Alleviating Water Shortage in the Southwestern United States: A Comparison of Potential Alternative Water Sources

Kavita Amin *

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Abstract

Over the last century, cities have grown dramatically, especially in the Southwest region of the United States. Managing natural resources, in particular, clean water supply has become a pressing problem for urban areas in arid and desert environments. Rising temperatures, changing weather patterns, more frequent and prolonged droughts have, and will continue to stress water supplies such as ground-water aquifers and rivers. Water supplies that have been manipulated and used to accommodate growing populations are predicted to run out soon. While change is slow due to the huge and interconnected systems that provide water to urban areas, it is imperative that humans find alternative water sources. These include solutions like desalination, treating of wastewater, and greywater recycling that allow for water supplies to be used over and over again while remaining local. Stormwater capture is also promising as it can be collected locally, be used to recharge groundwater, and prevent otherwise damaging overflow. Overall, swift action must be taken in the near future to ensure an adequate and sustainable water supply in the Southwest United States.

1 Introduction

Population growth has caused urban and suburban areas in the U.S. to swell in number and size, often placing an unsustainable demand on natural resources. Specifically, some of the fastest growth rates are in the Southwest due to its sunny weather, generally lower cost of living, and abundant real estate. From agriculture and sanitation to energy production and industrial processes, almost all of modern society relies on access to clean and predictable water resources [Gle10]. During the 20th century, the population in the states surrounding the Colorado River grew by an astronomical 762 percent (Fig. 1) [Gle10].

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[*] Advised by: Dr. James Truncer of Harvard University Extension School

These population booms are increasingly outgrowing the capacity of local water resources, and as a result, this region faces a pressing water shortage, posing severe challenges to ecosystems and communities. Simultaneously, local and state governments have subsidized access to water enabling population growth and economic development [Gle10]. The most rapid growth has occurred in cities like those in California, where from just 1990 to 2007 around 500,000 acres of farmland were converted to suburban and urban areas. Similarly, in the Colorado River Basin, around 2,000,000 acres of land were converted to urban areas in the states that draw from it [Mac20]. Even in places where water conservation was previously not deemed a priority, such as the Colorado River Basin in the Southwest, climate change is exacerbating water scarcity.

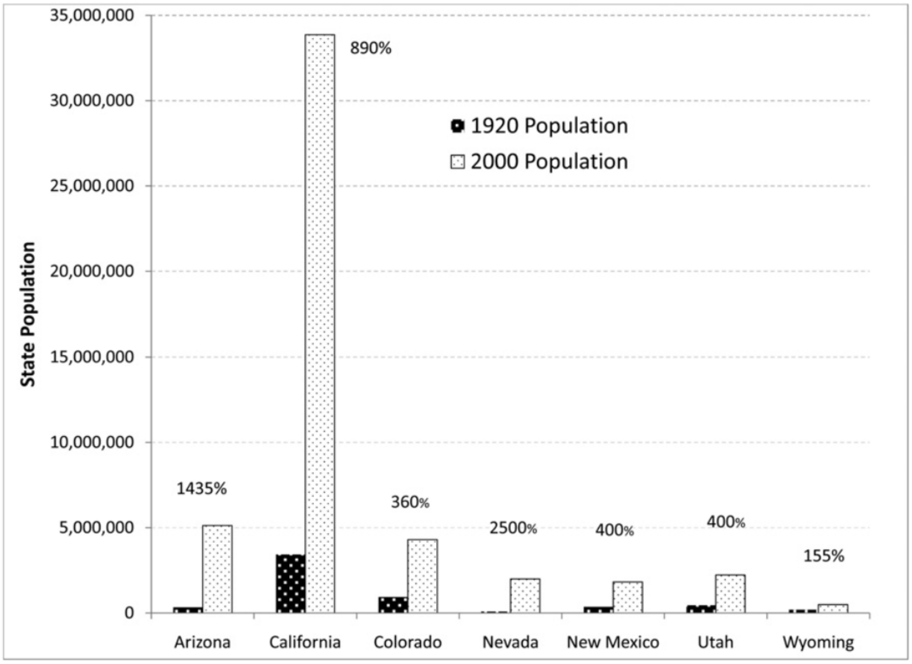

Figure 1: The population of the seven states that rely on the Colorado River Basin for water has risen 762 percent [Gle10]

In the American Southwest, groundwater reservoirs and major rivers are being rapidly depleted. During 2002, 2003, and 2007, long-term droughts occurred where the precipitation in the region was 25 percent or more below average [Mac20]. By 2050, the Colorado River is projected to decline by 10-30 percent, while the Salt River and Verde River will likely be greatly reduced. These larger river systems will have widespread effects on local waterways and watersheds that could be depleted in the future [Mar10]. Take for example, the high elevations that water must pass on its way to Los Angeles from the Colorado River which demands enormous electricity [Por20].

The strain on water supply sources will also be compounded by rising temperatures and more frequent droughts from climate change. Higher temperatures will cause surface water to evaporate more rapidly, changing weather patterns will result in longer and more frequent droughts, and reduced snowpack will mean less water is available to replenish rivers and groundwater [Gle10]. The increasing variability will make preparing for long periods of droughts more difficult, even though traditional buffers like reservoirs offer a backup source of water when water is low. It is important to note that perception of the climate crisis plays a key role in accelerating positive change. The variability in perception of climate change by region can prevent or accelerate swift action from taking place [Sem23].

Unfortunately, current water management strategies provide inadequate long-term solutions because the worst of water crises have been avoided in the short term, and cities have delayed significant structural changes by prolonging temporary management practices [Sem23]. Many cities are promoting population growth without ensuring that water will be sustainably available to support this increased demand. Additionally, reservoir capacity is shrinking due to sedimentation and many are at record lows. Another downside to reservoirs and other large storage is that they can lead to delayed public responses and pressure for change during times of water shortage since large reservoir storage capacity allows for droughts to go unnoticed [Kel21]. As a result, transitions towards sustainable solutions often get set back.

Similarly, public attention during times of water stress have not alone prompted effective change. In a study comparing the transitions toward water sustainability in major Southwestern cities, moves toward more sustainable options only occurred when paired with financial stress or when aligned with regulatory and political exposures [Gar19]. Also, water supply did not rebound when those pressures were lifted, because they usually persisted when temporary fixes were put into place.

Overall, current efforts to address the water supply shortage in the Southwest must expand in order to ensure long-term water availability to support local ecosystems and communities. As groundwater aquifers, snowmelt, and rivers dwindle, finding new sources of water is increasingly important to support the growing cities in the Southwestern United States. Successful, alternate sources of water have been explored in other regions around the world, but are not being implemented widely in the American Southwest yet. This paper investigates several key methods and strategies for water reuse and conservation in urban environments. Cost, effectiveness, possible side effects, and solutions implemented in other large cities will be evaluated. First, alternate sources of water like seawater desalination will be discussed. Then reuse options including greywater recycling, wastewater recycling, and stormwater capture as an alternative source of water will be explored. Challenges in terms of cost and public/political adherence will be covered, as well as examples of where these solutions have been implemented. Finally, the synergies and trade-offs between different alternative water resources will be discussed to assess how well they could work in the Southwest if implemented.

2 Research Findings

2.1 Seawater Desalination

Considering that the ocean is the most abundant source of water, looking to this as a potential resource is an important step. The high salinity of untreated saltwater makes it difficult to use for drinking or household consumption; for example, salinity of 500 ppm is considered fresh water while seawater can have a salinity of at least 35000 ppm [Shu12]. Desalination is one of the technologies that could allow seawater to supplement freshwater supply. Desalination can also have additional benefits such as removing dissolved minerals, heavy metals, pathogens, and other dangerous contaminants. While this technology is still being developed, desalination capabilities have improved greatly and are reflected in the amount of desalinated water produced worldwide. In 1945, only about 326 cubic meters per day were being desalinated; this number has grown to over 95.6 million cubic meters in 2016 [Meh20].

The most common methods of desalination are thermal distillation, electrodialysis, and reverse osmosis. The earliest methods utilized thermal desalination. Generally, seawater is heated so the water vapor separates from other compounds that have a higher boiling point. Multi-stage flash distillation is another method where water moves through a series of pressured chambers. This causes the brine water to "flash" to steam, which leaves the water as vapor [Shu12]. A similar technique, multi-effect distillation, does not change the temperature of the chambers, instead it reduces the pressure in each chamber to decrease the boiling point. The water vapor is then collected in tubes that condense it into freshwater [Shu12].

Membrane-based processes like electrodialysis and reverse osmosis have gained popularity as desalination technologies have evolved. Salt particles are separated from water molecules by being charged and transferred through an ion exchange membrane. After voltage is applied, negatively charged ions are attracted to the cathode while the positively charged ions are attracted to the anode causing the fresh water to be left behind. Reverse osmosis is soon predicted to become the most common method of desalination. In contrast to osmosis, where liquids on each side of the semi-permeable membrane want the solute concentrations to be equal, in reverse osmosis pressure is applied on the salt side to force the water through the membrane to the freshwater side, leaving other particles behind [Shu12].

These technologies have been successfully implemented around the world. For example, the Ashkelon Seawater Desalination Plant in Israel uses the reverse osmosis technology. It was designed to produce 330,000 meters cubed of potable water daily. The average price of water in U.S. dollars produced by the plant is 0.527 per meters cubed, and the total plant cost around 212 million dollars [Shu12]. Another desalination plant located close to Fujairah, United Arab Emirates also utilizes the reverse osmosis technology. It has the capacity to produce between 170,500 meters cubed and 454,000 meters cubed per day of water depending on the amount of power that the plant received. Due to the energy intensive processes, wind turbines with a recovery rate of approximately 88 percent were installed [Shu12].

Water desalination can also be used to supplement the water supply on a smaller and local level. The findings in a study that observed the use of desalinated water in a greenhouse can be applied to the needs of Southwestern cities and urban communities. The study conducted by Roca et al., 2016 focused on greenhouses located in the Mediterranean Basin, a region that has a similar climate to that of California. The methods for desalination combined that of solar stills and multi-effect distillation because solar stills would not provide enough water for a greenhouse if demand was not steady. The machines were activated based on expected consumption of water and the climate of the greenhouses to help ensure that the appropriate amount of water was available when needed. Overall, this study found that water demand could be met with the additional help of the multi-effect distillation method, however, it would result in additional costs. Those costs could decrease as efficiency and prevalence rise [Roc16]. In the Southwest, a huge portion of water consumption is used for lawn irrigation, so this water reuse method would be a feasible option because water for lawn irrigation requires less treatment than for other uses where potable water is required. Additionally, this water could also be used in homes and other buildings.

Several desalination projects have demonstrated the viability of seawater desalination in the U.S. For years, the town of Carlsbad, California has struggled to provide abundant access to fresh water due to droughts and increased demand. As a result, a desalination facility was built, and cost approximately 1 billion dollars to build and start operation. It produces around 50 million gallons of water for regions around San Diego daily [Kir20]. The town of Prescott Valley, Arizona has also been using water processed through desalination, treated wastewater, and harvested rainwater to recharge groundwater aquifers and irrigate local golf courses. In order to manage further use of the limited water supply, the town has proposed requiring developers to have a permit indicating their access to a steady supply of treated water before building new homes. In combination with recharging groundwater, this proposal would limit the strain on the groundwater in the first place [Gle10]. Overuse of groundwater in the Tampa Bay area has prompted the building of another desalination plant. This one has the capacity to produce 25 million gallons of freshwater daily. Additionally, the concentrated effluent that is produced by the plant is being diluted with recycled cooling water from a local electric power station to protect the environment from the harmful brine [Des17]. It is important to note that desalinated water often comes at a higher cost compared to that of treated fresh water. This plant is an example of the high cost of desalinated water; water from this plant is 4 times as expensive as local groundwater, despite being built for efficiency [Des17]. In order for seawater desalination to become a cheaper and a more efficient process, use of seawater desalination as an alternative water source must become more widespread. Plans for additional desalination plants are expanding, for example in California, officials have granted 34.4 million dollars to eight water desalination projects, some of which use sources of water other than the sea like briny groundwater [Kir20].

Seawater desalination is becoming increasingly common, and many countries in the Middle East have widely adopted desalination processes to augment their water supplies. For example, over 50 percent of water is sourced from the ocean in Kuwait, and in the United Arab Emirates 16 percent of water is acquired through desalination. The hot, dry, desert-like conditions are similar to those in the Southwestern United States and the results and effects of desalination plants in the Middle East can be compared to the Southwest. It is worth noting that the Middle East has particular operational advantages. First, operational costs are lower due to energy being cheaper. If the U.S. were to adopt similar practices, whether that be heating chambers, pressurizing tanks, or forcing water against the concentration gradient, the cost could be greater. Second, if the energy that powers these plants comes from traditional fossil fuels, the high use of energy can increase carbon dioxide emission and discharge can be dangerous if released unchecked into nature, so the environmental effects of this process must be kept in mind. In a study based in Iran, the city of Bandar Abbas had a water production flow rate of 89,000 cubic meters of water per day and produced high amounts of carbon dioxide emissions (100053.80 tons) [Meh20]. These desalination projects in the Middle East offer great examples and learnings that can be applied to desalination more widely in the Southwest United States.

There are environmental concerns to consider with the use of desalination. The discharge of highly concentrated brine back into the sea can harm ecosystems, so careful environmental monitoring and mitigation is necessary. In some cases, it can take 100 gallons of ocean water to produce 15-50 gallons of pure water [Des17]. If brine is released into the ocean, it can damage phytoplankton, invertebrates, fish communities, and other seagrass habitats. Shallow coastal areas that are densely populated are more sensitive to brine discharge as it is more difficult for brine discharge to be diffused into the surrounding area [Meh20]. An additional consideration is that water desalination plants emit sulfur dioxide and many types of nitrogen oxide gasses that can affect the surrounding environment. Ultimately, seawater desalination is a promising solution that could be implemented in the Southwest based on previous examples around the world, however, significant hurdles like cost and possible negative environmental effects must be carefully considered.

2.2 Greywater Recycling

As implied in the name, seawater desalination requires an abundant source of ocean water, thus, may not be an optimal alternative water reuse method for inland communities. Transporting seawater inland would be costly and require new infrastructure to be built, both of which would contribute to greenhouse gas emissions that could negate the positive environmental gains from utilizing desalination. A better alternative would be to consider greywater recycling for two main reasons - it can be utilized locally and is significantly more economical. Greywater is domestic wastewater that comes from household appliances, showers, sinks, dishwashers, and laundry machines, but water from toilets and kitchen sinks are not included due to the possibility of hazardous contaminants like bacteria and other microbes [Mac09]. According to the NIH, a person can consume anywhere from 15 gallons of water daily in low-income communities to several hundreds of gallons in more affluent areas, which is a great amount of water that could be recycled and reused [OP18]. Oftentimes, greywater is rendered useless by being sent directly to a water treatment plant when it is mixed with other wastewaters. Instead, the recapture and reuse of greywater should be more widely used to make water consumption in urban areas more sustainable.

Greywater can be captured and processed in a few different ways. One method uses a series of filters to make water safe to drink. This is known as potable water and the filters are made up of tiny, tightly packed pores that can capture harmful particles and contaminants, even those like microplastics. Some filters use what is known as nanotechnology which uses nanoscale materials that have the ability to sterilize water [Mac09]. When applied directly into communities and homes, the greywater is directed into a holding tank, similar to that of a septic tank. In the tank, waste is degraded and the clean water is passively pushed out by incoming greywater as it enters into the tank. In order for the clean water not to mix with the dirty water, the water is directed through a succession of baffles and then an outflow pipe [Mac09].

A second method of processing greywater relies on a naturally occurring cycle where water is filtered through natural substances of many different sizes to strain out the bigger particles. This leaves the water free of large contaminants and is safe for many uses. A similar method of greywater recycling is modeled after nature's processes by the greywater being routed into constructed wetlands adjacent to communities. As a result, many of the particles contaminating the water are degraded into organic matter by the microorganisms and plants living in these areas. Overall, this limits the use of septic systems, as part of the process is taken care of naturally which is cost efficient and ideal [Mac09].

Recycled greywater can replace freshwater for a number of household uses. Lawn irrigation and landscaping are currently one of the biggest uses of recycled greywater, as an idealistic, lush, green lawn aesthetic is what society has been taught to value despite its massive drain on the water system. Recycled water can also be used for toilet flushing and many other systems that allow for non-potable water use [Mac20]. In fact, recycled greywater use is not only limited to domestic consumption, it can also be used on a larger scale in institutional settings including manufacturing plants, office buildings, and schools [Mac09].

While seawater desalination is still extremely expensive, greywater recycling is much more affordable and can be implemented on both small and large scales. A single household greywater recycling system can involve a simple laundry-to-landscape model, whereas a more complicated and extensive system can produce cleaner water for more uses. Depending on the size of the household, a system that captures all greywater can cost between 5,000 dollars and 15,000 dollars [Nea19]. Additional costs occur when updating the construction and plumbing of existing structures to accommodate these technologies. Costs will come down as new efficiencies in technologies are discovered and implementation expands in urban areas. Greywater reuse technologies are most economical in multi-residential developments where facilities and systems are centralized, as opposed to neighborhood and rural settings where demand is sparse [Nea19].

For example, the Aspen Hall dormitory, located in Colorado State University, installed a greywater recycling system where the products were used for toilet flushing and irrigation in 2008. After the implementation of the new system, Aspen Hall reported that collection, plumbing, and distribution piping costs were 30 percent of the total capital cost [Nea19]. Using a 5,000 gallons per day sand filter with an estimated lifetime of 30 years, it was estimated that costs, including energy and maintenance, were around 4.49 dollars per 1000 gallons, and costs could be even less if water was purified to a lesser degree. This is less than typical treated water costs for a residential setting using upwards of 15,000 gallons per three months in Denver, as rates are around 5.84 dollars [Den23].

Size and design of greywater recycling systems will also have an effect on the efficiency and profitability of implemented systems. In a study conducted by Stec and Słyś, 2018, the efficacy and costs of greywater recycling and rainwater capture were compared and the control group where traditional water sources were only used was the least profitable. Take for example a trial conducted in Lisbon where the operating costs over 30 years were extremely high and exceeded the cost of installations like greywater recycling and rainwater capture. This being said, upfront costs for these unconventional systems may have been higher due to retrofitting existing buildings to fit the new systems. However, in the long run, the unconventional systems proved to be more profitable. When analyzing the effect of a system where rainwater harvesting was used for washing and garden watering and greywater recycling was used for toilet flushing, the size of the collection tank was found not to have an effect on efficiency. This was not the cause when only stormwater capture was used, and this might be due to the multiple sources of water making variability of available water lower. The study found that a tank of 11 meters cubed was the most efficient despite the number of people that were using it (2, 3, or 4), and the costs depending on the number of people only varied slightly. Additionally, this system was found to be approximately €21,000 - €43,000 cheaper than that of traditional systems [Ste22].

Similarly, in Madrid, traditionally water systems were not the most profitable investment and had the most expensive life cycle cost for a system designed to serve 3 or 4 people. However in the trial where recycled greywater was only used for toilet flushing for a home of 2 people it was the least profitable [Ste22], due to the fact that implementation costs were high but usage over the long run was lower due to less demand. So, trials where greywater recycling was used in combination with that of rainwater harvesting were the best financial choice. Therefore, if these systems were combined, operational costs were lower over the 30-year population due to the highest water savings being achieved. In general, greywater recycling is a great solution for household or local community-use due to its lower costs versus that of large-scale options like seawater desalination, however it is best when the supply and use of greywater is constant.

2.3 Wastewater Recycling

Wastewater recycling offers another option to preserve water and extend its usability before entering the water cycle again. This type of water requires further treatment due to the possibility of many toxic contaminants. Phosphorus and nitrogen, typically found in high amounts in wastewater, can be particularly detrimental to the environment as they can severely alter natural levels of these elements. At least one third of domestic wastewater contains these substances as a result of dishwashing, baths, and handwashing [Ari18]. The untreated sewage is captured before being mixed with other waste and discarded into nearby waterways (Best In Flow, 2012). Similar to the systems involved with recycled greywater, wastewater recycling can be used at the household and local community level. It works especially well in highly populated urban regions, like those found in the Southwest. Ecotanks that look and work similar to septic tanks can be installed for individual or groups of homes in local communities. For space efficiency, these tanks can be installed underground with a network of pipes that bring waste from neighboring households to be treated. Due to the small and customizable features of systems like these, communities that don't have the resources, space, and demand to connect to large scale facilities can still implement these solutions. One city that has started to implement eco tanks is Bangkok. Due to limited space in its densely populated areas, the underground capabilities allow many households to be connected without using much space [Bes13].

Recent innovative designs implementing wastewater recycling technology make this an attractive alternative water source. Creative designs that can be directly implemented in buildings and that don't require large land areas are on the rise. One design, known as WETWALL is a natural ecosystem that can contribute to urban water resilience. It can be installed on vertical spaces such as on building facades or empty walls. These installations can also improve air quality by absorbing toxins and carbon dioxide from the air which in turn can help mitigate climate change [Ari18]. This design aims to combine aspects of constructed wetlands into living walls to limit overall water consumption. The WETWALL structure is modeled after underground biological filters found in wetlands. The wetland concept is modified for the WETWALL installation by limiting surface area while maximizing filter depth. As a result of the limited surface area, the filtration materials are aerated to increase water retention time. Wastewater is added incrementally in low doses to avoid heavy saturation in the filter. There are some potential concerns to consider due to the compact nature of the WETWALL structure. Mainly, the module is at risk of oversaturation and clogging by suspended mineral and organic solids, such as biofilm and chemical precipitation. Both of these issues can be addressed by determining the appropriate hydraulic loading rate to use this technology most efficiently and allow for longevity of the module [Ari18].

The WETWALL module has three main sections. The first contains substances encased in a plastic liner and plywood walls to limit contact with the atmosphere. The second section contains materials surrounded by a polyester or PVC geotextile that is mounted on a steel grid. The last section consists of plants, of which native species are preferred to support biodiversity. They are often an environmentally friendly choice that can adapt well to the natural climate [Ari18].

The WETWALL technology is also superior to other methods of wastewater treatment in removing contaminants. When compared to other methods of wastewater treatment that removed between 31 percent - 34 percent of phosphate and nitrogen, this model removed between 69 percent - 71 percent of contaminants. These results can be attributed to the materials in the first and second part of the WETWALL like lightweight expanded clay. Overall, the WETWALL can occupy anywhere between 0.192 meters squared - 2.34 meters squared of space and a depth of only 0.0025 meters cubed per day - 0.36 meters cubed per day depending on the size and capabilities of the model [Ari18]. Therefore, this is a compact technology that can be built and installed in a multitude of places.

Despite the many benefits, especially in comparison to other alternate sources of water, the process of wastewater recycling presents a few challenges. When anaerobic digestion systems are used, gasses like hydrogen and sulfide are released. This results in unpleasant odors in the community, though are not harmful for human health [Mac09]. However, the byproducts of wastewater recycling can have a negative impact on the environment if methane control and discharge cleanliness are not taken into consideration. A simple solution includes using methane collection devices that can be installed above waste tanks to reduce odors while stopping it from contributing to greenhouse gas levels [Mac09]. The United States Environmental Protection Agency enforces water quality regulation ensuring standards of cleanliness that treated wastewater must achieve, and the responsible disposal of discharge. Discharge from treatment can be used in other ways as it is considered biomass. Organic matter from waste that comes from plants or animals is considered Biomass. It can be used as a source of chemical energy that can be converted to thermal energy [Mac09].

Arguably, the biggest challenge of implementing wastewater recycling is negative public perception, because opposition to solutions are highly stigmatized. Generally, Americans who are more accepting of purified recycled water are also those who have a strong belief in climate change. Additionally, some may be concerned about the future availability of water, but view the problem as a lack of urban planning and water allocation, and therefore not open to considering using recycled wastewater. Therefore, effective public outreach and education to the understanding of how water scarcity in the Southwest poses a threat to communities is needed for widespread acceptance of recycled wastewater. One of the fiercest oppositions of recycled wastewater occurred in the town of Toowoomba, Australia, in 2006. When the local reservoir was down to 20 percent and as a result of quickly depleting water supplies, city leaders decided to supplement the city's water supply with water reuse and wastewater recycling. Due to inadequate public outreach and education, when plans were leaked, the public responded with campaigns and votes against its construction [Sem23].

Furthermore, in Toowoomba, the negative perception of recycled wastewater has hindered its widespread use in many other places globally. Negative phrases like “toilet to tap” and “sewage beverage” have contributed to a stigma against wastewater reuse, and this brings to light the lack of education that the public has on solutions like these [Dis18]. Additionally, the lack of governmental regulation can cause public distrust and uncertainty. Both of these issues can be fixed with simple solutions like public education. The likelihood of use will increase if information includes detailed schematics and definitions of the treatment process, rather than persuasive campaigns that are politically motivated. Information on the concerns associated with water shortages paired with educational material on the urban water cycle will reinforce the idea that wide-spread water reuse is important [Dis18].

Despite these drawbacks, wastewater recycling has been successfully implemented around the world and in the Southwest. In one of the first major wastewater treatment facilities opened in Windhoek, Namibia, wastewater was blended with other sources when sent to the treatment plant. Since 1968, the plant has been operating successfully and was updated in 1996 to expand its capabilities as demand has grown with increased population [Dis18]. In the United States, Southwestern states have led the adoption of these technologies. For example, Big Spring, Texas currently has a fully operational plant with others operating partially and still more in planning. A major project is being constructed in the mountain resort town of Cloudcroft, New Mexico to address the increased water demand during holidays and weekends. This project is extremely versatile as treated water is combined with native water sources and supply can be manipulated with storage as it was designed to go straight to consumers while having the capabilities to be stored in an environmental buffer [Dis18]. Since 2008, the Orange County Water District in California has been using wastewater treatment to replenish the groundwater system. This is one of the most advanced water purification systems in the world and differs from previous systems as it directs purified water to underground aquifers, which helps to preserve current water supplies by preventing saltwater intrusion in underground resources. Around 100 million gallons per day can be produced by the system and distributed as drinking water for California residents [Dis18].

Like recycled greywater, recycled wastewater has many household uses, which makes this an attractive water reuse option. In Prescott Valley, Arizona, treated wastewater is being used to irrigate landscaping at local golf courses and to recharge the dangerously low groundwater aquifers [Gle10]). Treated wastewater can also be used on an industrial level. For example, the nuclear power plant located in Palo Verde relies solely on reclaimed wastewater in its cooling systems [Gle10]). From the many and diverse examples of wastewater recycling, it is clear that this technology can be implemented in a wide variety of communities throughout the Southwest to address their specific needs.

2.4 Stormwater Capture

As urban areas expand, concentrations of buildings and roadways heighten the amount and frequency of stormwater runoff while reducing the amount of available space for water to be absorbed back into the environment. This can cause waterways to erode and degrade risking water contamination when water quantities exceed typical volumes [Bro11]. In order to alleviate or prevent runoff quantity and improve water quality, water sensitive urban designs must be implemented. Stormwater harvesting is just one solution that can divert stormwater flow and allow it to be used before it encounters pollutants after being added to the sewage system. Stormwater capture involves the collection and utilization of rainwater runoff, typically from rooftop, parking lots, and other impervious surfaces. After stormwater is diverted and captured, it can be treated and used for mainly non-potable uses such as irrigation and toilet-flushing [Bro11]. Ultimately, if this technology is implemented widely throughout the Southwest, it has the potential to greatly reduce stress on the current water supply system, and can work to recharge groundwater aquifers and other water sources.

Stormwater harvesting schemes and dual storage systems are two common styles of stormwater capture. Stormwater harvesting schemes capture initial stormwater runoff known as capture-store, and control flow to provide water for urban uses as needed, known as balance-store. Single-store Stormwater Harvesting Schemes (SHS) are designed to work so both methods are integrated into one unit. When implemented for household use, water from the roof is directed into a rainwater tank and can then be pumped into the house for use. One of the benefits of Single Storage SHS is controlled storage and release of water based on demand patterns [Bro11]. In urban settings, space is limited to areas where water can be stored and must therefore need to be compact. In order to manage water use, the extraction rate of stored water must be fairly rapid. Typically, stormwater harvesting systems are designed for harvested water to be used within one day in order to be prepared for subsequent runoff events. Especially when using capture-store, storage should be emptied within 1.3 days in order to maximize yearly collection. If there is rapid runoff in short periods of time, water must be stored in large 'banks' like aquifers. This will allow the tank to be empty 90 percent of the time. If these aren't available, systems should be designed to release water slowly to provide a continuous supply to the user while leaving the storage tank empty 80 percent of the time [Bro11]. Dual Storage Stormwater Harvesting Schemes are similar to other stormwater capture systems in that stormwater is diverted to other storage systems like tanks and ponds. However, after stormwater is harvested, it can be treated and transferred to 'clean water' balancing storage before being used. One example of this on a large scale is aquifer storage and recovery [Bro11].

Due to the difference in demand and rainfall, stormwater capture must have large storage capabilities to keep up with demand during dry periods. However, this can be challenging in urban settings where space is limited, causing this to be an argument for not using stormwater. Therefore, when implementing stormwater use into urban settings, it is easiest and oftentimes the most effective use of space when stormwater harvesting systems are directly implemented in the planning stages of urban areas [Bro11].

While capturing stormwater will always be helpful in supplementing water supplies, collecting and using it efficiently will allow for more water to be utilized and make investments more worthwhile. According to a study conducted by Stec and Słyś in 2018, tank capacity plays a role in results compared to costs and other investments made. The impacts of alternative water systems in single family homes across eight cities in Europe were measured. In the most simple situation, where collected rainwater was used only for toilet flushing, a two-person home required a 9 meters cubed tank to be installed. As the number of people in a home increased, the capacity of the tank increased. A three-person home required a 13 meters cubed tank and a Four-person home required a 15 meters cubed tank to be installed. With this model, the study found that an increase in tank capacity causes the reliability of water to increase. In Lisbon, volumetric reliability of a tank for two people increased from 67 percent (where the volume of the tank was 1 meters cubed) to 98 percent (where the volume of the tank was 8 meters cubed). Similarly, in Madrid, a home for two that uses 70 meters cubed per day of water for toilet flushing has a reliability of 90 percent when the collection tank is 9 meters cubed. The study also found that when demand increases, reliability will only decrease a minimal amount, only 2 percent for a three-person home and 11 percent for a four-person home [Ste22].

This study also analyzed the utilization of collected rainwater for uses other than just toilet flushing like clothes washing and lawn irrigation (Fig. 2). Due to the dramatic increase in water use, reliability is understandably lower. In Madrid, the volumetric reliability of a system design for a two-person home is 37 percent, 35 percent for a home of three people, and 33 percent for a home of four people, therefore, the number of people using the system did not have a significant effect on its volumetric reliability. Similar results were observed in Lisbon and Rome partially due to lower average rainfall in these cities. Additionally, disparities between volumetric reliability were low, just like that of the first scenario where captured water was only used for toilet flushing. In both Rome and Lisbon, volumetric efficiency averaged around 45 percent. In the other cities that had rainier climates, volumetric reliability ranged from 82 percent to 86 percent in a system designed for two people. Where demand increased to four people results were lowered about 7-12 percent.

In general, differences in variability for the first scenario were caused by differences in overall rainfall for the selected cities. While Rome and Lisbon had the highest volumetric reliability due to higher annual rainfall, 99 percent and 98 percent respectively, Madrid still had a reliability of around 90 percent, despite being the city with the lowest annual rainfall and water only regularly flowing into the tank for about 10 months of the year. These results were aided by the fact that winters were warm, so water had the ability to flow to the system throughout the year. Though these cities are located in very different parts of the world, their climates are not as different as their distance might suggest. The cities in Europe are also challenged with growing populations and dwindling water supplies due to overuse and are working to find other sources to supplement their water supply. Overall, these results are extremely relevant to the Southwestern United States because the climates are similar, especially in southern Europe.

Water harvested through stormwater capture is best used for toilet flushing

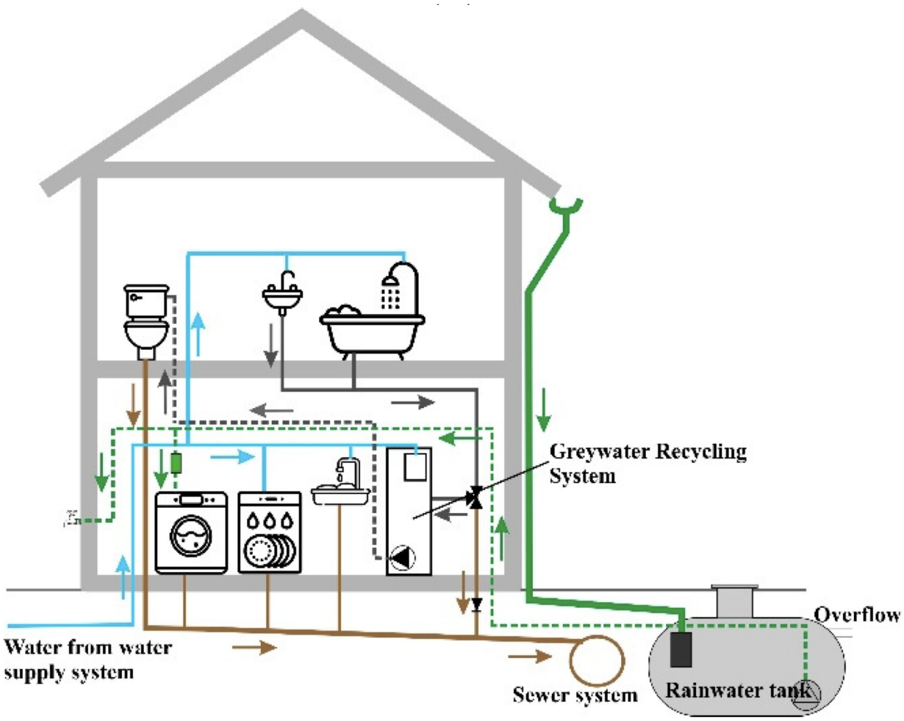

Figure 2: Alternative Water Sources in a Home [Ste22]

and other non-potable uses due to the low amount of treatment needed. To keep costs low, it is important to add these technologies during the building process, since connecting collected water to buildings requires customized designs. Los Angeles attempted to map out the costs of implementation with the Stormwater Capture Master Plan for the Los Angeles Department of Water and Power [Nea19]. Total costs include storage facilities, piping, and pumps, estimates ranged from 1,200 to 6,000 dollars per acre-ft depending on the types of stormwater collection needed for specific regions and neighborhoods (Neal, 2019). Though implementing stormwater capture into new construction will utilize the most harvested water, it is significantly less expensive to retrofit these systems into existing treatment plans as most urban areas consist of buildings that have the potential to be updated with these technologies. 32 projects were studied in Southern California and the cost of water per acre-foot for each system was calculated. The 2018 Southern California Water Coalition found that the average cost was around 1,070 dollars per acre-foot where 25 out of the 32 of the projects retrofitted stormwater capture technologies into existing buildings [Nea19].

3 Discussion

The many regions in the Southwest have their own unique climate and environments, so no single water-reuse method alone discussed in this paper will yield preferred and sustainable results. Instead, a combination of the four technologies should be used strategically to achieve the most optimal results. There is strong evidence to support that all four methods have yielded extremely positive results in various regions around the world when used in appropriate environments. In coastal regions where seawater is in abundance, seawater desalination is a favorable solution because it can be cleaned in large quantities and distributed in a similar fashion that regular potable water is. The most successful examples of this method have been implemented in the Middle East where water supplies are low while populations are growing. The cost of implementing desalination has fallen which now makes this a highly attractive option. Additionally, some of the new technologies involve small scale systems that can be implemented for individual use or in small communities where demand is moderate. However, it is important to consider that the desalination process requires substantial energy, potentially increasing reliance on non-renewable sources. Also, the discharge of concentrated brine into the sea can harm marine ecosystems, requiring careful environmental monitoring and possible mitigation.

Comparably, greywater, wastewater recycling, and stormwater capture are methods that can be implemented for both individual and wide-scale use, and allow water to be reused before it reaches the natural water cycle and thus are equally compelling sustainable water reuse options. Greywater and wastewater recycling can utilize non-toxic water from a variety of buildings like residential and office buildings, airports, and schools. Then water can go back into buildings to be used for toilet flushing, lawn irrigation, and other non-potable uses depending on their level of purification. Besides providing water, byproducts like biomass can be used as alternate sources of power. Additionally, household technologies that utilize plants and other natural materials, like the WETWALL system, can also help to purify the air. Stormwater capture has many of the benefits listed above, and can also help to lessen the severity that storm runoff has on city's sewage systems or prevent it from mixing with other toxic chemicals and polluting local waterways. While there are many benefits, the demand that household systems have are important to consider and will make the costs of installation worth it as they can oftentimes be just as or more expensive than existing water supplies. Moreover, solutions like stormwater capture will make the most sense in areas where there is regular rainfall unless large storage is available. Overall, these solutions are best used for in-land cities and communities that don't have direct access to large river systems or the ocean.

4 Conclusion

While most agree that many regions in the Southwestern United States are facing water shortages, it is hard to discern the best way to address these issues. In this paper sustainable water processing methods and sources are explored like seawater desalination, rainwater harvesting, greywater recycling, and wastewater recycling. It is imperative to also consider how various water reuse methods could be used in this region to support a growing population in the future given the strain on current water sources. Not only do water shortages have an effect on society, but also on the surrounding climate and any further disturbances would likely have a more striking negative impact on the ecosystem and climate change. In particular, harsh drought and warmer temperatures can worsen pest infestations and forest fires, which can cause entire forests to die off [Gle10]. For example, an estimated 14-18 percent of the Southwest's trees have suffered infestations and fires between 1984-2008 and this number is only expected to rise as climate warming continues and water supplies diminishes [Mac20]. Also, warming temperatures will accelerate snow melt which will provide less water to forests. This will compound the lack of water for forests as much of it is being diverted for human uses.

Each of these potential water reuse methods has yet to be implemented widely in the Southwest mainly due to high costs and limited current availability. Additionally, more research must be done on the individual cities and communities in the region in order to assess which solution will be the most effective. This is important because each of the solutions work best in different situations, and must be customized to consider the specifics of each location. Furthermore, in order for water use to become more sustainable, regulations and policies must be established that support responsible water consumption. This includes policies that limit the amount of water used by cities. Such policies need to expand to make developers prove that they have a sustainable source of water before building. Additionally, if population and development increase as predicted, even implementing these new solutions will not be enough to support the population comfortably Therefore, considering policies that limit population may be an important next step to ensure sustainability.

Moreover, in order to ensure that there will be a sufficient water supply in the future, cities will need to start conserving water on the household level. Greywater and wastewater recycling are great for repurposing water after it is used. Households and other buildings should also reduce their water use from the start. Further research must be done so most buildings can be outfitted with water efficient appliances. Additionally, advocacy for xeriscaping should increase. Xeriscaping is where native species are planted as opposed to traditional grass in yards to reduce water use for irrigation. The water crisis in the Southwest is expected to only worsen as populations increase and water supplies dwindle. Thus, it is imperative that a multifaceted approach be taken to reduce water consumption and find new sources of water, including utilizing new technologies like seawater desalination, greywater recycling, stormwater capture, and wastewater recycling.

References

[Ari18] J. A. C. A. Carvalho P. Rysulova M. Montserrat Canals J. Pérez Luque G. ... Farreras J Arias, Castellar da Cunha. Wetwall-an innovative design concept for the treatment of wastewater at an urban scale. *Desalination And Water Treatment, vol. 109*, 2018.

[Bes13] Best in flow: a six-pack of decentralized water management systems that deal with climate change turmoil by building local resilience. *Alternatives Journal*, 2013.

[Bro11] I Brodie. Stormwater harvesting and water sensitive urban design detention: a compatibility analysis. *In Proceedings of the 12th International Conference on Urban Drainage*, 2011.

[Den23] 2022 residential water rates. *Denver Water*, 2023.

[Des17] D Desonie. Sustainable water use. *Humans and the Natural Environment, Second Edition*, 2017.

[Dis18] L.N. Distler. Potable water reuse in albuquerque, nm: A large scale community survey to understand public perceptions and the impact of educational materials on acceptance. *Electronic Theses and Dissertations, University of New Mexico*, 2018.

[Gar19] Koebele E. Deslatte A. Ernst K. Manago K. F. Treuer G. Garcia, M. Towards urban water sustainability: Analyzing management transitions in miami, las vegas, and los angeles. *Global Environmental Change*, 2019.

[Gle10] P.H. Gleick. Roadmap for sustainable water resources in southwestern north america. *Proceedings of the National Academy of Sciences*, 2010.

[Kel21] E. Kellner. The controversial debate on the role of water reservoirs in reducing water scarcity. *Wiley Interdisciplinary Reviews: Water*, 2021.

[Kir20] K. Kirkland. Water management—conserving an essential resource. *Earth Sciences, Revised Edition*, 2020.

[Mac09] A. Maczulak. Sustainable wastewater treatment. *Environmental Engineering*, 2009.

[Mac20] G.M. MacDonald. Water, climate change, and sustainability in the southwest. *Proceedings of the National Academy of Sciences*, 2020.

[Mar10] Robles M. D. Majka D. R. Haney J. A. Marshall, R. M. Sustainable water management in the southwestern united states: Reality or rhetoric? *PLoS One*, 2010.

[Meh20] Mahdiraji H. A. Binaee S. Alipour V. Razavi Haji Agha S. H. Mehrgan, M. R. Modeling of environmental aspects related to reverse osmosis desalination supply chain. *Environmental Health Engineering and Management Journal*, 2020.

[Nea19] M.R. Neale. Assessing tradeoffs of urban water demand reduction strategies. *Doctoral dissertation, Colorado State University*, 2019.

[OP18] Acheampong M. A. deVries NK Oteng-Peprah, M. Greywater sharacteristics, treatment systems, reuse strategies and user perception—a review. *Water Air Soil Pollution*, 2018.

[Por20] Mika K. B. Escriva-Bou A. Fournier E. D. Sanders K. T. Spang E. ... Pincetl S. Porse, E. Energy use for urban water management by utilities and households in los angelese. *Environmental Research Communications*, 2020.

[Roc16] Sánchez J. A. Rodríguez-F. Bonilla J. De la Calle A. Berenguel M Roca, L. Predictive control applied to a solar desalination plant connected to a greenhouse with daily variation of irrigation water demand. *Energies*, 2016.

[Sem23] Jatrana S. King-T. J. Semasinghe, C. Exploring the associations between the perception of water scarcity and support for alternative potable water sources. *PLoS One*, 2023.

[Shu12] Kangwen Shu. International overview of seawater desalination plant by reverse osmosis technology. *University of Stavanger,*, 2012.

[Ste22] Słyś D Stec, A. Financial and social factors influencing the use of unconventional water systems in single-family houses in eight european countries. *Department of Infrastructure and Water Management, Rzeszow University of Technology*, 2022.