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Summary

Natural resources such as water and energy are critical for the function of urban systems and economic growth. However, these sectors have historically been managed separately, isolated from the influence of other sectors and sub-systems. The concept of urban nexuses in resource management has gained popularity in recent decades, highlighting the interactions between highly interlinked urban sectors. Research regarding the influence of social systems on resource management has also increased in recent years, but despite the growing popularity and relevance of these concepts in the face of climate change effects, their integration in resource management and infrastructure development is still limited. More research is needed regarding these interactions and their impacts on the availability of critical resources, especially within a local context.

Micronet water infrastructure (MWI) is a relatively new concept that has been suggested as a possible strategy for developing urban water systems that are resilient to the effects of climate change. The objective of this research is to determine if MWI could feasibly be implemented in the context of the Las Vegas Valley (LVV) region of southern Nevada, and if so, how this would impact the water-energy nexus (WEN) of the valley. To do this, the technical, economic, and governmental conditions of the valley were investigated to determine what type, at what scale, and where residential MWI could feasibly be implemented in the LVV, and assuming this was completed, the potential impacts of this project on the WEN of the valley was analyzed. Document analysis and review of available literature was the main methodology used to gather and evaluate data for this research.

Installing MWI was found to potentially have a more favorable impact on the WEN of the valley when compared with connecting additional homes to the centralized wastewater system. However, this analysis identified governmental conditions in the valley that constrain the feasibility of implementing residential MWI to supplement the centralized wastewater collection system. These results suggest the existence of a financial and structural “lock-in” of the valley’s water infrastructure system, which could contribute to increased vulnerability of the region’s water supply to the effects of climate change. More research is needed regarding how contextual factors and management decisions impact the availability of critical resources, and the development of strategies for identification and remediation of locked-in infrastructure systems will be critical for reducing the vulnerability of these systems to climate change.

Keywords

Water-energy nexus

Micronet water infrastructure

Greywater recycling

Water resource management

Socio-hydrology

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Abbreviations

ACH	air conditioning condensate harvesting
AFY	acre-feet per year
EPA	Environmental Protection Agency
GPCD	gallons per capita per day
GWR	grey-water recycling
IHS	Institute for Housing and Urban Development Studies
IRPAC	Integrated Resource Planning Advisory Committee
kWh	kilowatt hours
LCRB	Lower Colorado River Basin
LVV	Las Vegas Valley
LVVWD	Las Vegas Valley Water District
MBR	membrane bioreactor
MWI	micronet water infrastructure
O&M	operations and maintenance
RWH	rainwater harvesting
SNWA	Southern Nevada Water Authority
WEN	water-energy nexus

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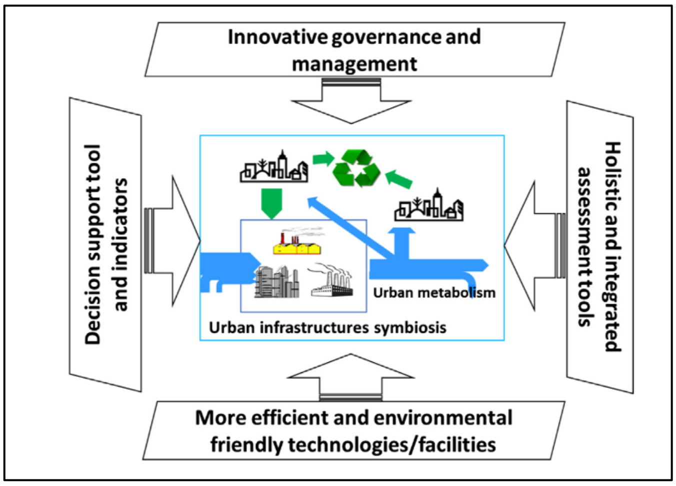
Chapter 1: Introduction

1.1 Background information and problem statement

Water scarcity is a growing concern for urban areas around the world, with up to 50% of the world's population projected to experience some state of water insecurity by 2050 (United Nations, 2018, as cited in Lindqvist et al., 2021). Urban water stress is primarily driven by changes in hydrological patterns and increasing demand, influenced by factors such as human-driven climate change, population growth, and urbanization (Garcia et al., 2019). These factors can result in urban water stress even in regions that have been historically water abundant, but cities that are located in arid or semi-arid regions that rely on seasonal precipitation to meet year-round water demands will be especially vulnerable to these impacts on already limited local freshwater resources (Lindqvist et al., 2021). Changing climatic conditions have resulted in increased frequency and duration of droughts in these regions, which when combined with higher temperatures and higher rates of evapotranspiration, increase the risk of water resource crises in urban metropolitan areas similar to the one in Cape Town, South Africa in 2018 (Pincetl et al., 2019).

To deal with the complexity of highly interlinked urban systems, urban managers and policy makers have historically managed resources as separate sectors, independent of influence from other sectors. However, this framework has shifted toward a "nexus-thinking" approach in recent decades as our understanding of the interconnectedness of urban sectors and complexity of climate change impacts has progressed (Fayiah, Dong, Singh, & Kwaku, 2020). The linkages between water and energy sectors are especially pronounced and research on this particular nexus has increased significantly in recent decades, especially in Europe and North America (Ding, Liang, Zhou, Yang, & Wei, 2020; Fayiah et al., 2020; Guven & Tanik, 2020; Huckleberry & Potts, 2019; Robb, Cole, Baka, & Bakker, 2021; Wang et al., 2021). However, research on the interactions between the technical infrastructure systems that provide these resources and the social systems that create and utilize them is under-developed (Blair & Buytaert, 2016; Lindqvist et al., 2021). The interactions within urban sectors as well as between urban and social systems can have implications for the broader sustainability and resilience of cites as a whole (Dong, Wang, Scipioni, Park, & Ren, 2018). Holistic resource management techniques will need to be developed in addition to innovation in technology to promote sustainable use of resources in urban systems as well as increase the resilience of these systems to the effects of climate change and population growth. Frameworks such as the one developed by Dong et al. (2018) have begun to emerge to aid this transition toward more efficient and sustainable infrastructure systems (Figure 1).

Figure 1. Holistic research framework for development of future infrastructure systems.



(Dong et al., 2018, p. 358)

Despite its growing popularity and relevance, integration of nexus thinking and socio-technical approaches into resource management and infrastructure development in cities is still challenging. In order for this shift in management to take place, economic favorability and substantial governmental support are crucial (Arden et al., 2021; Dong et al., 2018). Additionally, past decisions and actions taken by policy makers and urban managers can constrain the ability of current infrastructure systems to adapt to changing conditions, leading to a “lock-in” effect that is often difficult to combat (Markolf et al., 2018; Tellman et al., 2018). Therefore, more research into the interactions between these highly interconnected systems is needed to avoid depletion of critical resources such as water and energy, especially in relation to the local economic and governmental context.

1.2 Relevance of the research topic

The water-energy nexus (WEN) is a concept that recently gained attention worldwide following the Bonn conference in 2011 (Fayiah et al., 2020). Water and energy are critical resources for sustaining life and have a high level of influence on social and economic development, so sustainable management of these resources will be integral for ensuring urban resilience to the effects of climate change and population growth (Fayiah et al., 2020). Despite the vast volume of literature available on this topic, there are still few studies that have researched this nexus within its local context (Huckleberry & Potts, 2019). Additionally, resource management has been critiqued for being historically technocentric and not accounting for the influence that social systems can play on the supply and demand of resources (Markolf et al., 2018). Micronet water infrastructure (MWI) has been suggested as a potential solution for increasing the resilience of the water infrastructure systems in cities, but there have been few studies that have investigated the feasibility of this infrastructure at a household level or in systems where centralized water recycling infrastructure is already prominent (Oviedo-Ocaña, Dominguez, Ward, Rivera-Sanchez, & Zaraza-Peña, 2018). Therefore, this research intends to contribute toward these identified gaps in the literature.

The Las Vegas Valley (LVV) metropolitan region has been dealing with the impacts of a decades-long drought currently affecting the Colorado River Basin which supplies 90% of water used in this region. The Southern Nevada Water Authority (SNWA), which manages the water supplied to the LVV, has historically reserved conservation regulation for outdoor water use and has not acted to curb indoor residential water demand despite per capita water use remaining high when compared to other similar cities in the western US, such as Tuscon, Arizona (Lasserre, 2015). Indoor water currently accounts for approximately 40% of all water used in the valley, but there is little incentive to reduce this as wastewater in the valley is collected, treated, and returned to the Colorado River. This system does not encourage sustainable or efficient use of the water that is withdrawn for use in the valley, despite the critical role conservation of resources will have on the SNWA’s ability to meet future water demands (Lasserre, 2015; LVVWD, 2021).

Water security in the LVV will continue to decline due to population growth, climate change, and overallocation of water along the Colorado River (Joshi et al., 2020; Lasserre, 2015). Existing water resources are enough to meet the current needs of the valley, but will be unable to meet future needs, meaning that acquisition of future resources and reductions in water demand will be necessary to support the growth projected to take place in the valley in the coming decades (IRPAC, 2020). In addition to a threatened water supply, the ability to generate electricity at the Hoover Dam would be lost if the level of Lake Mead (the main reservoir for the Lower Colorado River Basin (LCRB)) falls below an elevation of 895 feet above sea level, according to the Bureau of Reclamation. The Hoover Powerplant is one of the country’s largest hydroelectric powerplants, and the energy generated here supplies power to about 1.3 million people across Nevada, California, and Arizona (Bureau of Reclamation, 2018). Therefore, finding solutions for reducing water withdrawals from the Colorado River are imperative for increasing the security and resilience of the WEN in the LVV and the surrounding states.

1.3 Research objectives and questions

In this thesis research, I will investigate whether implementing onsite residential MWI is a feasible way to increase resilience of the water and energy supply systems in the Las Vegas Valley in the US state of Nevada. To do this, I will be describing the technological, governmental, and economic conditions present in the LVV to determine what type, where, and at what scale MWI could feasibly be introduced in this region. Assuming this was completed, I will then analyze how this could impact the WEN of the region. This will be accomplished by answering the research questions outlined below in Box 1.

Box 1. Research question and sub-questions.

Main Research Question

What would be the potential impact of implementing residential micronet water infrastructure on the water-energy nexus given the current technological, governmental, and economic conditions of the Las Vegas Valley?

Sub-Questions

1. What micronet water infrastructure could feasibly be implemented in the Las Vegas Valley given the current technological, governmental, and economic conditions of this region?

2. How would the implementation of micronet water infrastructure identified in sub-question 1 impact the water-energy nexus of the Las Vegas Valley?

Chapter 2: Literature review

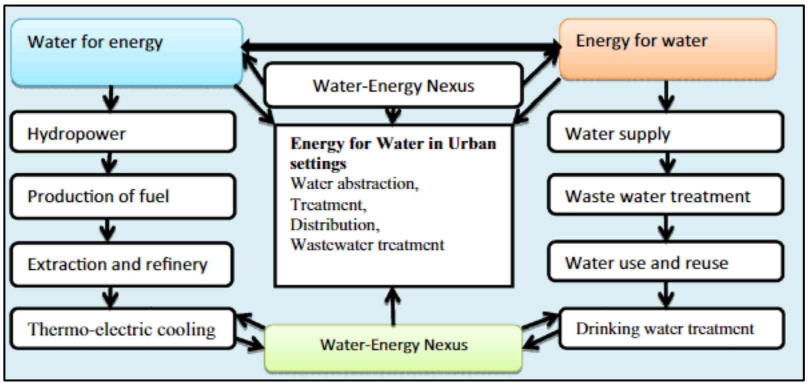
2.1 State of the science

2.1.1 The Water-Energy Nexus

2.1.1.1 The water-energy-nexus framework

In recent decades, pressure on essential resources has increased dramatically all over the world due to trends such as population increase, rapid urbanization, industrialization, and climate change (Ding et al., 2020; Fayiah et al., 2020; Robb et al., 2021; Wang et al., 2021). Urban sectors such as food, energy, water, and land have traditionally been managed independently, but due to the rise in environmental issues such as water scarcity, increased greenhouse gas emissions, and energy risk, a more integrated approach to resource management has risen in popularity, often referred to as "nexus thinking" (Wang et al., 2021). The urban nexus has been defined in a multitude of ways across the literature, but this concept is generally described as a tool used for resource management that highlights the interdependencies between resource sectors and visualizes the trade-offs and synergies between sectors in order to more efficiently and sustainably manage them (Fayiah et al., 2020; Robb et al., 2021; Wang et al., 2021). Two resource sectors that have been shown to be highly interlinked are water and energy (Ding et al., 2020; Fayiah et al., 2020; Guven & Tanik, 2020; Huckleberry & Potts, 2019; Robb et al., 2021; Wang et al., 2021). Water is required for every stage of energy production and energy is required for each stage of the treatment and provision of water as shown in Figure 2; therefore it is impossible to access one without an adequate supply of the other (Fayiah et al., 2020). The unsustainable consumption of these two critical resources is a crisis that threatens global security, with consumption predicted to increase by half by the year 2050 when compared to consumption rates in 2015 (Ding et al., 2020; Ferroukhi et al., 2015; Sperling & Berke, 2017). The linkages between water and energy sectors can help us pinpoint and address the causes of overconsumption and increase resource security (Fayiah et al., 2020; Wang et al., 2021).

Figure 2. Energy used for water provision and water used for energy provision in the urban WEN.



(Fayiah et al., 2020, p. 92)

2.1.1.2 The WEN and governance

The nexus concept is not fixed and can vary significantly between researchers and managers due to differences in objectives, perspectives, and approaches (Ding et al., 2020). The WEN is influenced by a multitude of elements, including environmental, social, political, economic, regulatory, and technical factors which determine how the nexus is managed (Fayiah et al., 2020). Despite being influenced by so many elements, energy and water systems have been historically managed independently of one another, and are often managed in segments that do not align with watersheds or that cross political boundaries (Huckleberry & Potts, 2019). Although the WEN is a topic that has been highly researched in many different parts of the world, studies that analyze nexus concepts in conjunction with their local governance contexts are still lacking (Huckleberry & Potts, 2019). This has been criticized as a major oversight in WEN research, as these systems are often reduced to oversimplified representations of inputs and outputs while ignoring socio-natural relationships and local power dynamics that have high levels of influence on resource representation and use (Robb et al., 2021). Geopolitics and rigid sectoral policies threaten our ability to effectively respond to effects of climate change, including increased drought severity and frequency (Huckleberry & Potts, 2019). One study that analyzed constraints of implementing the food-water-energy nexus in the LCRB in the American southwest found that fluctuations in one sector were not always aligned with fluctuations in another sector and were often limited instead by governmental constraints, demonstrated by food production which was dependent on successful acquisition of water *rights* rather than water *availability* (Huckleberry & Potts, 2019). In order to sustainably manage these resources, water and energy policy cannot be formulated separately from one another, but the tradition of independent sectoral policy has had lasting effects on resource management (Fayiah et al., 2020; Huckleberry & Potts, 2019).

2.1.1.3 The WEN and technology

Increases in technical capacity over the past two decades have also had a significant influence on the WEN field. Big datasets and complex analytical methods are now widely available, which is as much a challenge for WEN implementation as it is an asset. In order to cope with the size and complexity of data available for analysis, WEN investigations are often limited to strictly technical supply and demand relations such as life-cycle assessments, input-output analysis, econometric analysis, and optimization models (Ding et al., 2020; Robb et al., 2021). Additionally, the results of these analyses can be difficult to interpret and translate into policy by those without a technical understanding of the data (Fayiah et al., 2020; Robb et al., 2021). Some researchers fear that this rapid increase in technical capacity could threaten the development of the WEN concept by obscuring the socio-political influences that are so vital to the distribution and consumption of these resources (Robb et al., 2021). Difficulty in understanding the WEN is still pervasive in the field, and the myriad of analysis frameworks and techniques can exacerbate communication gaps between scientists and important stakeholders (Fayiah et al., 2020).

Despite these challenges, the nexus framework has huge potential for improving the governance and sustainable use of water and energy resources in the face of increasing pressures such as population growth and climate change (Wang et al., 2021). Cross-disciplinary research and open communication between researchers and policymakers will be key for sustainable management in addition to the inclusion of socio-political perspectives and consistency of data and analysis methods (Fayiah et al., 2020; Huckleberry & Potts, 2019; Robb et al., 2021; Wang et al., 2021).

2.1.2 A Socio-Hydrological Approach

2.1.2.1 Policy and governance

The dominant approach to water management in recent decades has been Integrated Water Resources Management (IWRM), but experts have critiqued this approach due to the treatment of human and hydrological systems as isolated (Blair & Buytaert, 2016; Lindqvist et al., 2021). Additionally, Robb et al. (2021) argues that the biggest oversight of the WEN approach is the lack of social perspective, with the goal being optimization of these strictly technically framed systems. A more holistic view of urban water systems includes an understanding of these systems as “comprised of both social and technical aspects” and highlights the role that management in addition to climatic drought can have on the occurrence of sustained or periodic water stress (Pincetl et al., 2019, p. 294). Because many policy measures that aim to address water scarcity often do not account for social impacts on water supply and demand, they can fall short of delivering solutions that last (Lindqvist et al., 2021). In order to more effectively and sustainably manage water resources in the long-term, a deeper understanding of how social systems interact and feedback with hydrological systems is necessary (Blair & Buytaert, 2016; Lindqvist et al., 2021; Markolf et al., 2018; Robb et al., 2021; Tellman et al., 2018; Xu, Gober, Wheater, & Kajikawa, 2018).

There are several phenomena that have been observed following the expansion of water supply capacities of cities that demonstrate the interconnectedness of hydrologic and social systems. These can include the "water rebound effect", from which improvements in resource use efficiency can result in higher rates of consumption, and "supply-demand cycles", where increased water capacity allows urban areas to expand, therefore generating more demand and ultimately increasing stress on water resources (Lindqvist et al., 2021; Tellman et al., 2018). These behavioral changes resulting from the perception of greater water availability by users is often not accounted for in water policy, and can result in "policy resistance", or the undesirable and unintentional outcomes or feedbacks that result from a policy that was well-intended (Lindqvist et al., 2021). These feedback loops that are created can often explain the lack of long-term effectiveness of water saving strategies in many cities, and these feedbacks can also result in unforeseen impacts in other sectors of highly interconnected urban systems (Blair & Buytaert, 2016; Lindqvist et al., 2021). Due to the high degree of complexity and uncertainty of modelling the interactions and feedbacks between water and society, they are often left out of policy development (Blair & Buytaert, 2016). However, inclusion of socio-hydrological models from the start can help policymakers craft more effective strategies for the sustainable evolution of water resource management (Blair & Buytaert, 2016; Xu et al., 2018).

2.1.2.2 Resilience and the robustness-vulnerability trade-off

When discussing the evolution of resource management in the face of global environmental issues such as water scarcity, increasing the resilience of infrastructure systems is often a primary focus. Resilience has been defined several ways in the literature, but Markolf et al. (2018) defines four key aspects of infrastructure system resilience: (1) the ability of the system to rebound to the system's pre-disturbed condition, (2) risk prevention and minimization through robustness building, (3) extending the performance of the system to deal with unexpected events, and (4) the long-term ability to adapt to external circumstances. However, climate change adaptation projects have traditionally focused only on the second concept of building hard infrastructure robustness, such as increasing the height of levees or adding more pumps to deal with sea level rise (Markolf et al., 2018). This techno-centric approach emphasizes strengthening infrastructure systems to withstand extreme events, which is an important aspect of climate change adaptation. However, this increase in robustness of hard infrastructure does not come without trade-offs, namely in the flexibility of infrastructure systems which can be critical in the face of variability, complexity, interconnectedness, and human behavior (Markolf et al., 2018). This can result in the "fallacy of control" where the ability of these technological systems to provide adequate protection is overestimated and fails to consider the variability of ecological and social systems, often resulting in people being placed in a position of elevated risk (Markolf et al., 2018; Tellman et al., 2018).

The rigidity and inflexibility of infrastructure systems that are designed to withstand a future that we cannot accurately predict results in increased long-term vulnerability to less frequent, higher magnitude events. The over-inflated sense of security that this physical infrastructure often provides can exacerbate hazards as was the case in Houston in the United States where flood maps were only able to predict about 50 percent of the damage caused by hurricane Harvey, leaving home and business owners in the floodplain unprepared for this event (Markolf et al., 2018). This rigidity can also lead to a “lock-in” effect of infrastructure systems, where past decisions and actions constrain the current system and its ability to adapt to changing conditions (Markolf et al., 2018; Tellman et al., 2018). This phenomenon has also been documented in Mexico City, where a history of management tactics aimed at increasing the robustness of the city’s water resource supply led to increased vulnerability to higher magnitude scarcity threats, intensified impacts of other interconnected risks, and vulnerability to unforeseen risks (Tellman et al., 2018). These case studies highlight the importance of understanding infrastructure systems as complex social, ecological, and technical subsystems that interact at different spatial and temporal scales (Blair & Buytaert, 2016; Lindqvist et al., 2021; Markolf et al., 2018; Robb et al., 2021; Tellman et al., 2018; Xu et al., 2018).

2.1.2.3 A socio-hydrological approach

Approaching resource management with this perspective in the face of climate change and increasing pressure on critical resources can help identify where lock-in of infrastructure systems has occurred and increase the ability of governments to craft sustainable policies that address underlying human-water interactions. Increasing the robustness of infrastructure systems is still important, but in order to avoid sunk costs of these projects, a deeper understanding of the social-ecological context is necessary (Markolf et al., 2018). It has been suggested that increasing resilience on an individual level could have a cumulative effect and result in long-term decreased vulnerability, and techniques such as coupling decentralized and centralized infrastructure could also have additional benefits (Blair & Buytaert, 2016; Markolf et al., 2018). Innovative solutions for adaptive strategies in the urban context will be necessary in the face of uncertain future conditions.

2.1.3 Micronet Water Infrastructure

2.1.3.1 Micronet water infrastructure for increasing urban water system resilience

With increasing water stress and scarcity in urban systems around the world, many cities have turned to acquiring “new” water resources through what are often economically costly and environmentally degrading means such as interbasin water transfers (Friedler, 2004). Therefore, many authors have argued that the focus of water management should instead shift to promoting conservation and increasing the efficiency of water use from existing resources (Arden et al., 2021; Cecconet, Callegari, Hlavínek, & Capodaglio, 2019; Friedler, 2004, 2008). Implementation of MWI has been suggested as a possible solution for filling these gaps and increasing the resilience of urban water systems to water stress and scarcity in cities (Falco & Webb, 2015). MWI is described as a “grid within a grid” and is similar in concept to microgrid energy infrastructure; they consist of small scale systems built *in addition* to existing centralized infrastructure rather than built as an *alternative* to centralized infrastructure as a decentralized system would be (Falco & Webb, 2015, p. 51). MWI can include technology such as greywater recycling (GWR), rainwater harvesting (RWH), and air conditioning condensate harvesting (ACH) systems that can be used to supplement existing water resources. These systems have recently been proposed as an alternative to sourcing water from distant locations or using more energy intensive technology such as desalination, and are less costly than a complete overhaul of aged existing centralized infrastructure (Arden et al., 2021; Cecconet et al., 2019; Falco & Webb, 2015).

These systems could be included as part of a solution to improve the resilience of urban water systems by increasing the redundancy of the system as shown in Figure 3. This reduces the likelihood that the entire system would fail due to a disturbance, whether in the form of climate change effects on the availability of water resources or in the event of contamination of a water supply (Falco & Webb, 2015). Centralized water infrastructure is particularly susceptible to water losses due to inefficiencies in transport, evaporation, and/or contamination. For example, the contamination of an open reservoir in Portland, Oregon forced the Portland Water Bureau to empty 50 million gallons of water, a costly and potentially avoidable event (Falco & Webb, 2015). In addition to increasing the technical resilience of the system, MWI could contribute to a behavioral change that would help to decrease water demand (Falco & Webb, 2015; Lindqvist et al., 2021). Bringing consumers into the supply system could help decrease the gap between perceived water availability and actual water availability, allowing consumers to make more educated decisions regarding their own water consumption (Lindqvist et al., 2021). Friedler (2004) showed that greywater reuse for toilet flushing in residential houses could reduce net urban water consumption by 10-20%, with additional greywater reuse for things such as non-food irrigation or laundry introducing further reductions. These water savings are significant in areas where local water resources are scarce (Cecconet et al., 2019; Friedler, 2004).

Figure 3. Conceptual framework of micro-utility value drivers.

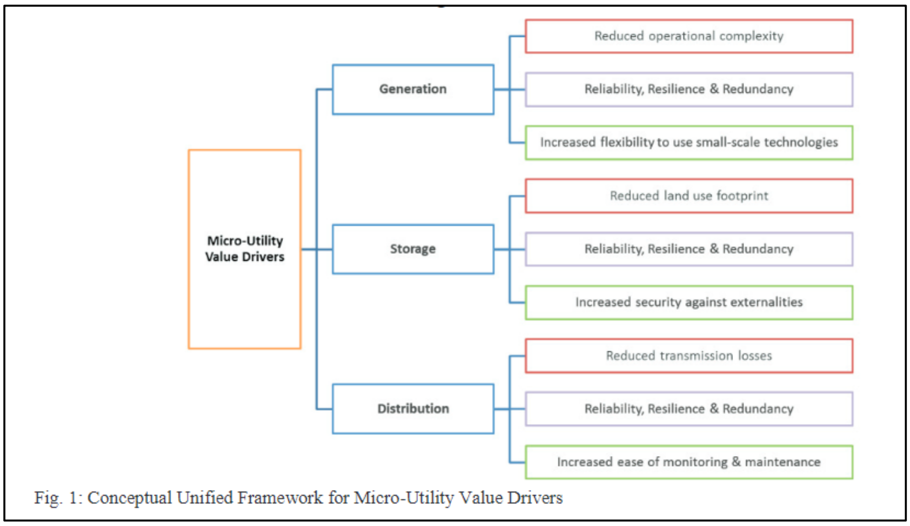


Fig. 1: Conceptual Unified Framework for Micro-Utility Value Drivers

(Falco & Webb, 2015, p. 51)

2.1.3.2 Micronet water infrastructure and the WEN

Micronet water infrastructure could also contribute to a reduction in energy demands related to water supply processes, including energy consumed for sourcing, transport, and treatment (Arden et al., 2021). Local sourcing, shorter transport distances, and lower flows to centralized wastewater treatment centers could all contribute to energy savings (Arden et al., 2021; Yu, Deshazo, Stenstrom, & Cohen, 2015). Some types of MWI such as certain GWR systems can be combined with other technology, including thermal recovery units which can offset energy needed for heating water, resulting in an overall energy demand decrease (Arden et al., 2021; Knutsson & Knutsson, 2021). MWI therefore has the potential to not only remain neutral in regard to energy grid burden but could also contribute to an overall reduction in energy demand when combined with centralized water systems.

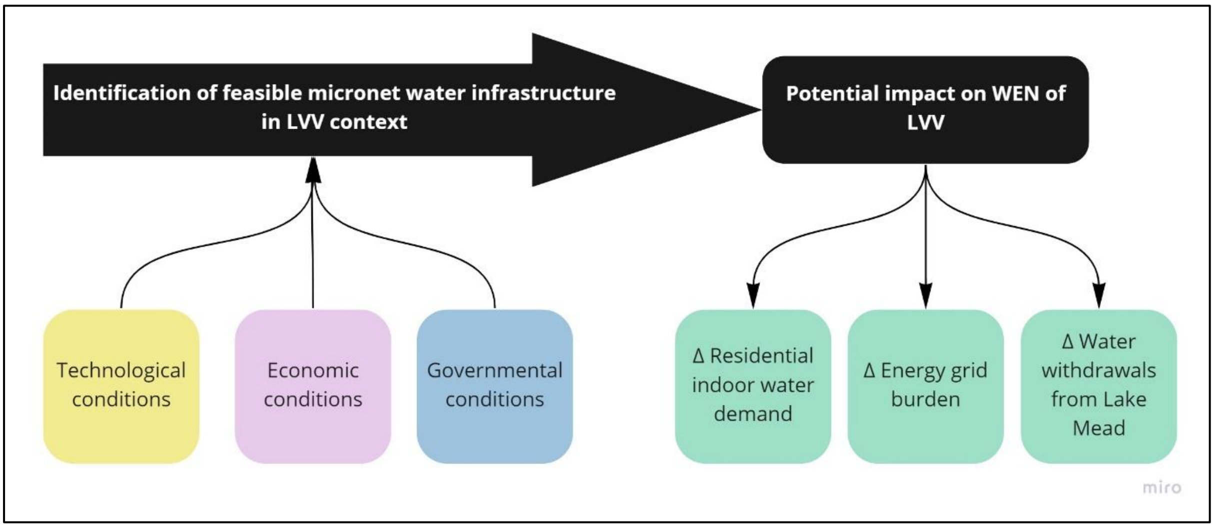
There are many factors that play a role in the successful implementation of MWI in the urban sphere. Not only do MWI projects need to be economically feasible, but they also need to be supported by governmental institutions and incentives and must not result in an increase in energy consumption for water supply (Arden et al., 2021; Craig & Richman, 2018; Oviedo-Ocaña et al., 2018). Additionally, there are many different types of MWI that may be more suitable for specific climates. For example, Arden et al. (2021) found that RWH and ACH are not feasible for use in areas such as the semi-arid southwestern US due to the lack of atmospheric water available, but membrane bioreactor (MBR) GWR systems are a cost-effective option. These factors influence the feasibility of MWI projects in their local contexts and the impact that MWI would have on the WEN of the area.

2.2 Conceptual framework

MWI is a relatively new concept and therefore there are still many technological, economic, and governmental barriers that prevent large-scale adoption of this infrastructure. There are many different forms of MWI that may be more or less efficient due to the climate in which they are implemented, and high capital costs have been a significant barrier for implementing this technology in the past, especially at the household level. Additionally, government support plays an important role in the feasibility of implementing this infrastructure on a large-scale, both through their regulatory and subsidiary capacity. For the implementation of MWI to be effective and improve the resilience of urban water systems to the impacts of climate change and population growth, it must not only improve the availability of water, but it also must not introduce additional burden onto other urban sectors.

Figure 4 depicts the independent and dependent variables identified for this research. On the left, the independent variables *technological, economic, and governmental conditions* interact to describe the local context. These factors determine what kind, at what scale, and where micronet water infrastructure could feasibly be introduced within the Las Vegas Valley. These variables were chosen because urban systems have been shown to be highly interlinked, and therefore it is not enough for this technology to simply exist that determines whether a project such as this could be completed. It is necessary to analyze the interactions between these conditions to determine if and what kind of MWI could realistically be introduced in this context. The dependent variables on the right, including the *change in residential indoor water demand, change in energy grid burden, and change in water withdrawals from Lake Mead* describe the impact this infrastructure could potentially have on the water-energy nexus of the Las Vegas Valley assuming the implementation of MWI feasible for the local context.

Figure 4. Conceptual framework.



Chapter 3: Research design and methodology

3.1 Description of the research design and methods

3.1.1 Case study description

This research aims to contextualize the economic and governmental conditions of the Las Vegas Valley in the US state of Nevada, and to determine where, at what scale, and what type of MWI would be technically feasible to implement given these conditions. Additionally, assuming this infrastructure is actualized, I will be investigating the impact this MWI would have on the WEN of the valley. This region was chosen to study due to increasing pressure on water resources of the valley. This urban area is located in the semi-arid southwestern US and is geographically bounded by the LVV landform. It encompasses three of the most populated cities in Nevada including Las Vegas, North Las Vegas, and Henderson, as well as other unincorporated towns in the area. This region is characterized by high summer temperatures, experiences an average 10cm of annual precipitation, and has few local water resources (Lasserre, 2015). The Las Vegas metropolitan area sources 90 percent of its water from the Colorado River at Lake Mead, an artificial reservoir created by the construction of the Hoover Dam in the 1930's. The remaining 10 percent of water is sourced from local groundwater. In 2021, the federal government declared a water shortage for the first time along the Colorado River due to the low water level of Lake Mead, which reached its lowest ever recorded elevation since being filled of 1,065 feet (SNWA, 2021b).

Figure 5. Map of the Colorado River Basin, which provides water to seven US states and Mexico.

(United States Geological Survey, 2016)

Changing climatic conditions in the western US have resulted in a decades long drought along the Colorado River. The two main reservoir systems along the river, Lake Powell in the Upper Basin and Lake Mead in the Lower Basin (Figure 5), had a combined capacity of only 32 percent at the end of 2021 (SNWA, 2021b). Climate scientists have predicted that drying conditions are likely to not only continue, but worsen in the coming decades, resulting in a more permanent shift toward aridification of the southwest (SNWA, 2021b). In addition to decreasing availability of water resources, this increase in aridic conditions will lead to increases in water demand from the agricultural sector that utilizes the Colorado River. Additionally, it is projected that the population of the LVV will continue to increase in the coming decades, subsequently increasing water demand within the valley. With a population already well over 2 million, the University of Nevada, Las Vegas (UNLV) Center for Business and Economic Research projects the LVV to grow to 3.02 million by 2035 and 3.38 million by 2060 (SNWA, 2021b). This combination of factors has resulted in depletion and decreased security of the valley's water resources and an increasing need for sustainable management strategies. In addition to the critical water resources that Lake Mead supplies, approximately 4 billion kilowatt hours (kWh) of hydroelectric energy is generated at the Hoover Dam every year, which is used by 1.3 million people throughout the southwest (Bureau of Reclamation, 2018). However, according to the US Bureau of Reclamation, if the elevation of Lake Mead falls below 895 feet, electricity will no longer be produced by the Hoover Powerplant and water will no longer flow to downstream users (SNWA, 2021b). Therefore, not only is conservation of water resources in Lake Mead important for meeting future water demand but also for meeting energy demands throughout the southwest.

Water purveyors of the region, including the SNWA and Las Vegas Valley Water District (LVVWD), have implemented strict conservation measures in recent decades to combat water scarcity. Most of the conservation measures implemented in recent years have been relating to consumptive water use, specifically outdoor water use. The Colorado River Compact of 1922 outlines the annual volume of water apportioned to each of the seven western US states (Arizona, California, Colorado, Nevada, New Mexico, Utah, and Wyoming) and Mexico that rely on the Colorado River for freshwater, but this agreement was created based on the historical average river flow from one of the wettest periods on record. This resulted in the river's resources being severely overallocated, which has only been compounded upon due to the drought conditions that have plagued this area for the past two decades and high rates of population growth (SNWA, 2021b). The SNWA operates within a water allocation of 300,000 acre-feet per year (AFY) from the Colorado River, but this allocation has recently been reduced by 21,000 AFY due to the federal shortage declaration in 2021 (SNWA, 2021b, p. 15). Water that is treated and subsequently returned to Lake Mead are labeled "return-flow credits", which do not count toward Nevada's annual consumptive use allotment of water (SNWA, 2021b). Because of this, the reuse of water at the onsite individual residential level has been discouraged, as approximately 90 percent of water that is used indoors in the valley is already captured and returned to Lake Mead (SNWA, 2021b). Therefore, water that is unable to be returned to the Colorado River, such as that used outdoors, has been the target of most water restrictions in the valley. This lack of consideration for the reuse of water resources within the valley has resulted in other benefits to be overlooked, including increased resilience, reductions in energy use, and demand reductions related to behavioral changes.

3.1.2 Research methods

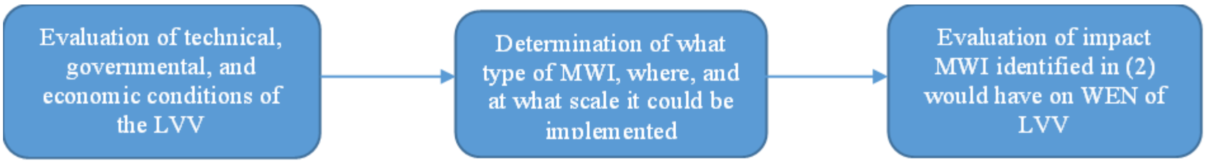
As described above, a case study approach was chosen for this exploratory feasibility research study. Single case studies can be advantageous due to their detailed analysis, enhancing our understanding of the "why" and "how"; in this case this method was chosen to gain a deeper understanding of the complex socio-hydrological interactions within the LVV and how these impact the management of water and energy resources (Ridder, 2017). The analysis of a single case study was chosen with the intent that should the findings be theoretically interesting, they can be expanded upon by other researchers. The comparison of one case to other cases may bring to light interesting commonalities or differences, which can be used to deepen our understanding of concepts studied, which Yin (2009) referred to as “replication logic” (Beker, Bryman, & Ferguson, 2012, p. 226). Specifically, a co-variational approach was decided upon for this research, with the intent to determine the potential effect that contextual variables would have on the WEN of this system (Blatter & Blume, 2008). The data collected for this analysis will consist of a combination of quantitative and qualitative data. Secondary data documentary analysis of 14 grey literature documents, including water agency plans and budgets, will be the main source of data collection for this research, listed in Table 1 below. Originally, collection of primary data through semi-structured interviews with local experts was expected to occur to supplement document analysis for triangulation purposes. However, it was not possible to do this for this study; a more detailed explanation is included in Section 3.3. The methodological steps of this research are depicted in Figure 6.

Table 1. Documents used in analysis.

Document Analyzed	Year Published
City of Las Vegas 2050 Master Plan	2021
IRPAC Recommendations Report	2020
LVVWD Capital Improvements Plan	2017
LVVWD Operating and Capital Budget FY 2021/22	2021
LVVWD Operating and Capital Budget FY 2022/23	2022
Nevada Revised Statute Assembly Bill No. 169	2015
SNWA Board of Directors Meeting Minutes Sept. 17, 2020	2020
SNWA Joint Water Conservation Plan	2019
SNWA Major Construction and Capital Plan	2020
SNWA Operating and Capital Budget FY 2021/22	2021
SNWA Operating and Capital Budget FY 2022/23	2022
SNWA Renewable Energy Report	2021
SNWA Water Resources Plan	2021
USEPA Guidelines for Water Reuse	2012

One of the tools used in the WEN analysis is the US Environmental Protection Agency’s (EPA) web-based tool called the Non-Potable Environmental and Economic Water Reuse (NEWR) calculator. This can be used to estimate the impact on energy and water consumption that the implementation of a water recycling system would have depending on factors including location, building, source water, and end use characteristics. This online tool was used to calculate the potential effect that the implementation of MWI systems at a residential scale would have on the WEN of the LVV.

Figure 6. Research methodological steps.



3.2 Operationalization of variables

The variables, sub-variables, and indicators identified for this research are described in the operationalization table below. This table also describes how the data gathered was coded, for example, information relating to “money set aside in the SNWA budget for new water resource projects” was coded as E5 for economic context indicator 5.

Table 2. Operationalization of variables

Variable	Sub-variable	Description of variable	Indicator	Data Type	Expected Impact on WEN
Technical context references: *(Allen, Christian-Smith, & Palaniappan, 2010; Arden et al., 2021; Cecconet et al., 2019; Craig & Richman, 2018; Friedler, 2008; Knutsson & Knutsson, 2021; Oviedo-Ocaña et al., 2018; Yu et al., 2015)*	Installation process	What kind of technical expertise would be needed to install these systems? What kind of buildings would be suitable for installation?	1. possibility of retrofitting 2. changes to existing infrastructure	binary binary	(+) (-)
	Scale	At what scale could these systems be implemented? Would it be individual residences/buildings or connected community grid?	3. single-unit vs multi-unit residence	ordinal	(+/-)
	Tech. combination possibility	Is there a possibility to combine these systems with other technology to decrease energy grid demand?	4. thermal recovery units	binary	(+)
	Maintenance requirements	How difficult/easy would it be to maintain these systems? How often would maintenance be required?	5. level of user involvement 6. frequency of maintenance	binary discrete	(-) (-)
Economic context references: *(Birks, Hills, Diaper, & Jeffrey, 2003; Craig & Richman, 2018; Jeong, Broesicke, Drew, & Crittenden, 2018; Lasserre, 2015; Oviedo-Ocaña et al., 2018; Yerri & Piratla, 2019; Yu et al., 2015)*	Cost of installation and maintenance	What is the amount of financial capital that would be required to invest in this technology?	1. capital costs (including materials and labor) 2. operation and maintenance costs	continuous continuous	(-) (-)
	Cost of water	Would money be saved due to decreased water costs?	3. monthly water costs per residence 4. cost of alternative water acquisition strategies	continuous continuous	(+) (+)
	Finances available for subsidies/incentives	How much money is available in the local water agency budget for subsidies or incentivization of implementation?	5. money set aside in SNWA budget for new water resource projects	continuous	(+)
	Water agency dependency on water sales	Is there a financial "lock-in" of the system? Would decreased water sales inhibit agency's ability to function?	6. SNWA and/or LVVWD operations budget	continuous	(-)
Governmental context references: *(Cecconet et al., 2019; Jeong et al., 2018; Lasserre, 2015; Lindqvist et al., 2021; Markolf et al., 2018; Tellman et al., 2018; USEPA, 2012)*	Government focus for water conservation	Is there existing focus on water conservation, and if so where?	1. policies/strategies related to water conservation 2. area of conservation focus	discrete nominal	(+) (+/-)
	Perception of water availability	How confident is the government in their ability to meet future water demand?	3. future water demand projected to be met with current resources 4. existing plans for alternative acquisition of additional resources	continuous binary	(+/-) (-)
	Adaptive capacity	Is the government able to adapt to risks of climate change?	5. consideration/ application of climate change in planning 6. "lock-in" effect	binary binary	(+) (-)
	Regulations	What are the requirements for water quality that recycled water would have to meet? Are there any regulations prohibiting this type of reuse?	7. water quality requirements 8. onsite non-potable reuse for single-family residence	continuous continuous	(+/-) (-)

Potential impact on WEN references: *(Arden et al., 2021; Birks et al., 2003; Craig & Richman, 2018; Falco & Webb, 2015; Jeong et al., 2018; Knutsson & Knutsson, 2021; Lasserre, 2015; Lindqvist et al., 2021)*	*Δ Residential indoor water demand	How would implementation change the demand of water? Is this demand change also behavioral?	1. estimated change in water demand per residence	continuous	N/A
	Δ Energy grid burden	How would implementation change the burden of water acquisition and dispersion on the energy grid?	2. estimated change in energy demand for SNWA 3. estimated change in energy demand per residence 4. estimated change in energy demand for LVV	continuous continuous continuous	N/A
	Δ Water withdrawals from Lake Mead	How would the implementation impact the volume of water being withdrawn from Lake Mead?	5. change in volume water withdrawn to meet demand 7. amount of water returned to Lake Mead (return flows)	continuous continuous	N/A

*Δ = change in

3.3 Challenges and limitations

The extent to which the findings outlined in this case-study research can be generalized is limited. This study seeks to understand potential impacts on the WEN that MWI could have specifically within the context of the LVV, therefore making it difficult to translate findings to other cities. However, this research could be used to influence future studies regarding the use of MWI and contextualized WEN studies in other regions to identify potential trends and mechanisms. When this research was designed, it was intended for secondary data collection to be the main source of data with personal interviews used as a supplement for improving the reliability and validity of the information collected. However, because of the limited availability of local LVV water resource experts, only one person/organization that was contacted for an interview responded, and they ultimately declined, challenging the reliability of the results. The short timeline for data collection and analysis also limited the breadth and depth of knowledge that could be gathered. The LVV is still recovering from the effects of the COVID-19 pandemic, which could impact the economic state of local water agencies and resources available in the valley. Finally, many of the documents analyzed contain some bias that will need to be acknowledged, as many of these were authored by the water purveyors of the valley who are motivated to appear competent and in control of the state of water resources in the LVV to their customers.

Chapter 4: Results, analysis, and discussion

4.1 LVV context: results and analysis

4.1.1 Technical context

Onsite GWR was chosen to investigate throughout this section based on Arden et al. (2021), who found GWR to be more feasible than RWH and ACH in this region due to the lack of atmospheric water available. The technical context in which onsite GWR could be feasibly implemented is described below.

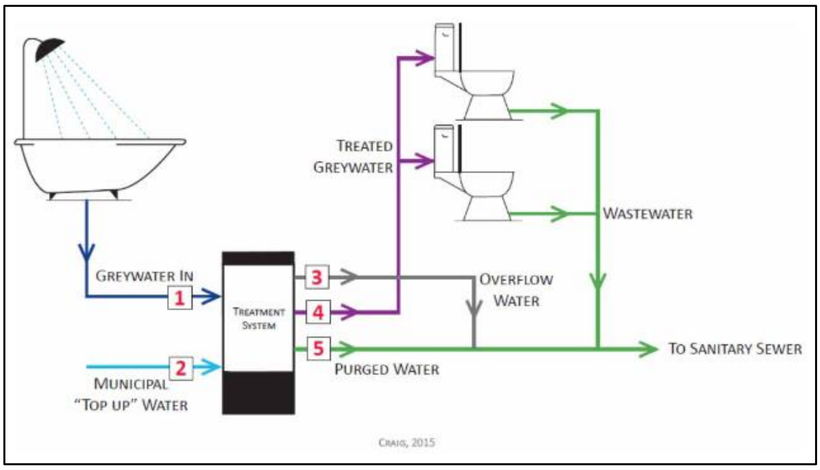
4.1.1.1 Installation process

Indicators: (1) possibility of retrofitting

(2) changes to existing infrastructure

Small scale GWR systems fit for use in buildings such as single-family homes generally include a collection system, a holding tank, and indoor and/or outdoor distribution systems (Knutsson & Knutsson, 2021; Yu et al., 2015). A diagram depicting an example residential-scale GWR system can be seen in Figure 7. Retrofitting is possible, but because it requires additional plumbing and reconfiguration of existing infrastructure, it is more expensive and difficult to install in older homes. Therefore, in most cases it is more favorable to install onsite residential GWR systems at the time of home construction (Knutsson & Knutsson, 2021; Yu et al., 2015). The City of Las Vegas estimates that 100,000+ new homes will need to be built by 2050 which could include these systems (CLV, 2021). Space can be a constraining factor regarding system installation, as room on the property for collection/treatment and holding tanks are required. However, because single-family homes in the western US tend to include yard and/or garage space, space for collection and storage tanks would likely not be a constraining factor. Additionally, because domestic greywater production is usually greater than non-potable consumption, treating only “light” greywater (for example, that collected from bathroom sinks) may be adequate to meet demand. This would result in the reduction of installation associated costs and system complexity, as well as allowing for use of smaller collection/holding tanks (Cecconet et al., 2019; Friedler, 2008). Friedler (2008) found that a tank with a volume of $1m^3$ was sufficient for systems used to treat water for toilet flushing in buildings of varying sizes.

Figure 7. Diagram of potential residential-scale greywater recycling system for non-potable water reuse.



(Craig & Richman, 2018, p. 5)

4.1.1.2 Scale

Indicators: (3) individual residence vs. community scale

In general, it has been shown that GWR systems installed in multi-family buildings or building clusters are more cost effective than those installed in detached units because of the high capital costs of these systems (Arden et al., 2021; Cecconet et al., 2019). However, because over 60% of housing units in Clark County (where the LVV is located) are single-family detached units, it is less feasible to target multi-family buildings or building clusters for GWR system installation; there are simply more single-unit detached residences in the LVV (Clark County Comprehensive Planning Department, 2020). Additionally, 45.6% of municipal metered water use in the LVV is attributable to single-family residences while only 16.3% of water is used in multi-family residences, making single-unit residences more feasible to target for this infrastructure (SNWA, 2021b, p. 32).

4.1.1.3 Technical combination possibilities

Indicators: (4) thermal recovery units

GWR systems can be combined with other technology such as thermal recovery units to offset hot water heating requirements and reduce the overall energy demand of these systems (Arden et al., 2021). Therefore, these types of units make GWR more attractive on a residential scale as it reduces the economic burden that these systems can have on users. A more detailed investigation of these potential energy savings is included in the analysis of the potential WEN impacts in Section 4.2.

4.1.1.4 Maintenance requirements

Indicators: (5) level of user involvement

(6) frequency of maintenance

GWR systems require routine maintenance, which can vary depending on the type and size of the system. Basic maintenance requirements for simple small-scale GWR systems include cleaning the filter and adding chlorine to the system. One pilot study conducted in Ontario, Canada where GWR systems installed in 22 homes (shown in Figure 7) found that the frequency of maintenance requirements for most users included cleaning toilet bowls weekly, refilling chlorine pucks every two to three months, and manually cleaning the filter once a month (Craig & Richman, 2018). Overall, 16 of 17 users in this study indicated that they considered the maintenance requirement to be reasonable, suggesting that maintenance would not be a constraining factor for GWR implementation in residential homes (Craig & Richman, 2018).

4.1.2 Economic context

4.1.2.1 Cost of installation and maintenance

Indicators: (1) capital costs (including materials and labor)

(2) operations and maintenance costs

Capital costs, including equipment and labor, of GWR systems in detached single-unit houses can vary widely depending on conditions such as the number of bathrooms, number of stories in the house, structural foundation, and labor rates in the area. There are currently very few resources that describe the technical and financial feasibility of small-scale GWR systems at the household level, so Yu et al. (2015) and Craig & Richman (2018) were selected as reference studies as they most closely resemble the context and scale of this research. Based on these references, the cost of installation for a small, commercially available GWR system in a typical single-family home with two bathrooms is estimated to be $2,000-6,500 USD (adjusted for inflation) as shown in Figures 14, 15, and 16 included in Appendix 2 (Craig & Richman, 2018; Yu et al., 2015). However, Yu et al. (2015) found that capital costs for these systems can go as high as $13,000 in some cases, demonstrating how widely installation estimates can range depending on building specifications.

Operations and maintenance (O&M) costs have a similarly wide range of values between which they can fall. Yu et al. (2015) estimates that O&M costs would fall between $250-1,100 USD per year, while Craig & Richmond (2018) estimate that O&M costs would fall instead between $10-200 USD per year (adjusted for inflation). With capital costs potentially going as high as $13,000, and O&M costs going as high as $1,100 per year, these costs would be constraining for many families, demonstrating the importance of government subsidization of these projects (Craig & Richman, 2018; Yu et al., 2015).

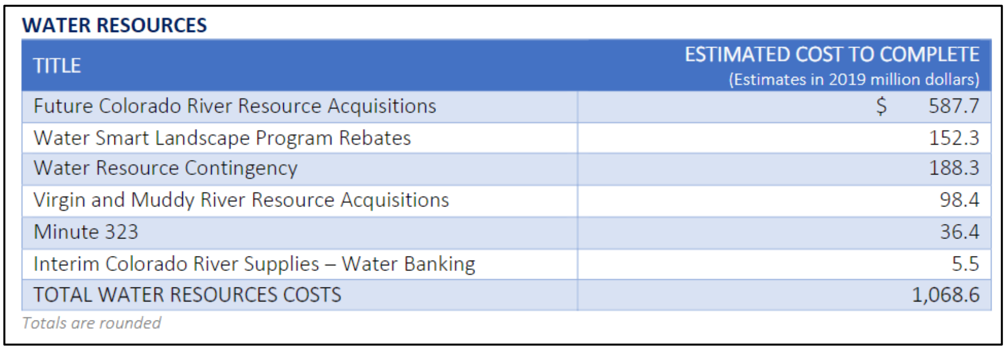
4.1.2.2 Cost of water

Indicators: (3) monthly water costs per residence

(4) cost of alternative water acquisition strategies

The average monthly volume of water delivered to a single-family residential LVVWD connection in 2021 was 10,210 gallons, with an approximate monthly water bill of $51 per residence or $612 per year (including all SNWA charges) (J. Bailey of SNWA, personal communication, July 13, 2022). The SNWA is Southern Nevada's wholesale water provider and does not regulate customer rates for the valley (SNWA, 2019). Therefore, as Southern Nevada's largest water purveyor supplying water to 70% of all residents in Clark County, the LVVWD average monthly customer usage and bill amounts were used as a proxy for all other areas of the valley (LVVWD, 2021). Additionally, the estimated cost of future and ongoing alternative water resource acquisition projects for the LVV is *$1,068.6 million*, as shown in Figure 8 (SNWA, 2020a, p. 14).

Figure 8. Estimated cost of water resource acquisition projects ongoing and planned by the SNWA.



WATER RESOURCES

TITLE	ESTIMATED COST TO COMPLETE (Estimates in 2019 million dollars)
Future Colorado River Resource Acquisitions	$ 587.7
Water Smart Landscape Program Rebates	152.3
Water Resource Contingency	188.3
Virgin and Muddy River Resource Acquisitions	98.4
Minute 323	36.4
Interim Colorado River Supplies – Water Banking	5.5
TOTAL WATER RESOURCES COSTS	1,068.6

Totals are rounded

(SNWA, 2020a, p. 14)

4.1.2.3 Finances available for subsidies/incentives

Indicators: (5) $ set aside in SNWA budget for new water resource projects

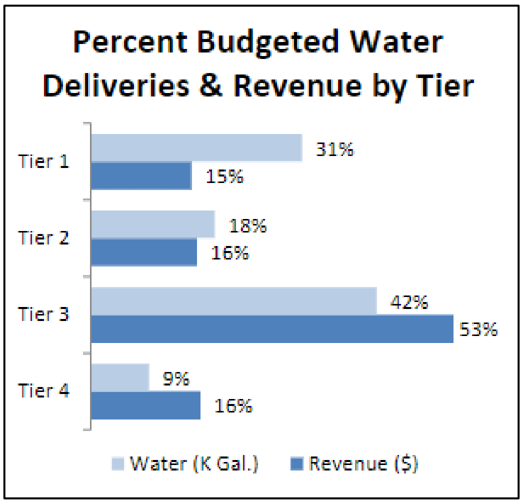
In 2019, the SNWA Board of Directors formed an advisory committee called the Integrated Resource Planning Advisory Committee (IRPAC), which consisted of 11 members that represented key local stakeholder groups, created to encourage community input on initiatives proposed by the organization (IRPAC, 2020). One of the recommendations outlined in the 2020 IRPAC Recommendations Report states that "the committee felt it was prudent to include a contingency amount that could fund additional Colorado River water resource opportunities if they become available, or additional conservation programs, such as new incentive programs or technology development/deployment" (IRPAC, 2020, p. 9). Following these recommendations, *$188.3 million* was reserved as contingency in the SNWA Major Construction and Capital Plan (MCCP) as shown in Figure 8 (SNWA, 2020a, p. 14). Therefore, this money could theoretically be used to subsize residential GWR system installations in the LVV.

4.1.2.4 SNWA dependency on water sales

Indicators: (6) SNWA or LVVWD operations budget

Water is a scarce resource in Southern Nevada, and with climate change and population growth increasing pressure on this resource, conservation of water will be important to meet future demand in the region. However, the SNWA and LVVWD, like any other water provider, rely on water sales for operational revenue. Essentially, "Less water sold is less money earned" for these agencies (Lasserre, 2015, p. 8). The LVVWD stated that "Tiered water rates represent a significant portion of the LVVWD's financial revenues, *accounting for approximately 70 percent of the organization's ongoing funding sources*" (LVVWD, 2021, p. 1.3). Additionally, the LVVWD conceded that "While conservation is important, from a revenue perspective, it is financially beneficial to the LVVWD to deliver water in the upper tiers", referring to the tiered customer consumption rates 3 and 4 which are priced in a way to encourage conservation (LVVWD, 2021, p. 3.4). The percentage of revenue impact for tiers 3 and 4 is higher than the percentage of water delivered as shown in Figure 9, meaning the LVVWD relies more heavily on selling water in these higher consumption tiers than the lower tiers despite also needing to encourage resource conservation. Therefore, large reductions in water sales in these higher tiers for higher consumption users would severely impact the LVVWD's ability to meet revenue demands for expenditures such as fixed debt payments.

Figure 9. Revenue impact and percent of water sold for each LVVWD consumption tier.



(LVVWD, 2021, p. 3.4)

4.1.3 Government context

4.1.3.1 Government focus for water conservation

Indicators: (1) policies/strategies related to water conservation

(2) area of conservation focus

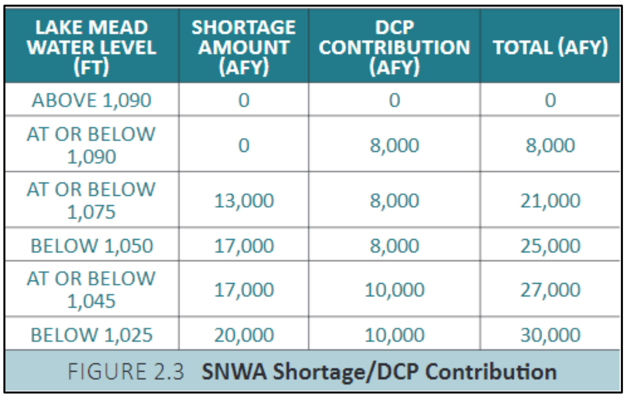
Climate change has resulted in persistent drought conditions and reduced flows throughout the Colorado River Basin over the past two decades, impacts which have been widely recognized at the federal, state, and local government levels. This has resulted in the passing of state and federal level legislation, including

> "the 2007 Interim Guidelines and the 2019 Drought Contingency Plan [that] require the states of Nevada, California and Arizona, as well as the country of Mexico, to take

> shortages and make contributions if Lake Mead levels drop below predetermined elevations to reduce the risk of water levels declining to critical elevations”. (LVVWD, 2021, p. 1.5)

These contributions are shown below in Figure 10. These compulsory shortages and contributions must be met following a federal shortage declaration by the Secretary of the Interior, which occurred for the first time in 2021 and is expected again in 2022 and subsequent years (SNWA, 2021b).

Figure 10. Lake Mead water level and associated shortage and contributions required by Nevada.



LAKE MEAD WATER LEVEL (FT)	SHORTAGE AMOUNT (AFY)	DCP CONTRIBUTION (AFY)	TOTAL (AFY)
ABOVE 1,090	0	0	0
AT OR BELOW 1,090	0	8,000	8,000
AT OR BELOW 1,075	13,000	8,000	21,000
BELOW 1,050	17,000	8,000	25,000
AT OR BELOW 1,045	17,000	10,000	27,000
BELOW 1,025	20,000	10,000	30,000

FIGURE 2.3 **SNWA Shortage/DCP Contribution**

(SNWA, 2021b, p. 15)

Beyond federal and state level conservation legislation, the SNWA and water purveyors of the region have developed their own strategies for improving conservation practices in the valley. Conservation as a means to increase future water resources for Southern Nevada is worked into every major document that is published by these organizations; in the 2021 SNWA Water Resources Plan alone conservation is mentioned over 30 times (SNWA, 2021b). The updated consumption goal identified by the SNWA for the valley is 86 gallons per capita per day (GPCD) by 2035, which they have adopted in hopes of enhancing the community’s water supply security (SNWA, 2021b). Although the SNWA does not set customer rates directly, they play a vital role in reaching these conservation goals through education, outreach, and development of incentive programs that are then implemented by its member agencies (SNWA, 2019). One of the largest ongoing programs spearheaded by the SNWA is the Water Smart Landscape Rebate project, which provides financial incentives for replacement of grass with water-efficient landscaping to reduce water consumption (SNWA, 2020a).

Nevada is allotted 300,000 AFY of water from the Colorado River as outlined in the Colorado River Compact. However, this is not a measure of water that is withdrawn from the river, but rather it is a measure of how much water is *consumed*. This language has allowed the SNWA to withdraw more than their allotted 300,000 AFY, as most of the water used indoors in the valley is collected through the municipal wastewater system, treated, and returned to Lake Mead. The volume of water consumed is measured as the difference between the amount of water that is withdrawn from the lake and the amount of water that is returned via this system, known as “return-flow credits”. Because of this system, water conservation efforts in the valley have not been equal in all sectors. The SNWA has focused on reducing “consumptive” water use, which accounts for about 60% of all water delivered by the agency, and includes outdoor water use and evaporative losses from air cooling systems (SNWA, 2021b). Incentive to reduce indoor residential water demand in the valley is lacking, which the SNWA acknowledged by stating that “the organization specifically targets consumptive water use…[to] maximize conservation gains, as well as staffing and funding resources needed to support those gains" (SNWA, 2019, p. 31). This analysis suggests that although there appears to be a high degree of motivation within the valley to conserve water resources for the future, indoor water conservation programs are not a priority. This has resulted in stagnation of conservation gains for residential single-service connections in recent years, and could potentially contribute to oversight of possible improvements in water use efficiency in the valley (LVVWD, 2021).

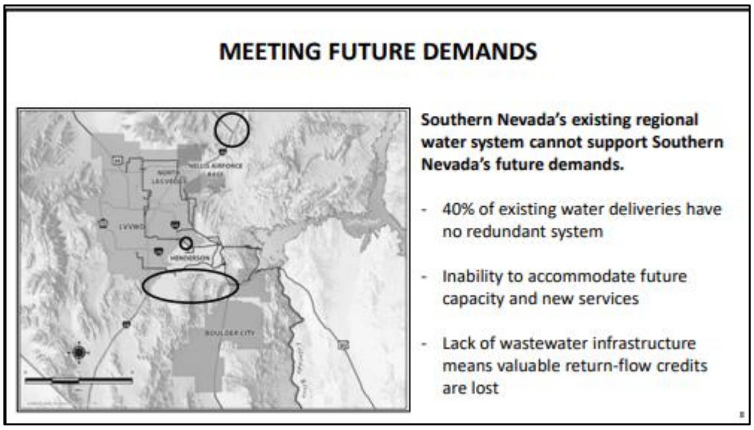
4.1.3.2 Perception of water availability

Indicators: (3) future water demand projected to be met with current resources

(4) existing plans for alternative acquisition of additional resources

The SNWA is aware that "The existing regional water system is sufficient to meet present-day demands; however, additional capacity is necessary to meet future demands" (IRPAC, 2020, p. 7). Because of this, the SNWA has investigated multiple scenarios under which current, temporary, and future resources will be needed to meet demand depending on water availability and consumption rates, but only under the highest flow and lowest demand scenarios will current, permanent resources be enough to meet demand through 2072 (SNWA, 2021b). This demonstrates the need for the LVV to acquire additional resources and reduce demand as the SNWA will not be able to accommodate future demand with rates of projected growth in the valley (Figure 11).

Figure 11. Presentation slide from the SNWA Board of Directors regular meeting on September 17, 2020.



MEETING FUTURE DEMANDS

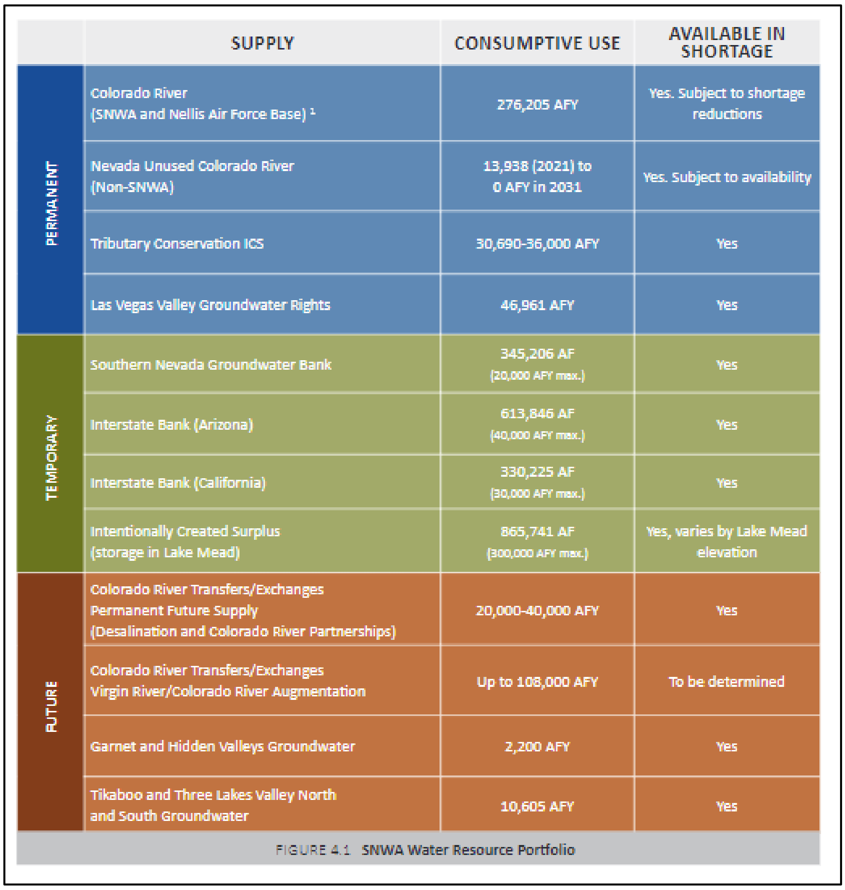
Southern Nevada's existing regional water system cannot support Southern Nevada's future demands.

- 40% of existing water deliveries have no redundant system
- Inability to accommodate future capacity and new services
- Lack of wastewater infrastructure means valuable return-flow credits are lost

(SNWA, 2020b, p. 8)

The SNWA already has several existing plans in place for acquiring additional future resources. These include plans for transfers and exchanges with other LCRB users for water rights, increased groundwater extractions, water banking, and intentional surplus creation summarized in Figure 12. They have also identified potential partnerships with other Colorado River users for water recycling and desalination projects in California and Mexico "to secure additional water supplies through investments" (IRPAC, 2020, p. 8). Some actions have already been taken in recent years in an attempt to protect the LVV's water supply, including installation of a low level intake and pumping station in Lake Mead to "mitigate impacts associated with a potential Lake Mead water level decline below 1,000 feet and potential water quality concerns during low reservoir conditions" (SNWA, 2021b, p. 17). In an attempt to alleviate the risk of inadequate water resources available to meet future demand in the valley, the SNWA has taken steps to diversify their water resource portfolio and has plans to continue doing so in the future. Conservation of current resources is also highlighted, as this will be important in determining the timing and need for temporary and future resources (SNWA, 2021b).

Figure 12. Permanent, temporary, and future water resources identified for development by the SNWA.



	SUPPLY	CONSUMPTIVE USE	AVAILABLE IN SHORTAGE
PERMANENT	Colorado River (SNWA and Nellis Air Force Base) [1]	276,205 AFY	Yes. Subject to shortage reductions
	Nevada Unused Colorado River (Non-SNWA)	13,938 (2021) to 0 AFY in 2031	Yes. Subject to availability
	Tributary Conservation ICS	30,690-36,000 AFY	Yes
	Las Vegas Valley Groundwater Rights	46,961 AFY	Yes
TEMPORARY	Southern Nevada Groundwater Bank	345,206 AF (20,000 AFY max.)	Yes
	Interstate Bank (Arizona)	613,846 AF (40,000 AFY max.)	Yes
	Interstate Bank (California)	330,225 AF (30,000 AFY max.)	Yes
	Intentionally Created Surplus (storage in Lake Mead)	865,741 AF (300,000 AFY max.)	Yes, varies by Lake Mead elevation
FUTURE	Colorado River Transfers/Exchanges Permanent Future Supply (Desalination and Colorado River Partnerships)	20,000-40,000 AFY	Yes
	Colorado River Transfers/Exchanges Virgin River/Colorado River Augmentation	Up to 108,000 AFY	To be determined
	Garnet and Hidden Valleys Groundwater	2,200 AFY	Yes
	Tikaboo and Three Lakes Valley North and South Groundwater	10,605 AFY	Yes

FIGURE 4.1 SNWA Water Resource Portfolio

(SNWA, 2021b, p. 42)

4.1.3.3 Adaptive capacity

Indicators: (5) consideration/application of climate change in planning

(6) "lock-in" effect

As touched on in Section 4.1.3.1, the SNWA is very aware of climate change and climate change related impacts on water resources in the LCRB, stating that

> "While preparing the 2021 Plan, the SNWA considered other factors related to water supply and demand conditions, including:
>
> •The potential impact of water supply reductions and reduced runoff due to climate change, particularly for Colorado River supplies; and
>
> •The potential impact of economic conditions, climate change and water use patterns on long-term water demands." (SNWA, 2021b, p. 2).

One of the goals identified in the LVVWD's strategic planning process is to "Anticipate and adapt to changing climatic conditions while demonstrating stewardship of our environment", which is used as a template to help define the goals of each individual department within the agency (LVVWD, 2021, p. 2.12). When planning for future water supply and demand scenarios, the SNWA "also includes expanded planning scenarios that reflect shortage impacts under variable hydrology (average, dry, extremely dry and climate change)" (LVVWD, 2021, p. 5.7). As an agency whose ability to function is directly tied to their ability to provide a resource that is extensively influenced by changing climatic conditions, the SNWA has made great efforts to understand the state of the science and decrease their own impacts by funding research and committing to decreasing their dependence on non-renewable energy sources (SNWA, 2021b).

Despite every effort to prepare for future conditions, water purveyors of the region are attempting to predict a future that is inherently uncertain. In an attempt to mitigate the risk of the region to water scarcity, the SNWA has poured resources into increasing the robustness of its infrastructure systems, exemplified by the installation of a third low level intake and pumping station that allows the valley to withdraw water from Lake Mead in the event that the lake level drops below 1,000 feet. However, increasing the robustness of the system could result in long-term increased vulnerability of the region by contributing to increased perceptions of water availability and decreased system flexibility. This could be further exacerbated by importing water resources from other regions and by the continued reliance on the return-flow credit system which allows Nevada to withdraw more than their allotted 300,000 AFY of water from the Colorado River. This mismatch in *perception* of water availability and *actual* water availability can result in a "supply-demand cycle", where increased water capacity allows for increased growth of urban areas, generating more demand and stress on already scarce water resources (Lindqvist et al., 2021; Tellman et al., 2018). Dr. Dale Devitt, a water and soil scientist at UNLV, highlighted this potential problem, asking

> "Is growth sustainable in a desert environment here in Southern Nevada? The answer is no. At some point we have to recognize that only so many people can live here. We aren't going to be able to conserve our way out of this…We're asking people to conserve water, and that's great. But if we're not going to protect those savings, and instead allow for them to support more growth, we're only putting ourselves in more trouble" (Lochhead, 2022).

Although robustness is an important component of urban resilience, enhancing *only* this aspect of infrastructure systems can lead to unintended consequences and increased vulnerability to future extreme events as discussed in Section 2.1.2.2. The overreliance on the return-flow credit system can result in a lock-in of decision cycles, meaning that past decisions that have led to a reliance on this system will continue to influence future decisions (Markolf et al., 2018; Tellman et al., 2018). This can be seen through the SNWA's recently adopted policy in 2017 to address water use in areas outside the LVV to maximize return-flow to Lake Mead (SNWA, 2021b). The reliance on return-flow credits has limited the scope of decision making for the SNWA, and because of this, alternative pathways may fail to be considered despite potential benefits (Markolf et al., 2018). This can be seen in many of the SNWA planning documents, demonstrated by the following quote:

> "While direct reuse of Colorado River water may have advantages over indirect reuse in terms of lower pumping cost, additional direct reuse does not extend Southern Nevada's Colorado River supply where return-flow credits are available. This is because an increase in direct reuse will reduce the amount of water available for indirect reuse through return-flow credits by a similar amount"(SNWA, 2021b, p. 26).

The decisions to reuse water indirectly by pumping recycled water back to Lake Mead is the agency's main priority, even sometimes directly contrasting with other company goals such as their commitment to reduce energy consumption (SNWA, 2021b). This structural path dependency is likely to continue constraining the system's ability to adapt to future changes, despite the SNWA's attempts to diversify Southern Nevada's water portfolio.

4.1.3.4 Regulations

Indicators: (7) water quality requirements

(8) onsite non-potable reuse for single-family residence

The legal requirements for non-potable unrestricted urban reuse of recycled water in Nevada is summarized in Figure 13 below. These requirements could easily be met with use of a gravity-driven membrane bioreactor (MBR) system followed by chlorine disinfection of domestic greywater (Cecconet et al., 2019). MBR systems have been shown to be very effective for wastewater contaminant removal, however, they also tend to be more expensive, complicated, and energy intensive than other treatment systems (Cecconet et al., 2019; Jeong et al., 2018). Because of this, some experts have suggested using other variations of this technology, for example, using a biomass concentrator reactor (BCR) which uses a filter rather than a membrane to separate solids and liquids in wastewater. This approach has been described as the "fit for purpose" approach, which may be most feasible for meeting these quality requirements while reducing costs and maintenance demands (Cecconet et al., 2019).

Figure 13. Water quality requirements for non-potable unrestricted urban reuse of treated water in Nevada.

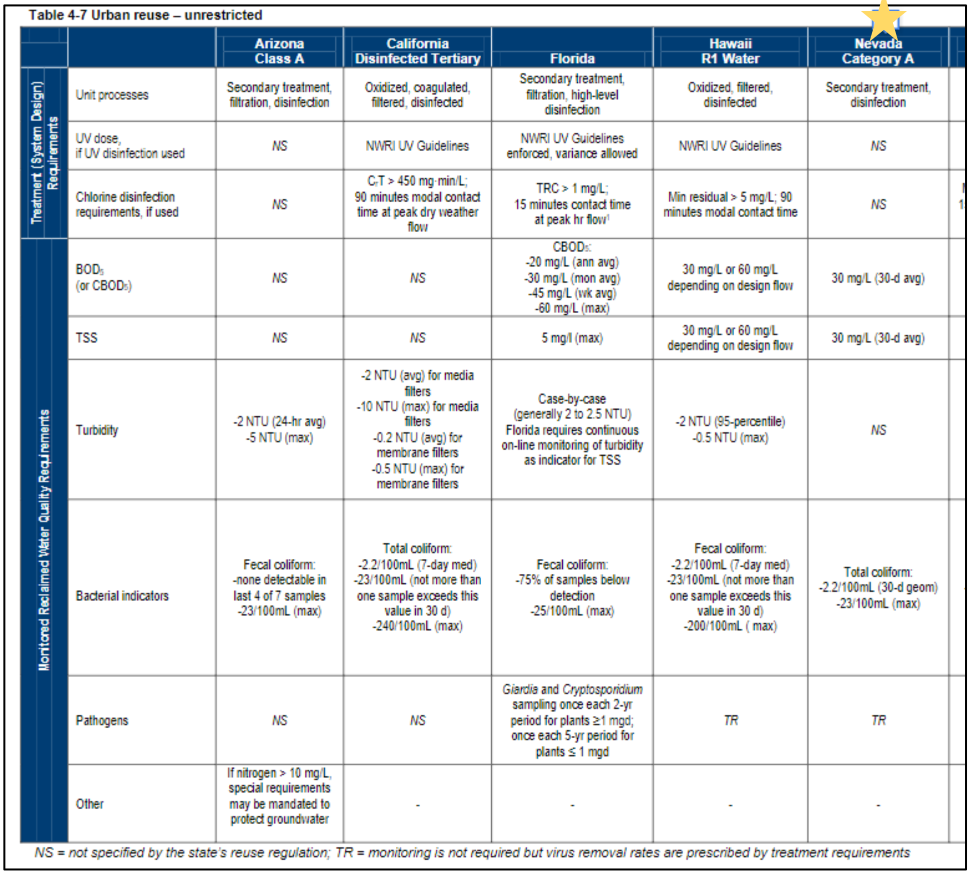


Table 4-7 Urban reuse – unrestricted

		Arizona Class A	California Disinfected Tertiary	Florida	Hawaii R1 Water	Nevada Category A
Treatment (System Design) Requirements	Unit processes	Secondary treatment, filtration, disinfection	Oxidized, coagulated, filtered, disinfected	Secondary treatment, filtration, high-level disinfection	Oxidized, filtered, disinfected	Secondary treatment, disinfection
	UV dose, if UV disinfection used	*NS*	NWRI UV Guidelines	NWRI UV Guidelines enforced, variance allowed	NWRI UV Guidelines	*NS*
	Chlorine disinfection requirements, if used	*NS*	C_RT > 450 mg-min/L; 90 minutes modal contact time at peak dry weather flow	TRC > 1 mg/L; 15 minutes contact time at peak hr flow[1]	Min residual > 5 mg/L; 90 minutes modal contact time	*NS*
Monitored Reclaimed Water Quality Requirements	BOD$_5$ (or CBOD$_5$)	*NS*	*NS*	CBOD$_5$: -20 mg/L (ann avg) -30 mg/L (mon avg) -45 mg/L (wk avg) -60 mg/L (max)	30 mg/L or 60 mg/L depending on design flow	30 mg/L (30-d avg)
	TSS	*NS*	*NS*	5 mg/l (max)	30 mg/L or 60 mg/L depending on design flow	30 mg/L (30-d avg)
	Turbidity	-2 NTU (24-hr avg) -5 NTU (max)	-2 NTU (avg) for media filters -10 NTU (max) for media filters -0.2 NTU (avg) for membrane filters -0.5 NTU (max) for membrane filters	Case-by-case (generally 2 to 2.5 NTU) Florida requires continuous on-line monitoring of turbidity as indicator for TSS	-2 NTU (95-percentile) -0.5 NTU (max)	*NS*
	Bacterial indicators	Fecal coliform: -none detectable in last 4 of 7 samples -23/100mL (max)	Total coliform: -2.2/100mL (7-day med) -23/100mL (not more than one sample exceeds this value in 30 d) -240/100mL (max)	Fecal coliform: -75% of samples below detection -25/100mL (max)	Fecal coliform: -2.2/100mL (7-day med) -23/100mL (not more than one sample exceeds this value in 30 d) -200/100mL (max)	Total coliform: -2.2/100mL (30-d geom) -23/100mL (max)
	Pathogens	*NS*	*NS*	*Giardia* and *Cryptosporidium* sampling once each 2-yr period for plants ≥1 mgd; once each 5-yr period for plants ≤ 1 mgd	*TR*	*TR*
	Other	If nitrogen > 10 mg/L, special requirements may be mandated to protect groundwater	-	-	-	-

NS = not specified by the state's reuse regulation; TR = monitoring is not required but virus removal rates are prescribed by treatment requirements

(USEPA, 2012, p. 4.26)

Despite extensive research available supporting effective contaminant removal of recycled water treated using different GWR systems, a bill was passed in Nevada in 2015 that allows the State Board of Health or a district board of health to restrict the use of greywater recycling systems in single-family residences. This applies if there is "(1) The reasonable potential for return flow to a river system or lake; (2) A requirement for return flow of effluent to a river system; or (3) An existing alternative program for recycled water" (NRS, 2015, p. 3). However, local governments are not given the power to prohibit use of single-unit residence GWR systems (NRS, 2015). Nevertheless, it is unlikely that the SNWA would support the approval of permits for onsite GWR systems in single-family homes or help subsidize the implementation of this technology in homes connected to their water reclamation system. Therefore, it would likely be more feasible to implement these systems in homes that are connected to private septic systems located further outside of the valley where expansions of the municipal system would be costly and difficult to build.

4.1.4 Analysis of context variables

The federal, state, and local levels of government are highly aware of the struggle that they will face in meeting future water resource needs of the LVV with current resources, as well as the impacts that climate change and population growth will have on these resources. Therefore, climate change and reduced availability of future water resources are highly integrated into all planning documents produced and used by the SNWA, Southern Nevada's main water provider. Conservation is central to the agency's future planning, and there have been several education and outreach programs as well as conservation initiatives that the SNWA has implemented to encourage conservation of resources. However, these efforts have mostly focused on reducing outdoor water consumption and have not addressed indoor water use. Additionally, although the regions water purveyors promote conservation, their ability to function is dependent on water sales; tiered consumption revenue alone accounts for nearly 70 percent of the LVVWD's funding. This means that a reduction in water sales due to reduced consumption directly impacts the ability of the water purveyors to complete projects or pay down debts. The SNWA's reliance on water sales for operational capacity provides a structural barrier for significant reductions in water use throughout the LVV.

Due to the location of the LVV in the semi-arid west, GWR is the most suitable form of MWI to be implemented in the valley, as RWH and ACH systems would not be effective in this environment. In the MCCP, the SNWA has reserved $188.3 million for investment in potential future water supply opportunities or to fund research or project trials of new technology to extend the valley's current water supplies. This contingency fund could be used to subsidize installation of residential GWR systems and reduce the economic burden that this would have on residents. Although costly, implementing direct reuse of greywater resources in the LVV would likely be less expensive than acquiring water resources from outside of the valley. The SNWA currently has plans to spend at least $1,068.6 million in projects to import water resources from outside the LVV and acquire additional Colorado River water rights from other users.

Although residential onsite GWR in the LVV may be technically and economically feasible, there are other structural roadblocks to implementing this in the valley. The systemic "lock-in" effect resulting from a heavy reliance on return-flow credits means that it is very unlikely that the SNWA would support any action that would reduce the amount of water that they can treat and return to Lake Mead, despite potential benefits that alternatives may provide such as a reduction in energy consumption. In fact, the SNWA decided to officially oppose the idea of household GWR in 2009 (Berzon, 2009). However, it may be feasible to install GWR systems in the estimated 14,500 homes in the LVV that are connected to private septic systems. Nonetheless, the SNWA, as part of their 2022-2023 Operating and Capitals Budget that was active as of July 1, 2022, has set the groundwork for a pilot septic conversion program to join these users with the municipal sewer system (SNWA, 2022, p. 1.6). Therefore, in the next section, I will investigate the potential impacts on the WEN of the valley of installing GWR systems in these homes and compare these results with the potential impacts of connecting these homes to the municipal wastewater system.

4.2 Potential WEN impacts: results and analysis

4.2.1 Installation of onsite GWR system vs connection of septic users to municipal wastewater infrastructure

4.2.1.1 Change in residential indoor water demand

Indicators: (1) estimated change in water demand per residence

There are an estimated 14,500 homes in the LVV that are connected to private septic systems, whose wastewater is not collected, treated, and returned to Lake Mead (SNWA, 2022). If a simple GWR system was installed in each of these homes and recycled water was utilized for toilet-flushing and/or outdoor irrigation purposes, an estimated 1,575-2,450 gallons of water could be saved per month per residence. For the entire valley, this could potentially reduce residential water demand by approximately 841-1,308 AFY (see Appendix 2 for all calculations). Given this reduction in residential indoor demand, it is estimated that each residence could save approximately $26-41 per year on water costs.

In addition to this potential reduction in potable water demand by utilizing recycled water, additional reductions may be observed from behavioral changes associated with an increased awareness of available water supply (Lindqvist et al., 2021). A similar phenomenon was observed in the Las Vegas area where per capita use dropped from 437 GPCD to 225 GPCD in just three years after metering was introduced (Lasserre, 2015). However, behavioral changes in per capita water use due to onsite GWR has not been directly measured, so it is therefore not possible to estimate how this could potentially impact the residential water demand at this time. There would likely be no direct change in residential water demand should these 14,500 homes be connected to the municipal sewage system, as the treated water would not be reused onsite but would rather be returned to Lake Mead as return-flow credits. Additionally, it is unlikely that the potential for water demand reductions due to a behavioral change would occur in this scenario, as no increase in responsibility of water supply and usage would occur.

4.2.1.2 Change in energy grid burden

Indicators: (2) estimated change in energy demand for SNWA

Should onsite GWR systems be implemented in the 14,500 homes currently using private septic systems, the reduction in energy needed to pump water to those residences would be proportional to the reduction in freshwater demand resulting from use of these systems. There would be no increased energy demand associated with an increase in contaminant concentration loading at the municipal treatment center as these residences would not be connected to the municipal wastewater system. Therefore, assuming a reduction in demand equal to 1,575-2,450 gallons per residence per month as calculated in Section 4.2.1.1, the SNWA could potentially reduce their energy use by 1.6-2.5 million kilowatt hours (kWh) per year. This equates to an annual savings of approximately $192,000-300,000 per year for the SNWA. However, considering that the expected energy costs for the SNWA for the 2022-23 fiscal year is $51 million, this only results in a savings of 0.4-0.6% (SNWA, 2022, p. 5.25). The SNWA is one of the state’s largest energy users, but energy accounts for only about 8.5% of the SNWA’s total operating budget (SNWA, 2022). Additionally, the SNWA is currently poised to provide an estimated $20 million to ibV Energy Partners to help fund a large scale solar photovoltaic facility project as part of a Power Purchase Agreement (PPA) which will allow the SNWA to purchase power from ibV below the market cost for a fixed 25-year term (SNWA, 2022). Therefore, it is unlikely that a reduction in energy use of this scale would be a significant source of savings given these developments.

If all estimated 14,500 residences using private septic systems were instead connected to the municipal wastewater system, approximately 4,084 gallons per residence per month could be collected. This increased volume of water would need to be treated by the SNWA and returned to Lake Mead, which would result in an increase in energy demand for the agency. The completion of this project could potentially result in an increase in energy consumption by approximately 11.6 million kWh per year for the SNWA, costing an estimated $1.4 million in additional expenditure.

Indicators: (3) estimated change in energy demand per residence

Installing a small-scale GWR system in these homes could result in a potential increase in energy demand of 172-267 kWh per residence per year, or an additional $21-32 per residence per year in energy costs. However, Craig & Richman (2018) found in their pilot study that it only took approximately 0.077 kWh per day to run the GWR system used in their study (used for toilet flushing only), which would result in an increase in energy demand of 28.11 kWh per residence per year, or $3.37 per residence per year (Craig & Richman, 2018). They also noticed that about 73% of the energy used to run this system was consumed on standby, and as the system only ran for about 15 minutes per day, there is potential to further reduce the energy demand of these onsite systems (Craig & Richman, 2018). If the GWR system implemented in these homes was combined with a thermal recovery unit, the energy demand of the system could potentially be completely offset and even reduce demand for the residence overall (Arden et al., 2021; USEPA, n.d.). Including a thermal recovery unit in each of these projects could result in a potential energy savings of 542-844 kWh per residence per year, or an annual savings of $65-101 per residence. If these 14,500 residences were instead converted to the municipal sewage system, there would likely be no change in energy demand for the individual residences.

Indicators: (4) estimated change in energy demand for LVV

If a simple GWR system was installed in each of the estimated 14,500 residences in the LVV that currently use a private septic system, the amount of energy that the SNWA would need for water delivery could potentially decrease by approximately 1.6-2.5 million kWh per year due to reduced water deliveries to these homes. However, the combined energy demand for these residences could increase by about 2.5-3.9 million kWh per year, resulting in a potential net increase of about *0.9-1.4 million kWh per year* for the LVV. This is congruent with expected results, as centralized wastewater systems tend to be more energy efficient than onsite systems (Jeong et al., 2018). However, if the GWR systems were installed in addition to a thermal recovery unit, this could potentially result in a reduction in energy demand of approximately 7.9-12.2 million kWh per year. This means that the overall energy demand of the LVV could potentially decrease by approximately *9.5-14.7 million kWh per year*.

If these residences were instead connected to the municipal wastewater system, the energy use of the SNWA could potentially increase by an estimated 11.6 million kWh per year, due to increased need for energy to treat and return the additional volume of water to Lake Mead. There would likely be no change in energy demand for each of the residences, meaning the overall change in energy demand of the LVV is estimated to be a net increase of approximately *11.6 million kWh per year*. It is worth noting that the SNWA has committed to sourcing 50% of their energy from renewable sources by 2030, of which they had met 24% of this requirement in 2021 (SNWA, 2020a, 2021a).

4.2.1.3 Change in water withdrawals from Lake Mead

Indicators: (8) change in volume water withdrawn to meet demand

(10) amount of water returned to Lake Mead (return flows)

If onsite GWR systems were installed in these homes, the amount of water withdrawn from Lake Mead to meet these demands would decrease by a volume proportional to the demand of potable water met by recycled water. This was identified in Section 4.2.1.1 above and could result in an estimated reduction in water demand of approximately 1,575-2,450 gallons per residence per month, or *841-1,308 AFY***.** This estimate would likely be even higher if water was reused for outdoor irrigation in addition to toilet flushing, and it does not include additional water reductions associated with changes in water use behavior due to increased awareness of water availability. If these homes were instead converted to the municipal wastewater system, there would likely be no change in water demand and therefore no expected change in the volume of water withdrawn from Lake Mead to meet demand.

If these GWR systems were installed, there would be no change in the volume of water returned to Lake Mead. However, if these homes were connected to the municipal sewage system, the estimated amount of water that could be collected, treated, and returned to Lake Mead would be approximately *2,181 AFY*. This means that the SNWA could potentially avoid negative financial impacts associated with a decrease in residential water demand as the same volume of water returned to the lake could then be withdrawn again due to the return-flow credit system discussed in Section 4.1.3.3. Both scenarios have the potential to help slow the rate of lake level drop in Lake Mead, also protecting the ability of the Hoover Dam to produce electricity.

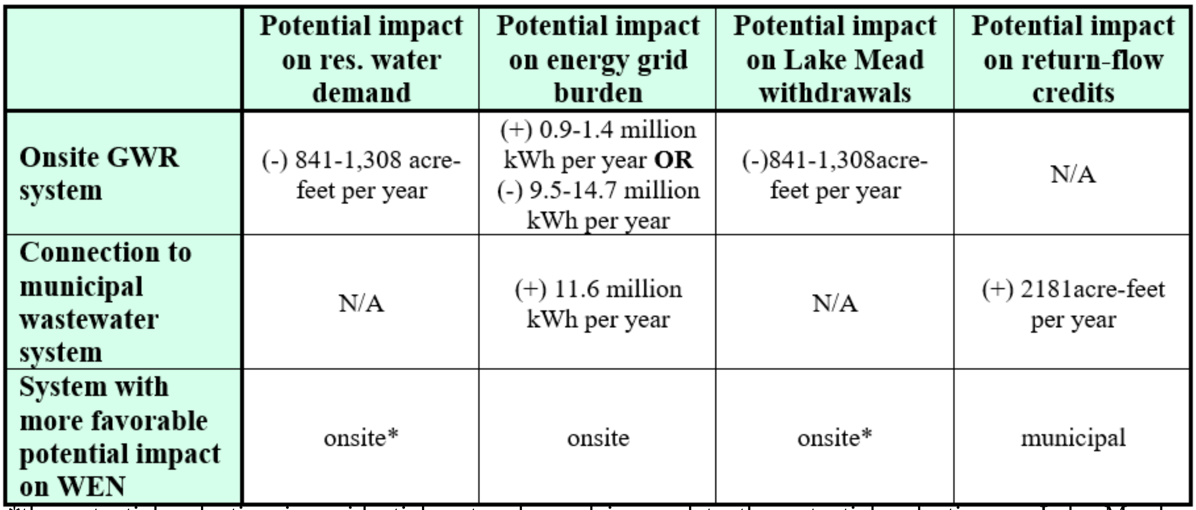
4.3 Discussion

4.3.1 Interpretation and implication of findings

In Section 4.1, technical, economic, and governmental variables were investigated to describe the local context of the LVV. This was done to determine if it would be feasible to implement MWI in the valley, and if so, what type, at what scale, and where this could realistically be completed. Given this information, the potential impacts that this project would have on the WEN of the LVV was investigated in Section 4.2. The major findings of this investigation are summarized and discussed here.

In Section 4.1.4, a detailed discussion of the major conclusions drawn from the first half of the analysis is presented. This analysis suggests that although it could be technologically and economically feasible to implement onsite non-potable GWR as a supplement to the municipal wastewater system, it is unlikely that the SNWA would support this initiative, making it infeasible to suggest this as a potential solution. However, there are approximately 14,500 houses throughout the valley that are connected to private septic systems, which the SNWA has recently targeted in a pilot project for conversion to the municipal wastewater system. This would allow them to collect, treat, and return the water used in these houses to Lake Mead for additional return-flow credits. Therefore, this research shifted focus away from investigating the potential impacts that implementation of onsite GWR in homes that are already connected to the municipal wastewater system could have on the WEN as initially intended. Section 4.2 instead investigates the potential impact that installing these systems would have on the WEN of the valley and compares this to the potential impacts of connecting these homes to the municipal sewage system. The major findings from the analysis conducted in Section 4.2 are summarized in Table 3 below.

Table 3. Summarized findings of potential impacts that conversion of 14,500 homes connected to private septic systems could have on the WEN of the LVV.



	Potential impact on res. water demand	Potential impact on energy grid burden	Potential impact on Lake Mead withdrawals	Potential impact on return-flow credits
Onsite GWR system	(-) 841-1,308 acre-feet per year	(+) 0.9-1.4 million kWh per year **OR** (-) 9.5-14.7 million kWh per year	(-)841-1,308acre-feet per year	N/A
Connection to municipal wastewater system	N/A	(+) 11.6 million kWh per year	N/A	(+) 2181acre-feet per year
System with more favorable potential impact on WEN	onsite*	onsite	onsite*	municipal

*the potential reduction in residential water demand is equal to the potential reduction on Lake Mead withdrawals, therefore water savings should not be counted twice

Based on these results, implementation of onsite GWR systems in the 14,500 homes that are currently connected to septic systems could have a more favorable impact on the WEN of the LVV when compared with connecting these homes to the municipal wastewater system. Onsite GWR systems would potentially have lower energy demands than increased connections to the municipal sewage system, and even potential savings, resulting in a lower overall burden on the energy grid of the LVV. For the residents of these homes, the inclusion of a thermal recovery unit with the GWR system would make the project more economically feasible due to the potential to reduce overall household energy consumption. If these homes were connected to the municipal wastewater system, the SNWA would absorb the impact of increased energy costs associated with higher water transport and treatment volumes. However, due to the PPA that the SNWA has entered with the energy provider iVb, when the photovoltaic plant comes online in 2023, they will be able to purchase energy at a reduced cost. Therefore, it is unlikely that this increase in energy demand would have a significant effect on the SNWA operating budget as their energy expenditure will decrease regardless due to this agreement.

Water consumption in the valley would decrease in both scenarios, however, it is likely that higher savings would be seen if these homes were connected to the municipal system as all the water that is used indoors could be captured and treated, rather than just a portion as would be the case with a simple onsite GWR system. It would be more beneficial for the SNWA to connect the homes to their municipal system as the water collected through this system would then be treated and returned to Lake Mead. Even if the water saving potential in each scenario were equal, meaning that the same amount of water would be available in Lake Mead for use, it would still be more beneficial to the SNWA for this water to pass through their system. This is because a reduction in water demand would result in a reduction in water sales for the SNWA, impacting their operational budget. With the current system, the SNWA can sell water to the LVV, collect, treat, and return most of that water to Lake Mead, and then re-sell that same volume of water back to the LVV without reductions in revenue because the water demand would remain constant. *This loop allows the valley to function and continue growing without having to make any major reductions in consumption, while at the same time protecting the operational capacity of the region's water purveyors, which are financially reliant on water sales*. Consequently, it is unlikely that the SNWA would help subsidize any projects related to onsite GWR within the valley, even if this scenario would be less costly than septic system conversions and despite other possible benefits to the WEN of the valley that this project could provide. This lack of consideration for alternative water saving strategies is exemplified by the agency's decision to formally oppose GWR on a household level in 2009 and why they have recently moved to begin septic system conversions throughout the valley, stating that they would support code changes to prohibit the installation of septic systems in the LVV in the future (Berzon, 2009; SNWA, 2022). Thus, *this research implies the existence of a financial and structural lock-in of the valley's water infrastructure system, which may threaten the water and energy security of the valley* in the face of future climate change and population growth related challenges.

4.3.2 Limitations of paper

Although this research has expanded upon existing knowledge of the WEN and complex interactions between contextual factors, specifically in the LVV region of Southern Nevada, there are some limitations that must be considered. Nearly all data collected for this research is from secondary sources, with the exception of one correspondence with a member of the SNWA. Initially, it was intended that semi-structured interviews would be conducted and analyzed in addition to the secondary data collected for increased validity and to include multiple perspectives that may not be visible through analysis of secondary sources only. However, only one response was received out of all the individuals/organizations that were contacted, and after several months of attempting to set up an interview with this organization, a response stating that it would not be possible was received in July. Therefore, this research was highly dependent on resources available online, most of them from the SNWA and the LVVWD, and includes limited perspectives outside of these agencies. Potential biases implicit in the data collected from these sources is therefore important to consider.

Additionally, the WEN estimations included in Section 4.2 are based on a variety of sources, including case studies and life cycle assessments found in the literature that were studied in different contexts. Variation in the potential impact of onsite GWR installation was therefore addressed in these estimates, and although these examples were chosen due to their similarity to the GWR system feasible for this research, it is unlikely that the exact same results would be observed in the context of the LVV. Therefore, the EPA's NEWR calculator and estimates based on SNWA water use approximations was also used to compare estimates and may be more reliable for the specific context of the LVV, but there will still be error associated with these calculations. All calculations are included in Appendix 2 for the purpose of replicability of this study.

Because urban systems and climate change are inherently complex and unpredictable, there are other variables that would likely influence both the feasibility and potential impact that onsite GWR would have on the WEN of the LVV that were outside the scope of this research. Factors such as the social acceptability of onsite greywater reuse could influence the feasibility of implementation, and interaction of the WEN with other urban sectors such as food (agricultural production is another large water consumer in the state) would also impact the outcome of this research. However, this research may still provide valuable information regarding the possible benefits of alternative greywater reuse systems within the LVV and could help to identify possible areas of vulnerability in the valley's water system.

Chapter 5: Conclusions

Many researchers have criticized traditional urban resource management for being technocentric and failing to consider the influence of social systems on the supply and demand of critical resources. It has been shown that urban systems are made up of complex interacting technological, social, and ecological spheres, and within cities, sub-systems interact with and influence other sectors. The WEN is one example of two deeply interlinked sectors that are highly influenced by social systems, and although this concept has been extensively researched, studies that analyze the WEN within its local context are still lacking. This is a gap that this research attempted to help fill using the conceptual framework included in Chapter 2 to describe these interactions. Additionally, the LVV's main water provider, the SNWA, has not acted in a significant way to encourage reduction of indoor residential water consumption in the valley, despite the importance of conservation for protecting the valley's future water supply. Micronet water infrastructure, such as onsite GWR, has been suggested as a possible approach for increasing the resilience of urban water infrastructure systems to the risks posed by climate change. MWI has the potential to help reduce the gap between perceived and actual water supply for consumers and therefore has the potential to contribute toward a reduction in indoor water demand. Reducing the gap between perceived and actual water availability may reduce the risk of the LVV to extreme drought events, as perception of water abundance would allow the LVV to continue growing and constrain the ability of the region to meet future water demand due to increasing pressure on available water resources.

The objective of this research was to determine whether MWI has the potential to increase the water and energy security of the LVV region of Southern Nevada, an area identified as being highly susceptible to the effects of climate change and population growth on its water resources. The main research question guiding this investigation was: *What would be the potential impact of implementing residential micronet water infrastructure on the water-energy nexus given the current technological, governmental, and economic conditions of the Las Vegas Valley?* To answer this, two sub questions guided the analysis:

1. What micronet water infrastructure could feasibly be implemented in the Las Vegas Valley given the current technological, governmental, and economic conditions of this region?

Based on the analysis presented in Section 4.1, the technological and economic resources of the valley make the implementation of onsite MWI at a residential scale feasible. Detached single-unit homes can be retrofit with small-scale, fit-for purpose GWR systems that would be effective at removing contaminants such that the recycled water would meet water quality standards for non-potable reuse required by the State of Nevada. The economic barrier for installing and maintaining these systems is a significant one, and it could take several decades for residents to see a return on investment given high capital costs and relatively low cost of water in the valley. However, the SNWA has a contingency fund of $188.3 million which has been set aside to aid in acquisition of water resources that could arise or to fund projects that are identified as having the potential to extend the valley's water supply. This fund could be used in part to subsidize the capital and/or O&M costs of these systems, significantly reducing the economic barrier of this infrastructure.

The SNWA acts as the region's main water provider, rather than the local municipalities as is common in other urban systems. The SNWA is fully aware of and proactive in planning for the effects of climate change on the water resources available to the LVV, especially in relation to the Colorado River from which the valley sources 90% of its water. The SNWA has acknowledged that the resources currently available to the valley will not be enough to meet the future demands of the valley and is planning to invest over $1 billion in projects and agreements with other water rights holders to acquire additional resources in the future. In addition to this, the authority has invested in conservation efforts to reduce outdoor water consumption within the valley to stretch existing resources. However, because the SNWA's operational capacity is highly dependent on the volume of water sold to purveyors of the LVV, and by extension consumers, reduction of indoor water consumption could be unfavorable because less water sold would result in lower revenue. Therefore, the SNWA is deeply reliant on their ability to capture, treat, and return water used indoors to Lake Mead, allowing them to withdraw more than their allotted volume of water from the river and avoid the negative financial impacts that indoor conservation on a large scale would have. Therefore, despite the technical and economic feasibility of implementing onsite GWR systems in homes as a supplement to the centralized system, it is unlikely that the SNWA would support this.

Due to this finding, the focus of this research had to shift. Rather than investigating the potential impact on the WEN of installing onsite GWR systems in homes already connected to the municipal wastewater system, the potential impact of installing these systems in homes operating on private septic systems was explored. The SNWA has recently developed a pilot project for septic system conversion, so the second half of the analysis compared the potential impacts of connecting each of the estimated 14,500 homes using private septic systems to the municipal wastewater system versus installing onsite GWR systems in these homes.

2. How would the implementation of micronet water infrastructure identified in sub-question 1 impact the water-energy nexus of the Las Vegas Valley?

The analysis completed in Section 4.2 suggests that the implementation of onsite GWR systems in each of the 14,500 homes could potentially be more beneficial for the WEN of the valley when compared with conversion of these homes to the municipal wastewater system. Connecting these homes to the existing system would likely allow approximately 2-3 times as much water to be collected and treated throughout the valley when compared to the onsite scenario, assuming no additional water use changes would be realized in the latter due to an increased awareness of water supply availability. However, connecting these homes to the municipal system could result in an energy demand 8-13 times higher than that of the onsite GWR scenario, and installing these systems in addition to a thermal recovery unit has the potential to result in a net *decrease* in energy demand for the valley.

Despite these estimates, it is still unlikely that the SNWA would subsidize installation of onsite GWR systems over the current septic conversion project. The factors discussed in Section 4.1.3 highlight these constraints, as returning recycled water to Lake Mead is more beneficial for the SNWA financially and in terms of return-flow credits. Additionally, due to the agreement that the SNWA has entered with the energy provider iVb, it is unlikely that the increased cost of energy associated with septic conversions would act as a significant deterrent for completion of this project.

Contribution to existing knowledge and recommendations for future policies and research

This research confirms the findings of previous research regarding the lack of consideration of WEN concepts in resource management decisions, indicated by the SNWA's reluctance to consider reuse of recycled water within the valley despite significant potential for energy demand reductions. Additionally, this research helped establish how MWI could increase the redundancy and flexibility of the LVV's water system by reducing the SNWA's reliance on return-flow credits and the valley's aging infrastructure. The failure of the SNWA to account for social influences on potential outcomes of decisions could lead to the occurrence of unintended consequences such as policy resistance or supply-demand cycles that could constrain the ability of these actions to deliver long-lasting solutions. This could result in the

SNWA accumulating sunk costs on infrastructure projects they have planned to move more water into the valley, including environmental degradation impacts associated with activities such as increased groundwater pumping. Furthermore, this research has helped to substantiate previous research regarding the lock-in of urban infrastructure systems due to decision-cycles, exemplified by the SNWA's refusal to consider possible actions unless they would enhance their ability to return water to Lake Mead, regardless of other potential benefits.

The LVV could look to other urban areas in the southwestern US where water conservation has been more successful, such as in Tuscon, Arizona where onsite greywater reuse is *required* in newly built homes. Policy development with an emphasis on collaboration, reiteration, and consideration of ecological health has been successful in terms of reducing water demand in Tuscon, which the SNWA may be able to integrate into their own strategies (Zuniga-Teran & Tortajada, 2021). Additionally, an increased willingness to consider and pilot alternative water saving projects could benefit the SNWA in the long-term by reducing the rigidity of the existing infrastructure system and policy motivations, helping to reduce the risk of the SNWA to incurring sunk costs or overestimating the protection provided by current infrastructure. Shifting focus from acquiring additional resources from *outside* the valley to improving efficient water use *within* the valley will be necessary, as addressing existing vulnerabilities that are endogenous to the LVV will be important for adapting to external risks posed by climate change. Although this research has built upon existing knowledge regarding MWI and management of the WEN within a local context, there is still much work to be done to further our understanding of how resource management decisions influence the growth of urban spaces and their vulnerability to the effects of climate change. Identifying cases of infrastructural lock-in and addressing these issues is an area of research that is still underdeveloped and building our knowledge of these issues could potentially enhance the ability of urban managers to increase resilience of urban systems to the impacts of climate change and population growth.

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Appendix 2: Additional material

Figure 14. Estimated costs for retrofitting installation of GWR systems in USD.

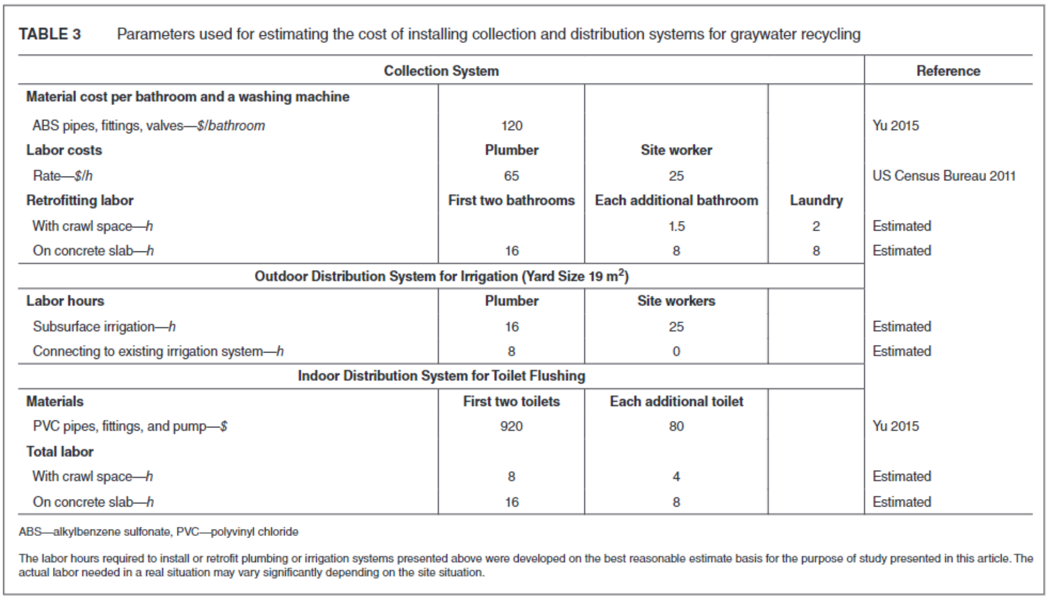


TABLE 3 Parameters used for estimating the cost of installing collection and distribution systems for graywater recycling

Collection System				Reference
Material cost per bathroom and a washing machine				
ABS pipes, fittings, valves—*$/bathroom*	120			Yu 2015
Labor costs	**Plumber**	**Site worker**		
Rate—*$/h*	65	25		US Census Bureau 2011
Retrofitting labor	**First two bathrooms**	**Each additional bathroom**	**Laundry**	
With crawl space—*h*		1.5	2	Estimated
On concrete slab—*h*	16	8	8	Estimated
Outdoor Distribution System for Irrigation (Yard Size 19 m^2)				
Labor hours	**Plumber**	**Site workers**		
Subsurface irrigation—*h*	16	25		Estimated
Connecting to existing irrigation system—*h*	8	0		Estimated
Indoor Distribution System for Toilet Flushing				
Materials	**First two toilets**	**Each additional toilet**		
PVC pipes, fittings, and pump—*$*	920	80		Yu 2015
Total labor				
With crawl space—*h*	8	4		Estimated
On concrete slab—*h*	16	8		Estimated

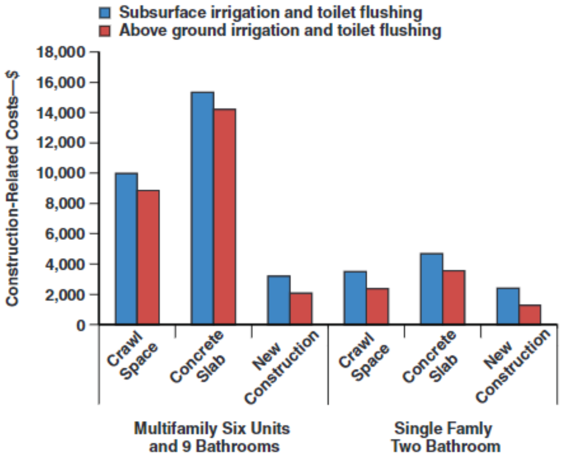
ABS—alkylbenzene sulfonate, PVC—polyvinyl chloride

The labor hours required to install or retrofit plumbing or irrigation systems presented above were developed on the best reasonable estimate basis for the purpose of study presented in this article. The actual labor needed in a real situation may vary significantly depending on the site situation.

(Yu et al., 2015, p. E440)

Figure 15. Estimated construction-related costs for GWR system installation in USD.

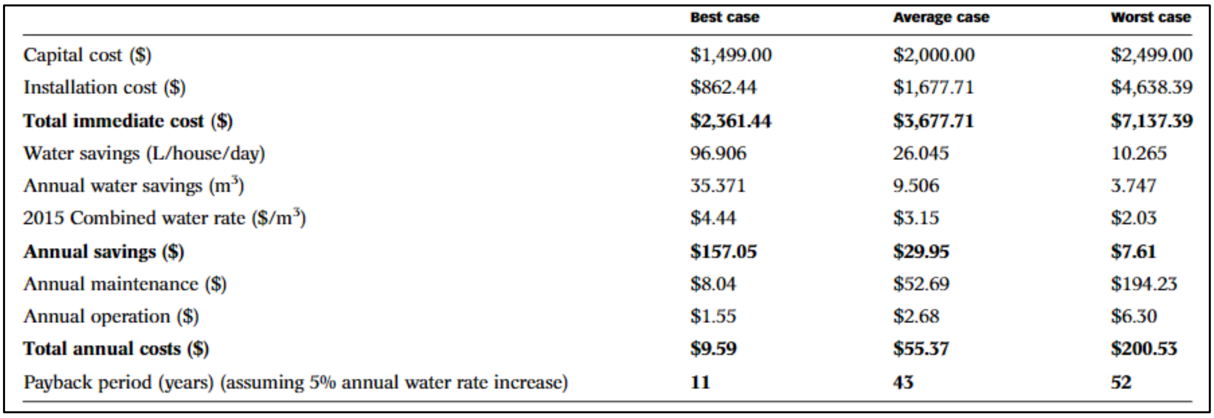
FIGURE 4 Construction-related costs for providing plumbing for raw graywater collection and treated graywater reuse for indoor and outdoor reuse or outdoor-only water reuse



A multifamily home with six units and nine bathrooms and a single-family home with two bathrooms that have crawl space, are built on a concrete slab, and are new construction are evaluated.

(Yu et al., 2015, p. E440)

Figure 16. Estimated costs for retrofit installation of GWR systems in homes with a mechanical room or basement (in CAD).



	Best case	Average case	Worst case
Capital cost ($)	$1,499.00	$2,000.00	$2,499.00
Installation cost ($)	$862.44	$1,677.71	$4,638.39
Total immediate cost ($)	**$2,361.44**	**$3,677.71**	**$7,137.39**
Water savings (L/house/day)	96.906	26.045	10.265
Annual water savings (m^3)	35.371	9.506	3.747
2015 Combined water rate ($\$/m^3$)	$4.44	$3.15	$2.03
Annual savings ($)	**$157.05**	**$29.95**	**$7.61**
Annual maintenance ($)	$8.04	$52.69	$194.23
Annual operation ($)	$1.55	$2.68	$6.30
Total annual costs ($)	**$9.59**	**$55.37**	**$200.53**
Payback period (years) (assuming 5% annual water rate increase)	**11**	**43**	**52**

(Craig & Richman, 2018, p. 16)

WEN Calculations

Onsite GWR:

Reductions in residential indoor water demand:

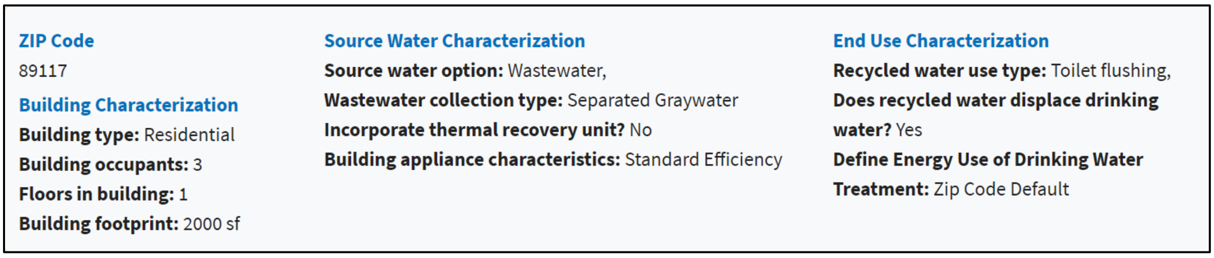
possible range based on literature sources =173-1410 AFY* = 3-26% reduction = $5.44-44.35 savings per residence per year

most likely to fall between 841-1308 AFY, which is a 15-24% decrease in demand (just from reusing water for toilet flushing), annual savings of $5-44 per residence per year

1. Literature estimations
   a. (Craig & Richman, 2018, p. 11)
      i. Average water savings 40.9 liters per day (*toilet flushing only*)
      ii. 40.9 liters/day * 0.264172 gallons/liter * 30 days/month = *324.14 gallons/ month*
   b. (Birks et al., 2003, p. 10)
      i. Average water savings 62.7 m^3 per year (*toilet flushing only*)
      ii. 62.7 m^3/ year * 264.172 gallons/m^3 / 12 months/year = *1,380.30 gallons/ month*
   c. (Knutsson & Knutsson, 2021, p. 20)
      i. Average water savings 19.99 m^3 per 2 months (*toilet flushing only*)
      ii. 19.99m^3/2 months * 264.172 gallons/m^3 / 2 months = *2,640.40 gallons/ month*
   d. (Jeong et al., 2018, p. 338)
      i. Average water savings 57.33 m^3/year (*toilet flushing + outdoor irrigation*)
      ii. 57.33 m^3/ year * 264.172 gallons/m^3 / 12 months/year = *1,262.08 gallons/ month*
   e. Estimate 324-2,640 gal/residence/month * 12 months = 3,888-31,680 gal/residence/year * 14,500 residences = 56,376,000-459,360,000 gal/yr = *173-1410 AFY*
2. NEWR
   a. The parameters used for this calculation are specified in Figure 17

b. 3 residents was chosen based on the number of average household size of 2.6-3.5 in Las Vegas (US Economic Development Administration, n.d.)
c. A standard building footprint of 2000 square feet (single story) was chosen to represent an average single-family home size in the US
d. Separated greywater for toilet flushing was investigated (no outdoor irrigation)
e. Average water demand for toilet flushing is approximately *1,575 gallons per residence per month* shown in Figure 18
    i. Assume that demand=water savings as greywater production > demand for toilet flushing
    ii. 1,575 gal/res/month * 12 months *14,500 residences = 274,050,000 gal/yr = *841 AFY*

Figure 17. Parameters used for the NEWR calculation.



ZIP Code
89117

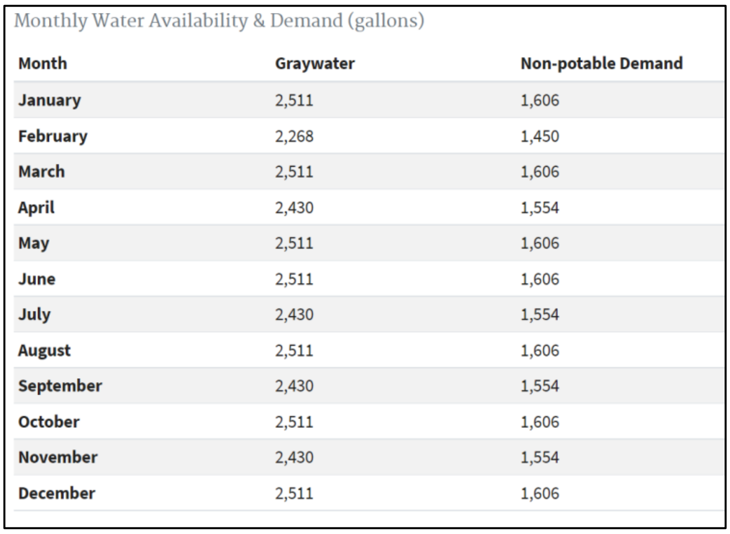
Building Characterization
Building type: Residential
Building occupants: 3
Floors in building: 1
Building footprint: 2000 sf

Source Water Characterization
Source water option: Wastewater,
Wastewater collection type: Separated Graywater
Incorporate thermal recovery unit? No
Building appliance characteristics: Standard Efficiency

End Use Characterization
Recycled water use type: Toilet flushing,
Does recycled water displace drinking water? Yes
Define Energy Use of Drinking Water Treatment: Zip Code Default

(USEPA, n.d.)

Figure 18. Monthly greywater availability and non-potable demand for toilet flushing calculated using NEWR.



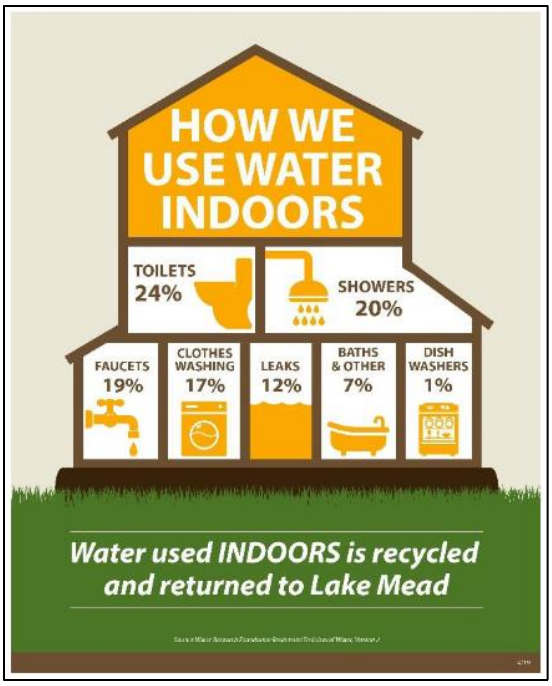
Monthly Water Availability & Demand (gallons)

Month	Graywater	Non-potable Demand
January	2,511	1,606
February	2,268	1,450
March	2,511	1,606
April	2,430	1,554
May	2,511	1,606
June	2,511	1,606
July	2,430	1,554
August	2,511	1,606
September	2,430	1,554
October	2,511	1,606
November	2,430	1,554
December	2,511	1,606

(USEPA, n.d.)

3. SNWA estimate
    a. Average water demand is 10,210 gallons per residence per month
    b. Estimated 24% of water used for toilet flushing as shown in Figure 19
    c. 10,210 gal/res/month * 24% = 2,450 gal/res/month * 12 months *14,500 residences = 426,300,000 gal/year = *1308 AFY*

Figure 19. Estimated percentage of indoor water used by sector in residential homes in the LVV.



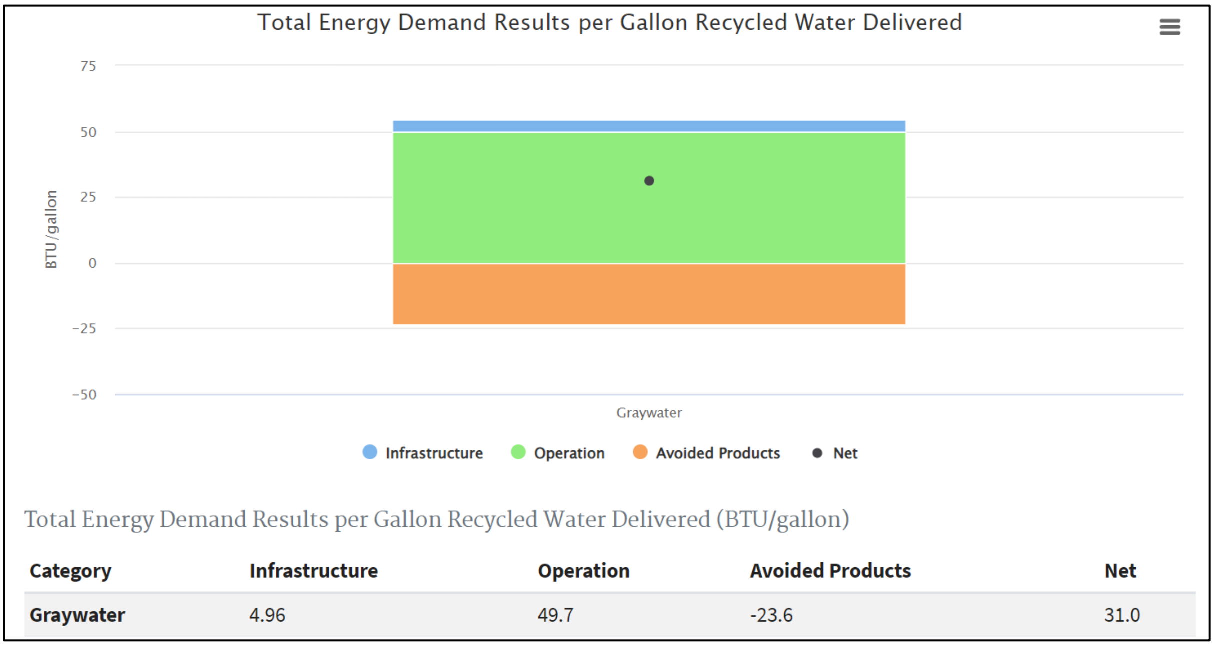
(SNWA, 2019, p. 4)

4. Average of NEWR and SNWA estimates: *2,012.5 gal/res/month* = *1,074.5 AFY*
5. Using the tier 1 consumption water rate set by the LVVWD (rate used for “lifeline” water, or water needed to satisfy indoor uses of small residence) of $1.40 per 1,000 gallons, the estimated annual savings per residence can be calculated (LVVWD, 2022, p. 3.2):
    a. 1,575-2,450 gal/res/month * 12 months / 1000 gallons * $1.40 = *$26-41 per residence per year*
    b. (average) 24,150 gal/residence/year / 1000 gallons * $1.40 = *$33.81 per residence per year*

<u>Change in energy grid burden:</u>

6. Residential
    a. NEWR calculator with the same parameters shown in Figure 17, the average energy demand for a GWR system would be approximately 31 BTU per gallon of recycled water delivered = 0.00908 kWh/gal recycled water delivered, shown in Figure 20
    b. 0.0090852 kWh/gal * 1,575-2,450 gal/res/month * 12 months = *172-267 kWh/res/yr* * 14,500 residences = 2,488,374-3,870,804 ~ *2.5-3.9 mil kWh per year*
    c. Average cost of electricity in LVV $0.12/kWh (USEPA, n.d.)
    d. 172-267 kWh/res/yr * $0.12/kWh = *~$21-32* in annual additional costs

Figure 20. Estimated total energy demand per gallon of recycled water delivered calculated using the EPA's NEWR tool.



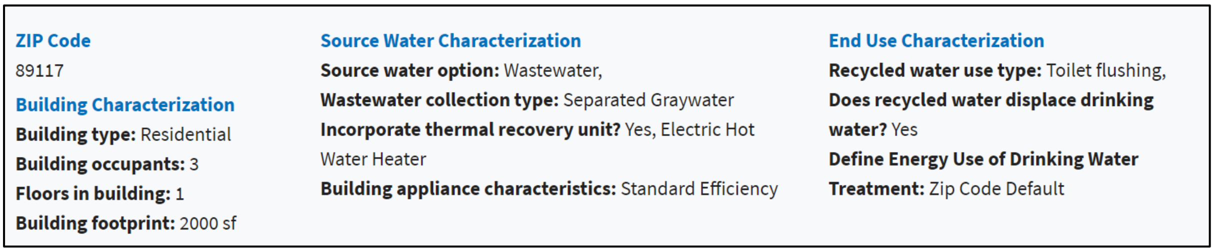
Total Energy Demand Results per Gallon Recycled Water Delivered (BTU/gallon)

Category	Infrastructure	Operation	Avoided Products	Net
Graywater	4.96	49.7	-23.6	31.0

(USEPA, n.d.)

e. Using the same parameters as the first calculation but with the addition of a thermal recovery unit (shown in Figure 21), the average energy demand of the system would become -97.9 BTU per gallon of water delivered (shown in Figure 22), or -0.02869166 kWh per gallon of water delivered
f. 0.02869166 kWh/gal * 1,575-2,450 gal/res/month * 12 months = *542-844 kWh/res/yr* * 14,500 residences = 7,862,949-12,231,255 ~ *7.9-12.2 mil kWh per year saved*
g. Average cost of electricity in LVV $0.12/kWh (USEPA, n.d.)
h. 542-844 kWh/res/yr * $0.12/kWh = *~$65-101* in annual savings

Figure 21. Parameters used for the NEWR calculation with the addition of a thermal recovery unit.



ZIP Code
89117

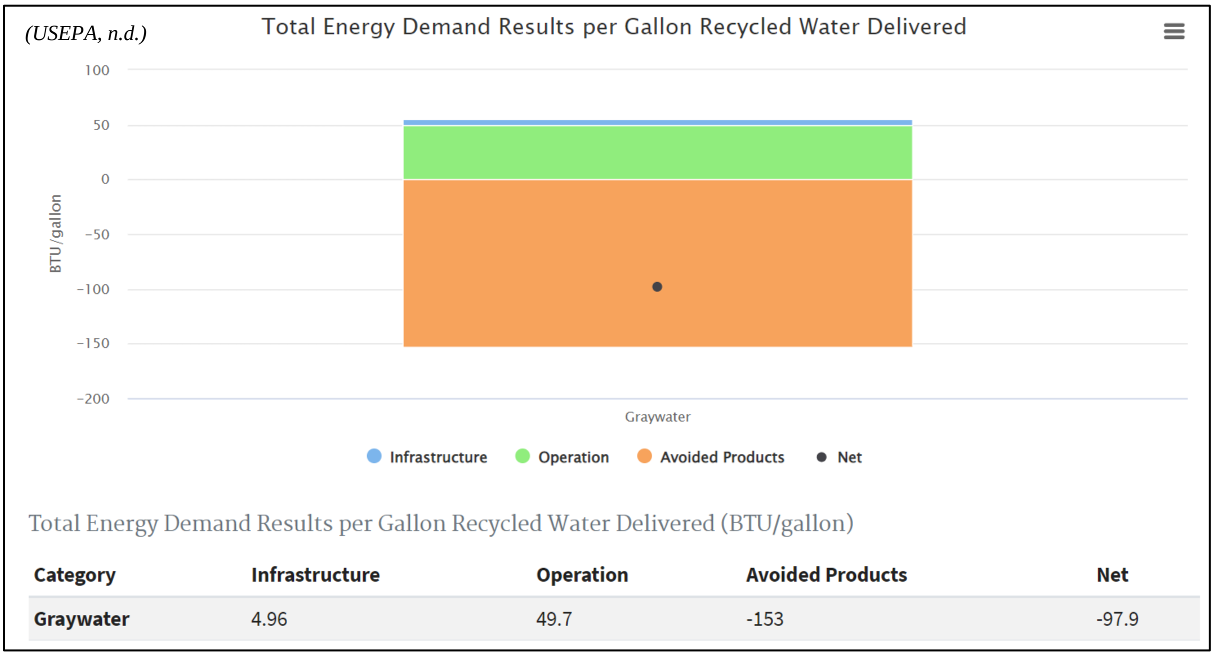
Building Characterization
Building type: Residential
Building occupants: 3
Floors in building: 1
Building footprint: 2000 sf

Source Water Characterization
Source water option: Wastewater,
Wastewater collection type: Separated Graywater
Incorporate thermal recovery unit? Yes, Electric Hot Water Heater
Building appliance characteristics: Standard Efficiency

End Use Characterization
Recycled water use type: Toilet flushing,
Does recycled water displace drinking water? Yes
Define Energy Use of Drinking Water Treatment: Zip Code Default

(USEPA, n.d.)

Figure 22. Estimated total energy demand per gallon of recycled water delivered with a thermal recovery unity incorporated calculated using the EPA's NEWR tool.



Total Energy Demand Results per Gallon Recycled Water Delivered (BTU/gallon)

Category	Infrastructure	Operation	Avoided Products	Net
Graywater	4.96	49.7	-153	-97.9

(USEPA, n.d.)

7. SNWA
    a. Reduction in energy demand is proportional to reduction in water delivered 1,575-2,450 gal/res/month = 0.004833498-0.007518775acre-ft/res/month
    b. Was unable to find energy consumption data for the SNWA, so best estimate is used
    c. Assume it takes 853.8 million kilowatt-hours of electricity per 439,187 acre-feet of water for delivering water (Tavares, 2009)
    d. 853.8 mil kWh/439,187acre-ft water = 1,944 kWh/acre-ft *0.004833498-0.007518775acre-ft/res/month * 14,500 res * 12 month = 1,634,960-2,543,270 kWh/yr = *~ 1.6-2.5 million kWh per year saved*
    e. 1.6-2.5 million kWh/yr * $0.12/kWh = *~$192,000-300,000* in annual savings
8. LVV (net)
    a. Without thermal recovery units: 2.5-3.9 mil kWh per year - 1.6-2.5 million kWh per year = *~900,000-1,400,000 kWh per year increase*
    b. With thermal recovery units: 7.9-12.2 mil kWh per year + 1.6-2.5 million kWh per year = *~9.5-14.7 million kWh per year decrease*

Change in lake mead withdrawals:

9. volume water withdrawn
    a. equal to the reduction in demand identified above, *~841-1308 AFY*
10. return-flow credits
    a. there would be no change in the volume of water returned to Lake Mead

Septic conversion

Reductions in residential indoor water demand:

Likely no change in indoor water demand

Change in energy grid burden:

1. Residential
    a. There would likely be no change in energy demand for individual residences if they were connected to the municipal wastewater system
2. SNWA
    a. Assume 40% of water demand is for indoor use (Figure 23)

Figure 23. Estimated percentage of residential water demand used indoors and outdoors.

(SNWA, 2019, p. 4)

    b. 40% of average residential demand 10,210 gal/res/month = 4,084 gal/res/month
    c. Was unable to find energy consumption data for the SNWA, so best estimate is used
    d. Assume 119.2 million kilowatt-hours of electricity used per 22,501 acre-feet of water to treat and send it back to the lake = 5,297.5 kWh per acre-ft (Tavares, 2009)
    e. 4,084 gal/res/month *14,500 res *12 months = 710,616,000 gal/yr = 2181 AFY
    f. 5,298 kWh/acre-ft * 2181 acre-ft/yr = 11,552,885 kWh/yr = *~11.6 million kWh per year increase*
    g. 11.6 million kWh/yr * $0.12/kWh = *~$1,392,000* in additional annual expenditure
3. LVV (net)
    a. *~11.6 million kWh per year increase*

<u>Change in lake mead withdrawals:</u>

4. volume water withdrawn
    a. likely no change in amount of water withdrawn to meet demand because there would be no change in demand
5. return-flow credits
    a. 40% of average residential demand 10,210 gal/res/month = 4,084 gal/res/month
    b. 4,084 gal/res/month *14,500 res *12 months = 710,616,000 gal/yr = *~2181 AFY*

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