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REVIEW ARTICLE

A comparison of strategies used and considered to mitigate droughts in California

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Abstract

While California has ideal weather for many activities, beaches, and mountains, the water shortage in the state has caused challenges for its growing population. The state has implemented some water saving measures but must do more to meet its needs as its population continues to increase. This paper explores what has been done and what might be done to seek more sources of water. Existing literature tends to examine individual options, instead of performing a broader comparison. This study uses comparative analysis to evaluate multiple approaches to mitigating the effects of drought in California, comparing cost information, technical maturity, and less easily quantified advantages and disadvantages. The study found that conservation, wastewater recycling, water transfer, and similar options have been used successfully in California in the past and should continue to be used. Because all those approaches except wastewater recycling are reaching their limits, the most feasible method to mitigate future droughts in California is increased use of wastewater recycling. However, it faces some emotional and political obstacles to its widespread use.

Keywords Drought mitigation · Water conservation · Water transfer · Wastewater recycling · Desalination

Introduction

California is known for its nearly perfect weather in areas such as Los Angeles and San Diego, skiing in areas such as Tahoe and Squaw Valley, and beaches in areas such as Venice Beach and Santa Monica State Beach. The state is considered by many to be one of the most ideal places in the USA in which to live, ranking first in desirable weather according to Osborn (2020). However, it is also known for wildfires, mudslides, and droughts (Zachos 2018). The droughts have become a larger issue in recent years as the state has experienced a larger shortage of water.

Droughts have been common in California's history. Using different methods, Stahle and Stahle (2013) and Stevens (1994) showed significant dry periods occurring between 1590 and the present and between 892 and the present, respectively. Increasing global temperatures are increasing the risk of severe droughts in California (AghaKouchak 2014; Diffenbaugh 2015).

To mitigate this, the state has increased water use restrictions and conservation as well as the price of water and the recycling of some water. These efforts have helped, but as the population continues to grow, the state needs to explore other options. This paper will examine some of the more frequently considered options that are available; comparing cost information, technical maturity, and less easily quantified advantages and disadvantages. This comparison will demonstrate that only wastewater recycling approaches economic competitiveness with existing water sources. This makes increased use of recycled wastewater the most feasible option to mitigate the risk of a significant water shortage if existing sources fall short, as they eventually must if the state population continues to increase. While water restriction, conservation, increased prices, and wastewater recycling are not the only options available, they are the ones that are affordable and reasonably manageable at this time.

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Background

The history of the area now called California shows that there have long been droughts. Smaller populations did not strain the water resources available to the extent that the greater populations have in recent droughts. In the more than 1000 years for which current methods are able to determine drought history, California has experienced droughts both longer and more severe than those that have occurred in the twentieth and twenty-first centuries. However, as shown in Fig. 1, until the mid-nineteenth century, the population of California was orders of magnitude smaller than it was at the end of the twentieth century. This difference in population made the impact of these earlier droughts much less severe. Figure 1 shows the rapid growth in California's population in the latter half of the nineteenth century and throughout the twentieth century.

Humans settled in California at least 15,000 years ago. Native Americans were the first known explorers and settlers in Coastal California. Though Native Americans manipulated their environment in ways that included some water management, their manipulations normally mimicked nature, and were limited in their extent (Regents of the University of California, 2011). The lack of written history from this time prevents assessment of how severe droughts impacted the California population, but that population was small enough that the impacts are likely to have been relatively small. Even when the Spanish made extensive colonization efforts beginning in 1542 with the arrival of Juan Rodriguez Cabrillo in San Diego, the population remained small enough for the available resources to support (National Park Service, 2020). California was sparsely populated until the discovery of gold in 1848, which created a large influx of settlers. (Rosenberg 2019).

Congress appointed John Wesley Powell to survey the West in the 1870s (Kaufman 2018). Powell found that "The West did not have enough water to support large cities, let alone agriculture." The few areas that would support agriculture in the West did not include any of California. He also predicted that there would be litigation over water rights and argued that the area should only be settled on a small scale. Interior Secretary Vilas suggested that all rivers in the West that passed through more than one state should be nationalized (Kaufman 2018).

Droughts have occurred in California for as long as data have been collected. These droughts affect each of the main sources of water in California. "California relies on three main, interconnected water sources: mountain snowpack, reservoirs, and aquifers" (EPA 2015). In dry years, reduced snowpack causes greater draw from reservoirs and aquifers, reducing the total amount of water stored in those. According to the EPA (2015), "In August 2015, the major reservoirs were at 17–62 percent of their historical average storage levels," and "Seventy-four percent of the groundwater well levels declined by more than 2.5 feet from the fall of 2011 to the fall of 2014." Though it has not yet happened, a long enough and severe enough drought coupled with continued population growth could exhaust these sources.

Stahle and Stahle (2013) examined tree ring data to determine that California has had droughts since 1590, not long after the arrival of Cabrillo. Figure 2 shows that these droughts occurred with the most extreme frequency from 1650 to 1690, 1750 to 1790, and 1850 to 1950.

Stevens (1994) based an analysis of droughts on preserved tree trunks. The outermost rings of the trunks were radiocarbon dated to determine when they were drowned by rising water levels, and the trunks' rings were counted to determine the ages of the trees when they were drowned, thus showing how long the area was dry and how long ago. The trunks in question were preserved by the water that

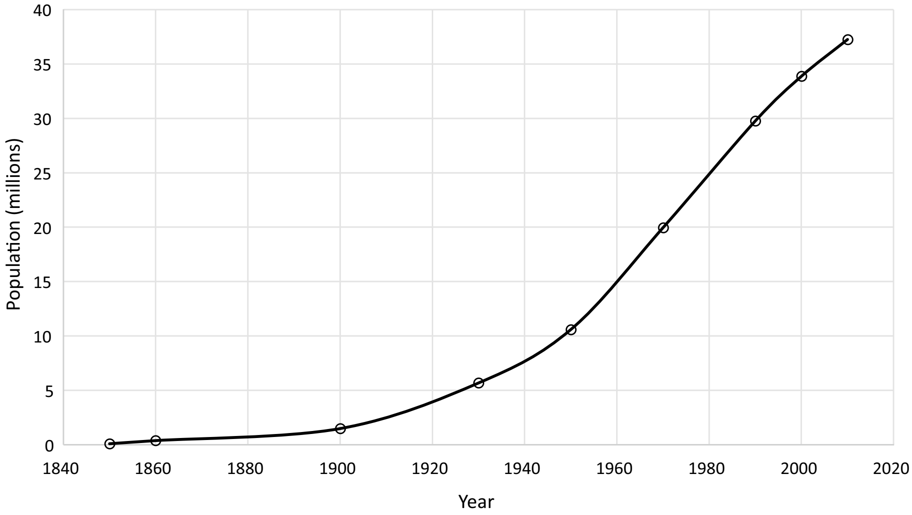

Fig. 1 California Population, 1850–2010. Note. Data from Rosenberg (2019) and U.S. Census Bureau (2021)

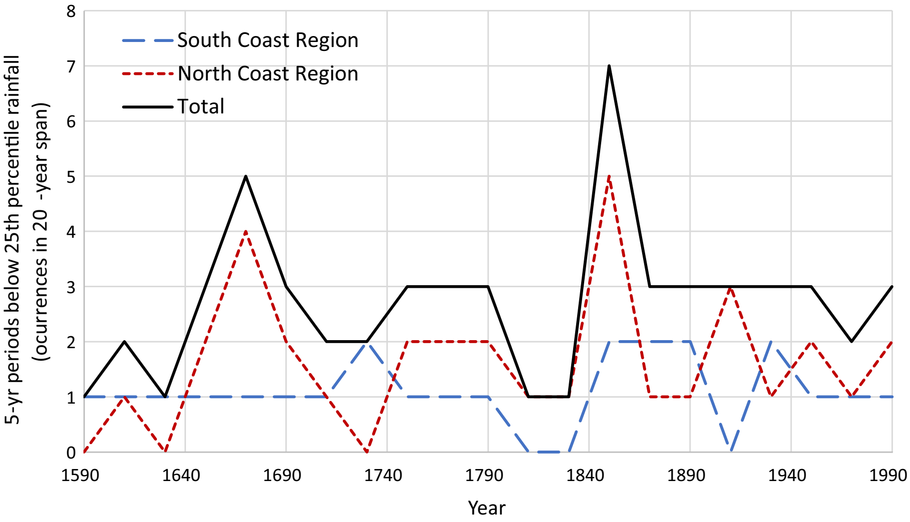

Fig. 2 California Drought Frequency, 1590–1990. Note. Data from Stahle and Stahle (2013)

was present except during the droughts in question. Stevens noted the following:

> …droughts lasting from 892 to 1112 and from 1209 to 1350. Judging by how far the water levels dropped during these periods - as much as 50 feet in some cases - [Scott Stine] concluded that the droughts were not only much longer, they were far more severe than either the drought of 1928 to 1934, California's worst in modern times, or the more recent severe dry spell of 1987 to 1992.

While droughts have occurred in California throughout its history, the people who lived there have survived them, though the lack of written history makes it difficult to know in detail what difficulties they suffered. When the population was much smaller, the droughts' effects were probably not as severe as those of more recent droughts. As the population grew, the lack of water during droughts became a more significant problem.

There is no reason a serious and sustained drought could not start now or soon. Since the population of California continues to grow, future droughts are likely to be more difficult to mitigate, and future droughts are likely to have more harmful results. Thus, public officials would be wise to consider drought mitigation strategies, their advantages and disadvantages, and how quickly they can be implemented if needed.

Literature review

Introduction to literature review

Relatively little scholarly literature exists describing California's history of drought before recent years, but those sources that were found agree that (a) droughts have been a part of California's climate for centuries and (b) global warming is increasing the risk of severe droughts in the state. Substantial literature exists describing possible approaches to mitigating the effects of drought in California and elsewhere, but the sources examined tend to focus on specific strategies, rather than on broad comparisons.

Literature about California's history of drought and its increasing risk of drought

Using different methods, both Stahle and Stahle (2013) and Stevens (1994) found that California has had severe droughts since well before the industrial revolution, including some that were worse than any experienced in recent history. AghaKouchak (2014) and Diffenbaugh (2015) both stated that water shortage risk is increased by global warming, on the water demand side by increased risk of hot years and on the water supply side by increased risk of dry years.

Literature about possible water shortage solutions

Three authors have addressed water transfer as a solution to water shortages. This solution is already in extensive use in California (Water Education Foundation 2020). Gohari (2013) stated that water transfer leads to the unintended consequence of increased water demand, making future drought consequences worse, and supported this conclusion with a system dynamics model. Mall (2019) showed an example of this outcome in California's Tulare Valley, in which economic factors have caused farmers to grow crops requiring more water despite water shortages. Sinha et al (2018) did not address unintended consequences as directly, but this conclusion is supported by their recommendation to use a market-based approach to allocate water rights and their conclusion that this will increase allocative and productive efficiencies.

The U.S. Environmental Protection Agency (2015) described many programs undertaken by cities and counties in California to encourage residents and businesses to conserve water. The California Department of Water Resources (2020) and the California Water Boards (2020) described statewide measures with the same goal, but using less direct approaches because the state does not have direct interaction with water consumers. The United States Geological Survey (USGS 2018) provided information on total water use and population in California showing the success of these conservation efforts.

Costwater (2020) compared the costs of building and operating wastewater treatment plants to those of building and operating ordinary water treatment plants. Carlton (2002) described the advantages and disadvantages of a proposed wastewater treatment plant in Orange County, California, and Wisckol (2019) described such a plant built in that county and its planned expansion. Nancarrow et al. (2009) investigated the behavioral response to wastewater for potable and non-potable uses, indicating emotional and political obstacles to its implementation. Costwater (2020) and Carlton (2002) concluded that recycled wastewater was not cost-competitive with other water sources, but Wisckol (2019) concluded that it was.

Konkel (2018) and Bothwell (2018) both suggested that stormwater capture may be a useful water resource. Both admitted that methods to remove pollutants from urban runoff water prior to using it to replenish aquifers must be developed in order to take advantage of this resource. Neither addressed usefulness of stormwater capture as a drought mitigation strategy, presumably because of the likely lack of stormwater to capture in a drought.

Collins (2017) explored another possibility, noting that desalination is in common use in the Mideast, where other sources of water are significantly more expensive than in the USA. Mezher (2011) examined the potential environmental impacts of desalination byproducts. El-Bialy et al (2016) analyzed multiple solar desalination methods. Lapuente (2012) investigated the construction and operating costs of seven Spanish desalination plants. The City of Santa Barbara, California (2020) and Newman (1998) provided information about the construction and operating costs of a desalination plant built in that city.

Collins (2017) described a project being studied to tow an iceberg from an Antarctic ice shelf to the United Arab Emirates to supply water. Winter (2019) described a similar project to tow an iceberg to Cape Town, South Africa. The latter project was described as ready to begin soon after obtaining an agreement from South Africa to purchase the water. In May 2022, no source was found stating that such an agreement had been reached or that the project was underway.

No source was found that did a comprehensive review of all or even a significant subset of the plausible drought mitigation options for California specifically or for water-poor areas in general. The literature found was narrower in focus, usually only examining one drought mitigation approach. This showed a gap in the body of knowledge on this subject.

Methodology

This paper uses comparative analysis, assessing each drought mitigation approach in cost per gallon of water, technical maturity, and other advantages and disadvantages. Conclusions and recommendations are made using these factors. Six approaches are compared, including two that are already in widespread use in California, two that are in limited use in California, and two that have been studied or proposed for use in California.

Cost per gallon information was retrieved from source literature for the approaches for which such data were available. These data were then converted to US dollars per gallon and adjusted for inflation to 2020 using the U.S. Inflation Calculator (2022). No cost information was found in the literature for less technically mature approaches, nor would any such data be regarded as reliable.

Technical maturity was assessed based on the descriptions of the work done on each approach in the source literature, using the Technology Readiness Level as defined by the National Aeronautics and Space Administration (NASA, 2020). The NASA Technology Readiness Level is a standardized method to assess the technical maturity of particular technological approaches. The levels range from 1, for approaches for which only the basic principles are known, to 9, for approaches that are already in use.

Other less easily quantified advantages and disadvantages were found in the literature. The most noteworthy of these were included in the discussion, providing context and background for the recommendation. Relying only on easily quantified metrics would have omitted important information from a comparative analysis.

Drought mitigation approaches used in California

Conservation

Various water conservation regulations have been made over the years, mostly at the local level. The first major statewide conservation law was the Sustainable Groundwater Management Act, signed by Governor Brown in 2014. This Act required local governments to create and execute plans to manage aquifers so that the amount of water drawn does not exceed the amount added by natural processes, thus ensuring that the aquifers are not depleted. This goal is to be met by 2040 for critically overdrawn aquifers and 2042 for other aquifers. (California Department of Water Resources, 2020). This law allows the state to assume control of aquifer management if it deems a local government's plan or execution unacceptable, after providing opportunities to that local government to correct any identified deficiencies. (Groundwater Exchange, 2020).

In 2018, Governor Brown signed Senate Bill 606 and Assembly Bill 1668. While these laws recommended an indoor use of 55 gallons per person per day, there was no way to enforce this limit, so the state simply raised water prices and implemented a scale that allowed higher charges per water unit usage for higher amounts of usage than for lower amounts of usage. Of course, this limit included the outdoor water usage as well, since each residence has only one water meter for both indoor and outdoor usage. (California Water Boards 2020).

In an effort to encourage efficient water usage, various water districts provide rebates for things such as high-efficiency toilets, high-efficiency clothes washers, smart irrigation controllers, and rain barrels. (California Water Service 2020b). The state also has time of day watering restrictions (California Water Service 2020c), and has prohibited certain uses of water, including any outdoor use that causes runoff outside irrigated areas, use of water to clean driveways or sidewalks, outdoor watering within 48 h of rainfall, and others. (California Water Service 2020a).

Wastewater recycling

Non-potable. Though less expensive per gallon than potable water, using non-potable recycled water requires an additional set of mains and extra plumbing for each user, making capital costs high and imposing some of those capital costs on the users. (Šteflová 2018). However, it is in use by some California state and local entities for uses such as watering public building lawns and street medians. Though there may be opportunities for more state and local entities to use non-potable water for these applications, the high capital costs of this approach make it impractical for wide residential use.

Potable. Costwater (2020) found recycled wastewater to be higher in both construction and operating costs. Carlton (2002) found that the cost of water from a proposed wastewater recycling facility in Orange County, California was projected to be almost three times the cost of groundwater, and greater than all but the most expensive sources of imported water. However, Wisckol (2019) reported the cost of recycled water from an existing plant in that county to be well below that of imported water. This difference in costs was probably due to advances in water recycling technology in the years between 2002 and 2019.

An important element to the political acceptability of wastewater treatment is the public's emotional reaction to close personal use of wastewater, sometimes called the "yuck factor." This emotional barrier can also apply to food grown with non-potable recycled wastewater, limiting its acceptability for irrigation. (Nancarrow et al. 2009). Carlton (2002) also mentioned the "yuck factor" in his description of the advantages and disadvantages of the proposed wastewater recycling facility in Orange County, California. Despite these concerns, California recycled 714,000 acre-feet in 2015, including 219,000 acre-feet for agricultural irrigation (California Environmental Protection Agency 2020), and the Orange County, California facility is pumping recycled wastewater into the aquifer from which the county draws water for potable use (Wisckol 2019).

California recycling totals for 1995 from the United States Geological Survey (USGS 2018) and for 2015 from the California EPA (California Environmental Protection Agency 2020) show that recycled water use grew from approximately 5.9% to approximately 12.5% of total water use. Regrettably, data from these sources are incomplete for other years, and these sources' data do not agree in subcategories for 2015. However, it is clear from these sources that the use of recycled water in California is generally increasing, and that the bulk of recycled water use is for irrigation.

Desalination

Desalination is often considered as a source of water for cities with access to ocean water. It is in use in the Middle East, where other sources of water are scarce enough to be much more expensive than in California (Collins 2017). A reverse osmosis desalination plant was built in Santa Barbara, California, operated briefly in 1992, then placed in standby mode until it was refurbished in 2017. At that time, the plant began supplying 3125 acre-feet of water per year to that city (Santa Barbara 2020). Desalination by solar distillation and by conventional reverse osmosis methods have been considered. Desalination creates concentrated brine as a byproduct, which can have harmful effects on the environment (Mezher et al. 2011).

Solar desalination. El-Bialy et al. (2016) analyzed multiple solar desalination methods and found that both passive and active solar desalination methods were cost-competitive with commercial water sources in Egypt and Saudi Arabia. However, the costs they calculated are not cost-competitive with commercial water sources in Los Angeles, San Diego, San Francisco, or San Jose (Circle of Blue 2019), even assuming that the prices of land and labor in those cities are no higher than those in Egypt and Saudi Arabia.

Conventional desalination. The average cost of water from seven Spanish desalination plants found by Lapuente (2012), including capital and operations and maintenance costs is significantly less than from commercial water sources in the four California cities researched, when adjusted for inflation (U. S. Inflation Calculator 2022). It is unclear if these can be directly compared because land costs, construction costs, and labor costs are likely to differ between Spain and California.

The city of Santa Barbara constructed a desalination plant in the late 1980s in response to the drought occurring at that time. It was ready to operate in 1991, but because the drought ended, it was placed in long-term standby mode until 2015. In 2015, reactivation work began, allowing the plant to begin operation in 2017. The plant uses "diluted and diffused brine discharge" to mitigate potential environmental damage done by its discharge. (Santa Barbara 2020).

Newman (1998) estimated the cost of water from the Santa Barbara, California, desalination plant, the cost of water purchased from the State Water Project, and the cost of water from the desalination plant powered by a proposed ocean current turbine. Newman's estimate for the ocean turbine was unrealistic because it assumed a 100% efficient turbine 35 miles from the plant with no transmission losses, so that estimate was not used. Because more recent data for the desalination plant cost are available, Newman's estimate for that cost was also not used. Newman's estimate for purchased water was adjusted to 2020 dollars (U. S. Inflation Calculator 2022) and compared to cost information for desalinated water from the city of Santa Barbara (2020) in Table 1:

Table 1 Comparison of Santa Barbara Water Costs

Water source	Water Cost (2020 dollars)
State Water Project (Newman, 1998)	$0.0043/gal
Desalination plant, including bond payment (Santa Barbara, 2020)[a]	$0.0076/gal
Desalination plant, not including bond payment (Santa Barbara, 2020)	$0.0037/gal

Data from Newman (1998) and Santa Barbara (2020), adjusted for inflation (U.S. Inflation Calculator, 2022)

[a] Bond repayment to last 20 years

Table 1 shows that desalination is cost-competitive with purchased water for the city of Santa Barbara with respect to operating costs, but not when the costs of repaying its initial infrastructure investments are considered.

Effectiveness of drought mitigation

The United States Geological Survey (USGS 2018) tracked the total California water usage in California and found that the total water usage in the 2010–2019 drought was essentially unchanged from the usage in the 1985–1992 drought despite a large population growth, indicating a substantial reduction in the use per person. Figure 3 shows the total water use, water use per person, and population in California from 1985 to 2015.

Figure 2 shows that the conservation efforts and wastewater recycling programs used in California from 1985 to 2015 successfully decreased the per capita water use enough to offset the state's population increase. This leads to the question of whether these reductions have had negative effects, such as reductions in agricultural output or standard of living. Figure 4 addresses these questions.

Regrettably, California crop totals reported to the U.S. Department of Agriculture based on data compiled by the California County Agricultural Commissioners are incomplete (USDA, 2022). Figure 4 shows per capita crop sales (adjusted for inflation) for two subsets of California crops. Subset 1 is the set of crops for which data exist for the entire

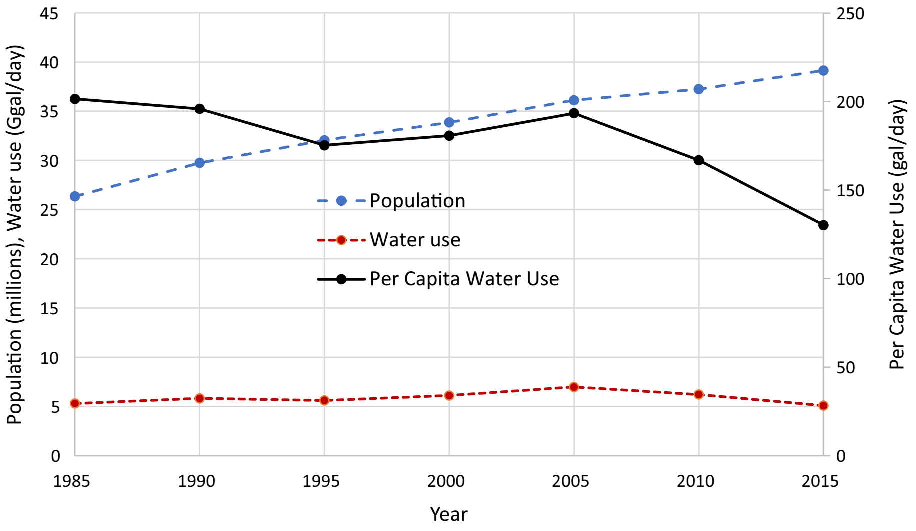

Fig. 3 California Population and Water Use, 1985–2015. Note. Data from USGS (2018)

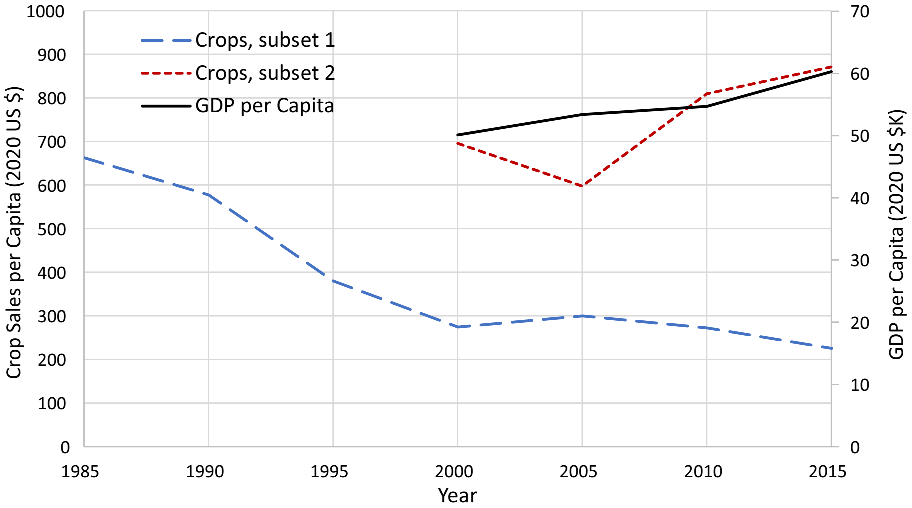

Fig. 4 California per Capita crop sales and per Capita GDP. Note: Data from U.S. Department of Agriculture (2022) and U.S. Bureau of Economic Analysis (2022), adjusted for inflation (U. S. Inflation Calculator 2022)

relevant period, and Subset 2 is the set of crops for which data exist in each relevant year from 2020 to 2015. Subset 1 crops account for 12.7% of the reported crop sales in 2015, and subset 2 for 49% of those sales. For Subset 1, the sales significantly decreased from 1985 to 2000, and continued to decrease slightly from 2000 to 2015. Subset 2 sales, which include Subset 1 sales, increased moderately from 2000 to 2015. Neither set of sales appears to correlate well with either per capita or total water use in California. Thus, it is possible, but not known, that the marked decrease in Subset 1 sales from 1985 to 2000 reflects a transition from those crops to other crops, or is caused by some other factor or factors unrelated to water conservation and recycling measures.

Per capita Gross Domestic Product (GDP) is a common measure of standard of living (Corporate Finance Institute 2020). Because the way GDP was measured changed in 1997, the U.S Bureau of Economic Analysis does not carry pre-1997 data for state GDPs (USBEA, 2022). Figure 4 shows that California's per capita GDP increased steadily from 2000 to 2015, despite a reduction in per capita water use. There may be lifestyle impacts from water conservation that are not captured by the GDP per capita metric. For example, some people may prefer conventional appliances to low-flow versions. Correlating the impact of these preferences with any standard of living metric is beyond the scope of this article.

Though conservation and efficiency programs have been successful at reducing California's per capita water use, these approaches have inherent limits, beyond which such impacts are unavoidable, because crops need water to grow and people need water for health and hygiene. If the state's population continues to grow or if California sees a more severe drought than it has in recent decades, other sources of water will be necessary.

Figure 5 compares the costs of all the drought mitigation approaches technologically mature enough that they have been used at more than laboratory scale. The cost data for commercial sources in Egypt and Saudi Arabia are not directly relevant to drought mitigation in California, but are included for thoroughness. The remaining cost information shows that solar desalination is not competitive with conventional desalination (in either location for which data were found), with purchased water in Santa Barbara, California, or with wastewater recycling in Orange County, California. From the information available for California locations, wastewater recycling has the lowest cost.

Other Water Sources Considered for Drought Mitigation

Stormwater capture

Though stormwater capture has been proposed as a method to increase water supply, this approach requires further technological development to remove pollutants from urban runoff in order to make that water safe for aquifers (Bothwell 2018; Konkel 2018). Also, stormwater capture is not necessarily useful in a drought, because of the lack of stormwater to capture. Though some "snow droughts" affect snowpack without significantly changing rainfall (National Integrated Drought Information System, 2020), this inherent flaw and the need for technological development limit the practical utility of stormwater capture as a drought mitigation strategy.

Icebergs

No reliable cost data are available on the towing of an iceberg from a polar region to an arid region, since it has never been done. So far, only towing of small icebergs short distances to protect oil and gas wells has been done. However, the United Arab Emirates (UAE) is seriously considering a plan to tow a billion-ton iceberg from an island in the

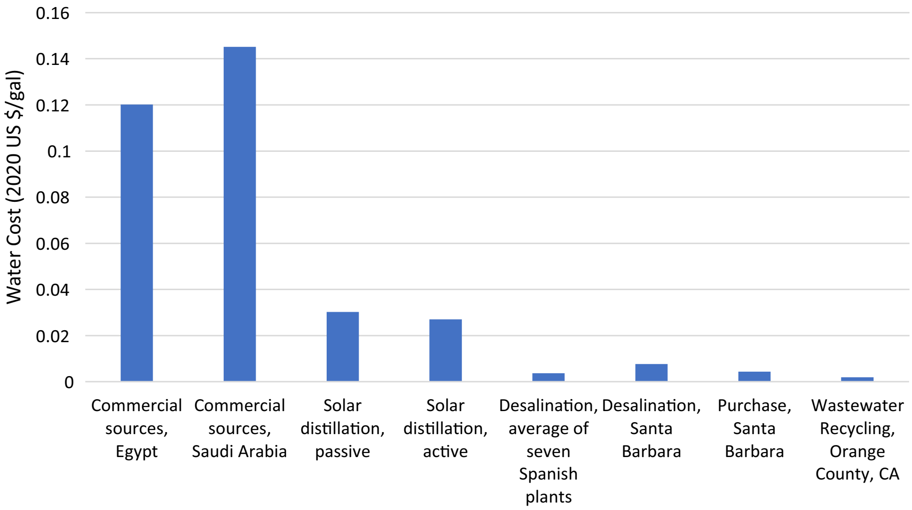

Fig. 5 Water Cost Comparison. Note. Data from El-Bialy et al. (2016), with commercial source costs reduced by a factor of ten to correct an assumed typographical error, Lapuente (2012), Newman (1998), and Santa Barbara (2020), adjusted for inflation (U. S. Inflation Calculator 2022)

Antarctic Ocean to the UAE to provide drinking water (Collins 2017), and a private entrepreneur claims to have a reasonably well-developed plan to tow a 125-million-ton iceberg from the Antarctic region to Cape Town, South Africa (Winter 2019).

The UAE is one of the most arid countries on Earth. Its water needs are currently being met by a combination of groundwater expected to be exhausted in 15 years and desalination plants (Collins 2017). Cape Town is also in need of water, with significant restrictions on its residents' water use (Winter 2019).

The hydrodynamic drag of an iceberg and therefore the number of tugboats and the amount of fuel they must burn to tow it are proportional to the square of its linear dimensions (Techet 2005), as is the iceberg's rate of melting (Physics Classroom 2021). The volume of ice an iceberg contains is proportional to the cube of its linear dimensions. Therefore, the cost of water per gallon from this source improves as the iceberg size increases. However, since towing even a relatively small iceberg is a technically difficult feat, it is unclear how large an iceberg it is practical to tow.

Since desalination is in common use in the UAE, it has demonstrated economic feasibility there, but not at California's water prices. This suggests that though iceberg towing is apparently competitive enough in the Mideast and Africa to be studied seriously, it is unlikely to be a cost-competitive solution for California.

Advantages and disadvantages of California drought mitigation approaches

Many approaches to mitigating the effects of droughts in California have been used or seriously considered. Some are well-understood, "tried and true" methods such as conservation measures, others are more speculative, such as towing icebergs from polar regions to California. Their costs vary, and they each have advantages and disadvantages. Table 2 summarizes the cost, the technology readiness level, and other notable advantages or disadvantages of the approaches used or seriously considered to mitigate droughts in California.

Conclusions

Since California is and will continue to be subject to droughts, it must find ways to provide usable water for residents. While conservation has worked well so far, it has inherent limits. As California population continues to grow or if California has a drought more severe than in recent decades, conservation will not be sufficient. Increased wastewater recycling for non-potable uses may be beneficial, but is unlikely to be practical for widespread use. Increased use of recycled wastewater for potable uses appears to be cost-competitive with other existing water sources. Because wastewater treatment plants reuse existing water, they are not deprived of water during droughts to as great an extent as many other water sources. Therefore, increased wastewater recycling appears to be the most feasible drought mitigation strategy for California. However, wastewater recycling faces political and emotional obstacles to widespread use (the "yuck factor"). Droughts arrive with essentially no notice, their durations are not predictable, and it takes several years to build a wastewater recycling plant. Therefore, if this strategy is adopted, it would be wise to consider investing in such plants before they are urgently needed (Table 2).

Desalination is not currently cost-competitive with other water sources for California, if one includes its relatively high initial infrastructure costs. It has a high level of technical maturity from extensive use in places drier than California and from limited use within the state. Droughts arrive with essentially no notice, their durations are not predictable,

Table 2 Summary of California drought mitigation approaches

Approach	In use in California	Cost[b,c]	TRL[a]	Advantages	Disadvantages
Conservation	Yes	N/A	9	Successful so far	Inherently limited
Transfer from other areas	Yes	\$0.0045/gal \$0.0035/gal and varies	9	Successful so far	Ineffective vs. widespread drought
Wastewater Recycling	Yes, Limited	\$0.0019/gal	9	Successful so far, Re-uses existing water	Political feasibility ("yuck factor")
Desalination	Yes, Limited	\$0.0076/gal	9	Successful so far	Cost, not feasible inland
Stormwater capture	No	Unknown	4		Technical development needed, limited in dry periods
Iceberg towing	No	Unknown	3		Technical development needed, not feasible inland

[a] Technology Readiness Level (see Table 3)

[b] Santa Barbara 2020 dollars, including bond payments (Santa Barbara 2020)

[c] Orange County, California, 2020 dollars (Wisckol 2019)

and it takes several years to build a desalination plant. Therefore, if this strategy is adopted, it would be wise to consider investing in such plants before they are urgently needed.

Stormwater capture faces technical challenges because of the pollutants contained in stormwater runoff. Droughts tend to reduce the amount of stormwater available to capture, though some droughts affect snowpack more than local rainfall. Because of these two disadvantages, this is not a competitive approach at this time.

Iceberg-towing at the scale needed to supply a large population with water has not yet been demonstrated to be technically feasible or economically competitive. More technical development and demonstration are needed before this approach can be seriously considered for California. However, if places other than California try it, California can and should pay attention to its costs, successes, and failures, in case it becomes a practical alternative for California in the future.

Based on the analysis above, California and its local governments that share responsibility for water management and drought mitigation should immediately begin or increase investments in potable wastewater recycling. This is the most cost-effective drought mitigation strategy currently available. The construction of recycling plants should begin immediately because droughts are unpredictable, and such plants take several years to build. These governments should also work to mitigate possible emotional responses to wastewater recycling by informing the public of its benefits, building on successes in Orange County and elsewhere (as other wastewater recycling projects are undertaken, presumably successfully), and being transparent regarding how contaminant and microorganism levels in recycled wastewater compare to levels in water from other sources. California should continue to monitor desalination, stormwater capture, and iceberg towing efforts undertaken elsewhere in case one of these approaches becomes economically competitive and technically feasible with changing technology. However, California should not attempt to execute any of these approaches unless that happens.

Table 3 Technology readiness level definitions

TRL	Definition	Hardware description	Exit criteria
1	Basic principles observed and reported	Scientific knowledge generated underpinning hardware technology concepts/applications	Peer reviewed publication of research underlying the proposed concept/application
2	Technology concept and/or application formulated	Invention begins, practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture	Documented description of the application/concept that addresses feasibility and benefit
3	Analytical and experimental critical function and/or characteristic proof of concept	Analytical studies place the technology in an appropriate context and laboratory demonstrations, modeling, and simulation validate analytical prediction	Documented analytical/experimental results validating predictions of key parameters
4	Component and/or breadboard validation in laboratory environment	A low fidelity system/component breadboard is built and operated to demonstrate basic functionality and critical test environments, and associated performance predictions are defined relative to the final operating environment	Documented test performance demonstrating agreement with analytical predictions. Documented definition of relevant environment
5	Component and/or breadboard validation in relevant environment	A medium fidelity system/component brassboard is built and operated to demonstrate overall performance in a simulated operational environment with realistic support elements that demonstrates overall performance in critical areas. Performance predictions are made for subsequent development phases	Documented test performance demonstrating agreement with analytical predictions. Documented definition of scaling requirements
6	System/sub-system model or prototype demonstration in an operational environment	A high fidelity system/component prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate operations under critical environmental conditions	Documented test performance demonstrating agreement with analytical predictions
7	System prototype demonstration in an operational environment	A high fidelity engineering unit that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate performance in the actual operational environment and platform (ground, airborne, or space)	Documented test performance demonstrating agreement with analyticalpredictions
8	Actual system completed and "flight qualified" through test and demonstration	The final product in its final configuration is successfully demonstrated through test and analysis for its intended operational environment and platform (ground, airborne, or space)	Documented test performance verifying analytical predictions
9	Actual system flight proven through successful mission operations	The final product is successfully operated in an actual mission	Documented mission operational results

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