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The cost of alternative urban water supply and efficiency options in California

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Abstract

Urban communities, farms, businesses, and natural ecosystems depend upon adequate, reliable, and affordable supplies of clean water. As populations and economies grow and as climatic changes alter both water supply and demand, traditional options for meeting freshwater needs are becoming less available, reliable, and effective. As we approach peak water constraints on traditional water supplies, more efforts needed to reduce water demands through a wide range of conservation and efficiency technologies and policies, and to develop alternative, non-traditional water sources. A key factor in the adoption of these strategies is their economic feasibility; yet, only limited and often confusing data are available on their relative costs. To fill this gap, this analysis evaluates the costs of four groups of alternatives for urban supply and demand based on data and analysis in the California context: stormwater capture; water recycling and reuse; brackish and seawater desalination; and a range of water conservation and efficiency measures. We also describe some important co-benefits or avoided costs, such as reducing water withdrawals from surface water bodies or polluted runoff in coastal waterways. While difficult to quantify, such benefits are economically relevant, and we highlight areas where further research and analysis are needed to improve estimates presented here. All of the water-use efficiency options are far less costly than traditional or alternative supply systems with the exception of some of the most expensive landscape water reduction options. The water treatment and reuse systems and the urban stormwater capture projects are more costly per unit of water produced but still less expensive than seawater desalination—the most expensive option evaluated.

Introduction

As peak water limits and pressures over freshwater resources grow and as traditional sources of supply become harder to find and obtain, new strategies to expand water supply and reduce water demand are receiving increased attention and scrutiny (Gleick and Palaniappan 2010). Recent work to evaluate these options in California suggests that shifting to these alternatives has the potential to reduce pressures on natural ecosystems, increase the reliability of both agricultural and urban water systems, and resolve political tensions over water policies (Cooley *et al* 2009, Gleick *et al* 2014, Heberger *et al* 2014).

Economic feasibility is a key factor in the adoption of these alternatives, and several studies have estimated their relative costs. For example, Perrone and Rohde (2016) found that proposed managed aquifer recharge projects in California had a median cost of \$0.33 per cubic meter, although costs were highly variable depending on the source water, i.e., surface water (\$0.27 per cubic meter), stormwater (\$1.26 per cubic meter), wastewater (\$0.71 per cubic meter), and a blend of two or more source waters (\$0.32 per cubic meter). Cooley and Ajami (2012) examined the cost of proposed and recently-constructed seawater desalination plants in Australia and in the United States and found that costs varied dramatically from \$0.89 to \$5.30 per cubic meter. Arroyo and Shirazi (2012) found that the production cost of brackish groundwater desalination in Texas ranged from \$0.29 to \$0.63 per cubic meter. Comparing costs across these studies are hindered by differences in analytical approach, assumptions, and a host of site-specific factors. In addition, cost estimates for urban water-efficiency measures are not typically available in ways that can be directly compared to supply-side measures.

We provide here a research framework for comparing different supply and demand options, and we assess estimates of the costs of four groups of alternatives: stormwater capture; water recycling and reuse; brackish and seawater desalination; and a range of urban water conservation and efficiency measures in the California context, expressed in dollars per unit water provided or saved. These estimates are produced by collecting and analyzing recent project cost proposals, actual costs of new projects, and selected current literature. Some of these options also provide important co-benefits, such as reducing water withdrawals from surface water bodies or polluted runoff in coastal waterways. While the economic values of most environmental costs and benefits are not well documented, such benefits are economically relevant, and we highlight areas where further research and analysis are needed.

Methods and approach

The methods used here to estimate the levelized (annualized) cost of water are modified from the well-developed work in energy economics. This method converts a stream of costs and benefits into an equivalent uniform annual value, accounts for the full capital and operating costs of a project or device over its useful life, and allows for a comparison of alternative projects with different scales of operations, investment and operating periods, or both (Jaffe and Stavins 1994, Short *et al* 1995, Gillingham *et al* 2009). For each alternative, a ratio of net costs (cost minus benefits) to the output achieved in physical terms is determined. For the purposes of this assessment, the output is a unit of water in the case of a new supply, or a unit of water *savings* in the case of an efficiency measure. The levelized cost of water is expressed as 2015 dollars per cubic meter of water. The methodology for evaluating water-supply and efficiency options are described below and additional details are provided in Cooley and Phurisamban (2017).

Water-supply projects

For water-supply projects, the cost of water is developed from the capital required to build a facility, the associated operation and maintenance (O&M) costs over the facility lifetime, replacement costs, a discount rate, expected facility lifetime, water production capacity, and water yield. Capital costs are fixed, one-time expenses needed to bring a project into operation and include structures, land, equipment, labor, and allowances for unexpected costs or contingencies, typically assumed to be 20 to 30 percent of a project's cost. We adopt a 6% discount rate, which is recommended by the California Department of Water Resources for economic and financial analyses involving proposed water projects (California Department of Water Resources (CDWR) 2008). Although this rate is relatively high, it is chosen to maintain conceptual consistency between DWR-funded projects and those funded by other sources.

These costs are annualized over the life of the project and divided by the water production capacity. For projects that are currently in operation, average annual O&M costs are used when possible; otherwise, we use values from the most recent year available. The O&M costs are also annualized over the life of the project and divided by the annual water yield. The annualized capital and variable costs are then combined to generate the cost of water in 2015 dollars per unit water. Because project- and site-specific factors affect the cost of projects, we include the 25th and 75th percentiles of the cost range for each water-supply option, which are represented in this report as the low and high values, respectively.

As an additional point of reference, it would be informative to compare these alternative water-supply options with the cost of building new large-scale traditional supply additions, such as dams. The potential for such options in many regions, including California, is now extremely limited, because the best sites have typically already been developed, significant subsidized funding from federal agencies is no longer available, and regulatory restrictions to protect remaining ecologically valuable rivers constrain new dam development. In addition, computing the costs of new projects is complicated, as it is for the systems evaluated here, by uncertainties over construction and financing costs, the actual water yield of new dams, and a wide range of impacts that are difficult to quantify, including lost ecological valuation. Nevertheless, a rough estimate of the projected costs of the most likely new surface water storage projects in California is on the order of $0.40 to $0.80 per cubic meter, excluding additional costs of moving and treating stored water to end users, using the water, and then treating subsequent wastewater (California Department of Water Resources (CDWR) 2007, 2014c).

Water efficiency measures

We define here a water-efficiency measure as an approach or technology that reduces the amount of water required to produce a good or service. For most water uses, improved efficiency is a direct alternative to new or expanded physical water supply and can also be evaluated using the levelized-cost approach. For this analysis, 'conserved water' refers to the water savings associated with an efficiency measure. We calculate the cost of conserved water from efficiency savings based on the incremental cost of purchasing and installing a new water-efficient device and

Table 1. Description of non-residential water efficiency measures evaluated in this study.

	Description
Toilet	Device for removing human waste
Urinal	Device for removing human waste
Showerhead	Overhead perforated nozzle for spraying water on the body
Clothes washer	Device for washing clothes that uses a horizontal rather than vertical axis, thereby reducing the amount of water required to submerge clothes
Landscape conversion	Replacing cool-season turfgrass or other high water-use plants with plants that use less water
Faucet aerator	Device placed on a faucet to restrict flow rates
Pre-rinse spray valve	Device used in commercial and institutional kitchens to remove food waste from dishes prior to dishwashing
Medical steam sterilizer modification	Jacket and chamber retrofit kit to reduce water use for disinfecting equipment used in hospitals, clinics, and laboratories while in ready/stand by mode
Connectionless food steamer	Device used in the food sector that captures and reuses steam to heat food
Ice machine	Typically a plumbed machine for generating large volumes of ice
Waterless wok stove	Device commonly used in Asian restaurants that uses air rather than water for cooling
Rotary nozzle	Device that can be placed on most pop-up sprinklers to slowly deliver multiple rotating streams of water rather than a fixed spray
Water broom	Device that uses high-pressure water for cleaning hard surfaces, rather than a traditional hose and nozzle

any changes in operation and maintenance costs resulting from the investment (excluding water bill payments). This cost is annualized over the life of the device and divided by the average annual volume of water conserved, resulting in an estimate of the cost of conserved water expressed in 2015 dollars per unit water.

Many measures are available to reduce residential and non-residential water use. We examine the cost of conserved water for reducing water distribution system losses and for implementing various end-use efficiency measures in the residential and non-residential sectors. For the residential sector, we examine high-efficiency toilets, showerheads, clothes washers, dishwashers, and landscape conversions. For the non-residential sector, we examine a set of efficiency measures for common end uses found in a wide range of businesses, as well as some devices for specific commercial, industrial, or institutional end uses. Table 1 provides a short description of each of the non-residential efficiency measures evaluated in this study. Additional measures with high water- and energy-saving potential, such as cooling tower retrofits, were not included in this study due to data limitations.

Data on water savings are based on available literature, industry estimates, operational experience, and expert advice. The cost of the efficiency measures is based on a review of technologies available from retailers (additional detail on the methodology and data sources can be found in appendix B of Cooley and Phurisamban (2017)). Accurate, transparent, and consistent assessments of water-efficiency measures are needed to demonstrate the performance, and ultimately the value, of these investments.

For most efficiency measures, we assume that the customer is in the market for a new device because the old device has reached the end of its useful life, referred to as natural replacement. To estimate water savings and incremental cost under natural replacement, we develop two scenarios: a baseline and an efficient scenario. For the baseline scenario, we assume that the customer replaces the old device with a device that uses the same amount of water. For our efficient scenario, we assume that the customer replaces the old device with a new, efficient model. Annual water savings are then calculated as the difference in water use between the two options, multiplied by the estimated average frequency of use. The incremental cost is the cost difference between a new efficient and a new inefficient device and is based on price surveys of commercially available models[3].

As noted above, natural replacement is assumed for most measures. For some measures (i.e., faucet aerators, water brooms, some landscape conversions, and medical steam sterilizer modifications), we assume that the customer would not have made the investment otherwise. In these cases, the cost analysis is based on the full cost of the efficiency measure.

Efficiency measures are evaluated from the perspective of the customer. We do not, however, evaluate water bill savings as a benefit to customers. Instead, we calculate the cost of conserved water based on the investment required of the customer and any changes in operation and maintenance costs the customer would experience from the investment. Water bill savings are not included in this analysis because we are solving for the

[3] We note that 3.5 gpf toilets are no longer available, and thus we were unable to determine the incremental cost of the more efficient device. We therefore assume that a new 3.5 gpf toilet would be 10% less expensive than a new 1.6 gpf toilet based on Gleick et al (2003).

comparative cost of water supply. Additional co-benefits (e.g., ecosystem benefits) are not evaluated here but could further improve the economics of making these investments.

Some efficiency measures have a 'negative' cost, which means that reductions in operation and maintenance expense that accrue over the lifetime of the device exceed the cost of the water efficiency investment. This is especially true for efficiency measures that save customers energy, but also for those that provide savings in labor, fertilizer or pesticide use, and reductions in wastewater treatment costs—sometimes called 'avoided costs.' For example, a high-efficiency clothes washer costs more than a less-efficient model; however, over its lifetime it uses less energy and produces less wastewater than inefficient models, thereby reducing household energy and wastewater bills[4]. Over the estimated 14-year life of the device, the reductions in energy and wastewater bills are more than sufficient to offset the cost of the more efficient model, resulting in a negative cost of conserved water.

Data sources and limitations

The analysis here is based on the cost and yield of water-supply projects and conservation and efficiency measures implemented in California and related regions. Many such projects have been pursued in California, which provides a good data set. Additional specific information on some of these projects and data sources is available in (Cooley and Phurisamban 2017). Data sources for efficiency measures include end-use and field studies, market price search, and other online resources. Data for water-supply projects are developed from analyses by state agencies and local water utilities. To the extent possible, we rely on actual project costs. We also evaluate data from proposed projects, which may not represent final costs resulting from design changes or errors, construction delays, regulatory and price effects, or other factors.

There are often additional costs and benefits for some water-supply and efficiency options that are inadequately quantified and thus could not be included here. We try to identify these explicitly. For example, all water withdrawals from natural ecosystems impose a 'cost' that is rarely and inconsistently evaluated and almost never included in water prices (Baron *et al* 2002, Richter *et al* 2003, Farber *et al* 2006). A stormwater capture project may reduce polluted runoff into waterways, which reduces downstream water treatment costs and provides environmental benefits. A recycled water project could produce environmental benefits by reducing the discharge of treated wastewater into an estuary or the ocean. Integrating these benefits into the economic analysis would cut the cost of water. Conversely, the reuse of recycled water in an upper watershed could reduce water available for important downstream uses, such as for fish habitat or recreation, and integrating these costs may increase the cost of water. Additional, often site-specific, research is needed to quantify these costs and benefits.

Stormwater capture

For more than a century, stormwater has been viewed as a liability, and most urbanized areas were designed to remove this water as quickly as possible for both protection of water quality and flood relief. Urban runoff washes pesticides, metals, and other pollutants into inland and coastal waterways. Both the US Environment Protection Agency (US EPA) and the California State Water Resources Control Board (State Water Board) have determined that 'stormwater and urban runoff are significant sources of water pollution that can threaten aquatic life and public health' (California State Water Resources Control Board (SWRCB) 2014). Moreover, capturing stormwater can provide a number of indirect benefits, including enhancing wildlife habitat, reducing the urban heat island effect, improving community cohesion, and reducing greenhouse gas emissions (Center for Neighborhood Technology (CNT) 2010).

New efforts are underway to use stormwater to augment local supplies. Rain barrels or cisterns can be used at a household or building scale to capture and store water onsite. Bioswales and spreading basins can capture stormwater on a larger scale. In 2009, the State Water Board set a California goal to increase the annual use of stormwater over 2007 levels by over 600 million cubic meters (500,000 acre-feet) by 2020, and over one billion cubic meters by 2030 (California State Water Resources Control Board (SWRCB) 2013). For context, total urban water use in California is currently approximately 7.5 billion cubic meters per year, with around 60 percent going to the residential sector, 15% to commercial use, and the remainder to industrial, large landscapes, and conveyance losses. They are now implementing a strategy to better manage this resource and optimize its use over the next decade (California State Water Resources Control Board (SWRCB) 2016). In addition, California's 2012 Rainwater Capture Act (AB 275) authorizes residential users and public and private utilities to install and operate rainwater capture systems for landscape use. Regulatory agencies, such as the Los Angeles Regional

[4] While some pay a flat charge for wastewater services, others pay a rate based on an estimate of the volume of wastewater generated. Based on a survey of wastewater utilities serving 10.3 million Californians, we estimate that the population-weighted average cost for wastewater service is \$0.92 /m^3 (\$3.49 per thousand gallons) for residential customers and \$1.12 /m^3 (\$4.24 per thousand gallons) for non-residential customers.

Table 2. Stormwater capture and reuse cost.

	Sample Size	Stormwater capture and recharge ($\$/m^3$)			Groundwater pumping and treatment ($\$/m^3$)	Total cost ($\$/m^3$)		
		Low	Median	High		Low	Median	High
Small Project ($\leqslant$1.85 million m^3)	8	\$0.48	\$0.95	\$1.04	\$0.28	\$0.76	\$1.23	\$1.32
Large Project (8.0–10.0 million m^3)	2	\$0.19	\$0.20	\$0.21		\$0.46	\$0.48	\$0.49

Notes: All cost estimates are rounded to the nearest cent and are shown in year 2015 dollars. Low and high costs represent the 25th and 75th percentile, respectively, of the estimated cost range. However, we report the full cost range for large stormwater capture projects as only two projects are included in this analysis. Groundwater pumping and treatment are based on a median cost of $0.08/m^3 and $0.19/m^3, respectively. Data on stormwater capture and recharge are from the California State Water Board FAAST database for Proposition 84 Storm Water Grant Program, the Department of Water Resources Proposition 84 Implementation Grant Program and Proposition 1E Stormwater Flood Management, and the Los Angeles Department of Water and Power Stormwater Capture Master Plan. Data on groundwater pumping and treatment costs were calculated based on OCWD (2015), Upper Kings Basin IRWM Authority (2013), LACFCD (2013), City of Pasadena (2011), LADWP (2010), and MWDSC (2007). Basic groundwater treatment involves an addition of chlorine and polyphosphates if contaminants in the water do not exceed the Maximum Contaminant Levels (MCLs) under the Safe Drinking Water Act. For high-quality groundwater, treatment cost would be minimal.

Water Board, are offering incentives for additional stormwater capture by basing Clean Water Act compliance on the volume of stormwater captured.

Local efforts to capture stormwater for surface and groundwater are also expanding. For example, the Fresno-Clovis metropolitan area captures and recharges about 21 million cubic meters a year (California Department of Water Resources (CDWR) 2014d), while the Los Angeles Department of Water and Power and its partners actively capture about 35 million cubic meters of stormwater annually and plan to recharge an additional 84 million to 140 million cubic meters per year by 2035 (Geosyntec Consultants 2015). An analysis by Garrison *et al* (2014) suggests that stormwater capture in urbanized Southern California and the San Francisco Bay Area could add 520 million to 780 million cubic meters per year to local water supplies.

Cost of stormwater capture

Our analysis evaluates 10 proposed stormwater detention and recharge projects from throughout California, supported by a range of state and local grant and finance programs.

Table 2 shows the range of cost estimates for centralized stormwater capture projects, such as spreading basins. Projects are grouped by size, defining small projects as those with an annual yield of 350,000 to 1.85 million cubic meters and large projects as those with an annual yield of 8 to 10 million cubic meters (no projects between these size categories have been developed). We do not include estimates for individual distributed stormwater capture systems, such as rain barrels or cisterns that may be installed at a household- or building-scale, due to data limitations.

Variability in project type, design, and location results in a wide range of costs for stormwater capture projects. The cost of small centralized projects ranges from \$0.48 to \$1.05/m^3 with a median cost of \$0.95/m^3. Projects at the higher end of the cost range reflect those requiring additional infrastructure to convey stormwater to recharge areas. Large centralized projects exhibit significant economies of scale with a much lower cost of \$0.19 to \$0.21/m^3 and a median cost of \$0.20/m^3.

In addition to the cost to capture and store stormwater, we add the cost to treat it to drinking water standards before use in order to make a comparable comparison with the other options evaluated here. These costs will vary based on groundwater quality, well depth, and other factors. We estimate that groundwater pumping would cost \$0.08/m^3 and treatment would cost \$0.19/m^3. Thus, the total cost of small projects ranges from \$0.76 to \$1.32/m^3 with a median cost of \$1.23/m^3. The total cost of large projects ranges from \$0.46 to 0.49/m^3 with a median cost of \$0.48/m^3.

As noted earlier, some costs and benefits have not been quantified, including reducing pollution in nearby waterways, avoiding the cost of Clean Water Act compliance, providing habitat, minimizing flooding, beautifying neighborhoods, and providing recreational opportunities. Integrating such co-benefits into the economic analysis would further reduce the cost of water from stormwater projects. We also note that if stormwater or wastewater does not need to be treated to potable standards, the costs presented here will be substantially lower.

Recycled water

The terms 'water reuse' and 'water recycling' are used interchangeably to refer to wastewater that is intentionally captured, treated, and beneficially reused. Municipal recycled water refers to municipal wastewater collected from homes and businesses and piped to a reclamation facility where it is treatment to meet the standards needed for reuse. Some forms of wastewater can be reused onsite with little or no treatment. For example, a home may have a graywater system that collects wastewater from a clothes washer and uses it to irrigate a garden, or an office building may be equipped with a wastewater treatment system to reuse a portion of the wastewater for flushing toilets and other non-potable applications. This analysis focuses solely on municipal recycled water because limited data are currently available on the costs of individual onsite reuse systems.

Recycled municipal water in various forms has been used for more than a century around the world. The city of Windhoek, Namibia has used recycled water directly for a portion of their urban water supply for more than three decades (Jiménez and Asano 2008). Israel now recycles and reuses over 80 percent of their urban wastewater for industrial and agricultural purposes (Reznik *et al* 2017). The earliest uses of recycled water in California were for agriculture (Newton *et al* 2012) and today there are many recycled water applications, including for geothermal energy production, groundwater recharge, landscape and agricultural irrigation, and industrial use. Between 1970 and 2009, the beneficial use of recycled water increased almost fourfold, due in part to changes in state law and policy to support water recycling infrastructure, production, and use. According to the most recent statewide survey, California beneficially reuses about 880 million cubic meters of recycled water per year (State Water Board and DWR 2017) and an analysis by Cooley *et al* estimated that the technical potential for water reuse in California was at least an additional 1.5 to 2.2 billion cubic meters per year (Cooley *et al* 2014). As noted earlier, current urban water use in California is around 7.5 billion cubic meters per year. Seventy percent of water reuse in California is for urban use and groundwater recharge; 30 percent is for the agricultural sector.

Cost of water recycling and reuse

Data on the cost of water recycling projects were developed from direct correspondence with water agencies, published documents on agency websites, and water recycling project grant proposals. While recycled water projects have been in operation for decades, complete cost information for older projects is not available. In addition, we do not evaluate projects outside of the United States because of non-comparable costs of land, labor, energy, and other factors. We provide here the cost of proposed projects as well as project upgrades designed to augment water supplies. A total of 13 projects are evaluated: seven non-potable reuse projects and six indirect potable reuse projects. The source water for most projects in this analysis is secondary effluent from nearby wastewater treatment plant.

Non-potable reuse requires less treatment than other types of reuse and is distributed to customers in a separate water distribution system typically for landscape and agricultural irrigation, habitat restoration, and certain industrial processes, such as for concrete production and cooling water. For indirect potable reuse, high-quality wastewater is put into an environmental system, such as an aquifer or reservoir, and then treated again to drinking water standards before distribution. Indirect potable reuse has been practiced in California since the early 1960s, and a growing number of projects are using this approach (Crook 2010). Projects like the direct potable reuse system in Namibia are not yet proposed for California, where significant non-potable demands can be met at lower cost and with less public concern.

Table 3 shows cost estimates for non-potable and indirect potable water reuse projects. Water recycling for non-potable reuse is typically less expensive than indirect potable reuse because of the lower treatment needs. However, non-potable reuse projects that cannot take advantage of an existing distribution system may cost more than indirect potable reuse project because of the need to build or expand such a system. The cost of small, non-potable reuse facilities (under 12 million cubic meters capacity) ranges from \$0.44 to $0.93/m^3$, with a median cost of $\$0.48/m^3$. Expanding non-potable reuse may require the installation or extension of a separate water distribution system, which would result in an additional cost of $\$0.77/m^3$[5]. Thus, the total cost for a small, non-potable reuse project would range from \$1.21 to $1.70/m^3$, with a median cost of $\$1.25/m^3$. Project costs for large projects are not available; however, economies of scale may reduce overall costs.

The costs of small indirect potable reuse projects range from \$1.21 to $\$1.80/m^3$, with a median cost of $\$1.50/m^3$. The cost of larger projects ranges from \$0.91 to $\$1.28/m^3$, with a median cost of $\$1.06/m^3$. Energy is often the single largest O&M expense, accounting for 30% to 55% of the O&M costs. If the water is used to

[5] Costs are based on three projects in our non-potable reuse project sample and seven other 'purple pipe' (separate non-potable water distribution systems) projects from Proposition 84 Round 1 and 2 implementation grant proposals. Low-end value reflects costs from our sample of non-potable reuse projects. We note that the cost of a distribution system is typically driven by the length of that system rather than the volume of water delivered; however, in the absence of better data, we normalized the cost by volume of water delivered.

Table 3. Water recycling and reuse cost.

	Sample size	Non-potable reuse facility ($/m^3)			Distribution ($/m^3)	Total cost of non-potable reuse ($/m^3)		
		Low	Median	High		Low	Median	High
Small Project (⩽ 12 million m^3)	7	$0.44	$0.48	$0.93	$0.77	$1.21	$1.25	$1.70
		Indirect potable reuse facility ($/m^3)			**Conveyance, groundwater pumping and treatment ($/m^3)**	**Total cost of indirect potable reuse ($/m^3)**		
		Low	Median	High		Low	Median	High
Small Project (⩽12 million m^3)	3	$1.21	$1.50	$1.80	$0.37	$1.59	$1.88	$2.17
Large project (>12 million m^3)	3	$0.91	$1.06	$1.28		$1.28	$1.43	$1.66

Notes: All cost estimates are rounded to the nearest cent and are shown in year 2015 dollars. Low and high costs represent the 25th and 75th percentile, respectively, of the estimated cost range. Distribution for non-potable reuse refers to the median cost of a purple-pipe distribution system. Additional costs for distribution, pumping, and treatment for indirect potable reuse refers to the median cost of operating and maintaining finished water pumps and pipelines to transport water to an environmental buffer (e.g., a groundwater recharge basin or reservoir), plus the cost to extract and treat the groundwater. The low and median costs for small non-potable reuse projects are the same due to rounding. Data on the cost of water recycling projects were developed from direct correspondence with water agencies, published documents on agency websites, and water recycling project grant proposals. Data on the cost of distribution is based on three projects in our non-potable reuse project sample and seven other purple pipe projects from Proposition 84 Round 1 and 2 implementation grant proposals. We note that the cost of a distribution system is typically driven by the length of that system rather than the volume of water delivered; however, in the absence of better data, we normalized the cost by volume of water delivered. Conveyance, groundwater pumping, and treatment costs were drawn from OCWD (2015), Upper Kings Basin IRWM Authority (2013), LACFCD (2013), City of Pasadena (2011), LADWP (2010), and MWDSC (2007).

recharge groundwater prior to use, there is an additional cost of $0.37/m^3 to convey the water to a groundwater basin, extract it from the aquifer, and treat it to drinking water standards. Thus, the total cost for small indirect potable reuse projects range from $1.59 to $2.17/m^3 with a median cost of $1.88/m^3. The total cost for large indirect potable reuse projects ranges from $1.28 to $1.66/m^3, with a median cost of $1.43/m^3.

Non-quantified costs and benefits of water reuse projects can include the reduction of pollution discharges into coastal areas and the ocean and the potential to improve groundwater quality by recharging groundwater aquifers with highly-treated wastewater. Integrating these benefits into the economic analysis would reduce the costs calculated here. Conversely, recycling and reusing water in an upper watershed could reduce water available for important downstream uses, such as for fish habitat or recreation, potentially increasing the final cost of water.

Because wastewater can be treated to highly purified levels, it is technically feasible to directly return that water to the drinking water system, as done in Namibia. The most significant barrier to this is public opinion and the absence of a regulatory framework, rather than any technical or water-quality obstacle. If direct potable reuse becomes feasible, the costs discussed here would likely be lower because of the potential to greatly reduce or eliminate the need for additional distribution and treatment costs associated with indirect potable reuse systems.

Desalination

Desalination refers to processes that remove salts from water. Most commercial plants focused on seawater or brackish water desalination (table 4). Modern plants typically use reverse osmosis membranes. Interest in desalination in California began in the late 1950s. The state's first commercial desalination plant treated brackish groundwater for residents of Coalinga in Fresno County (Crittenden *et al* 2012). By 2013, there were 23 brackish groundwater desalination plants, with a combined annual capacity of 170 million cubic meters (California Department of Water Resources (CDWR) 2014b). Seawater desalination has so far had only limited application in California. There were four seawater desalination plants with a combined capacity of 690,000 cubic meters in operation along the California coast in 2013 (CDWR 2014b). More recently, the Carlsbad desalination plant, which has a capacity of 69 million cubic meters, has been in operation since December 2015, and another set of plants are in various stages of planning and review (Pacific Institute 2015).

Table 4. Relative salinity of water.

Type of water	Relative salinity (mg/l TDS)
Freshwater	Less than 1,000
Brackish water	1,000–30,000
Seawater	30,000–50,000
Natural brine	1,000 to slurries

Table 5. Seawater and brackish water desalination cost.

	Sample size	Brackish water desalination facility ($/m^3)			Integration ($/m^3)	Total cost of brackish water desalination project ($/m^3)		
		Low	Median	High		Low	Median	High
Small Project (⩽20 million m^3)	11	$0.73	$1.22	$1.40	$0.09	$0.83	$1.31	$1.49
Large project (>20 million m^3)	5	$0.68	$0.82	$0.99		$0.77	$0.91	$1.08
		Seawater desalination facility ($/AF)			Integration ($/AF)	Total cost of seawater desalination project ($/AF)		
		Low	Median	High		Low	Median	High
Small Project (⩽20 million m^3)	3	$2.01	$2.13	$3.31	$0.16	$2.17	$2.29	$3.47
Large project (>20 million m^3)	5	$1.53	$1.57	$1.90		$1.69	$1.72	$2.06

Notes: All cost estimates are rounded to the nearest cent and are shown in year 2015 dollars. Low and high costs represent the 25th and 75th percentile, respectively, of the estimated cost range. Integration cost is based on the median cost to integrate the desalinated water into the drinking water distribution system. For large-scale desalination projects, the low and median costs appear to be the same due to rounding.

Cost of desalination

Seawater desalination costs vary widely with the salinity of the water, labor and land costs, assumptions about energy and equipment O&M costs, and financing options. The data presented here are for California and are based on engineering estimates and operational information from local facilities. Other regions will have different conditions and cost details. Data on brackish water desalination facilities are more readily available because water districts have been treating brackish groundwater for several decades. However, the capital cost for facilities that have been in operation for more than ten years is difficult to obtain and may not be relevant for estimating current costs. For these projects, we include the cost of expansion, although note that these values likely reflect the lower bound of new project costs.

We estimate that the cost of large seawater desalination facilities, defined as those with a capacity of at least 12 million m^3, ranges from $1.53 to $1.90/m^3, with a median cost of $1.57/m^3. The cost of smaller seawater desalination plants ranges from $2.10 to $3.31/m^3, with a median cost of $2.13/m^3 (table 5). Seawater desalination plants must also be integrated into utility drinking water systems, which adds around $0.16/m^3 raising the total cost of large systems to between $1.69 and $2.06/m^3, with a median cost of $1.72/m^3.

Brackish water has lower salt and total dissolved solids (TDS) levels than seawater, reducing its cost relative to seawater desalination. We estimate that the cost of a large project with a capacity of more than 20 million m^3 per year ranges from $0.68 to $0.99/m^3, with a median cost of $0.82/m^3. Smaller projects range from $0.73 to $1.40/m^3, with a median cost of $1.22/m^3. Integrating such a facility into the drinking water distribution system adds about $0.09/m^3; less than for seawater desalination because brackish plants are typically located closer to the existing water distribution system. Total costs for a small brackish desalination project ranges from $0.83 to $1.49/m^3, with a median cost of $1.31/m^3. The total cost for a large brackish desalination project ranges from $0.77 to $1.08/m^3, with a median cost of $0.91/m^3.

Urban water efficiency

Water conservation and efficiency are valuable for meeting existing and future water needs in urban areas (Heberger *et al* 2014). California has made considerable progress in implementing water conservation and efficiency, as seen from the decline in residential water use (including both indoor and outdoor) from 620 liters per person per day (lpcd) in 2000 to under 500 lpcd in 2010 (California Department of Water Resources (CDWR) 2014a).

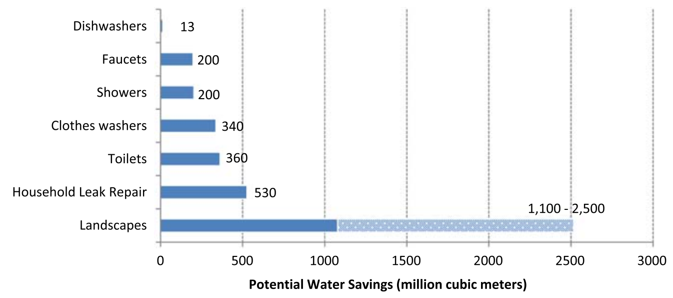

Figure 1. Potential residential water savings by end use. Source. Based on data in (Heberger *et al* 2014). Notes: figure shows household water savings and does not include potential water savings from the non-residential sector or from reducing losses in water distribution systems. Potential water savings for landscape efficiency improvements are shown as a range based on assumptions about the extent of landscape conversions.

Table 6. Residential water conservation and efficiency measures.

Efficiency measure	Statewide water savings (1,000 m^3 per year)	Measure water savings (liters per year)	Cost of conserved water (\$ per m^3) Low	High	Notes
Toilet	360,000	18,000	−\$0.51	−\$0.16	13 lpf to 4.9 lpf
		2,600	\$0.95	\$3.70	6.1 lpf to 4.9 lpf
Showerhead	210,000	5,300	−\$2.45	−\$2.30	9.5 to 7.6 lpm
Clothes washer	330,000	27,000	−\$0.61	−\$0.15	
Dishwasher	14,000	1,600	\$9.67	\$15.66	
Landscape conversion	1,100,000–2,500,000	72–95	−\$3.69	−\$2.08	\$22 per square meter
			\$0.47	\$1.18	\$54 per square meter

Notes: All cost estimates are rounded to the nearest cent and are shown in year 2015 dollars. Measure water savings for landscape conversions are based on converting a square foot of lawn to a low water-use landscape. Because outdoor water savings are influenced by climate, we use a simplified landscape irrigation model to characterize water savings in five cities: Fresno, Oakland, Sacramento, San Diego, and Ventura. For data sources, see appendix B of Cooley and Phurisamban (2017).

Despite this progress, there is still substantial untapped potential to reduce demand for water in urban areas without reducing the services and benefits that water provides (Gleick *et al* 2014). A recent study by (Heberger *et al* 2014) found that the technical potential to reduce California urban water use ranged from 3.6 to 6.4 billion cubic meters per year compared to average (2001–2010) current urban use of around 11 billion cubic meters. Between 70% and 75% of the potential savings, or 2.7 to 4.4 billion cubic meters per year, are in the residential sector. As shown in figure 1, water savings are possible for every end use within the home. Non-residential urban users could save between 910 million to around 2.0 billion cubic meters per year. Repairing leaks in water distribution systems also cuts water losses, although insufficient data are currently available to quantify the potential water savings.

Cost of urban water efficiency measures

Residential efficiency measures

Table 6 shows the cost of conserved water for residential water conservation and efficiency measures. Several efficiency measures have a 'negative cost,' which means that they save more money over their lifetime than they cost to implement. All indoor efficiency measures reduce wastewater flows, and some, such as showerheads and clothes washers, also reduce hot water usage. A negative cost indicates that the savings in household energy and wastewater bills exceed the incremental cost of the efficiency measure[6]. Similarly, in some cases, reductions in fertilizer, pesticide, and maintenance costs can also offset some or even all the installation cost of a low water-using landscape.

[6] While some cities charge a flat fee for wastewater service that is independent of the volume of wastewater treated, others have a volumetric or even tiered rate. Based on a survey of 22 California cities representing more than a quarter of the state's population, we estimate that the population-weighted average wastewater cost is \$3.49 per 1,000 gallons.

The cost of efficient showerheads is highly negative, making it among the most cost-effective efficiency measure available. Replacing older showerheads using 2.5 gallons per minute (gpm) (9.5 liters per minute (lpm)) with a model that uses 2.0 gpm (7.6 lpm) would save an estimated 210 million cubic meters per year at current population and use levels. These devices are relatively inexpensive and provide large financial savings over their estimated 10-year life due to reductions in energy and wastewater costs. Replacing older showerheads that use more than 2.5 gpm and/or installing showerheads that use less than 2.0 gpm, which are widely available, would provide even greater savings.

High-efficiency toilets and clothes washers are less cost effective than showerheads but still far cheaper than new supply options, and they provide much greater potential statewide water savings. Complete market penetration of high-efficiency clothes washers and toilets in California would save an estimated 330 million cubic meters and 360 million cubic meters per year, respectively (Heberger *et al* 2014). While a new front-loading clothes washer is more expensive than a standard model, this cost is more than offset by lower wastewater and energy bills, such that the cost of conserved water ranges from -\$0.61 to -\$0.15 per cubic meter. Similarly, the cost of conserved water for replacing older toilets that use 13 lpf or more ranges from -\$0.51 to -\$0.16 per cubic meter saved. Replacing toilets that currently use 6 lpf is more expensive due to reduced water savings. This suggests that targeting toilet replacement programs to homes built before 1992 when the 6 lpf standard went into effect would provide the greatest water savings at the lowest cost.

Table 6 shows the range of costs of reducing outdoor water use by converting lawns to low water-use landscapes. We characterize water savings in five California cities with a range of climatic conditions (Fresno, Oakland, Sacramento, San Diego, and Ventura) and estimate that annual water savings from landscape conversions in these cities range from 72 to 95 liters per square meter. Statewide, landscape conversions would reduce annual water use in California homes by 1.1 to 2.5 billion cubic meters (Heberger *et al* 2014). The cost of installing a low water-use landscape ranges from \$32 to \$54 per square meter, while installing a new lawn would cost about \$11 per square meter. If the consumer is in the market for a new landscape, as may occur after a lawn dies or when buying a new home, then the incremental cost would be as low as \$22 per square meter; i.e., the difference between a new lawn and a new low water-use landscape. If the customer replaces an existing healthy lawn, then the cost would be \$54 per square meter. At \$22 per square meter, the cost of conserved water is -\$3.69 to -\$2.08 per cubic meter with the negative cost being due to substantial reductions in fertilizer and maintenance costs; i.e., avoided costs from reduced fertilizer use and maintenance far outweigh the cost of the landscape conversion. At \$54 per square meter, the cost of conserved water is \$0.47 to \$1.18 per cubic meter.

Nonresidential efficiency measures

California's urban non-residential sector (commercial, industrial, and institutional users) uses approximately 3.1 billion cubic meters of water annually—about 28% of state urban water use[7]. Heberger *et al* (2014) found that efficiency measures could reduce non-residential water use by 30% to 60%, saving an estimated 910 million to 2.0 billion cubic meters per year. The estimated statewide water savings for the non-residential sector is less than for the residential sector, which was estimated at 2.7 to 4.4 billion cubic meters per year; however, the water savings for individual efficiency measures tend to be much larger for the non-residential sector than for the residential sector. For example, a single efficient ice machine would save an estimated 49,000 liters of water per year—nearly 10 times as much water as would be saved by installing an efficient showerhead in a home. Likewise, an efficient medical steam sterilizer would save up to 2.5 million liters per year, at least 30 times more than could be saved by retrofitting an entire home with efficient appliances and fixtures.

Table 7 shows the cost of conserved water for some non-residential water conservation and efficiency measures. We find that many non-residential measures also have a negative cost and are highly cost effective. Several efficiency measures for restaurants—such as food steamers, waterless wok stoves, and ice machines — offer significant financial savings over their lifetime. For example, an efficient connectionless food steamer, which operates as a closed system that captures and reuses steam, would save about 200,000 liters of water and 14,000 kWh of electricity per year (Food Service Technology Center (FSTC) 2016), resulting in a cost of conserved water of -\$11.36 to -\$10.91 per cubic meter. Conversely, toilet and urinal replacements are less cost effective than other measures. However, as with the residential sector, targeting high-use customers and devices would increase the cost effectiveness of these measures.

Water loss control

Throughout the world, high-quality water is lost from distribution systems that leak. A survey of 85 California utilities found that real water losses averaged 170 liters per service connection per day (Sturm 2013)[8]. Water loss

[7] Authors' calculations based on 1998–2010 average. Data from California Department of Water Resources (CDWR) (2014a).

[8] Real losses are physical losses of water resulting from leaks, breaks, and overflows in the pressurized system and the utility's storage tanks. Apparent losses, by contrast, refer to water that is used but is not properly measured, accounted for, or paid for.

Table 7. Non-residential water conservation and efficiency measures.

Efficiency measure	Measure water savings (liters per year)	Cost of conserved water (\$ per m^3) Low	High	Notes
Toilet	20 000	−\$0.55	−\$0.06	13 to 4.8 lpf
	2 900	\$1.47	\$5.29	6.1 to 4.8 lpf
Urinal	10 000	\$0.79	\$1.48	2.7 to 0.47 lpf
Showerhead	16 000	−\$2.46	−\$2.30	9.5 to 7.6 lpm
Faucet aerators	6 100	−\$0.99	−\$0.55	8.3 to 3.8 lpm
Pre-rinse spray valve	26 000	−\$1.39	−\$0.94	8.3 to 5.4 lpm
Medical steam sterilizer modification	1 700 000–2 500 000	−\$1.03	−\$0.99	
Food steamer	200 000	−\$11.36	−\$10.91	Boiler-based to connectionless
Ice machine	49 000	−\$2.92	−\$0.91	
Waterless wok	640 000	−\$0.85	−\$0.71	
Clothes washer	140 000	−\$1.30	−\$0.91	Top-loader to front-loader
Landscape conversion	72–95	−\$3.69	−\$2.08	Assumes \$22 per square meter
		\$0.47	\$1.18	Assumes \$54 per square meter
Rotary nozzle	7 900–15 000	\$0.16	\$0.84	
Water broom	190 000	\$0.13	\$0.28	

Notes: All cost estimates are rounded to the nearest cent and are shown in year 2015 dollars. Water savings for landscape conversions are based on converting a square foot of lawn to low water-use landscapes. Because outdoor water savings are influenced by climate, we use a simplified landscape irrigation model to characterize water savings in five cities: Fresno, Oakland, Sacramento, San Diego, and Ventura. See appendix B of Cooley and Phurisamban (2017) for methodology and assumptions.

rates vary based on several factors including the age of the system, the materials used, and the quality of maintenance programs. Studies suggest that leak detection surveys could reduce annual water losses by over 600,000 liters per kilometer surveyed at a cost of \$190 per kilometer (Sturm 2015)[9]. Assuming that leak detection and repair are an ongoing process, we estimate that the cost for this measure is about \$0.32 per cubic meter[10]. In addition to deferring or eliminating expenditures on new supply and treatment infrastructure, reducing water losses can also protect public health and reduce flood damage liabilities. These co-benefits, not quantified here, would further reduce the cost of conserved water from a distribution system leak detection program.

Summary and conclusions

As traditional sources of water become costlier and less available, alternative water supplies and efficiency measures are being evaluated and pursued. There are significant opportunities to develop a range of options to meet a region's current and future water needs, depending on economic, technical, social, and political factors. We provide here for the first time a comprehensive research assessment of the comparative costs of stormwater capture, recycled water, seawater and brackish water desalination, and urban water conservation and efficiency in the California context. Some of these options also provide additional important co-benefits or avoided costs, such as reducing water withdrawals from surface water bodies or polluted runoff in coastal waterways. While the economic values of most environmental costs and benefits are not well documented, they are economically relevant, and we highlight areas where further research and analysis are needed.

Figure 2 compares the cost of alternative water supplies and efficiency measures. Large stormwater capture projects are among the least expensive of the water supply options examined, with a median cost of \$0.48 per cubic meter. Seawater desalination projects, by contrast, are the most expensive water-supply options examined, with a median cost of \$1.72 per cubic meter for large projects and \$2.29 per cubic meter for small projects. Brackish water desalination is typically much less expensive than seawater desalination due to lower energy and treatment costs. Generally, the cost of municipal water recycled water projects are in between those of stormwater capture and seawater desalination. Non-potable reuse is typically less expensive than potable reuse due to the lower treatment requirements; however, the distribution costs for a non-potable reuse system could increase the cost of that water.

Urban water conservation and efficiency measures offer significant water savings and are often the most cost-effective ways to meet current and future water needs. Indeed, many residential and non-residential measures have a negative cost, which means that the financial savings over the lifetime of the device that result

[9] Based on work with 13 California utilities.

[10] This estimate does not include the cost to repair the leak, as the utility would have fixed the leak regardless of when it was discovered.

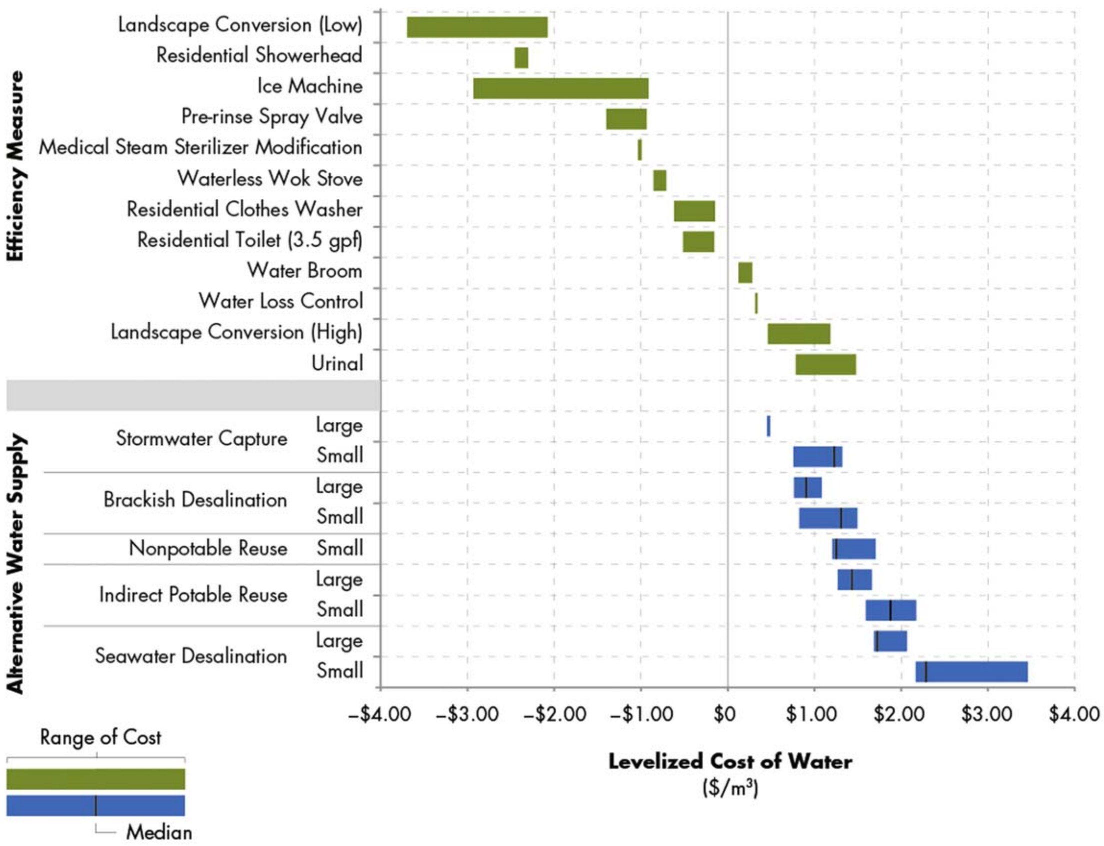

Figure 2. Levelized cost of alternative water supplies and water conservation and efficiency measures, in 2015 dollars per cubic meter. Notes: All values are rounded to two significant figures. Costs for water supplies are based on full-system cost, which includes the cost to integrate the supply into a water distribution system. Ranges for water supplies are based on 25th and 75th percentile of project costs, except for large stormwater projects, which include the full cost range of the two projects. Conservation and efficiency measures shown in this figure represent only a subset of the measures examined in this study due to space limitations. Cost ranges for water conservation and efficiency measures are based on varying assumptions about the incremental cost and/or water savings associated with a measure. A rough estimate for the cost of new traditional storage systems in California is between $0.40 and $0.80 per cubic meter, excluding additional required costs of treatment, distribution, and use.

from lower wastewater and/or energy costs exceed the incremental cost of the more efficient device. Financial savings from high-efficiency showerheads and clothes washers are especially high. Landscape conversions in residential and non-residential settings can also have a negative cost, depending on the cost of the conversion and reductions in maintenance costs. Even when landscape conversions are costly, we find that the cost of conserved water is often less expensive than many new water-supply options. While leak detection in the water distribution system is more expensive than some of the other efficiency measures, it is also highly cost-effective when compared to most traditional water-supply projects.

More regions around the world are reaching or exceeding the physical, economic, ecological, and social limits of traditional supply options. A broader portfolio of options is now being considered, away from traditional sources of supply and toward more sustainable options including improving water-use efficiency, water reuse, and stormwater capture. While final decisions about addressing water supply and demand will always depend on local economic, political, technological, and environmental factors, improved understanding of the economics of these alternatives will be vitally important. The methods and data presented here can provide a framework for contributing to those decisions.

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