

# Urban Water Revolution: Sustainable Water Futures for California Cities

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**Abstract:** California has consistently altered natural water resources to provide water for its growing population and to support the fifth largest economy in the world. However, the old ways of coping with the California's urban water needs—overdraft of groundwater, stream depletion, and greater imports—will no longer meet the demands of the 21st century. We examine California's water history and present several promising solutions to the challenge of urban water security: a combination of conservation and efficiency, desalination, stormwater capture, water reuse, and water banking. These options for urban water, including direct potable reuse, will help dry cities in California and elsewhere achieve more sustainable and diversified water supply portfolios. Pilot and demonstration-scale projects, along with innovations in systems management and new regulations, point the way toward more resilient water supplies for dry cities. Movement toward regional collaboration, implementation of new technologies, and new regulatory regimes are helping to realize a one-water vision. Different cities will develop their own water supply portfolio options appropriate for their geography, values, and urban form on a path toward meeting the urban water challenges of this century. DOI: [10.1061/\(ASCE\)EE.1943-7870.0001715](https://doi.org/10.1061/(ASCE)EE.1943-7870.0001715). This work is made available under the terms of the Creative Commons Attribution 4.0 International license, <https://creativecommons.org/licenses/by/4.0/>.

## Introduction: California's Storied History with Urban Water

California has a rich and storied history with water resources development. From the Gold Rush to the 21st century, access to water has always been essential to the state's burgeoning population and economy. Throughout this period—from the 1880s with the formation of irrigation districts to the present day with large metropolitan regions—the state has struggled to provide adequate fresh water for cities, agriculture, and the environment (Lassiter 2015; Starr 2015). The legacy of infrastructure and regulations are evolving today as California communities invest in reinvented urban water infrastructure. This revolution provides lessons in ways that water-stressed cities in arid and semiarid climates around the world can meet future water needs in more sustainable ways than in the past.

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Note. This manuscript was submitted on May 27, 2019; approved on December 9, 2019; published online on May 7, 2020. Discussion period open until October 7, 2020; separate discussions must be submitted for individual papers. This paper is part of the *Journal of Environmental Engineering*, © ASCE, ISSN 0733-9372.

## California's Early 20th Century Water Landscape: Building Infrastructure for Urban Growth

California's geography and demographics shaped the present-day water infrastructure. Two-thirds of the annual precipitation falls in the northern third of the state while much of Southern California is desert terrain. Seventy percent of the state's population lives in large coastal urban areas while most of the state's agriculture is situated in the sunbaked Central Valley (Department of Water Resources 2014). California simply couldn't become habitable and productive without a statewide water system of heroic magnitude (Starr 2015).

Large-scale infrastructure development to bring water from the mountains to urban areas began early in the 20th century (Fig. 1). Notable achievements include the Los Angeles Aqueduct from the Owens Valley with its first water deliveries in 1913, San Francisco's Hetch Hetchy Aqueduct (completed 1934), which diverts water from the western slopes of the Sierra Nevada Range, and the East Bay's Mokelumne Aqueduct (completed 1929). Southern California was also served via the Colorado River Aqueduct with its first deliveries in 1939. By any measure, these were massive undertakings that required new engineering approaches, building dams in remote areas, and laying pipes and channels through challenging terrain. The Hetch Hetchy system, for example, required 20 years for construction (San Francisco Public Utilities Commission 2005).

These projects resulted in vast changes to the urban landscape. The San Fernando Valley was annexed by the City of Los Angeles in 1913, and water from the Owens Valley transformed this barren landscape into rich cropland, which then was rapidly converted to urban development as Los Angeles' population grew (Kahrl 1979). A second change in the urban landscape occurred during and after World War II. California experienced unprecedented military and industrial growth resulting in migration and population increase (Starr 2015). After the war many personnel involved in wartime production or engaged in the Pacific Theater decided to make California their home. The postwar defense industry spurred the state's economic engine through aviation, aerospace, and electronics. Since 1962 the state has been the most populous in the nation (Starr 2015).

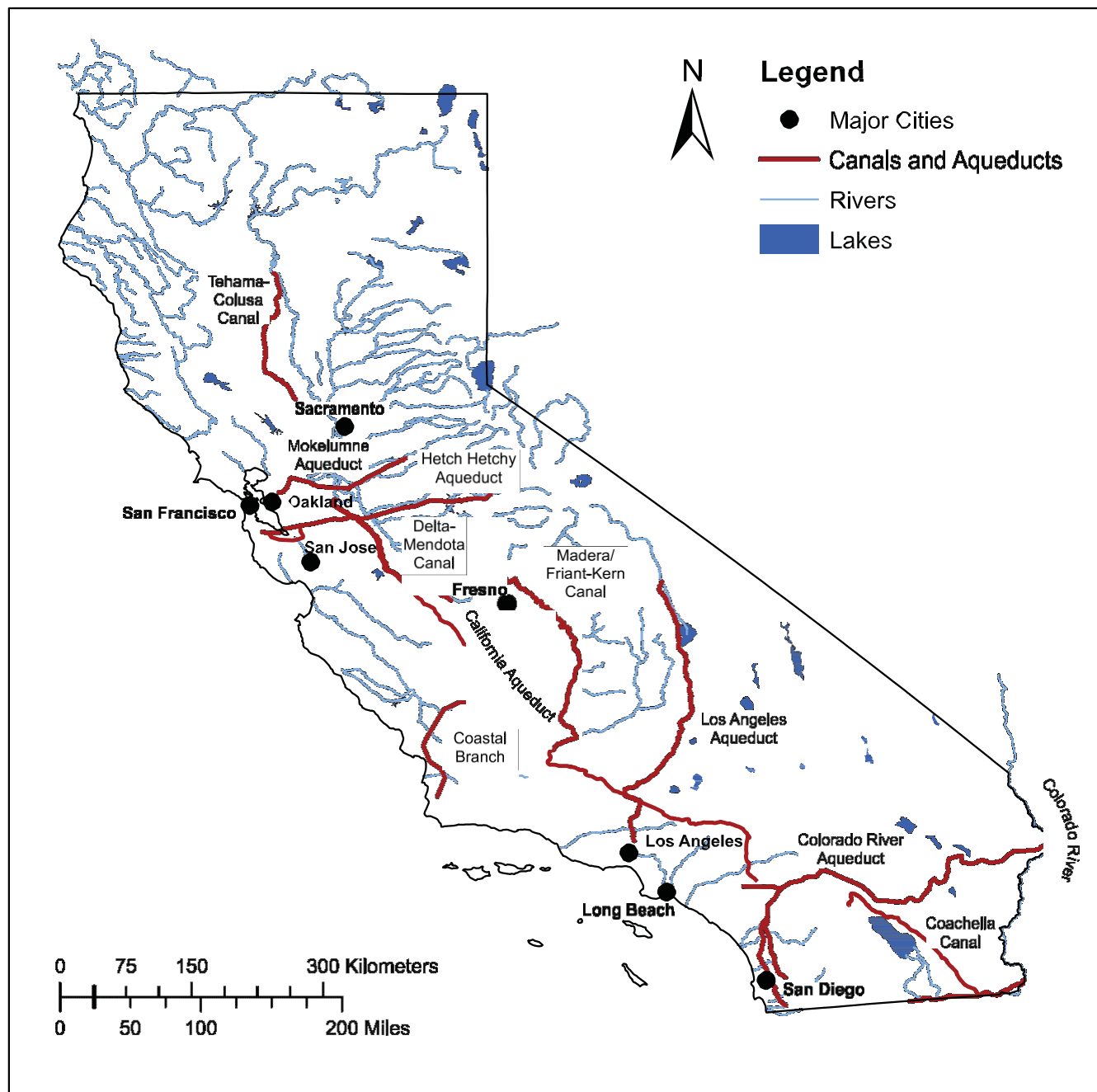


Fig. 1. (Color) Map of major California water resources conveyance structures. Geospatial data was adapted from the California Department of Water Resources (DWR) and the US Census Bureau.

### California's Later 20th Century Water Landscape: Curtain Call on Big Dams and Aqueducts

The post-WWII economic and population boom in California stressed water deliveries throughout the state. Rising to this challenge was Edmund G. "Pat" Brown, California's governor from 1959 to 1967. A centrist in politics and devoted to building the state's infrastructure, he is referred to as the "Architect of the Golden State" because of his investments in major public works projects and higher education. In his first inaugural address in 1959 he said, "Development of our water resources is crucial to every segment of our state :: I will soon present a water program, which is rational, realistic, and responsive to the needs of all people of the State" (Brown 1959). In 1961 Governor Brown initiated the

State Water Project with its central feature being the California Aqueduct, a vital aquatic lifeline and one of the most significant public water projects in world history (Starr 2015; Water Education Foundation 2019). The 715-km (444-mi) long aqueduct includes the world's biggest lift station (Water Education Foundation 2019) to move water almost 610 m (2,000 ft) over the Tehachapi Mountains before splitting into a west branch serving Los Angeles and other cities along the coast, and an east branch serving the Inland Empire cities.

While California embarked on the State Water Project, the Bureau of Reclamation was building a network of dams and canals in the Central Valley: Shasta Dam (completed 1945), Friant Dam (1942), and San Luis Dam (1968) (Bureau of Reclamation 2017). But with the completion of the New Melones Dam in 1979, the era

of big dam construction was over. At the close of the 20th century, the state had over 1,200 mi of aqueducts, pipelines, and canals that moved water great distances for agriculture, industry, and cities. In consequence, the state's current water infrastructure is vast, highly complex, integrated, and decentralized at the state, regional, and local levels (Hanak et al. 2018; Pincetl et al. 2016). The challenge facing the state is for each sector—agriculture, industry, and cities—to manage its water sustainably and for greatest benefit for equity, economy, and the environment. This discussion focuses on the urban water supplies specifically as 95% of the population in California (as of 2010) lives in urban areas (US Census Bureau 2012) and large urban suppliers often have the finances to invest in new infrastructure.

## California's 21st Century Water Landscape: Sustainable Urban Water Supplies

Myth and folklore have been a part of California's debate on water management since the late 1800s, including whether humorist Mark Twain really said after visiting California that "whiskey is for drinking, and water is for fighting over!" One common misperception in popular culture is that California is running out of water—in fact the state is running out of abundant cheap water. Another common misperception is that a single water-use sector can be blamed for California's water problems whereas in reality opportunities exist for all sectors to better manage water (Hanak et al. 2009).

California water is now at a crossroads, with 20th-century infrastructure and management no longer appropriate for 21st-century realities. Throughout the 20th century, California's de facto approach to sustain urban growth and manage drought was to overdraft groundwater, deplete streams and rivers, and seek water imports. But these approaches have proved unsustainable (Department of Water Resources 2014). California's 21st century urban water landscape is changing dramatically with many notable events including historic back-to-back droughts in 2007–2009 and 2012–2016, growing concerns about the impacts of climate change on water supply, and regulatory actions on reserving water for ecosystems. Thus, in recent years, the state's governors, civic leaders, and courts have reacted to ever-increasing water stress and conflict with varying approaches. Against this backdrop cities have taken to reimagining their water systems with an emphasis on more locally-sourced water to achieve greater self-sufficiency and reliability. By studying communities around the state, we identify five approaches taken by cities to achieve more sustainable water systems:

- Enhanced conservation and efficiency;
- Water reuse, especially potable reuse;
- Stormwater capture for water supply;
- Desalination, both brackish water and seawater; and
- Water banking.

For example, in 2008 following an especially dry year in 2007, Los Angeles realized the need to rethink existing and future water supplies to meet demands in the face of climate change, growing population, and stressed ecosystems. Championed by Mayor Antonio Villaraigosa, the city embarked on a visionary plan (Gold 2011). The strategy to secure the city's water supply is to develop locally sustainable water supplies by conservation and maximizing water recycling and enhancing stormwater capture to reduce demand for imported water (Villaraigosa 2008). Current Los Angeles Mayor, Eric Garcetti, announced a "Green New Deal," that sets aggressive goals of recycling 100% of the city's wastewater for beneficial use and sourcing 70% of the city's water locally by 2035 (Office of Los Angeles Mayor Eric Garcetti 2019). Other cities have similar strategies with each plan dependent on antecedent conditions, values, and

geographical realities. San Diego, for example, has limited local supplies and few aquifers for groundwater storage and is embracing sea-water desalination and indirect potable reuse (San Diego County Water Authority 2016). We explore these five sustainability approaches with success stories and lessons learned. By exploring these topics, we provide a roadmap for cities in California as well as other cities around the world.

## Conservation and Efficiency: Getting by with Less

One opportunity for increased urban water supply in California is water conservation and efficiency. We define conservation as overall reduction in water use while water efficiency is using less water to complete the same task (e.g., minimizing the water used to flush a toilet).

### State of Practice

Historically, California's conservation and efficiency efforts have been driven by drought. Drought response in California began in earnest with the 1976–1977 and 1987–1992 droughts (State of California Department of Water Resources 1993). The severity of these droughts focused attention of the public and institutions on the need for greater sustainability in using existing water supplies while maintaining the state's environmental resources (Dziegielewski et al. 1993). During the 1987–1992 drought, for example, Los Angeles and San Diego instituted several long-term efficiency activities such as offering rebates for low flow toilets, summer water rate surcharges, and distributing information on water-efficient landscaping. In addition, Los Angeles encouraged short term conservation by restricting lawn watering hours and increasing water rates by 15%–25% (Shaw et al. 1992). San Diego's drought measures were more focused on working with large water-use customers individually to reduce consumption (Shaw et al. 1992). In addition to local measures, these severe droughts also prompted statewide actions such as water use efficiency standards and updates to plumbing codes (Gonzales and Ajami 2017).

The recent 2012–2016 California drought also brought new efficiency and conservation initiatives. In July 2014, the State Water Resources Control Board required mandatory reporting of water usage by urban water suppliers to help statewide water supply planning (California State Water Resources Control Board 2014). In April 2015, and for the first time in the history of the state, Governor Jerry Brown mandated that urban water suppliers reduce their water consumption, with an overall goal of 25%. Exact conservation requirements varied between 8% and 40% for each utility and were based on their 2013 water use, accounting for conservation that had already been achieved (State of California 2015). The state essentially achieved this goal overall (24.3%), and though there was varying success among water suppliers, this drought-induced conservation was critical to avoiding supply shortages (Palazzo et al. 2017). Water use rebounded slightly, but not to pre-drought levels, suggesting the decrease in water use was because of permanent efficiency measures in addition to changes in human behavior and temporary conservation. This rebound effect suggests conservation can be a flexible source of water during drought (Gonzales and Ajami 2017).

The 2012–2016 drought led to many innovations and improvements in water management (Lund et al. 2018). After the drought restrictions were lifted, the state laid out long-term measures for water suppliers to improve water conservation and efficiency and strengthen drought contingency plans (State of California 2016). As a follow-up to that action, on May 31, 2018, Governor Brown signed legislation for new indoor water use standards of 190 L (50 gal.) per capita per day (gpcd) by 2035 (State of



California 2018). The drought also illuminated the need to reduce outdoor water use in urban areas. Urban water use in California varies seasonally; use in the summer months is about twice that in the winter largely because of landscape irrigation (Legislative Analyst's Office 2016). Further, outdoor water use is a significant proportion of total household use; it was estimated to be about 54% of single family residential water use in Los Angeles (Mini et al. 2014). To encourage outdoor water efficiency, water districts offer rebates for replacing high-water using landscapes, e.g., lawns, with low water-using plants appropriate for the area. Typical rebates are ~\$11–21/m<sup>2</sup> (\$1–2/sq ft) (Los Angeles Department of Water and Power 2019d; Valley Water 2019h). The Metropolitan Water District spent \$350 million on this program and currently offers ~\$21/m<sup>2</sup> (\$2/sq ft) (Metropolitan Water District of Southern California 2019e); in 2015 the Los Angeles Department of Water and Power augmented that to \$40/m<sup>2</sup> (\$3.75/sq ft) during the height of the recent drought (Jessup and DeShazo 2016).

The consequence of these coupled efficiency gains and drought-related conservation actions since 1990 is a long-term decrease in per capita urban water use. For example, despite an increase in population of 1.1 million from 1991 to 2010, the City of Los Angeles' water use remained constant (Los Angeles Department of Water and Power 2016). Water suppliers within the Bay Area Water Supply & Conservation Agency (BAWSA) reduced per capita consumption and overall use despite population growth of 10.5% from 2004 to 2018 (Fig. 2; Bay Area Water Supply & Conservation Agency 2019). The Metropolitan Water District of Southern California, the major wholesaler of imported water to 19 million southern Californians, also forecasts a continued population growth with a downward trend in per capita water use (Metropolitan Water District of Southern California 2016). Between 2016 and 2040, population in the Metropolitan Water District's service area is expected to grow 15% and per capita consumption drop to about 500 L (132 gpcd). While conservation measures yield about 386 million m<sup>3</sup>/yr [(313,000 acre-ft/year (AFY))], the demand because of population increase is about 521 million m<sup>3</sup>/yr (423,000 AFY) (Metropolitan Water District of Southern California 2016).

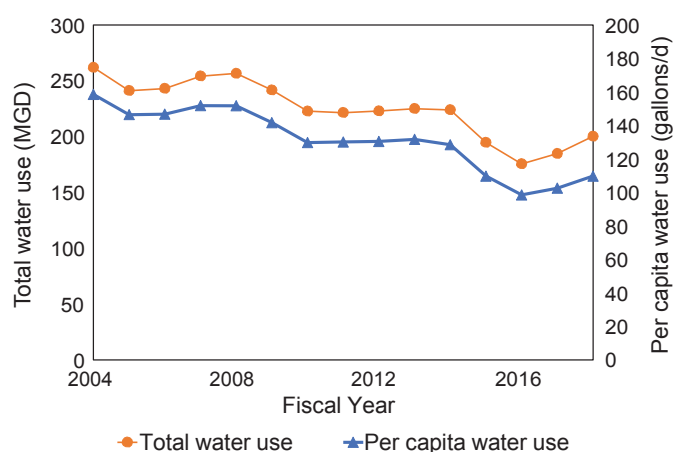


Fig. 2. (Color) Overall water demand for water suppliers within the Bay Area Water Supply & Conservation Agency (BAWSA) has decreased since 2004 because of conservation efforts despite 10.5% population growth. BAWSA is an agency that represents 26 cities, water districts, and utilities in Alameda, Santa Clara, and San Mateo counties that purchase water from the Hetch Hetchy system. (Adapted from Bay Area Water Supply & Conservation Agency 2019.)

## Outlook

While there is a decreasing trend in per-capita urban water use across the state, there is still opportunity to increase conservation and efficiency (Hanak et al. 2018). We can draw on lessons learned from Australia after the Millennium drought as per capita use in Australian cities was about 238–400 L/d (63–106 gpcd), compared to 440–670 L/d (116–176 gpcd) in Californian cities in 2010 (Cahill and Lund 2012). As high efficiency appliances are installed and indoor water use approaches practical limits, conservation tactics are shifting to target outdoor irrigation, not only for residences but also in commercial, industrial, and institutional uses (Gober et al. 2016). Reductions in outdoor water use can be encouraged by outdoor water use restrictions, water pricing, and/or sustainable landscape rebates that lead to landscape conservation in the form of turf removal and climate-appropriate landscaping (Cahill and Lund 2012). Additional water savings can result from leak detection and mitigation programs. In 2016, it was estimated that 12% of residential water supply in the US was lost to leaks (DeOreo et al. 2016).

Improved technology and a better understanding of human behavior can play a role in enhanced conservation. For example, as we saw in the recent historic 2012–2016 drought, public awareness of drought conditions can lead to behavioral conservation. The availability of new data sources and the internet-of-things have allowed researchers to quantify these impacts. For example, researchers have measured drought saliency and its impact by quantifying media coverage and Google-search frequency of water- and drought-related issues and linking these trends to water use behavior and conservation (Quesnel and Ajami 2017).

Likewise, smart meters provide a way to better quantify demand, detect leaks, and provide consumer feedback. In-home displays can motivate conservation by providing greater awareness of consumption and setting a target (Davies et al. 2014). Consumer information on water use and social norming can influence conservation. Rather than general information about the importance of conservation, emphasizing the water consumption among the same ingroup, e.g., local home owners, can encourage better behavior. Social norms-based interventions, i.e., behavior based on widely held beliefs about what the majority of other people do, can be harnessed to change behavior and encourage conservation (Lede et al. 2019).

## Water Reuse: An Evolution from Conventional to Uncharted Waters

Water reuse is a critical and rapidly growing new source of water supply. The practice of water reuse includes water recycling, which we define as the process of intentionally repurposing municipal wastewater for use more than one time. Water reuse is typically divided into potable and nonpotable practices; potable reuse is a general term for recycled water to augment drinking water supplies while nonpotable reuse refers to all other applications. The first applications for recycled water consisted of irrigating crops or landscapes; current uses include a variety of indoor or outdoor uses, such as cooling, flushing toilets, and supplementing drinking water supplies.

### Nonpotable Reuse

Water reuse in California began as a strategy to manage growing volumes of wastewater in cities built before wastewater treatment was widely available. In 1891, the City of Fresno adopted the European practice of sewage farming, wherein untreated wastewater—recognized as a valuable supply of both water and nutrients—was applied to farmland to grow alfalfa (City of Fresno 2019). Other cities adopted similar practices over the coming decades, including

using wastewater to irrigate urban landscapes. As water treatment technologies advanced over time, cities gradually incorporated more of this technology to address growing aesthetic and public health concerns with reusing or disposing of untreated wastewater, e.g., in 1932 San Francisco switched to using disinfected secondary-treated effluent for irrigating Golden Gate Park (Hyde 1937). By 1937, one quarter of Californian cities with populations of 10,000 people or larger irrigated with recycled water, most of which underwent some level of treatment (Hutchins 1939).

As urban growth expanded outward from city centers, conveying recycled water to its point of use posed challenges. Especially in Northern California, cities most commonly used inexpensive open channels to convey the recycled water. However, by the 1930s, officials recognized the public health risk associated with this practice and recommended recycled water instead be conveyed through a pipeline network (Hutchins 1939). Following this guidance, more cities built pipelines, primarily to supply recycled water to large users of nonpotable water near the water recycling facilities, such as adjacent refineries or golf courses. After exhausting demands for nonpotable water closest to the water recycling facility, some cities built out new pipeline networks to deliver recycled water to users farther away from the treatment plant. One of California's earliest examples of this practice, often called dual distribution, is found in Orange County: in the 1980s, the Irvine Ranch Water District built the first dual distribution system using purple pipes to distinguish them from other utility pipes (Peterson 2014). Today the district's dual distribution system comprises more than 640 km (400 mi) of pipeline serving 95,000 m<sup>3</sup>/d (25 million gal./day (mgd)) of recycled water to over 5,500 metered connections (Irvine Ranch Water District 2019a, b).

Despite the existence of dual distribution networks in several Californian cities, other cities have hesitated to build these expansive pipeline systems. In particular, water managers often struggle to justify the projects' hefty price tag—on the order of \$0.62–6.2 million/km (\$1–\$10 million/mi) to install pipelines in densely-developed urban areas (Bischel et al. 2012; Bradshaw and Luthy 2017). Moreover, various water conservation efforts that utilities encourage, e.g., low-flow toilets and turfgrass replacement programs, reduce the demand for nonpotable water these dual distribution projects aim to satisfy, and managers worry that large, centralized nonpotable recycled water infrastructure could become stranded assets because of lack of demand (Tran et al. 2017).

## Potable Reuse

The challenging economics of dual distribution systems for nonpotable reuse projects, combined with the problem of groundwater overdraft, led California cities to pioneer potable reuse nearly 60 years ago. In 1962, the Los Angeles County Sanitation Districts and the Water Replenishment District of Southern California completed the Montebello Forebay Groundwater Recharge Project. The project included building the Whittier Narrows Water Reclamation Plant, which produced 167,000 m<sup>3</sup>/d (44 mgd) of secondary-treated effluent that was sent to nearby groundwater recharge ponds, also called spreading basins—the first to publicly advertise this as “water reuse” (Lassiter 2015). After percolating into the ground and entering the aquifer, the recycled water became part of the existing municipal water supply and helped address overdrafting of groundwater. Facing similar challenges of groundwater overdraft and sea water intrusion, the Orange County Water District developed Water Factory 21 (1976), the nation's first potable reuse project in which recycled water was injected into the aquifer rather than passive percolation through a spreading pond (Mills and Watson 1994).

The success of the Montebello Forebay Groundwater Recharge Project and Water Factory 21 inspired other Californian cities to consider potable reuse projects in the 1990s, though not all would come to fruition. Potable reuse proposals in San Diego, Los Angeles' San Gabriel Valley, and the San Francisco Bay Area's Dublin-Pleasanton communities stalled because of public opposition (Harris-Lovett and Sedlak 2015). In contrast, in western Los Angeles, the West Basin Municipal Water District's potable reuse plans succeeded. In 1995 the West Basin Water Recycling Facility started producing 12.5 mgd of recycled water for salt water barrier projects, which, like Water Factory 21, both combatted seawater intrusion and augmented groundwater supplies. This was the state's first potable reuse project to employ a process now called full advanced treatment, wherein secondary or tertiary-treated wastewater effluent undergoes a three-step process of microfiltration, reverse osmosis, and ultraviolet light with an advanced oxidation process. The full advanced treatment train is notable for producing recycled water that meets or exceeds all drinking water standards. Building on West Basin's success, the Orange County Water District adopted the full advanced treatment train at the Groundwater Replenishment System that came online in 2008. The district sends this recycled water to both groundwater recharge ponds and injection wells in the county. Starting with a production capacity of 265,000 m<sup>3</sup>/d (70 mgd), which the district has since expanded to 380,000 m<sup>3</sup>/d (100 mgd) and plans to expand to 490,000 m<sup>3</sup>/d (130 mgd), the Groundwater Replenishment System is by far the single-largest potable reuse facility in the world (Orange County Water District 2019).

## Outlook

Building on a long history of successful water reuse, state policies set up California for substantial growth in water reuse over the coming decades. In the United States, there are currently no federal water quality standards specific to recycled water. As of 2017, only 14 states have water reuse policies (CDM Smith 2017), and California arguably has the most formalized and comprehensive reuse regulations. The state's regulations for nonpotable reuse were promulgated in 1978 and most recently updated in 2014. Additionally, the state has recently finalized regulations for potable reuse for configurations with an environmental buffer, called indirect potable reuse, including rules for groundwater recharge in 2014 and reservoir water augmentation in 2018 and 2019. These regulations make the prospect of potable reuse more tenable to water utilities, which are risk-averse and would seek to minimize regulatory uncertainty before investing in recycled water infrastructure.

In light of the new statewide regulations, both the City and County of Los Angeles are planning large indirect potable water recycling operations at their coastal facilities. The Metropolitan Water District in partnership with the Sanitation Districts of Los Angeles County is planning a regional recycled water program that would distribute up to 570,000 m<sup>3</sup>/d (150 mgd) through 96 km (60 mi) of trunk pipelines to inland spreading grounds (Metropolitan Water District of Southern California 2019f). The City of Los Angeles in 2019 announced plans to retrofit the city's Hyperion treatment plant to produce up to 640,000 m<sup>3</sup>/d (170 mgd) of recycled water including new pipelines to replenish the city's groundwater basins (Los Angeles Department of Water and Power 2019c; Office of Los Angeles Mayor Eric Garcetti 2019).

California has not yet developed regulations for potable reuse with no environmental buffer, called direct potable reuse. But the state is taking concrete steps toward that goal, most recently by completing an updated proposed regulatory framework in 2019 with new direct potable reuse regulations by 2023 for “raw water augmentation,” meaning placement of recycled water into pipelines or aqueducts that



deliver water to a water treatment plant (California State Water Resources Control Board 2019). At the same time the state is working in parallel to develop regulations for “treated drinking water augmentation,” meaning the placement of recycled water into the water distribution system—also referred to as “flange-to-flange” direct potable reuse. The idea is to build a single regulation package with criteria that address a range of direct potable reuse scenarios as well as a uniform application of health-protective criteria.

In addition to an enabling regulatory environment, the state has set explicit goals for the scale of total water reuse for either potable or nonpotable purposes. With the first statewide goals established in 1991, the state’s current goals are to use 1.8 billion m<sup>3</sup>/yr (1.5 million AFY) of recycled water by 2020 and 3 billion m<sup>3</sup>/yr (2.5 million AFY) by 2030, representing approximately a doubling and tripling, respectively, of recycled water volumes produced in 2015 (California State Water Resources Control Board 2017). Toward these goals, as of 2014, 11 utilities, which collectively serve approximately two-thirds of the state’s population, are planning various projects to increase their water reuse from 0.37 billion m<sup>3</sup>/yr (300,000 AFY) to 0.74–1.1 billion m<sup>3</sup>/yr (600,000–900,000 AFY) by 2035 (California Urban Water Agencies 2014).

With more regulatory clarity and explicit state reuse goals, more cities are moving ahead with these types of projects. As of 2018, California has approximately ~0.26 billion m<sup>3</sup>/yr (208,000 AFY) of groundwater recharge projects permitted, with an additional 0.26 billion m<sup>3</sup>/yr (213,000 AFY) of groundwater recharge and 0.14 billion m<sup>3</sup>/yr (116,000 AFY) of surface water augmentation projects planned (Fig. 3). Many of these projects plan to use full advanced treatment to produce recycled water. However, other cities, such as Los Angeles, are evaluating opportunities to use alternative treatment technology that uses ozone and biologically activated carbon filtration instead of membranes. This alternative technology may produce similarly high-quality water while reducing costs and energy use by approximately 60% (Bradshaw et al. 2019). Moreover, the membrane-free treatment does not produce a concentrate byproduct, the management of which can be a primary barrier for adopting membrane-based reuse applications. Either a membrane-free treatment train or an economical concentrate management technology is critical for the adoption of potable reuse projects in inland cities or other places where discharging concentrate to the ocean, the most common management practice, is not an option.

Nonpotable reuse will also expand, though the scale of individual projects will likely shrink. While a dual distribution system worked well for the city of Irvine, others have found that laying new pipes for city-wide, nonpotable water is too expensive (Bischel et al. 2012). Because of this, decentralized nonpotable water reuse is gaining in popularity at the building/neighborhood scales such as large tech campuses and office buildings in California (Fig. 4). Decentralized systems can be especially economical when serving densely-populated spaces or for new construction projects rather than retrofits. Examples of these decentralized systems are at Facebook, Stanford University, and the Salesforce Tower in San Francisco (Stanford Engineering 2019; Swezey and Lamprecht 2019). Facebook’s system recycles 61,000 m<sup>3</sup>/yr (16 million gal./year) for irrigation of 5.3 ha (13 acres) of rooftop gardens and gathering spaces at its Menlo Park headquarters (Fig. 4; Swezey and Lamprecht 2019). Another example of a decentralized, building-scale system is San Francisco’s Living Machine wetland, which produces 19 m<sup>3</sup> (5,000 gal.) recycled water/day for toilet flushing at the San Francisco Public Utilities Commission’s headquarters (San Francisco Public Utilities Commission 2018b). When complete, the Salesforce Tower will feature the largest on-site water

recycling system in a commercial high-rise building in the US with 114 m<sup>3</sup>/d (30,000 gpd) for irrigation, cooling, and toilet flushing (Flynn 2018). In urban districts with a high concentration of industrial water users, water recycling facilities may benefit from developing different grades of recycled water, tailored to the needs of the industrial customers. The Edward C. Little Water Recycling Facility in Los Angeles pioneered this concept: the facility currently produces 151,000 m<sup>3</sup>/d (40 mgd) of five different qualities of recycled water for the applications of irrigation, seawater barrier, high-pressure boilers, low-pressure boilers, and cooling towers (West Basin Municipal Water District 2019).

To accelerate reuse, WaterReuse California identified strategic areas for action—research, regulations, regional planning, and funding—that have the potential to double the use of recycled water in the state once the potable reuse regulations are complete (California State Water Resources Control Board 2019; WaterReuse California 2019). More broadly, the EPA recently promulgated a draft National Water Reuse Action Plan to enhance water security through integrated resource management (USEPA 2019).

### Stormwater Capture for Water Supply: From Flood Control to Opportunity

Another potential option to increase water supply and reliability in California is to capture and treat urban runoff, or stormwater. Stormwater is generated when rain flows over surfaces such as roofs, parking lots, and roads, and does not infiltrate into the subsurface. Traditionally, California cities were engineered to convey stormwater rapidly away from city centers to reduce flood impacts, which is why many urban surface waters were channelized in the 20th century (Fig. 5). For example, in Los Angeles, historic floods caused massive property damage and loss of human lives in 1914, 1934, and 1938, motivating channelization of over 447 km (278 mi) of the Los Angeles River and its tributaries (Cram 2012). While large channels and conduits are effective for flood control, quick conveyance of polluted stormwater poses a risk to coastal water quality, endangers coastal ecosystems, and weakens coastal economies that depend on tourism revenue. But stormwater is increasingly viewed as a valuable resource, that when captured, stored, and treated correctly, can alleviate water supply shortages (Fig. 5). Because of the great promise of stormwater as a resource, California has committed to increasing the use of stormwater by at least 0.62 billion m<sup>3</sup>/yr (500,000 AFY) by 2020 and by at least 1.23 billion m<sup>3</sup>/yr (1,000,000 AFY) by 2030 from 2007 levels (California State Water Resources Control Board 2009). This 1.23 billion m<sup>3</sup>/yr (1,000,000 AFY) is approximately equivalent to double the water the City of Los Angeles uses annually (Los Angeles Department of Water and Power 2018).

### State of Practice

There are two classifications of stormwater capture systems, divided by size and spatial distribution: (1) centralized systems such as spreading basins, and (2) smaller distributed systems, often called green infrastructure, such as biofilters, infiltration trenches, or porous pavement. Centralized systems provide an advantage to decentralized systems for water supply, particularly in California where rainfall is seasonal and infrequent and where large storm events make up most of the precipitation, requiring substantial storage. In addition, centralized facilities may have space to house the necessary systems to treat stormwater prior to use. Centralized stormwater capture systems are typically paired with subsurface storage. Subsurface storage in shallow aquifers is ideal compared to storage in surface reservoirs as storage capacity already exists

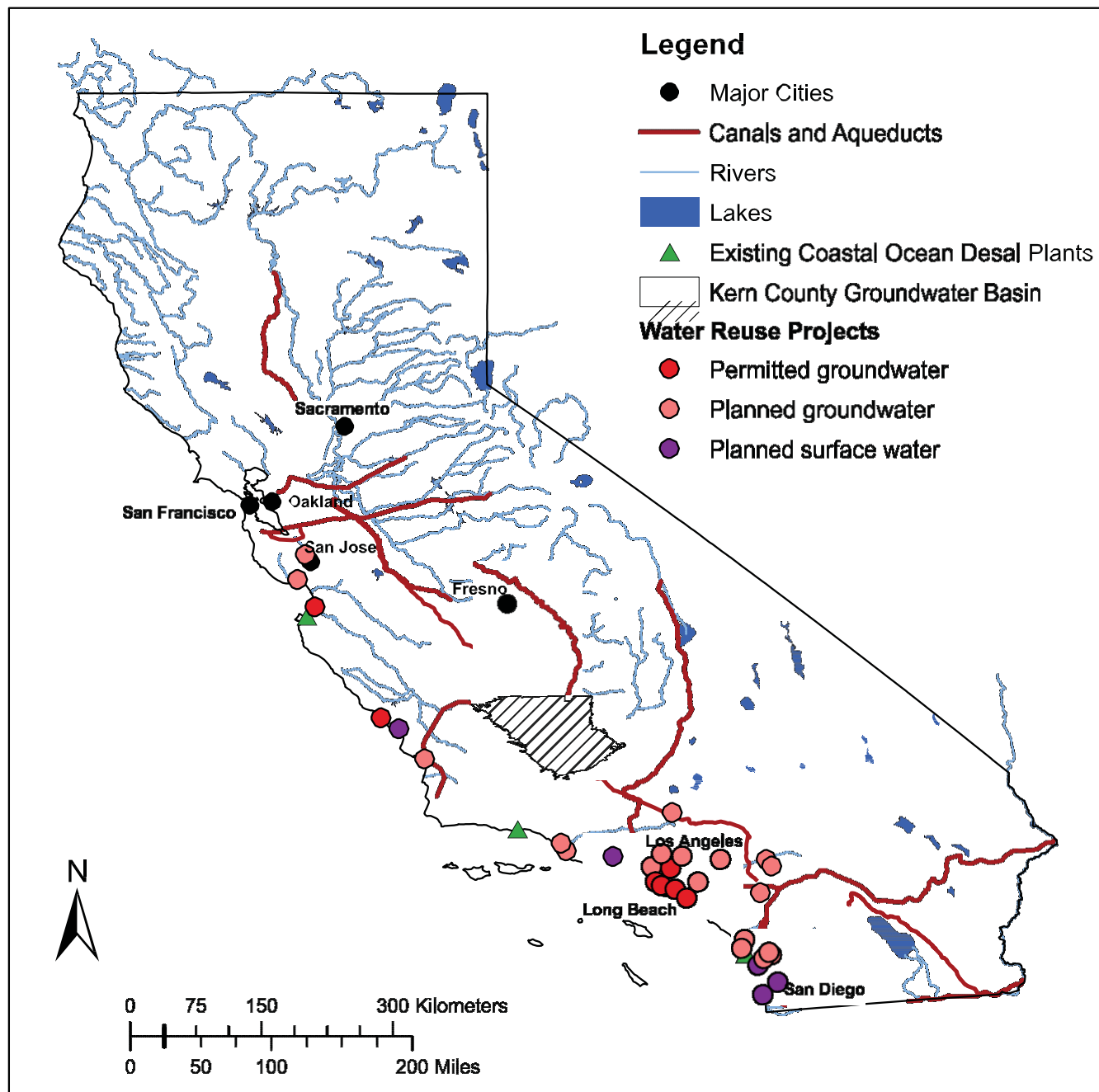


Fig. 3. (Color) Existing and planned water reuse projects in California as well as existing coastal ocean desalination facilities. Recycled water is either stored in surface water reservoirs or groundwater basins. Geospatial data was adapted from the California Department of Water Resources (DWR) and the US Census Bureau. Water reuse data was taken and adapted from Water Reuse California (WaterReuse California 2018). The San Joaquin groundwater basin within Kern County is used extensively for water banking, collecting water from Northern California via the California Aqueduct, from the Central Sierra via the Friant-Kern canal, and from the Kern River.

and doesn't require large infrastructure construction (Luthy et al. 2019). Decentralized systems can also be used to augment municipal water supply, particularly where they are designed to infiltrate into subsurface reservoirs. In addition to water supply benefits, decentralized systems can benefit water quality at the watershed scale (Gallo et al. 2020; Mika et al. 2018; Wolfand et al. 2018, 2019). Both centralized and decentralized stormwater capture systems green the urban landscape, providing aesthetic, human health, and environmental health benefits (Bell et al. 2018; McGarity et al. 2015).

Currently, many water agencies employ stormwater capture as an alternate water supply to reduce stress on imported or local

surface waters. For example, Los Angeles' water supply is currently a combination of imported water (from the Owens Valley, Northern California, and Colorado River), groundwater, recycled water, and stormwater. The Los Angeles County Department of Public Works currently operates over 30 spreading basins, some over 100 years old, that serve as groundwater recharge facilities (Los Angeles Department of Public Works 2019). As of 2015, Los Angeles actively captured 29,000 acre-ft of stormwater annually for recharge of the San Fernando aquifer via spreading basins (Geosyntec Consultants 2015). Active recharge combined with incidental recharge (35,000 AFY) totals about 10% of the city's water





Fig. 4. (Color) Facebook's nonpotable reuse system (a) comprises microscreening, membrane bioreactors, reverse osmosis, and UV disinfection with chloramine and mineral adjustment; (b) The system is designed for 61,000 m<sup>3</sup>/yr (16 million gal./year) for irrigation of 5.3 ha (13 acres) of rooftop gardens and gathering spaces. This is an example of distributed water reuse, which is gaining popularity at large tech campuses and office buildings in California. (Images by authors.)



Fig. 5. (Color) (a) Historically, urban stormwater has been managed for flood control with large pipes, concrete channels, and aqueducts, such as the Los Angeles River; (b) Increasingly, stormwater is viewed as a resource, and may provide water for beneficial uses as well as ecosystem services, for example, the Los Alamitos Percolation Ponds in San Jose (Images by authors.)

demand. The city demonstrated an additional 68,000–114,000 acre-ft of stormwater could be captured by 2035. Stormwater will continue to be a key piece of Los Angeles' water supply—in 2018 voters approved a stormwater parcel tax for Los

Angeles County that will generate over \$300 million/year to support projects that collect and clean stormwater (Agrawal 2018).

In Northern California, Valley Water infiltrates about 62 million m<sup>3</sup>/yr (50,000 AFY) of local runoff through their recharge ponds,



compared to total water supplies of 320 million m<sup>3</sup>/yr (260,000 AFY) (Santa Clara Valley Water District 2016). Other agencies in California including Orange County Water District, San Bernardino County Flood Control District, and Chino Basin Water Conservation District also rely on stormwater capture for water supply (Southern California Water Coalition Stormwater Task Force 2018). Conversely, because of spatial constraints and pressing water quality issues posed by its combined sewer system, San Francisco's approach to stormwater management has mainly focused on distributed stormwater capture projects, which may also contribute to recharging groundwater aquifers. Right now, San Francisco's water supply is primarily surface water; 85% from the Hetch Hetchy reservoir and aqueduct, and about 15% is from local surface waters (San Francisco Public Utilities Commission 2018a). But groundwater is a part of San Francisco's future water supply portfolio, as they are currently developing a groundwater pumping system to extract 15,000 m<sup>3</sup>/d (4 mgd) of groundwater from the North Westside Basin (San Francisco Public Utilities Commission 2018a). Stormwater capture for groundwater recharge will be critical for ensuring the long-term sustainability of San Francisco's plans. Opportunities for stormwater capture go beyond San Francisco proper; the NRDC estimated that distributed green infrastructure systems in the San Francisco Bay Area could provide 0.28–0.49 billion m<sup>3</sup>/yr (229,000–400,000 AFY) by 2030 (Garrison et al. 2009).

Capture and use of stormwater can be economical, particularly when compared to high-cost alternatives such as seawater desalination. But costs can vary significantly depending on project type and scope. A 2018 report by the Southern California Water Coalition surveyed existing stormwater capture projects and found that project costs ranged from \$0.048/m<sup>3</sup> (\$59/acre-ft) to more than ~\$200/m<sup>3</sup> (\$250,000/acre-ft). The median cost, however, was \$0.87/m<sup>3</sup> (\$1,070/acre-ft), which is cost-competitive with some imported water supplies. Retrofit projects where existing facilities are upgraded or expanded tend to be more cost-effective [median of \$0.49/m<sup>3</sup> (\$600/acre-ft)], while distributed systems tend to be more expensive [(\$20/m<sup>3</sup> (\$25,000/acre-ft))] (Southern California Water Coalition Stormwater Task Force 2018).

## Outlook

California is committed to capitalizing on stormwater as a resource, and several cities within the state have also made this pledge. Capture of stormwater provides several advantages for supply in California. First, it is an untapped source of new water, and the cost of capturing this water in centralized facilities can be relatively inexpensive. Stormwater capture can also provide flood protection, help meet federal water quality regulations, and provide green space for habitat/recreation.

While stormwater harvesting shows much promise, widespread deployment of stormwater capture for beneficial use faces challenges beyond costs. Stormwater must be treated to appropriate water quality standards depending on the beneficial use. Stormwater contains a unique suite of pollutants, which are picked up as it runs off urban land uses. Examples include nutrients, metals, fecal indicator bacteria, and trace organic contaminants such as pesticides and corrosion-inhibitors. Of particular concern are human pathogens, which pose a risk to human health, and relatively polar organic contaminants, which are freely mobile in the subsurface. Cities lack experience with basin-wide urban runoff capture, treatment, and recharge; thus, new systems need to be designed and monitored in ways that are protective of groundwater (Luthy et al. 2019).

New treatment technologies have been developed to target removal of stormwater pollutants such as biochar or other reactive media filters (Grebel et al. 2013). New technologies are easily coupled with "smart" technologies for dynamic management of

stormwater capture systems. For example, detention basins with autonomously controlled outlets may be drained in anticipation of a large precipitation event, or closed to increase residence time of water and ensure sufficient treatment (Kerkez et al. 2016). These technologies show promise, but few have been demonstrated at a field or pilot scale, instead relying on data from laboratory experiments.

## Desalination: A Drought-Proof Supply

References to desalination date back thousands of years, but its implementation for California urban water supply is relatively new (Kumar et al. 2017). Water desalination is divided into seawater (i.e., ocean) and brackish water desalination, depending on the salinity of the water source.

### Seawater Desalination

Seawater desalination is typically an option of last resort for augmenting urban water supplies because these systems are energy intensive and costly. In addition to having a high energy footprint, ocean desalination poses several environmental challenges with water intake and concentrate discharge. Open ocean seawater intakes can result in impingement and entrainment of marine organisms. In addition, brine or concentrate, the waste stream from seawater desalination, is about twice as dense as seawater itself and can accumulate on the seabed if not adequately mixed, harming marine organisms. However, seawater desalination is attractive where few options are available and where imported water itself is energy intensive, such as in Southern California. In places with uncertain deliveries desalination is considered "drought-proof." Thus, as with other water supply alternatives, decisions about desalination are dependent on costs, geography, options, and public opinion. Recent droughts in California have sparked renewed interest in ocean desalination but many proposals have been controversial, questioning the relative value as compared to potentially cheaper and more environmentally friendly alternatives (Szeptycki et al. 2016).

The example of San Diego highlights key factors for choosing ocean desalination: technology advancements, few alternatives, and sustainability and environmental considerations. In terms of technology, advancements in reverse osmosis technology, which uses a semipermeable membrane and high pressure to allow diffusion of water but holds back salts, is more cost effective than older thermal distillation systems. The energy required for the reverse osmosis step has dropped nearly eightfold since the 1970s (Phillip and Elimelech 2011).

In terms of options, San Diego lacks enough rainfall for stormwater capture to make a significant impact on the city's water supply, and the local geology isn't favorable for groundwater recharge. Thus, along with potable reuse, the city embarked on ocean desalination, resulting in the largest desalination plant in the US in Carlsbad, California, north of San Diego. The 190,000 m<sup>3</sup>/d (50 mgd) plant, which has been delivering water since December 2015, provides about 8% of San Diego's water, was built at a cost of \$1 billion including a major 16-km (10-mi) pipeline to deliver the water to the county's aqueducts. In 2019 the cost of this desalination water is \$1.9–2.2/m<sup>3</sup> (\$2,302–2,559/acre-ft) depending on the amount purchased (San Diego County Water Authority 2019).

When first built, the Carlsbad plant used cooling water from the adjacent Encina Power Station as the source water and discharged comingled brine to the ocean through the power station channel. This mitigated the environmental impacts of Carlsbad's seawater intake and brine disposal. With the power station decommissioned,

the plant is considering options on seawater intake and brine discharge (Poseidon Water 2017). Studies of brine discharge at the site show no changes in biological indicators. One conclusion is that to minimize environmental impacts discharge should target locations where anthropogenic activity has already impacted the natural environment (Petersen et al. 2019).

Additional seawater desalination plants are being considered along the coast, specifically at Huntington Beach and the Monterey Peninsula. However, these plants are controversial because of their potential marine impacts and energy demand. The California desalination policy favors subsurface intakes to reduce entrainment of larval fish, fish eggs, and other plankton (California State Water Resources Control Board 2015). But such systems are costly and larger systems may need screened open-water intakes owing to the size and cost of subsurface intakes, for which California policy requires after-the-fact mitigation for any impacts of entrainment (Szeptycki et al. 2016). An open ocean intake proposed for Huntington Beach would cost as much as the desalination plant itself (Poseidon Water 2019), while a subsurface seawater intake would be twice as expensive (Independent Scientific Technical Advisory Panel 2014). So, while technology advancements have reduced concerns about treatment costs, siting seawater desalination plants remains challenging.

### Brackish Desalination

Considering these factors, communities are alternatively looking at brackish water desalination instead of ocean water desalination because it is less costly, uses less energy, has fewer environmental impacts, and is not limited to coastal communities. For example, the Alameda County Water District produces 38,000 m<sup>3</sup>/d (10 mgd) from brackish groundwater. Because the brackish water has low salt content compared to seawater the costs are much less, about \$0.40/m<sup>3</sup> (\$500/acre-ft) (Alameda County Water District 2014). In addition, the concentrate is less salty than seawater, so discharge to an estuary or the ocean via commingling with wastewater discharge is feasible to mitigate environmental impacts (Rodman et al. 2018). The Calleguas Water District in Ventura County and the Inland Empire Utility Agency in San Bernardino County manage concentrate from brackish water desalination through long, salinity management pipelines (brine lines) to the ocean where there is adequate dilution with seawater for treatment (Calleguas Municipal Water District 2019; Santa Ana Watershed Project Authority 2019).

In the Bay Area, a partnership of five agencies is investigating whether regional brackish desalination is feasible (Contra Costa Water District 2014). They have identified a proposed site in eastern Contra Costa County where a treatment facility can provide 38,000–76,000 m<sup>3</sup>/day (10–20 mgd). A significant consideration was a location that could supply the water with low salinity, low energy costs, few permitting issues, and gain public acceptance. The project would utilize existing intake structures, pipelines, and outfalls and discharge would be blended with effluent from one or more of the nearby wastewater treatment plants. The costs for a 76,000 m<sup>3</sup>/day (20 mgd) plant would be about \$200 million, providing regionally-distributed water at about \$1.46/m<sup>3</sup> (\$1,800/acre-ft) with about one-third of the costs for regional distribution (Contra Costa Water District 2014; Valley Water 2019g). Having determined the project is technically feasible, the agencies are weighing the potential new supply with other options in their water portfolios (Contra Costa Water District et al. 2014).

### Outlook

For now, the future of desalination appears to be few ocean desalination facilities and many more brackish water plants. With phaseout

of once-through-cooling, the collocation of ocean desalination next to existing power plants will be rare. As of 2013 there were 23 brackish water desalination plants in California with 3 others in design or construction and 18 more proposed (Department of Water Resources 2014; DePoto and Gindi 1991). In contrast, beyond San Diego the only operating coastal ocean desalination plants are in Santa Barbara [11,400 m<sup>3</sup>/day (3 mgd)] and San City near Monterey [1,140 m<sup>3</sup>/day (0.3 mgd)]. While ocean desalination could contribute more to urban water supply, the extent to which this will happen is uncertain. Plans for Huntington Beach and Doheny Beach in Orange County, and the Monterey Peninsula project, are further along in terms of planning and discussion with perhaps another 12 in earlier stages of planning (Cooley and Donnelly 2012). The California public lacks adequate understanding of the benefits, costs, and limitations of desalination (Szeptycki et al. 2016). This highlights the need to fill knowledge gaps to inform decision-makers and the general public about the full costs and benefits of seawater desalination compared to other sources of water supply, and to recognize when it is truly needed (Szeptycki et al. 2016).

### Groundwater Banking: Out of Region but Not Out of Mind

Among the options discussed, groundwater banking is unique in that it involves out-of-region storage with deposits and withdrawals taking advantage of the state's water distribution infrastructure. This involves the deliberate storage of surface waters during wet years and withdrawal in dry years. The process may entail direct recharge with percolation ponds, or by in-lieu recharge wherein surface supplies are provided to groundwater users in lieu of pumping groundwater. The amount of groundwater that otherwise would have been pumped becomes banked water (Hanak and Stryjewski 2012). California's Water Code allows water marketing and banking provided sellers have the right to use the water and the water they sell is "wet," meaning not an unused "paper" right, and buyers must have the means to get the water from source to destination. California's groundwater banking operations in the Central Valley are hailed as the most successful in the world. A common element to the success of these operations is that the banked water is imported from a source outside the groundwater basin (Thomas et al. 2001). Water banking takes advantage of available, unused storage capacity and existing state-wide infrastructure with new infrastructure installed to complete cross-basin transfers (Fig. 6).

### State of Practice

The largest groundwater banking operations in California are centered in Kern County, near Bakersfield, and serve cities in both Northern and Southern California. Physical factors that make Kern County ideal for groundwater banking include geology and proximity to imported water supplies and delivery systems (Austin 2013; Parker 2010; Vaux 2002). As illustrated in Fig. 3, the California Aqueduct (State Water Project) is on the west, the Friant-Kern Canal (Central Valley Project) and Kern River on the east, and a Cross Valley Canal links these units. Because of excessive over-drafting in the 20th century, the groundwater aquifer in Kern County has a vast amount of groundwater storage potential with depth to groundwater of 50–200 m. It is closed, meaning no loss to surface waters once water is placed in the ground (Christian-Smith 2013; Scanlon et al. 2016).

Twenty groundwater banking operations are located in Kern County (Parker 2010). Some of these programs are for reliability of in-district supplies and others are partnerships between Kern





Fig. 6. (Color) Water banking facilities at the Semitropic Water Storage District allow water storage in Kern County, CA, and reverse flow of stored water back to the California Aqueduct. (Image by authors.)

County water districts and outside entities. The outside entities provide capital to help construct and maintain the banking infrastructure and bank their own surplus water in the groundwater basin. The participating water districts use the infrastructure and fees collected from their partners to help meet their consumptive use needs in return (Parker 2010). The three largest water banks—Arvin-Edison, Kern, and Semitropic—have a combined storage capacity of about 3.7 billion m<sup>3</sup> (3 million acre-ft) (Christian-Smith 2013; Kennedy/Jenks Consultants 2011; Semitropic Water Storage District 2018). Water banking capital costs are much lower than surface reservoirs and once the water is recharged there are no evaporative losses, which can exceed 0.9 m/year (3 ft/year) in Kern County (J. Gianquinto, personal communication, 2017).

In addition to these groundwater banking operations in the Central Valley, groundwater banking efforts are underway in urban areas, including those by the Water Replenishment District of Southern California and Orange County Water District (Austin 2013). Urban water banks can capitalize on the availability of recycled water in addition to traditional water sources, as previously discussed.

## Outlook

Water banking will likely become more common, particularly because it provides a way to take advantage of wet years and can help moderate swings in precipitation. Climate models for California predict a whiplash of drier dry spells interspersed with wetter wet years (Swain et al. 2018). Recharge banking systems can take advantage of those wet years. In 2019 for example, surface reservoirs were full and could not store more water (California Department of Water Resources 2019). This highlights an opportunity for coordinated effort to use more of the flood runoff to recharge groundwater. However, recharge projects require measured deliveries and large flows can be missed (Parker 2010). Another issue is ensuring water quality is consistent when water sources are traded or blended; the state has a nondegradation policy for pump-back water that is put into the California Aqueduct, although blending within the aqueduct can be considered for groups coordinating inputs to maintain or improve water quality (Wisheropp 2016).

In urban areas, land with high recharge potential should be reserved to capture high flow events and restore groundwater resources. One key example of this is Zone 7 Water Agency in Livermore-Amador Valley, which is reserving former and future

quarry properties for groundwater recharge operations as they become available (Church et al. 2014).

## Conclusion: An Expanded Toolkit for Urban Water Challenges

California's 21st-century urban water landscape is looking much different than earlier years. Elected officials, utilities, and water agencies recognize the challenges of maintaining the state's economic growth and social well-being in the face of uncertain water deliveries because of climate change, population increase, and competing demands for water imports. While much remains to be done, cities are taking actions to secure more sustainable water supplies. Cities will continue to diversify their water portfolio options, with strategic efforts differing by region and community preference (Fig. 7). The strategies outlined here can help address these goals. These changes will be transformative, such as the long-term plan for the City and County of Los Angeles to capture stormwater for water supply and recycle all their wastewater with the provision of 70% local water by 2035 compared to 10%–15% historically.

In general, conservation and efficiency are the most economical solutions to reduce water demand and therefore better utilize urban water supply (Cooley et al. 2019). Large stormwater capture projects are the next most cost effective at about \$0.40–0.81/m<sup>3</sup> (\$500–1,000/acre-ft) (Southern California Water Coalition Stormwater Task Force 2018). Seawater desalination is the most expensive with costs in the range of \$1.87 to over \$4.06/m<sup>3</sup> (\$2,300 to over \$5,000/acre-ft) depending on size and technologies for intakes and discharges, while brackish water desalination is much less expensive because of lower energy and treatment costs, ca. \$0.81–1.30/m<sup>3</sup> (\$1,000–1,600/acre-ft) (Cooley et al. 2019; Schmalz 2018; Szeptycki et al. 2016). Generally, the cost of municipal water recycling is between that of stormwater capture for water supply and seawater desalination (Cooley et al. 2019). Nonpotable reuse is less expensive than potable reuse because of fewer treatment requirements, but the high cost of building separate nonpotable reuse pipe networks makes potable reuse attractive in the future.

However, as noted, the outlook for each strategy has implementation issues and there is no one-size-fits-all approach to sustainable water futures. One clear need is to develop an implementable “One Water” approach to managing urban water. Too often cities or water districts optimize around one aspect of the water portfolio, which is a legacy of water, wastewater, and stormwater often being locally managed by different entities. Further, cities and departments are reluctant to give up or share ownership. A possible solution is for sustained, regional discussions and actions on the potential, payoff, and partnerships for better integrated water management. That is, teaming together as opposed to going alone can provide benefits in terms of risk, reliability and resilience (Gonzales and Ajami 2019).

The Monterey/Salinas region along California's Central Coast is an example of a new era of “One Water” management that is using all the water it can get to achieve more sustainable supplies. Termed “Monterey One Water,” expansions to the wastewater treatment facility include advanced water purification for indirect potable reuse via groundwater replenishment. This project is the first of its kind to not use just wastewater but a variety of waters from the region including stormwater, food industry processing water, and agricultural drainage water. The local utility already provides recycled water for irrigation of 4,860 ha (12,000 acres) of freshly edible food crops, and the \$100 million expansion for indirect potable reuse helps sustain that by bringing in more sources of water for reuse, while protecting the quality of the regional groundwater basin. This is a model project of regional collaboration.

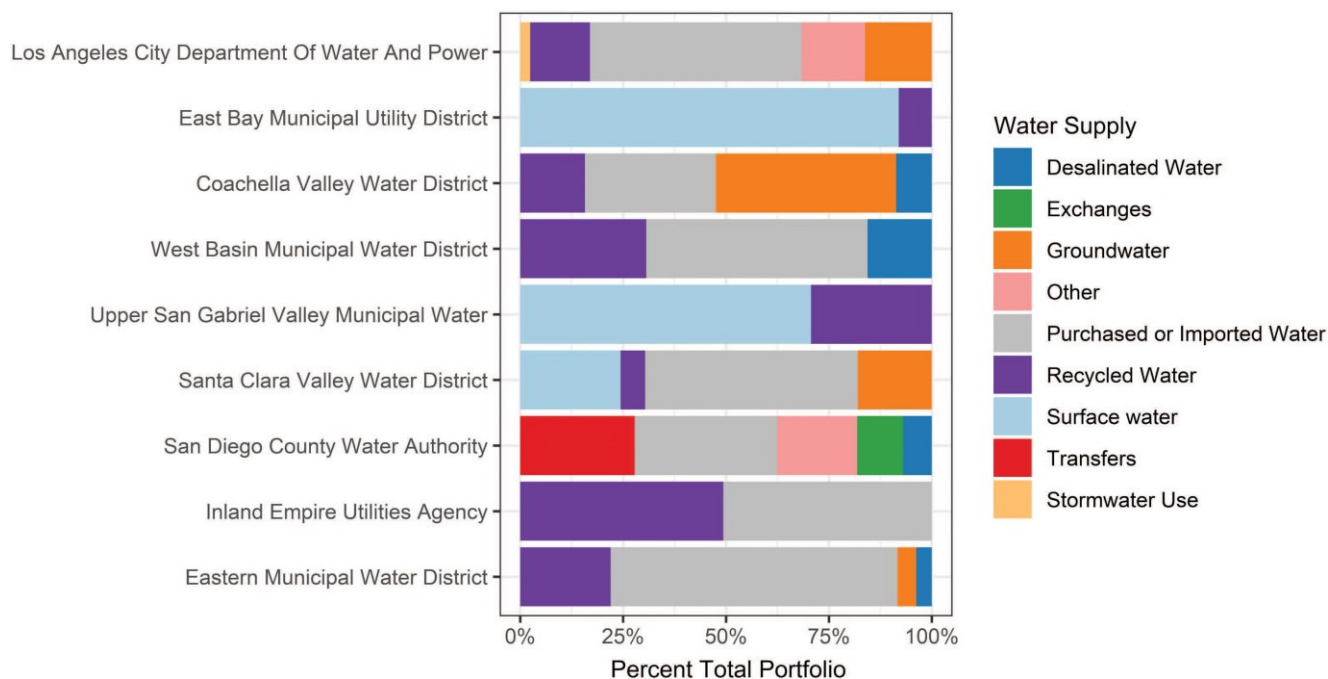


Fig. 7. (Color) Projected water supply portfolios for select water management agencies in 2040. Data extracted from California's Water Use Efficiency data portal for submitted 2015 Urban Water Management Plans. The category "other" includes conservation and member agency supplies for wholesalers. Each water supplier has a different approach to water supply planning, with some focused on few sources and others with a broader portfolio depending on geography, values, and existing urban form. (Data from California Department of Water Resources 2015.)

Decentralized and centralized systems for water reuse and reliable processes for stormwater capture, treatment, and recharge will benefit from new technologies. But new water supply approaches require that some cities take the risk of being the first to pioneer new technologies and management structures (Kiparsky et al. 2013). Such efforts are prompted by severe water stress and the ability to pay for new approaches that are expensive compared to older subsidized options. As illustrated by examples from California, new approaches are more readily adopted once a period of piloting and demonstration-scale projects have shown benefits (Luthy and Sedlak 2015). This lowers the financial risk and costs of failure, and lowers the barrier to wider adoption. A broader view of urban watershed stewardship is needed for protection of stormwater and wastewater from toxic substances, leading to a view that whatever enters these systems will need to be removed as part of an expanded water supply portfolio (Harris-Lovett and Sedlak 2015).

Communities throughout California are actively progressing toward more sustainable water management, largely by adopting the five key practices discussed in this paper. Conservation and efficiency are one essential piece, particularly to limit outdoor water use and minimize leaks in distribution networks. Stormwater capture and treatment can be valuable in coastal cities where stormwater management can provide benefits beyond water supply such as water quality improvement and urban green spaces. California continues to be a leader in water reuse, and upcoming state and federal policies will further promote growth in water reuse. The trend is for centralized potable reuse at the city- and district-scale, and nonpotable reuse in decentralized, on-site systems, e.g., at tech campuses, large buildings, and office parks. Desalination, once a last resort, is becoming more economical and technologically feasible, particularly for brackish sources. Lastly, groundwater banking showcases the importance of taking a holistic view when

managing statewide water resources. All together, these five metaphorical "taps" will make California's water portfolio more sustainable and diversified—essential qualities for addressing the state's 21st-century urban water challenges.

## Data Availability Statement

All data, models, and code generated or used during the study appear in the published article.

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