater recharge (Bradshaw & Luthy 2017). The only known spatial analytical study of recycled water is an econometric analysis of Florida's water reuse capacity from 1996 to 2012 (Kuwayama & Kamen 2016). In this study, water quality and scarcity were investigated at the county level. While water supply was found to be a driving factor for Florida's dedication to recycled water production, so too was water quality. Specifically, the authors noted that water quality in impaired streams may be improved by the addition of treated recycled water (due to dilution), especially during times of reduced precipitation. The authors also noted that regions with a large urban population have increased industrial activity with a corresponding increase in industrial recycled water production. Kuwayama & Kamen (2016) recommended that an evaluation of recycled water production be completed at the facility level for further insight. The present research study fills this gap, by outlining a methodology to model the spatial pattern of recycled water production at the facility level to find gaps in distribution and identify potential areas for expansion of recycled water production as a way to increase public water supply. A case study of

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recycled water production in Florida and California is presented.

Since the 1940s, US water consumption has doubled due to population growth resulting in added stress to water management systems (Montagna *et al.* 2002). Florida's population of 18.8 million in 2010 and the current estimated population of 20.6 million people (USCB 2016a) represents a ~9% population increase over six years. Nearly 88% of Florida's population is served by public water supply (Dieter *et al.* 2018). Florida relies heavily on groundwater stored in the Floridian Aquifer and other aquifers, and its current water supplies are at risk for depletion by 2025 due to groundwater withdrawal to furnish municipal water supply (Koch-Rose *et al.* 2011). The use of recycled water is one water management practice employed to meet this demand, and was first introduced in Florida at the Tallahassee Reclaimed Water Farm in the 1960s as a means to irrigate agriculture (Toor & Rainey 2009). In 2010, Florida ranked fourth in the USA for total freshwater withdrawal according to a 2010 United States Geological Survey (USGS) report on water use in the USA (Maupin *et al.* 2014). By 2015, Florida withdrew 15,300 mgd to meet demand (11,500 mgd from surface water and 3,770 mgd from groundwater) (Dieter *et al.* 2018), still ranking fourth for water withdrawal, but ranking first in the USA for recycled water distribution (FDEP 2016).

Florida's prominence in recycled water use may be counterintuitive as the state receives ample precipitation ranging from 1,278 mm in the southwest to 1,475 mm on the east coast annually (Cannon 2012; NOAA 2016). High recycled water production in Florida is likely related to the resource's dual role as a means to increase supply and improve surface water quality through discharge of highly treated wastewater to impaired surface streams (Kuwayama & Kamen 2016). Distribution of recycled municipal wastewater in Florida is monitored by five Water Management Districts (WMDs) (Figure 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). In 2009, Florida maintained 426 domestic wastewater treatment facilities that generated recycled water products (Figure 1) (FDEP 2010).

Since the late 1800s, California has used 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. In 2010, California ranked first in the USA for total freshwater withdrawal (Maupin *et al.* 2014). From 2010 to 2016, California's population increased 5% from 37.3 to 39.3 million residents (USCB 2016b). By 2015, California withdrew 28,800 mgd (11,300 mgd from surface water and 17,400 mgd from groundwater), a decrease of 1,150 mgd from 2010 likely related to Governor Jerry Brown's order to reduce urban water use by at minimum 25% from 2013 levels, as a response to the protracted drought. Domestic use decreased 17% (680 mgd) due to statewide water use reductions, irrigation use decreased by 18% (4,070 mgd), and irrigated acreage decreased by 10% from 2010 to 2015. Further, a shift from surface water (down by 64%) to groundwater (up by 64%) for irrigation water occurred during this period (Dieter *et al.* 2018).

Considering all uses, in 2010 over 80% of California's municipal water was withdrawn from surface waters such as lakes, reservoirs, and rivers (Klausmeyer & Fitzgerald 2012), which dropped slightly to 75% in 2015 (Dieter *et al.* 2018). In keeping with water conservation measures put in place to address the 2015 drought, the state was ranked second in the USA during 2015 for recycled water distribution (FDEP 2016). The use of recycled water for groundwater recharge, as a barrier to saltwater intrusion, agricultural irrigation, industrial reuse, and recreational impoundments, can relieve some of the burden of demand for fresh/surface water supplies that are at risk of depletion or are limited due to short- or long-term drought.

California receives from one-tenth to one-third the precipitation received by Florida, with a population nearly twice the size. Annual precipitation ranges from a minimum of 60 mm at Death Valley to a maximum of 541 mm in the humid continental areas around Lake Tahoe (Cannon 2012; NOAA 2016). Its climate is more varied, largely due

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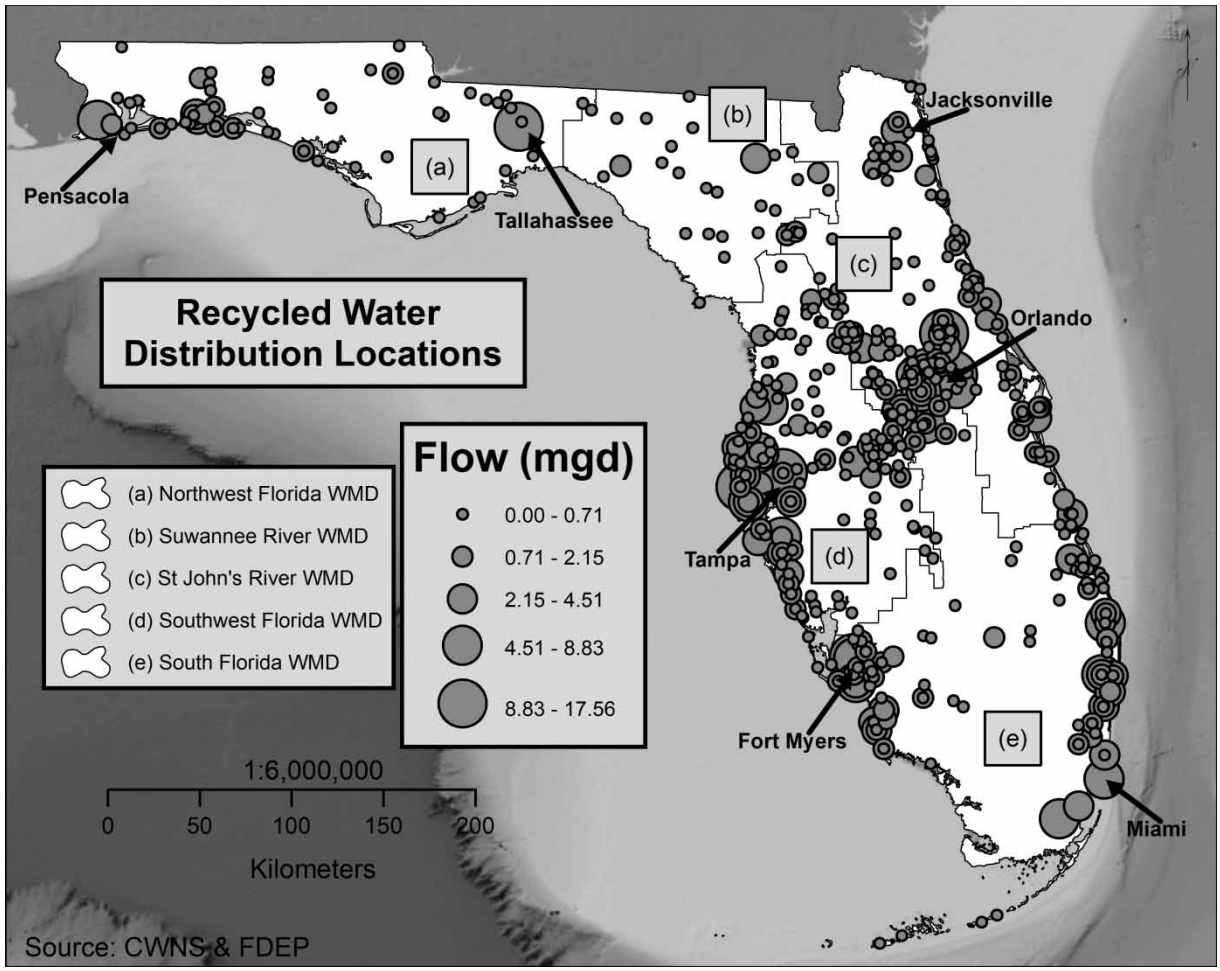

Figure 1 | Florida Water Management Districts and recycled water production (3.78 mL/d = 1 mgd).

to elevation and orographic effects, with Steppe (Köppen BSh/BSk), Desert (Köppen BWh/BWk), Mediterranean (Köppen Csa/Csb), Continental (Köppen Dsb/Dsc), and Polar (Köppen Ef) climates represented state-wide. High spatial variability in climate, and California's reliance on surface water over groundwater, results in immediate and significant impacts of drought on supply. Over the last few decades, California's drought instances have increased due to climate change and global hydrological weather systems (Gude 2017). Consequently, California has invested in recycled water infrastructure as a means to increase drought resilience (Schwabe & Connor 2012).

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 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 (CalEPA) SWB 2013). RWBs produce recycled water products in eleven categories; agricultural irrigation, landscape irrigation, groundwater recharge, industrial use, seawater intrusion barrier, golf course irrigation, natural system restoration and wetlands and wildlife habitat, recreational

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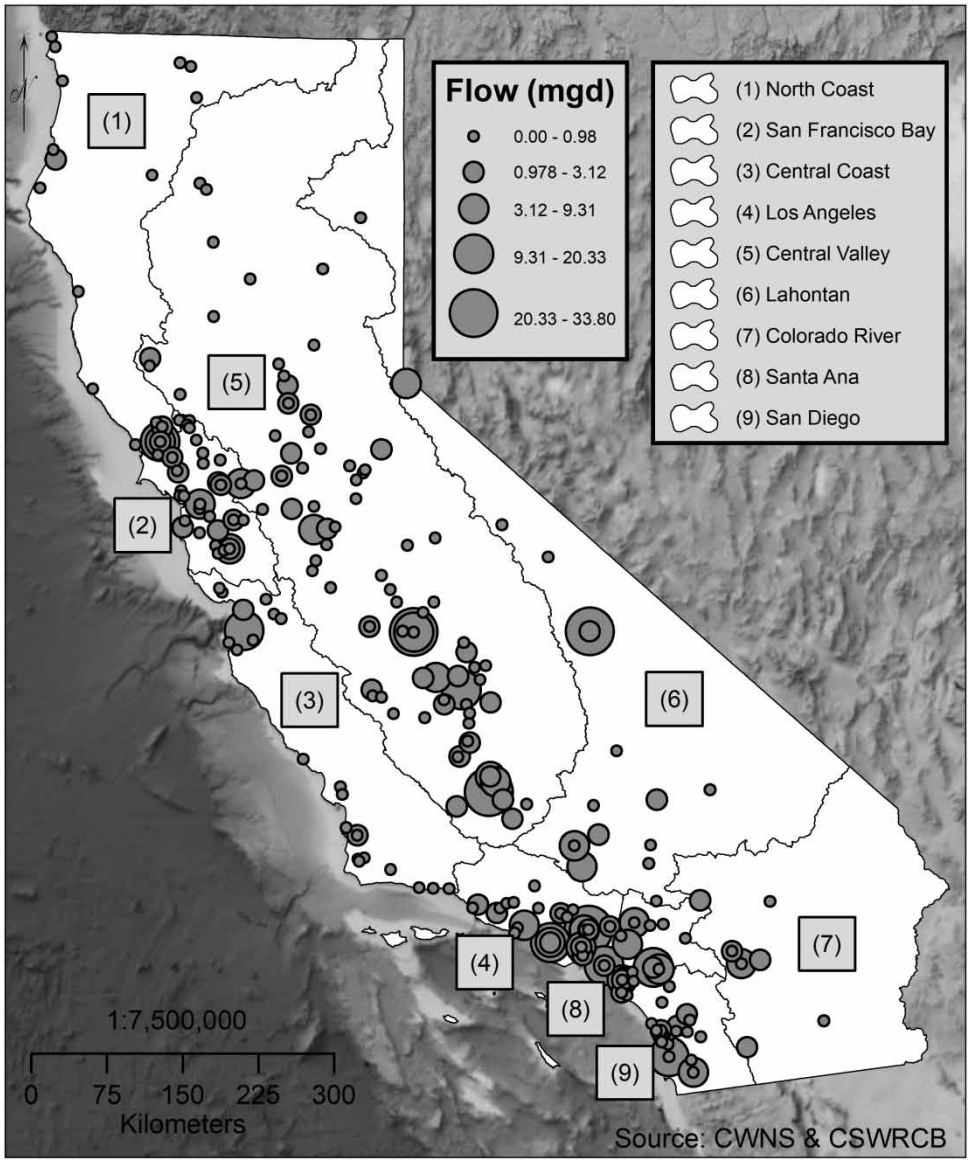

Figure 2 | California Regional Water Boards and recycled water production (3.78 mL/d = 1 mgd).

impoundment, geothermal energy production, commercial use, and other uses. In 2009, California maintained 228 Publicly Owned Treatment Works (POTW) facilities that produced recycled water (Figure 2) (Newton *et al.* 2011).

METHODS

Florida's POTW locations, population total, and National Pollutant Discharge Elimination System (NPDES) permit numbers 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 3). Florida's 2009 Reuse Inventory was obtained from the Florida Department of Environmental Protection (FDEP). It contained information for the distribution of recycled water, which included: name of POTW, WMD location, type of recycled water product, volume of flow in millions of gallons per day (mgd), NPDES permit number,

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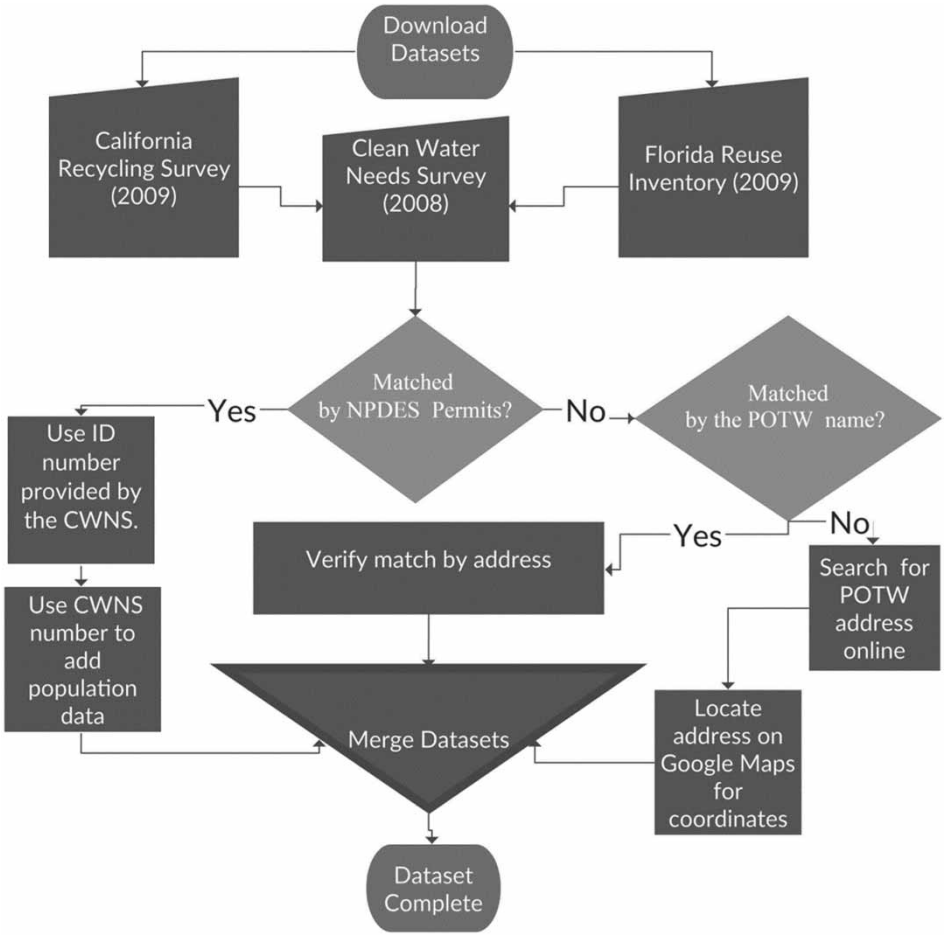

Figure 3 | Flowchart for dataset organization procedures.

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.

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 3). California's 2009 Municipal Wastewater Recycling Survey was downloaded from California Environmental Protection Agency's department of State Water Resources Control Board (California State Water Resources Control Board (CSWRCB) 2012). The survey contained information for the distribution of recycled water, which included: name of POTW, 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.

Descriptive statistics were calculated to summarize the mean and variance for volume of flow at Florida's WMDs and California's RWBs. A one-way analysis of variance (ANOVA) with Tukey *post hoc* tests were used to compare volume of recycled water products produced by Florida's WMDs and California's RWBs. All bivariate data were

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analyzed with Statistical Package for the Social Sciences (SPSS) Version 23 (IBM Corp. 2014).

Kernel density estimation (KDE) was used to identify hotspots of water reuse. The Quartic Kernel was selected because its shape gradually reduces the influence of nearby points and it 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 and flow normalized by population served using 15 points per cluster. KDE is representative of the regional system in that every facility is accounted for in the model and production volume (flow) is used as an intensity variable to weight each facility, so that those with higher flows would contribute more to the KDE surface. All data were analyzed with CrimeStat IV (Levine 2015).

RESULTS

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. Together, Florida's POTWs produced a total flow of 674.26 mgd in 2009, distributed as multiple recycled water products. Mean production ranged from a low of 0.34 mgd in Suwannee River WMD to a high of 1.13 mgd in South Florida WMD (Table 1). With the exception of South Florida, WMDs in Florida have POTWs of similar size. POTWs in the Suwanee River WMD are consistently small, while flows from POTWs in the largest districts (South Florida, St. John's River, and Southwest Florida) vary as much as five orders of magnitude.

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 4(a)). 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 4(b)). 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 4(c)). 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 4(d)). 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 4(e)).

Each district produced recycled water for every category of product. 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 5). 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 recycled water

Table 1 | Descriptive statistics for recycled water production (flow in mgd) for Florida's Water Management Districts (WMD)

WMD	# POTW	Mean	Variance	Minimum	Maximum	Median	Total 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
Suwanee 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

#POTW refers to the number of Publicly Owned Treatment Works.

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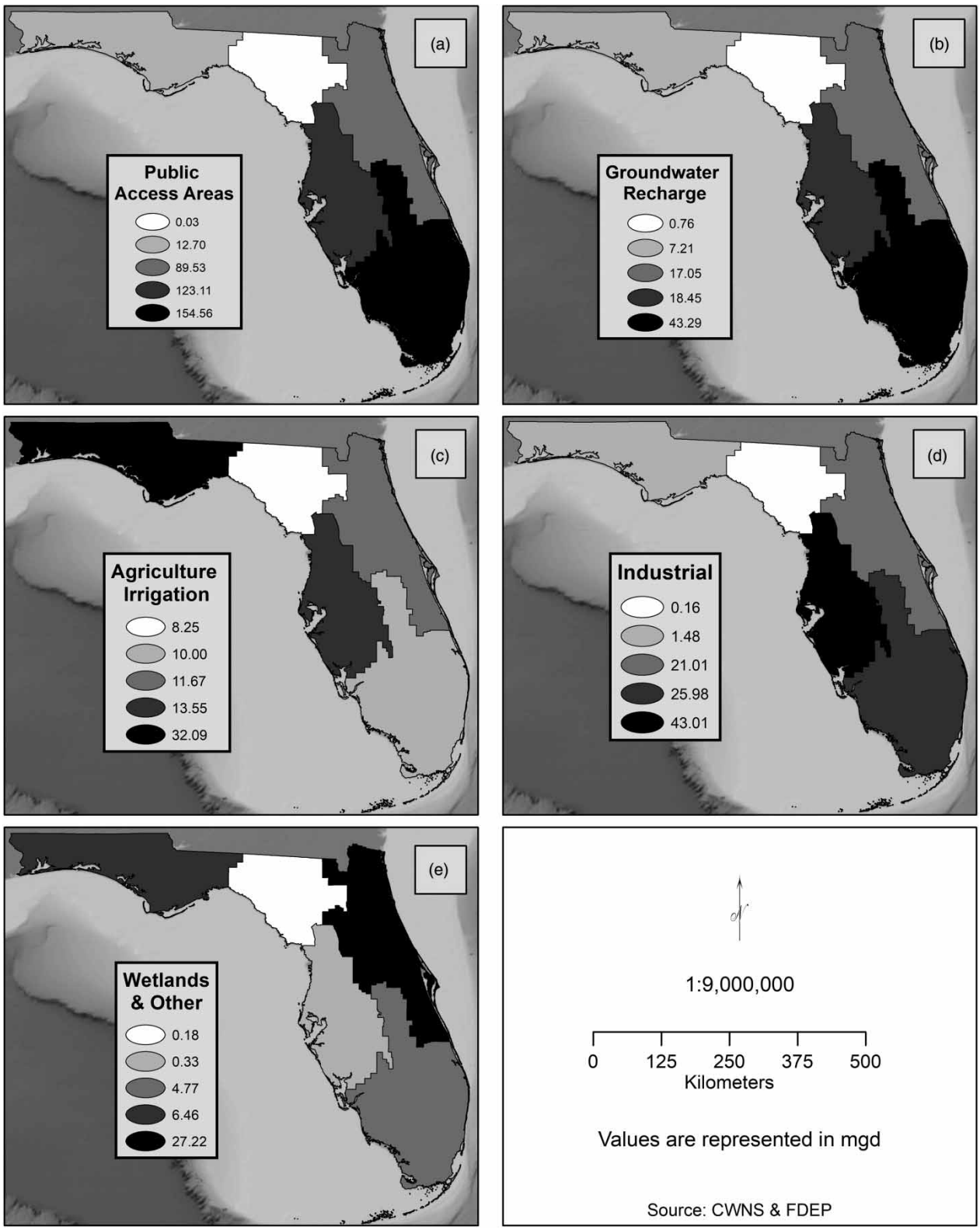

Figure 4 | Recycled water products in Florida (2009): (a) public access areas, (b) groundwater recharge, (c) agricultural irrigation, (d) industrial uses, (e) wetlands recharge and other (3.78 mL/d = 1 mgd).

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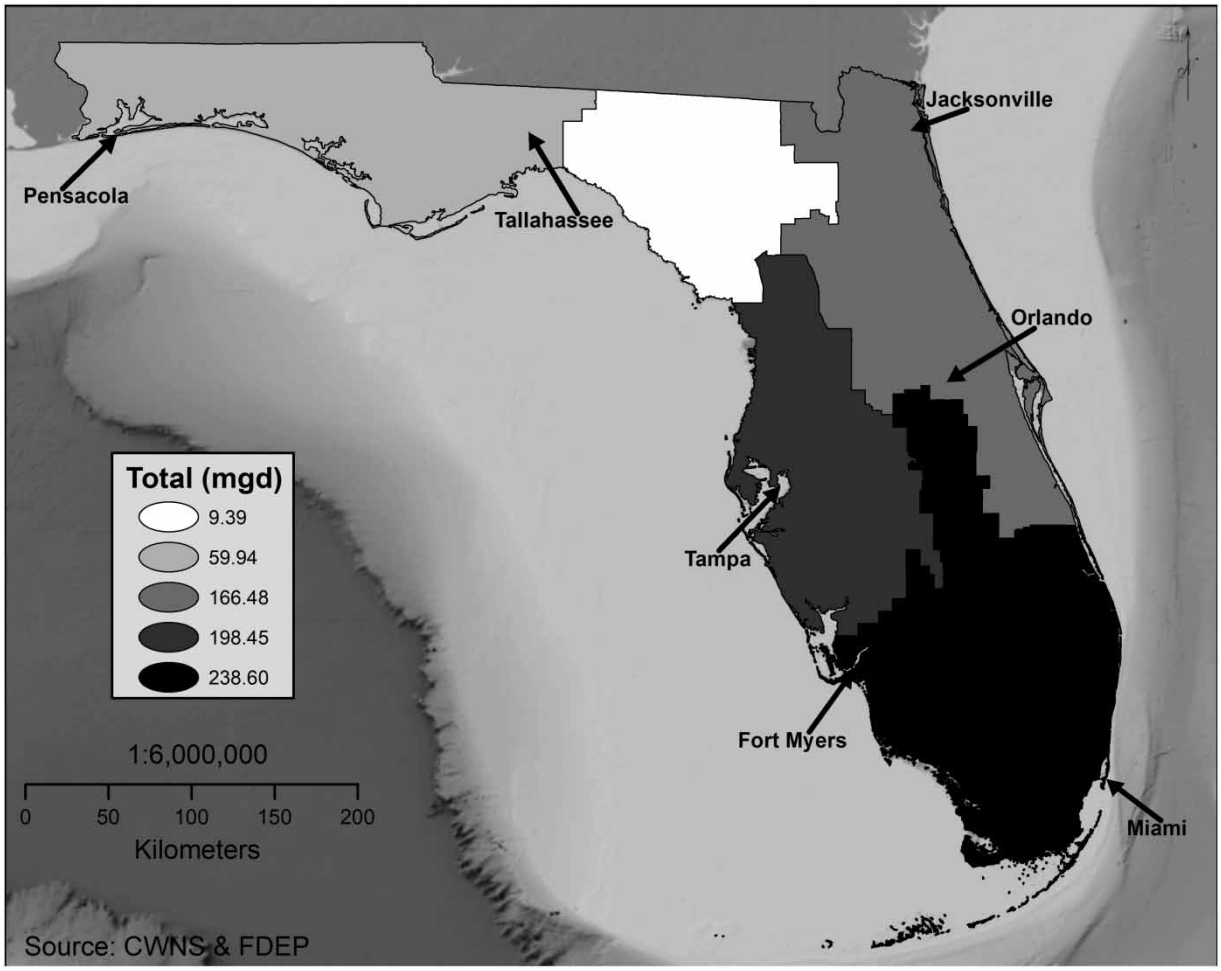

Figure 5 | Florida total flow (mgd) per district (3.78 mL/d = 1 mgd).

production in South Florida (higher) and St. John's River (lower) WMDs.

Hot spots for flow (mgd) were located around major cities in Florida (Figure 6(a)). Dark areas have the greatest production, whereas light areas have lower production. Normalization was performed to remove the effect of population size. When flow data were normalized by population served, high per capita production was identified in Suwannee River WMD, followed by Orlando, Tampa, and Fort Myers (Figure 6(b)), likely due to the lower population in the Suwannee River WMD. Population density (Figure 7) correlates well with many areas of high recycled water production, with the exception of higher per capita production in north central Florida (Suwanee River WMD) due to agricultural (irrigation) use, and low per capita production along the southeastern coast (South Florida WMD), especially along the Miami to West Palm Beach corridor.

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. In 2009, California's recycled water production was 597.48 mgd, distributed as multiple recycled water products. Mean production ranged from a low of 0.64 mgd in Central Coast RWB to a high of 4.31 mgd in Santa Ana RWB (Table 2). WMDs in California were variable in the production capacity of its member POTWs. San Francisco Bay and Lahontan contained many low producing facilities, while Central Valley, Santa Ana,

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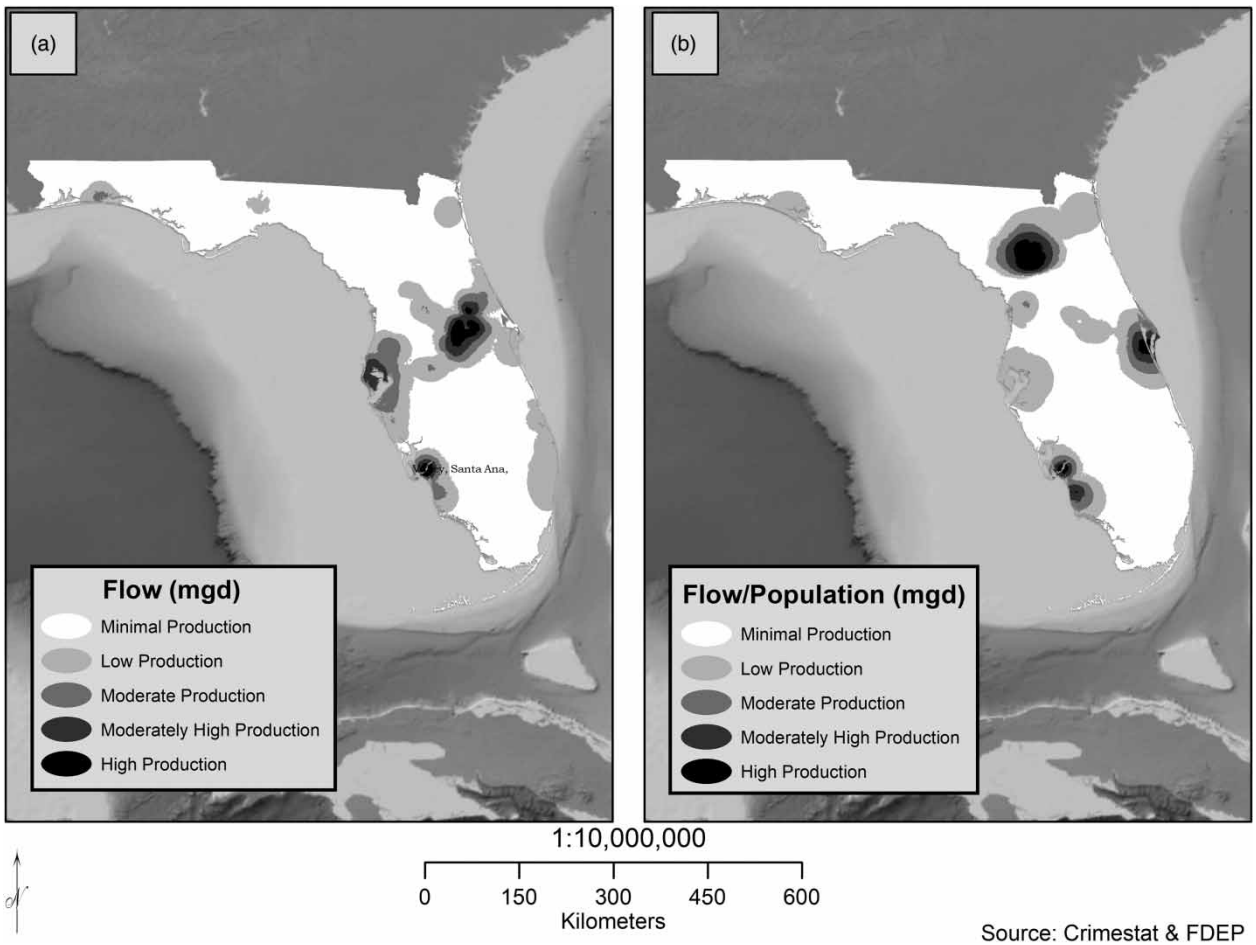

Figure 6 | Florida kernel density estimation of recycled water production for (a) flow (mgd) and (b) flow/population served (mgd) (3.78 mL/d = 1 mgd).

and Los Angeles had larger facilities on average, with a mix of very large and very small facilities. Comparison with production in Florida (Table 1) reveals that California has fewer facilities than Florida, but its facilities tend to be larger.

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 8(a)). 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 8(b)). 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 8(c)). 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 8(d)). 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 8(e)). 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 8(f)). 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

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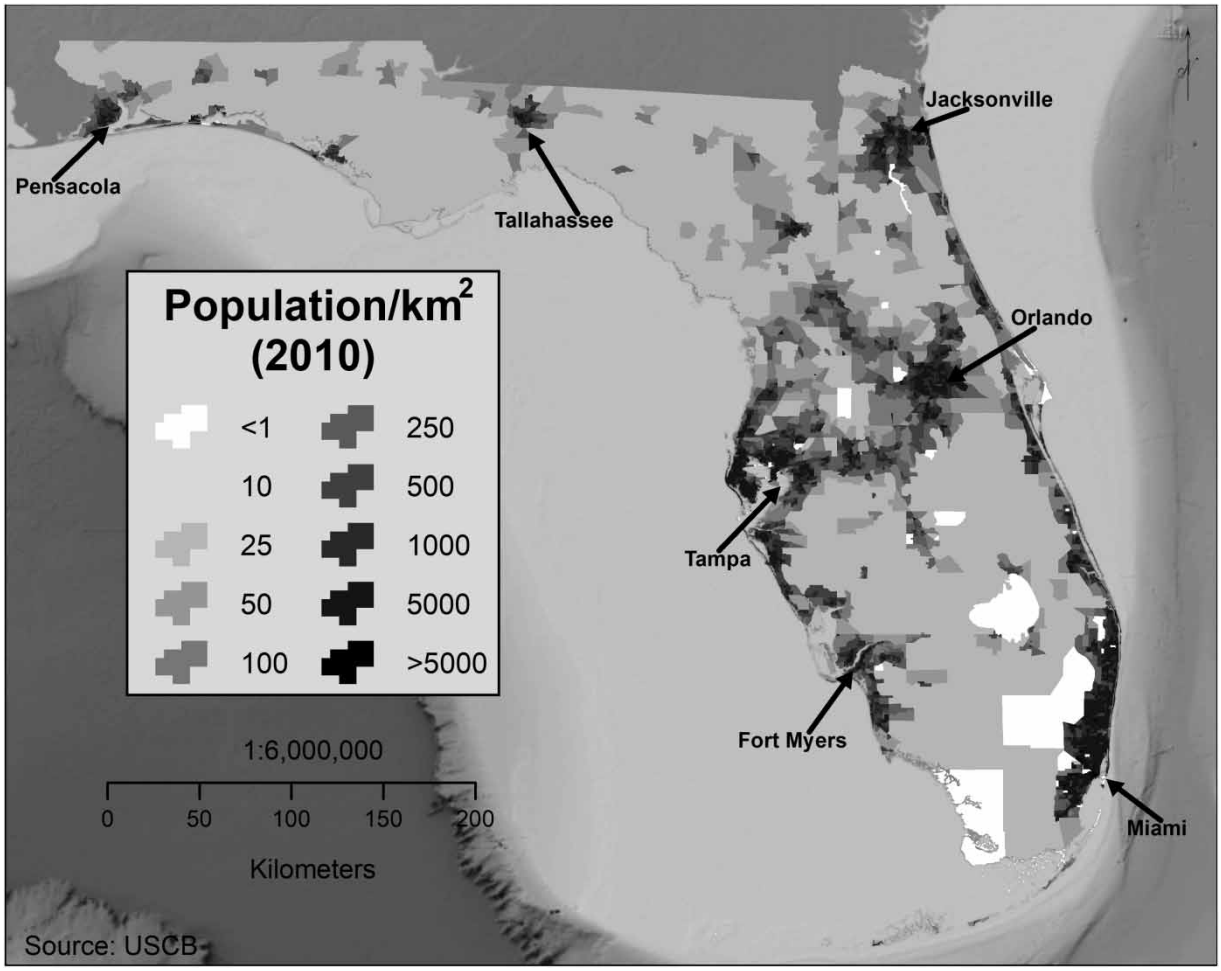

Figure 7 | Florida population density (2010 United States Census).

Table 2 | Descriptive statistics for recycled water production (flow in mgd) for California's Regional Water Boards (RWB)

RWB	# POTW	Mean	Variance	Minimum	Maximum	Median	Total 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

#POTW refers to the number of Publicly Owned Treatment Works (3.78 mL/d = 1 mgd).

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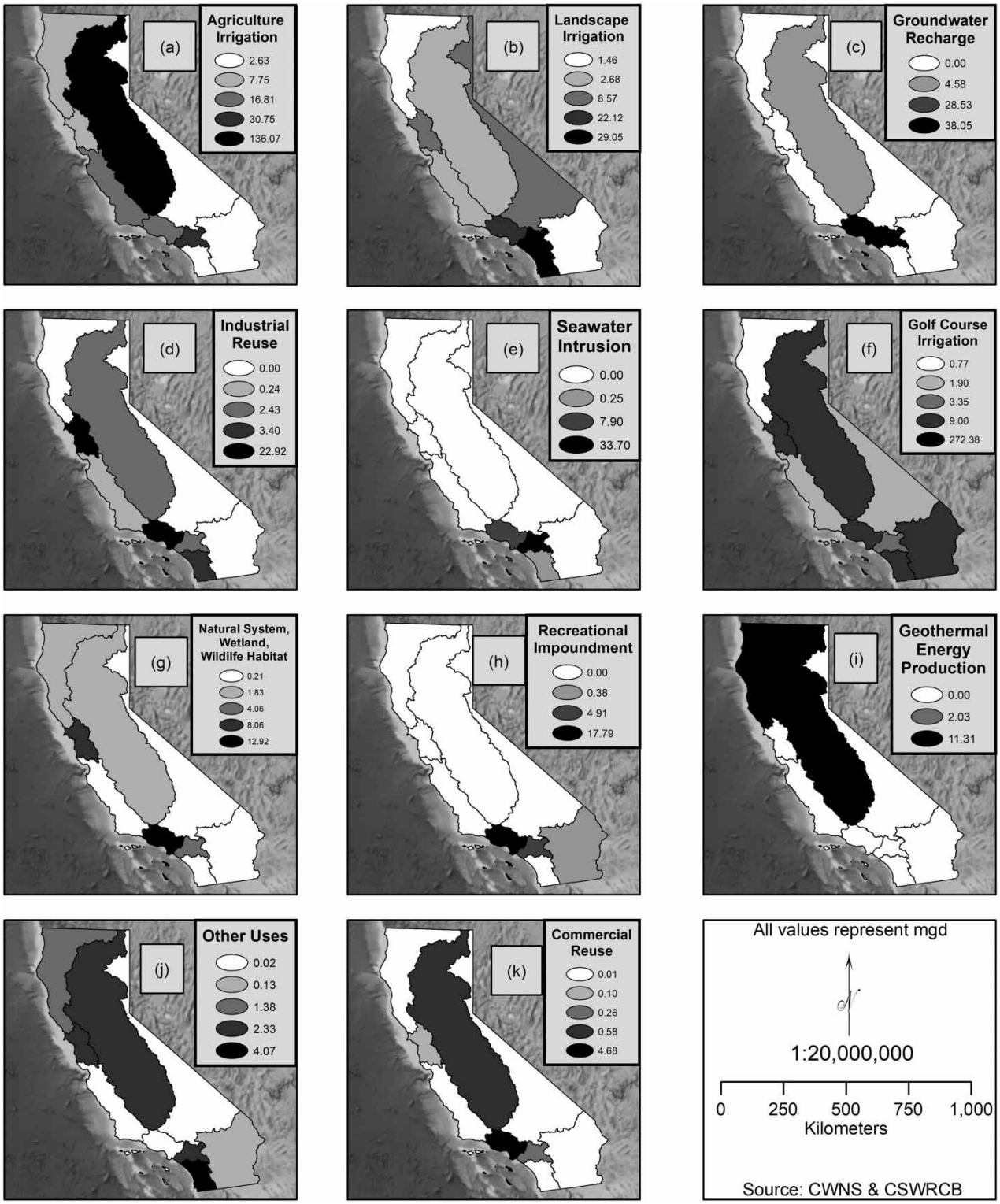

Figure 8 | Recycled water products in California (2009): (a) agricultural irrigation, (b) landscape irrigation, (c) groundwater recharge, (d) industrial reuse, (e) seawater intrusion barrier, (f) golf course irrigation, (g) natural system restoration, wetlands, and wildlife habitat, (h) recreational impoundment, (i) geothermal energy production, (j) other uses, (k) commercial reuse (3.78 mL/d = 1 mgd).

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Angeles RWB at 12.91 mgd (46%) (Figure 8(g)). 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 8(h)). 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 8(i)). 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 8(j)). 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 8(k)).

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 9). ANOVA

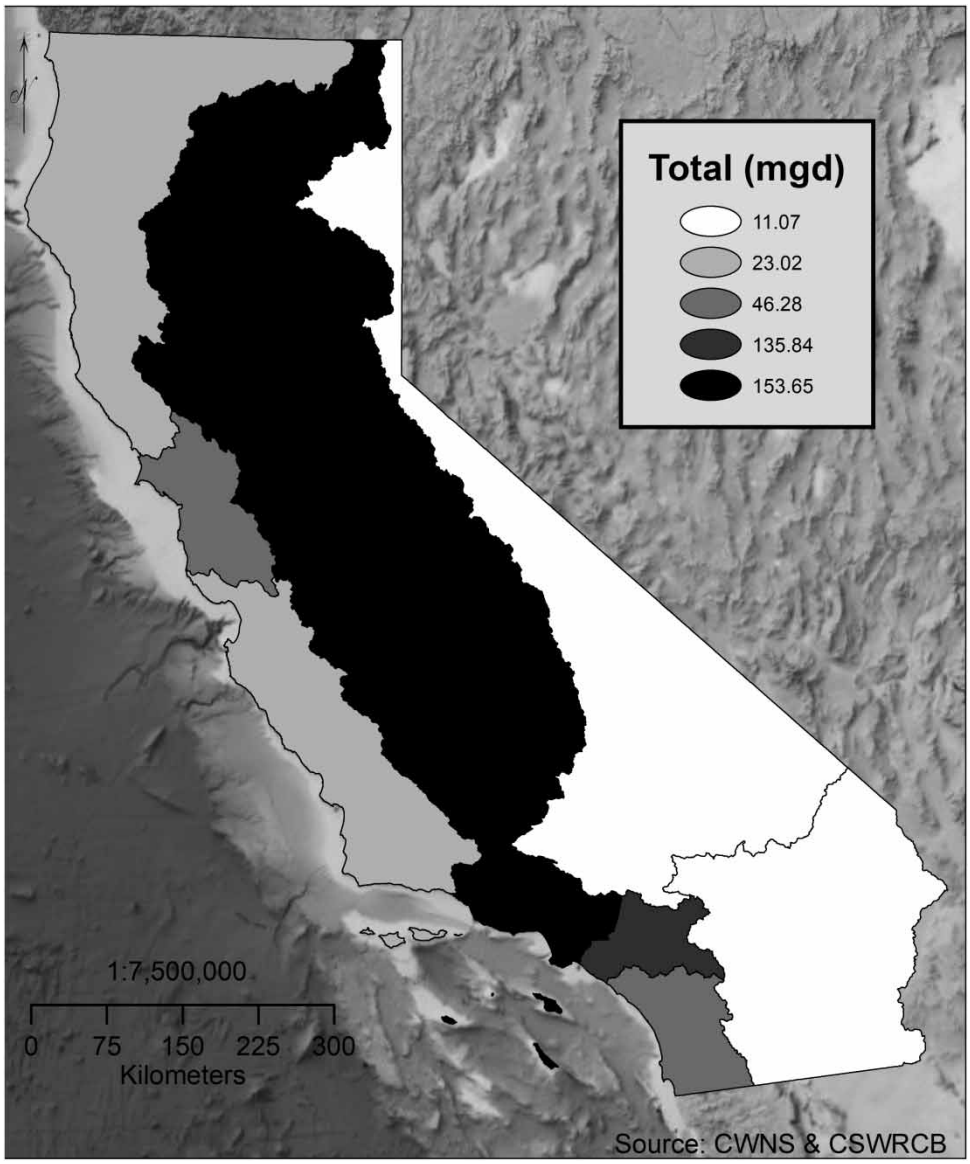

Figure 9 | California total flow (mgd) per district (3.78 mL/d = 1 mgd).

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results indicated significant differences in recycled water production between RWBs. Tukey *post-hoc* tests further show significant differences ($p < 0.05$) between recycled water production in Santa Ana RWB (higher) and San Francisco Bay, Central Coast, Central Valley, and Lahontan RWBs (lower). The Central Coast RWB had the lowest per unit production at 0.64 mgd.

Hot spots for flow (mgd) are located throughout the Central Valley region and around major cities in California (Figure 10(a)). Dark areas have the greatest production, whereas light areas have the least production and may be areas for increased production. Flow data were normalized by population served (Figure 10(b)) and showed a similar pattern. The majority of distribution occurs in the intensely agricultural Central Valley (Fresno and Bakersfield) region; the areas for potential expansion are the northern and southeastern regions. Population-normalized flow data highlight very high per capita production of recycled water around Bakersfield, CA, and low per capita production in the Ventura to San Diego corridor along the southwestern coast, one of the most densely populated regions of the state (Figure 11).

DISCUSSION

Analysis of Florida's recycled water production showed minimal distribution 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

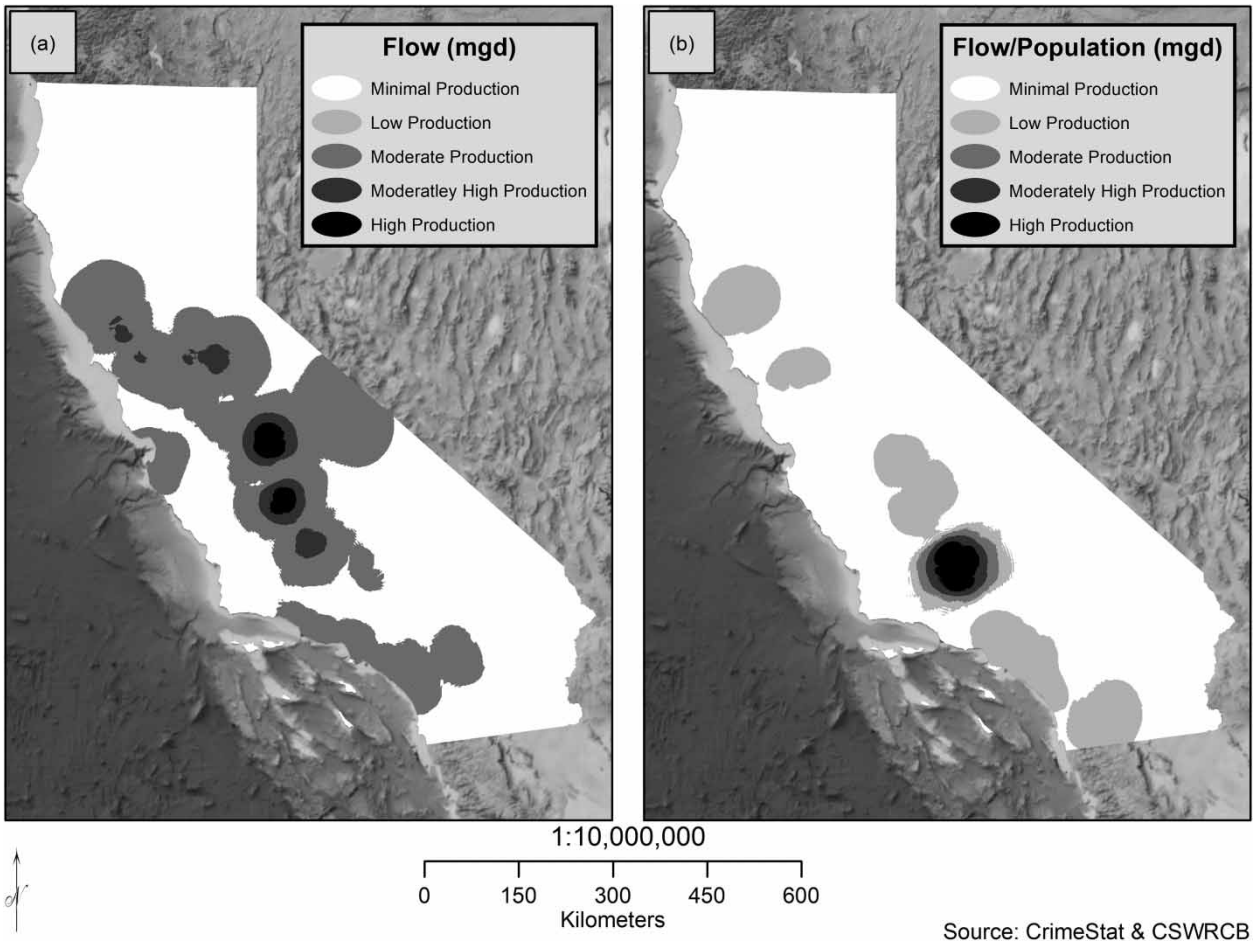

Figure 10 | California kernel density estimation for (a) flow (mgd), (b) flow/population served (mgd) ((3.78 mL/d = 1 mgd).

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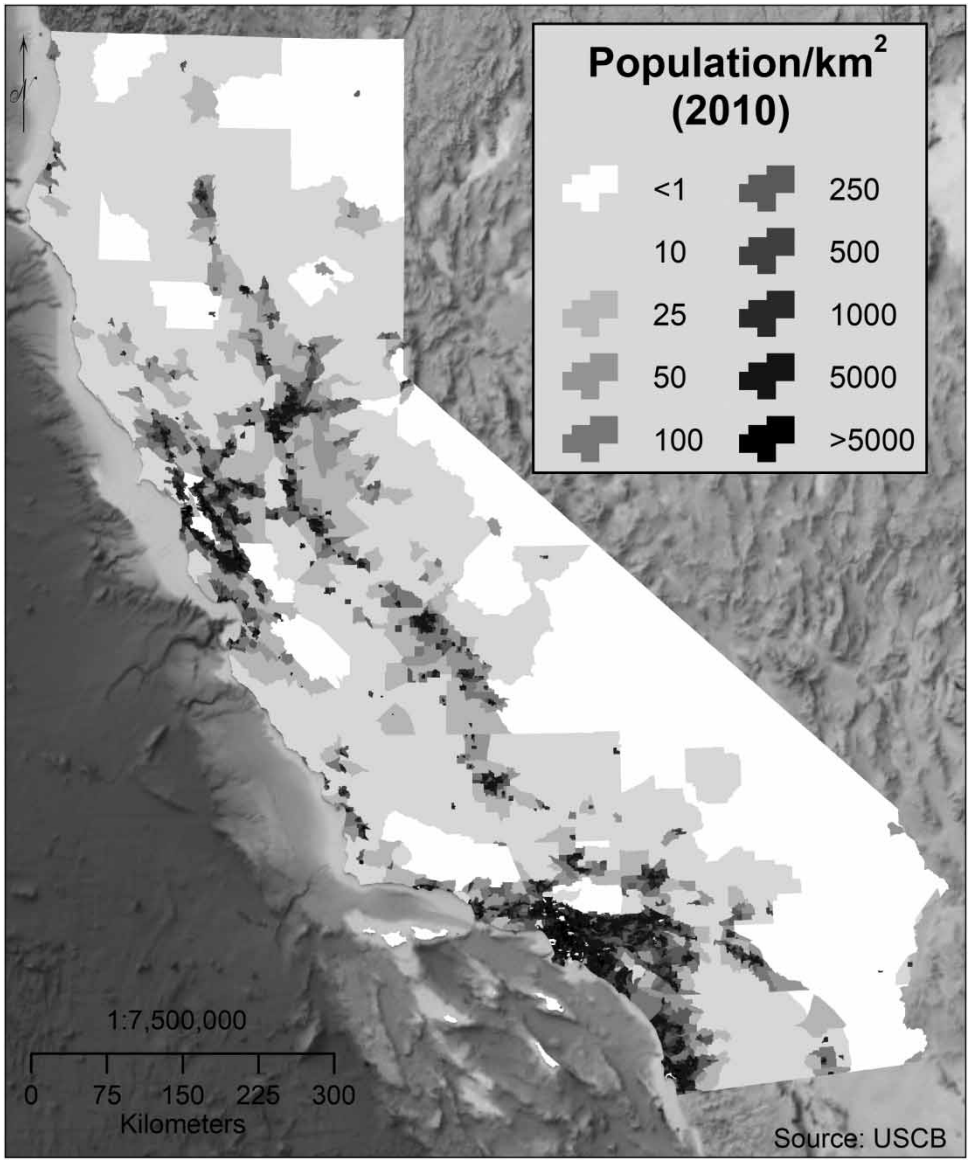

Figure 11 | California population density based on 2010 United States Census.

bulk of Florida's precipitation, demand for water reuse products may be low.

KDE results indicated that hot spots for water reuse typically coincide with major cities, with one notable exception in Miami. Normalizing by population served showed a similar overall pattern indicating that in Florida, 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. Reduced consumptive use of water through increased use of recycled water for applications such as saltwater intrusion barriers, wetland restoration, and groundwater recharge is recommended.

Similar to the positive association between population density and production observed in Florida, the same pattern is generally observed in California. One exception to

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this pattern is in areas of high recycled water use for agricultural irrigation, such as in Suwanee River WMD in Florida (Figure 6(b)) and California's Central Valley RWB (Figure 10(b)). Analysis of recycled water production in California showed minimal distribution to Lahontan RWB. This may be attributed to land use in Lahontan RWB, which is primarily desert, has a low population density, and includes federal lands, such as Death Valley National Park and Mojave National Preserve.

Central Coast RWB 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. An increase in production of recycled water in the Central Coast RWB may provide sufficient reserves to allow for transfers to other adjacent RWBs with higher demand.

Furthermore, Santa Ana RWB's significantly higher production over San Francisco Bay, Central Coast, Central Valley, and Lahontan RWBs, can be attributed to a large mean value (4.31 mgd), resulting from 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, however this peak becomes more subdued when population is taken into account. After accounting for population, the Santa Ana region visually merges into the Ventura to San Diego corridor where we have identified a trend of relatively low per capita production of recycled water.

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 capita in Bakersfield. Hot spots for recycled water use occur predominantly along coastal cities (Napa, San Francisco, Monterey, and to a lesser degree Los Angeles) and the agricultural hub of the Central Valley (Sacramento, Fresno, Bakersfield, and California City). Areas for potential expansion are the North Coast RWB (geothermal energy production and seawater intrusion), Central Coast RWB (seawater intrusion barriers and irrigation), Colorado River RWB (golf course irrigation), and Los Angeles and San Diego RWBs.

Use of recycled water is an appropriate way to mitigate limited water resources during times of drought. California's drought situation improved somewhat through 2016 and 2017, but as of February 2018, approximately 48% of the land area is under moderate to severe drought, with over 24 million residents in drought areas (Tinker *et al.* 2018). Wasteful water practices continue to be prohibited (California Executive Order B40-13), and recycled water production capacity should continue to be developed as a way to promote resiliency to the effects of climate change and increase stability in freshwater supplies.

Comparison of recycled water use in California and Florida reveals differences in products and production facilities. 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 industry compared to other US states, while Florida's economy relies largely on tourism which could explain the aesthetic need for irrigation of public access areas. Recycled water is 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.

Water demand in both states is projected to increase along with population, tempered by new conservation measures supported by policy. The percentage of the population in California served by public water supply has increased from 62% in 1950 to 87% in 2015, suggesting that demand for public water will continue to increase as consumers shift from private to public water sources (Dieter *et al.* 2018). In Florida WMDs, projections of water demand include increases of 5.6% from 2009 through 2010 in Northwest Florida WMD (Marella *et al.* 1998), and increases of 31% from 2010 to 2035 in Suwanee River

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WMD (North Florida Regional Water Supply Partnership 2010). In 2015 only 1% of all irrigation water came from recycled wastewater, used in only ten US states (California, Florida, Arizona, Texas, Utah, Nevada, New Mexico, Colorado, Kansas, and Illinois), with California and Florida making up 43 and 29% respectively, of the total. From 2010 to 2015, US recycled water use for irrigation increased from 472 to 669 mgd, a 42% increase (Dieter *et al.* 2018). These numbers indicate a growing acceptance of recycled water use, at least among uses that do not involve direct consumption.

One limitation of this study was lack of access to recycled water data more current than 2009 for California. Once more recent recycled water data for California are released, we recommend reanalysis of California's recycled water production, with a view to assessing increases and decreases over time and space, especially considering the recent prolonged drought. Florida recycled water data are available through 2016 and a future study will analyze temporal changes from 2009 to 2015. To our knowledge, this is the first time that KDE has been applied to examine recycled water production spatially. This is an innovative application of a widely accepted analytical method, with applications to other states or production facilities. Limitations may include physical or infrastructure barriers as the KDE implies a gradual transition, however service areas for each facility have a distinct cut-off. This was modeled in the KDE using a Quartic kernel function, which has a distinct cut-off at a given distance from the facility.

CONCLUSIONS

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. Production capacity depends on a variety of factors, one of which is wastewater generation, the raw material for recycled water. Generally, wastewater increases with population, and therefore we identify high population areas with low per capita recycled water production as prime areas for expansion of water reuse. KDE is a useful method to assess the spatial patterns of recycled water production using a weighted hot spot analysis, and identify potential areas for expansion. This analysis revealed that 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. KDE 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 phosphorus) 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 was considered for public water supply distribution in municipalities across Florida, California, and other coastal or drought-stricken states. The methods presented in this research are applicable in other communities and states, and in addition to their use in identifying target areas for expansion, results may be used to plan a focused public education campaign to promote acceptance of recycled water use.

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