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Orange County Water Resilience: A Comparative Study of Desalination and Wastewater Management

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ABSTRACT

The persistent effects of population growth, climate change, and diminishing freshwater sources have made water scarcity a critical issue worldwide. In California, sustained droughts have overtaxed the water sources crucial to its economic, social, and agricultural infrastructure. This, in turn, has increased the need for sustainable water resources, and the ongoing depletion of vital groundwater resources has left the state over-reliant on interstate imports and unsustainable in the long term. However, two methods have emerged that could potentially replenish California's depleting water sources: reverse osmosis (RO) desalination and wastewater management. Exploring the history, development, and efficiency of these methods, this paper aims to gauge and compare the effectiveness of these two water extraction systems. By evaluating each method's energy efficiency, cost, sustainability, and political feasibility, we aim to determine the best option for both Orange County specifically and California generally moving forward. While RO desalination can provide high volumes of freshwater, it has drawbacks, including extreme energy costs and the potential destruction of marine environments. Wastewater management, on the other hand, provides more energy-efficient, cost-effective, and environmentally sustainable freshwater. However, it faces significant backlash from public skepticism around initiatives like the "toilet to tap" campaign. This paper concludes that a hybrid approach featuring both methods contingent on environmental and infrastructural conditions would best address California's water concerns, but it also argues for the clear prioritization of wastewater management over RO desalination in the most feasible cases.

Introduction

Water is essential to the sustainability of life, ecosystems, and development. Industries in every sector of the modern economy rely heavily on the presence of bodies of water to sustain their goods, services, and supply chains, proving essential to the functioning of our modern economy (Gleick, 2003). However, access to water per capita has gradually diminished over time, a phenomenon caused largely by decreased death rates and diminishing access to bodies of freshwater for various populations worldwide (Postel, 2000). The greatest freshwater source, glaciers, is also rapidly declining due to climate change, contributing to rising sea levels and reduced freshwater availability (Huss & Hock, 2018). Compounding these already dire conditions, the frequency of severe weather events is expected to increase commensurate with expected changes in global temperatures (IPCC, 2021). California, where roughly a third of the nation's fruits and three-fourths of the nation's fruits and nuts are grown (CDFA, 2022), hosts a Mediterranean climate characterized by variable weather patterns, leaving it particularly susceptible to drought. Despite the rare but significant precipitation that the state experienced in 2023, pervasive water challenges still remain, as the recent precipitation is nowhere near enough to restore the state's depleted groundwater basins, which account for 40% of the state's water supply (Hanak et al., 2019).

With state leadership recognizing the crisis, measures have been taken to preserve the dwindling water supply. For instance, the recent Executive Order N-4-23 suspended flood diversion regulations to allow for floodwater capture, but this by itself will not resolve the issue of scarcity (Governor's Office of California, 2023). Given the unreliability of annual snowpacks and the looming threat of drought, floodwater capture may prove entirely inoperative (Mann & Gleick, 2015). In the long term, CA officials and other concerned parties have turned primarily to two potential solutions: desalination and wastewater management (Hanak et al., 2019).

By surveying the available literature, this paper assesses the efficiency, viability, sustainability, and longevity of each strategy in order to make an evidentiary recommendation for CA policymakers to pursue. Based on current data, wastewater management is overall the more efficient option when factoring in both acre-feet per input yields and environmental sustainability, but RO desalination, especially if combined with sustainable hybrid energy sources, could also be a viable option in cases where little to no water infrastructure is available (Cooley et al., 2019).

Overview and History of Reverse Osmosis Desalination

Desalination is a process that converts saltwater to freshwater by separating the saline content from sourced saltwater through various methods (National Academies of Sciences, Engineering, and Medicine, 2008).

Dry landscapes that have to sustain a significant population, such as Spain and Israel, resort to reverse osmosis (RO) technology in their desalination plants to take advantage of their coastal environments (Fritzmann et al., 2007). Reverse osmosis occurs by using a large amount of pressure to force saltwater through a semipermeable membrane through which salt particles cannot pass: the water or solvent transferred through the membrane becomes purified freshwater (Miller, 2003).

In practice, such as at the Carlsbad plant in California, RO desalination follows a fairly standardized process. First, seawater is collected through large pumps. In these pumps, screens filter out fish, seaweed, and other debris. Then, this water undergoes pre-treatment to remove impurities that could damage the membranes (San Diego County Water Authority, 2016). After treatment, high-pressure pumps move the water toward and through the membranes, which separate the salt from the water. The freshwater is then collected from the tank while the brine waste is pumped out into the ocean (Cooley & Donnelly, 2019). Next, the freshwater undergoes post-treatment, in which minerals or other additives are added in order to meet health standards (Cooley & Donnelly, 2019). Finally, the treated freshwater is pumped into local water supplies (San Diego County Water Authority, 2016).

The prospect of using osmosis to remove salt from seawater was first experimented with at UCLA in 1949, with the intent of achieving the Kennedy administration's goal of discovering solutions to the water shortages plaguing the country (Seidel et al., 2001). However, membranes were ineffective due to their high flux, or flow rates, which risked the leakage of contaminants into the purified solution, and the efforts were largely abandoned in the 1950s in favor of electrodialysis and thermal desalination (Miller, 2003). In the 1960s, the process of reverse osmosis was invented by researchers at UCLA who developed the first reverse osmosis membranes, allowing water to pass through the membrane instead of the salt (as it does in regular osmosis) (Seidel et al., 2001), and the federal government soon invested in small-scale plants in California, Texas, and Florida. Due to the extreme energy cost of the process and the prohibitive manufacturing cost of the membranes, all of these plants failed (Seidel et al., 2001).

It wasn’t until the 1990s that breakthroughs in membrane technology and energy recovery systems mitigated the operational costs enough to allow for the proliferation of RO desalination throughout the U.S., the Middle East, Northern Africa, and Australia (Ghaffour et al., 2013). With federal backing in the U.S. secured courtesy of the Water Desalination Act of 1996, large-scale plants were developed in coastal regions nationwide (U.S. Department of the Interior, 1996). Coastal states like California and Florida began seriously exploring desalination as a sustainable solution to meet their growing water demand (Cooley & Donnelly, 2019).

In 2015, the Claude "Bud" Lewis Carlsbad Desalination Plant, located near San Diego, became the largest desalination plant in the Western Hemisphere. The plant provides about 50 million gallons of fresh water per day, supplying around 10% of the region’s water needs (San Diego County Water Authority, 2016). The Carlsbad plant exemplifies California's approach to using RO desalination as part of a larger water management strategy, which also includes conservation, recycling, and water imports (Cooley & Donnelly, 2019).

However, California's experience with desalination has not been without challenges. The energy-intensive nature of the process and concerns about environmental impacts, such as the disposal of brine into the ocean and the potential ramifications for marine life, have sparked debate (Lattemann & Höpner, 2008). Environmental groups have also raised concerns about the costs of desalinated water, which tend to be higher than other water sources, leading to questions about the long-term sustainability of desalination as a primary water source (Cooley & Donnelly, 2019).

Overview and History of Wastewater Management

Wastewater management collects various forms of wastewater, including wastewater generated by households, agriculture, and manufacturing facilities, and purifies them, making them safe for reuse or release back into the environment (Ghaffour et al., 2013). Especially in arid regions, wastewater recycling has proved critical to maintaining dwindling freshwater supplies (Wang et al., 2017).

Unlike the relatively modern practice of desalination, wastewater management has a history that dates back to ancient civilizations. The Romans and Indus Valley civilizations developed crude sewage systems, but the modern incarnations of the practice began in the 19th century, most of which were spurred on by public concerns over outbreaks of waterborne diseases like typhoid and cholera (Baker, 2005). In turn, cities across the globe developed structured sewage systems; the first sewage plan was constructed in London in 1865 and relied on a rudimentary form of filtration (Gandy, 2004).

The first major breakthrough in the practice was the development of activated sludge in the 1920s, a process that relies on bacteria to break down the organic matter in wastewater (Metcalf & Eddy, 2014). Various forms of it still see widespread use today (Mara, 2004).

With the notable exception of the 1948 Truman-era Federal Water Pollution Act, wastewater management procedures went largely unregulated throughout the first half of the twentieth century. However, public outcry over the polluted Cuyahoga River catching fire prompted the passage of the 1972 Clean Water Act, which set comprehensive release standards, revolutionized wastewater management processes across the U.S., and set aside significant federal funds to invest in wastewater management infrastructure (Hoffman, 2010).

In the 1980s and 1990s, federal investments prompted the development and proliferation of tertiary treatment processes, which use various forms of filtration including chlorination, UV disinfection, and even reverse osmosis, to further purify wastewater sources (Asano et al., 2007). The substantial increase in effectiveness of these new methods, which were able to remove nutrients like nitrogen and phosphorus as well as trace metals from water sources, brought wastewater recycling into the international spotlight as municipalities in arid regions around the world, from the Middle East and Australia to California, invested heavily in the new technology (Ghaffour et al., 2013).

California has also led way in wastewater treatment. The 2008 Groundwater Replenishment System (GWRS) is one of the most cost-effective yielding and cleanest such schemes to date (California State Water Resources Control Board, 2020). A hybrid system that couples microfiltration technology with UV disinfection and reverse osmosis is implemented, under the GWRS, as the final stage of sewage treatment in conjunction with percolation facility infiltration for reuse within the community (California State Water Resources Control Board, 2020).

Despite its ecological benefits, wastewater recycling is often maligned by the public due to psychological fears of contamination, its perceived energy inefficiency, and the process's treatment costs (Patterson et al., 2016). Nevertheless, the increasing urgency of water scarcity, technological advancements, and comprehensive public awareness programs have made wastewater recycling more attractive in recent years (Baker et al., 2016).

Comparison

Yield/ Energy Efficiency

RO desalination guarantees adequate freshwater production, and coastal areas are almost always understood to be having a reliable saltwater feed. For example, the Carlsbad Desalination Plant in California produces about 50 million gallons of freshwater a day, which is around 10 percent of the water required in that region (California Coastal

Commission, 2015). If the former seems good, one must remember that this process is very energy intensive; it takes more energy to transfer merged water through a porous membrane, making them quite expensive to the market posteriorly (Davenport & Wang, 2022).

On the other hand, sewage treatment, such as the GWRS in California, has proved to be much more energy efficient. GWRS produces about 100 million gallons of fresh water daily, becoming approximately one and a half times larger than Carlsbad (California State Water Resources Control Board, 2020). Freshwater production is comparable in both technologies; however, wastewater recycling is the more energy-competitive technology with respect to existing infrastructure use and energy consumption (Ghaffour et al., 2013).

Cost (Maintenance)

Desalination via RO involves much more in terms of initial capital investment and continuing operating and maintenance costs. A complication with RO systems, involving high-pressure systems (and semi-permeable membranes requiring near-continuous replacement), means compounded operational and maintenance costs. For example, the operational cost of the Carlsbad Plant is approximately $2,000 per acre-foot. On the other hand, conventional costs for alternative water resources range between $300 and $1,000 for the same volume(Gleick et al., 2015).

In contrast, reclaimed water does provide an economically viable option. Rather than concentrating on the extraction of a saline component, the microfiltration approach eliminates suspended particulates, most notably with ultraviolet disinfection to target disease-causing microorganisms in wastewater. The GWRS, located in Orange County, produces water with a reasonable cost of $850-1,100 per acre-foot, making it one of the more affordable alternatives (California State Water Resources Control Board, 2020). In addition, wastewater recycling systems are not as laborious in the way of ongoing maintenance. Advancements leading to stability improvements over time make them less fussy with fouling mechanisms than desalination systems (Ghaffour et al., 2013).

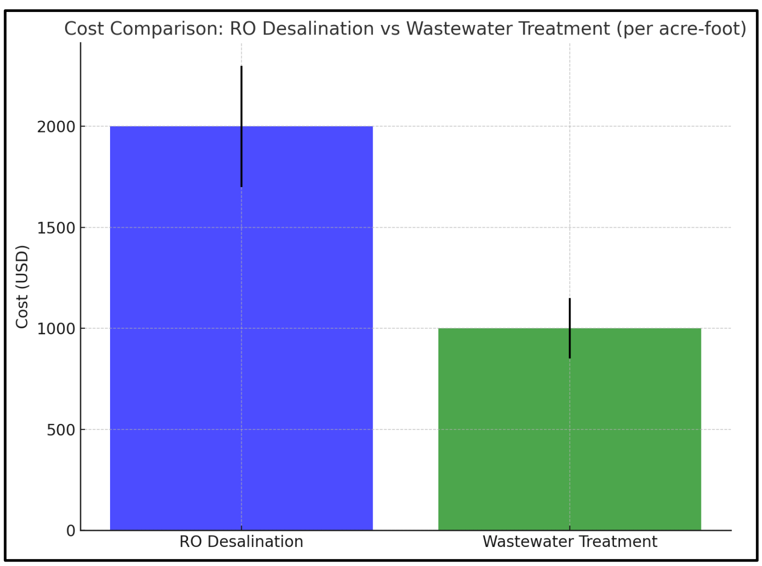

Figure 1. Bar graph comparison of treatment cost per acre-foot of raw water. Cost of RO desalination estimates around $2,000 while wastewater treatment is half as costly

Sustainability

By nearly all metrics, wastewater recycling is more environmentally friendly than RO desalination. This advantage arises primarily from the fact that wastewater recycling draws from and replenishes existing water supplies, minimizing ecological damage, while RO desalination converts its water supply entirely from non-potable saline sources. Such systems as GWRS offer not only a reliable water source, but also assistance in recharging groundwater levels, which are an essential resource within drought-stricken areas such as California (California State Water Resources Control Board, 2020).

Wastewater recycling produces fewer byproducts than desalination, which generates substantial amounts of brine. This highly concentrated salt byproduct is frequently pumped back into the ocean. The high salt content of brine can severely disrupt the chemical balance of seawater and adversely impact marine organisms (U.S. Department of the Interior, 2017).

Still, reverse osmosis desalination is among the most carbon-intensive per cubic meter of produced water due to poor energy efficiency of the desalination process itself. The efficiency of seawater reverse osmosis has been greatly boosted with the advent of modern membrane technology and the optimal energy recovery systems, but overall energy consumption and the associated carbon emissions are still far greater than for recycled wastewater. Fresher brine disposal into the ocean is another major drawback of seawater reverse osmosis (Ghaffour et al., 2013). For this reason, in most cases, wastewater recycling is a sustainable solution for water management.

Metrics	Wastewater Recycling	Reverse Osmosis Desalination
Brine Production	Minimal (approximately 10-20% of inflow)	40-50% of inflow (high concentration)
Environmental Impact of Byproducts	Low (beneficial for water systems)	High (affects marine ecosystems)
Carbon Emissions (g CO_2/m^3)	50-70 g CO_2/m^3 (estimated)	700-1,200 g CO_2/m^3 (depends on energy source)
Energy Consumption (kWh/m^3)	0.5 - 1.0 kWh/m^3	3.5 - 5.0 kWh/m^3
Water Quality	High-quality potable water possible	High-quality potable water
Sustainability	Highly sustainable	Less sustainable due to ecological impact

Political Feasibility

RO desalination enjoys political support from select technology and energy companies that view the process as more profitable than wastewater recycling. In particular, technology companies in Silicon Valley regard RO desalination as an exciting entrepreneurial opportunity. The company that patents technology to make the process more energy-efficient or commercially viable stands to gain billions in revenue from private and public contracts (Gleick, 2018). Additionally, energy companies benefit from the steady demand generated by desalination plants, which bolsters energy prices in the market. Together, these groups create a formidable lobbying force for desalination advocates, making the process especially attractive to large banks, investment firms, venture capitalists, and other financial interests (Perry et al., 2019).

Conversely, RO desalination tends to be supported predominantly by wealthy communities that can absorb or offset the high costs of the process. Given that RO desalination is often cost-prohibitive without significant public subsidies, it is generally limited to affluent coastal communities, such as Carlsbad and Huntington Beach in California (Baker et al., 2020). Moreover, RO desalination is considered essential in arid regions lacking readily convertible or accessible wastewater infrastructure, such as Spain, Saudi Arabia, the UAE, and Israel; however, the success of desalination efforts in these areas varies significantly (Salameh & Yousef, 2018).

Nonetheless, support for RO desalination is far from unanimous. Concerns about its environmental impact—particularly brine disposal—along with significantly higher costs and high energy consumption have led to persistent resistance from environmental groups, local community leaders, and some policymakers (Zhou et al., 2020). Furthermore, worries about access gaps created by RO desalination, which can only be funded by affluent communities or politically charged public subsidies, have led critics and researchers to conclude that the adoption of the process could exacerbate regional, socioeconomic, and racial inequalities (Patel & Koggel, 2019).

Despite its efficiency, cost-effectiveness, and sustainability, public reaction against wastewater management has been well-documented for decades. This skepticism was notably exemplified by the failure of the 2000 Toilet to Tap campaign launched in Los Angeles due to widespread concerns over water quality. Shortly after its public announcement, the campaign faced significant opposition from local leaders, politicians, and the media, leading to its cancellation (Thompson et al., 2019). While public perception of wastewater recycling has improved, especially in light of pressing water scarcity issues, distrust in the process remains a significant barrier to its adoption. Water experts now recommend pairing wastewater recycling initiatives with broader awareness and education campaigns, which can increase costs and extend implementation timelines (Zhao et al., 2021).

In Orange County specifically, wastewater recycling has proven politically feasible and widely supported, largely due to the success of the Groundwater Replenishment System (GWRS). The GWRS is often cited as a model for innovative water management and has received significant backing from both local and state governments. Its ability to provide a reliable water supply in a drought-prone region, coupled with its low environmental impact and cost-effectiveness compared to RO desalination, has made it politically favorable, helping to overcome the persistent "toilet-to-tap" stigma (California Department of Water Resources, 2018).

Final Recommendations and Conclusion

To effectively address water scarcity, Orange County should adopt a balanced approach that combines both wastewater recycling and desalination. However, there should be a greater emphasis on expanding wastewater recycling efforts due to its economic and environmental benefits. Expanding wastewater recycling is essential, as the Groundwater Replenishment System (GWRS) serves as a successful model for sustainable water management (California Department of Water Resources, 2018). Increasing investment in advanced wastewater recycling facilities will reduce reliance on imported water and ensure a sustainable water supply. Furthermore, it is necessary to implement public outreach programs to alleviate lingering concerns about the safety of recycled water, thereby gaining broader community acceptance and support (Zhao et al., 2021).

While wastewater recycling should take precedence, improving desalination technology can serve as a valuable complement to these efforts. Desalination offers an opportunity to diversify water sources, particularly in areas with abundant seawater and limited existing water infrastructure. However, technological advancements are needed to reduce energy consumption and minimize environmental impacts, such as those caused by brine disposal (Zhou et al., 2020). Orange County could benefit from supporting pilot programs aimed at enhancing the efficiency and sustainability of desalination processes. Additionally, pursuing federal or state funding to develop better energy recovery systems and eco-friendly brine management methods would be beneficial (Perry et al., 2019).

An integrated water management strategy is vital for creating a resilient and diverse water portfolio in Orange County. This strategy should encompass a combination of conservation, stormwater capture, groundwater replenishment, wastewater recycling, and, when necessary, desalination (Gleick, 2018). Encouraging policies that prioritize water reuse and conservation, while maintaining minimal reliance on desalination, will help balance long-term sustainability with immediate water needs, ultimately resulting in a more robust water system.

Lastly, legislative and financial support from both federal and state governments should continue to play a crucial role in facilitating wastewater recycling projects. By providing grants, tax incentives, and low-interest loans, government authorities can make water reuse and advanced treatment technologies more affordable and politically viable across California, including Orange County (Thompson et al., 2019). This ongoing support will not only foster innovation but also ensure that sustainable water management practices can effectively meet the challenges posed by water scarcity.

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