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Artificial Recharge of Groundwater with Recycled Municipal Wastewater in the Pajaro Valley

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This Master's Project

Artificial Recharge of Groundwater with Recycled Municipal Wastewater in the Pajaro Valley

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Abstract

The Pajaro Valley, located along California's Central Coast, is the State's 5th most productive agricultural region. Groundwater is the main source of water for the region, and due to high agricultural demand, the Pajaro Valley is facing groundwater depletion and rapid seawater intrusion. Artificial recharge of recycled water into groundwater aquifers in other locations has proven to be an effective method of mitigating groundwater depletion and seawater intrusion while providing a sustainable water supply. Two methods of artificial recharge with recycled water exist: direct injection and surface spreading (infiltration). Case studies of both methods of recharge were analyzed to determine the benefits, issues and solutions associated with each project type. Direct injection is very effective when used as a seawater intrusion barrier to exert hydraulic pressure on seawater, preventing it from flowing inland. As evidenced by several case studies, clogging can be significant in direct injection wells, but well design and maintenance can effectively address clogging. Surface spreading basins require less engineering and have lower operating costs than direct injection, and they are able to accommodate fluctuating flows of water, unlike direct injection wells. Clogging of the infiltration basin surface is inevitable, as demonstrated by the case studies, but this type of clogging is relatively easy to remedy with regular basin maintenance. Based on the information gained from the case studies, the Pajaro Valley is a feasible basin for both direct injection, in the form of a seawater barrier, and surface spreading operations. A dual project featuring both a seawater barrier directly along the coast and a surface spreading basin further inland is recommended to provide the highest possible defense against saltwater intrusion while taking full advantage of all recycled water production to recharge the groundwater aquifer and supplement water supplies.

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Introduction

Groundwater depletion in the Pajaro Valley is a critical issue that is threatening water supplies for farmers and other users and is resulting in rapidly progressing saltwater intrusion. Recycled water is a largely untapped water source that could be used to protect the critically overdrawn groundwater stores. Artificial groundwater recharge is the most direct way to address groundwater depletion with recycled water. Artificial recharge can be utilized to raise groundwater levels, prevent seawater intrusion, supplement water supplies and remain in long term storage for future use or drought mitigation.

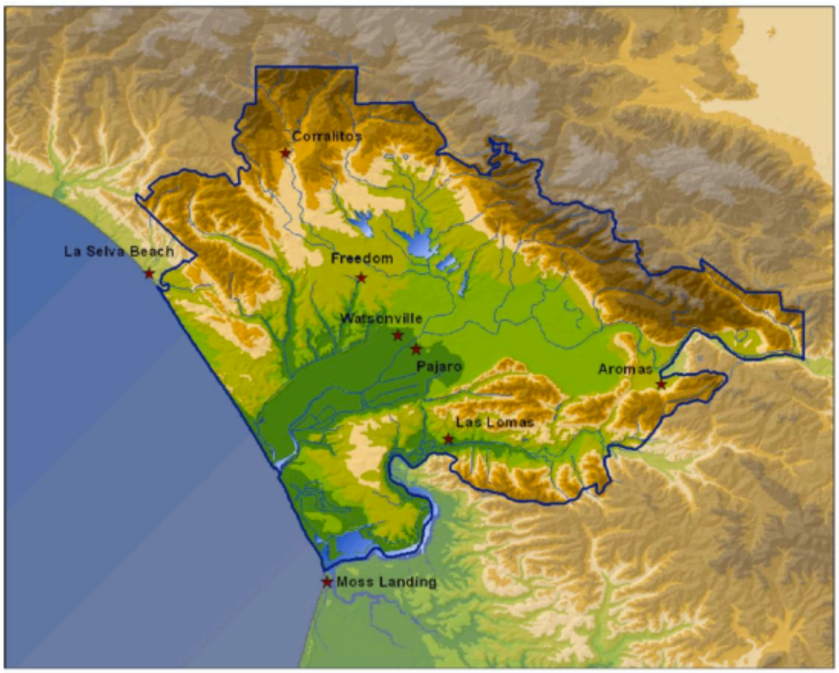

Figure 1: Pajaro Valley Groundwater Basin Boundary Map

(Levy and Christian-Smith, 2011)

The Pajaro Valley Groundwater Basin (Fig. 1) serves as the primary water source for a predominantly agricultural stretch of land along the California Central Coast. The basin spans approximately 310 square kilometers, and includes Northern Monterey County, Southern Santa Cruz County and a small part of San Benito County (Pajaro Valley Water Management Agency, 2014; Pajaro Valley Water Management Agency, 2012). Agricultural fields make up thirty percent of the land within the Pajaro Valley, and the agricultural sector accounts for eighty-five percent of the water demand in the Pajaro Valley Basin (Pajaro Valley Water Management Agency, 2012; Levy and Christian-Smith, 2011). Municipalities in the Pajaro Valley, of which

Watsonville is the largest, also rely on groundwater supplies (Martin, 2014). Existing sources of basin recharge include rainfall infiltration and seepage from surface streams and irrigation water (Pajaro Valley Water Management Agency, 2014). However, infiltration only occurs in certain locations where soils are permeable (relatively impermeable clay soils are characteristic of the region) or where the groundwater aquifer lies close to the ground surface (Pajaro Valley Water Management Agency, 2014). These recharge sources have been unable to keep up with demand, and nearly twice as much water is pumped out of the groundwater basin than is being recharged each year (Levy and Christian-Smith, 2011).

In addition to farmers and other water users being faced with dwindling water supplies, overdraft of the basin has allowed for saltwater intrusion as the basin empties and drops below sea-level (Levy and Christian-Smith, 2011). As the groundwater becomes more saline, it is less available for irrigation, especially for the valuable salt-intolerant crops (e.g., strawberries) that are abundant in the region (Levy and Christian-Smith, 2011; Martin, 2014). Saltwater has already pushed almost 5 kilometers inland into the Pajaro Valley Groundwater Basin (Fig. 2), and continues to intrude at a rate of 30 to 76 meters per year (Martin, 2014). The Pajaro Valley is the fifth most productive agricultural area in California, and agriculture is imperative to the economy of the region, so it is important that the groundwater be sustainably managed to ensure that farmlands remain viable (Pajaro Valley Water Management Agency, 2012).

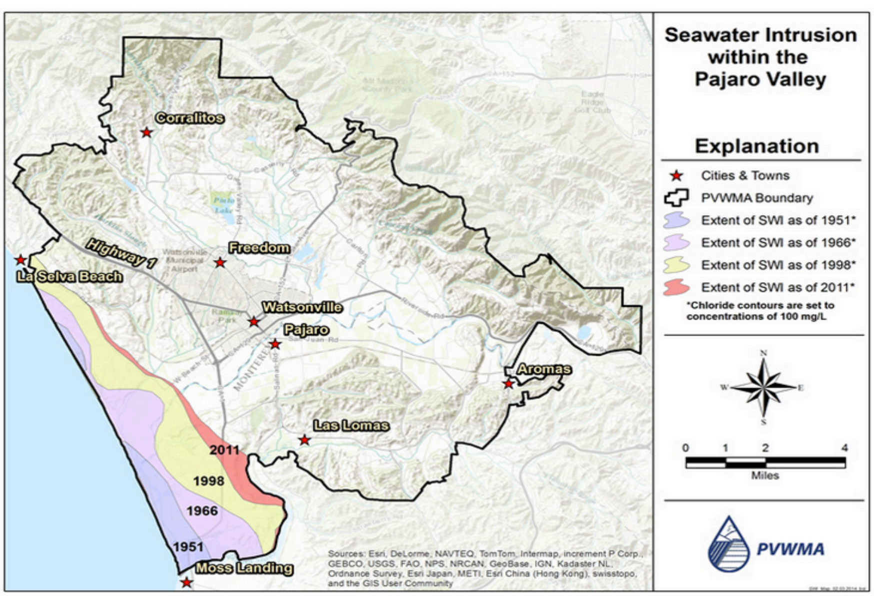

Figure 2: Seawater Intrusion in the Pajaro Valley

(Pajaro Valley Water Management Agency, 2014)

Two methods of artificial recharge with recycled water that could be feasible for the Pajaro Valley Groundwater Basin will be explored in this project: direct injection and surface spreading. Direct injection is a process in which recycled municipal wastewater (which has undergone tertiary and advanced treatment) is injected directly into the groundwater aquifer via injection wells (Johnson, 2009b). The water then remains in the groundwater aquifer until it is pumped out for use. The injection wells can also be used to directly prevent saltwater intrusion by acting as a seawater barrier. To form a seawater barrier, injection wells are lined up along the divide between saltwater and freshwater, and the injected fresh water takes up the space that the saltwater would otherwise encroach on (Johnson, 2009b).

Surface spreading entails pumping recycled municipal wastewater (in most cases tertiary treated) to a recharge pond where it percolates through the soil into the groundwater basin (Johnson, 2009a). Surface spreading takes advantage of the groundwater basin for storage with the added benefit of natural in-aquifer treatment processes, which provides multiple benefits over the current proposal of building new above-ground recycled water storage tanks adjacent to the water treatment facility (Pajaro Valley Water Management Agency, 2014). The Pajaro Valley Water Management Agency recently considered the possibility of pumping recycled water to Harkins Slough, an existing percolation pond that currently only captures surface runoff (Pajaro Valley Water Management Agency, 2014). The agency removed this option from consideration because the wells at Harkins Slough are in need of repair and upgrade, which must be done before any new projects can be implemented at the site (Pajaro Valley Water Management Agency, 2014). However, Harkins Slough serves as a potential site for a combination of recycled water and surface water infiltration.

The Pajaro Valley's Coastal Distribution System distributes recycled water to agricultural lands for irrigation (Pajaro Valley Water Management Agency, 2014). Irrigation with recycled water has been very successful; however, one major downfall is that the supply of recycled water and the demand for irrigation water don't always match up (Pajaro Valley Water Management Agency, 2014). The demand for water in the daytime exceeds the amount of water that can be produced by the recycled water facility, and at nighttime the opposite is true (Fig. 3) (Pajaro Valley Water Management Agency, 2014).

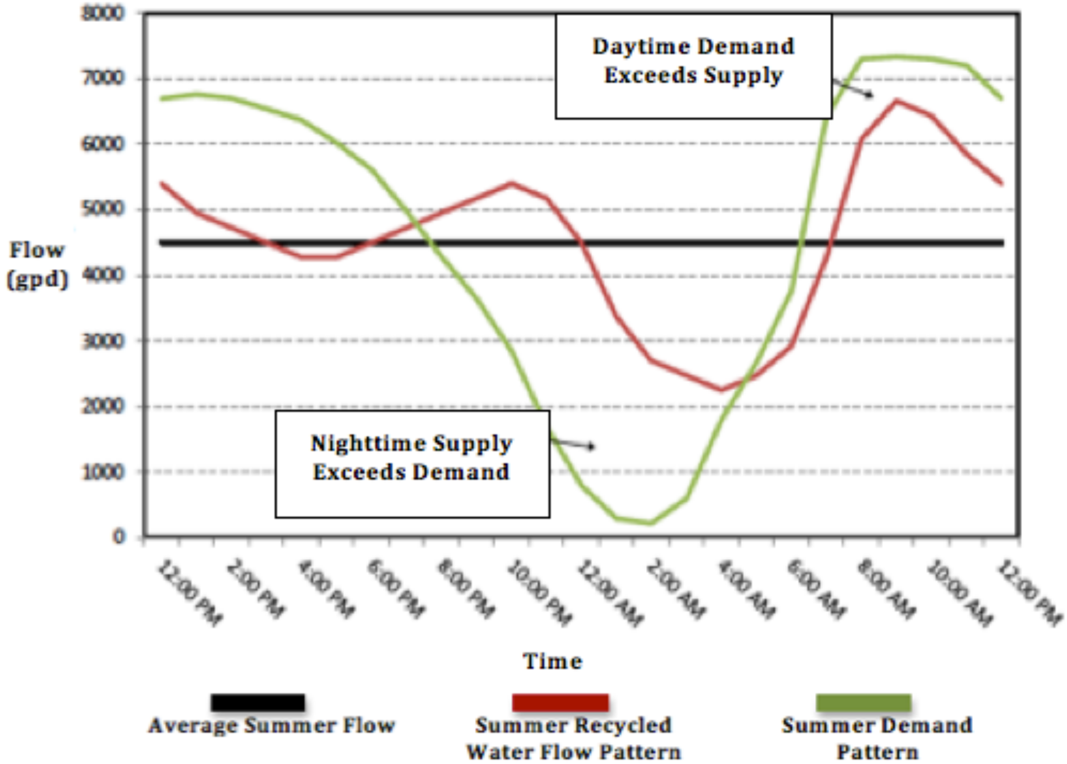

Figure 3: Recycled Water Supply/Demand Gap in the Pajaro Valley During the Summer

(Figure adapted from Pajaro Valley Water Management Agency, 2014)

Because there is very little storage at the facility, excess secondary treated water is discharged into Monterey Bay (Pajaro Valley Water Management Agency, 2014). This is a waste of valuable water supply that could be recycled and utilized, and is an important area of opportunity to increase the water supply; my research will consider how to leverage this untapped water source by establishing an understanding of how recycled water can be fully utilized to prevent groundwater depletion through artificial recharge.

At issue here is the question of how recycled water can be utilized for artificial recharge in the Pajaro Valley. To answer this question, I will analyze case studies for both direct injection and surface spreading, and then apply the lessons learned from these case studies to determine feasibility and implementation recommendations for the Pajaro Valley. While I will be comparing the advantages, disadvantages, costs and other feasibility measures of surface spreading and direct injection, I will compare implementation of these projects to the costs and implications of allowing groundwater depletion to progress. This approach allows me to demonstrate that while the costs for these projects are high, the costs of allowing groundwater depletion to continue is detrimental, and that these recycled water projects are ultimately an investment in the continued economic viability of the Pajaro Valley. In the section below, I will begin with an overview of how recycled water can be used for groundwater recharge.

Recycled Water for Groundwater Recharge

Recycled water is gaining attention as an alternative water source as water managers and policy makers try to find ways to alleviate water scarcity. It is becoming a general consensus that the technology to produce recycled water has become so advanced that wastewater is now a valuable resource, not a liability (Asano and Cotruvo, 2004). Non-potable use of recycled water (e.g., irrigation) has been in practice for a long time, and the attention is now shifting to indirect potable reuse projects including groundwater recharge (Amy et al., 2011). Indirect potable reuse is the use of recycled water for potable purposes after it has passed through an environmental buffer, such as a groundwater aquifer (as opposed to direct potable reuse, which relies on an engineered barrier) (Amy et al., 2011). Recycled water has been used for groundwater recharge in California for over 50 years, during which time numerous studies have concluded that recycled water is safe to use for groundwater recharge (Sanitation Districts of Los Angeles County, 2011).

Recycled Water Treatment Process

Wastewater undergoes extensive treatment prior to being utilized for groundwater recharge, although treatment processes and technology vary by location. The treatment process for recycled water in the Pajaro Valley begins at the Watsonville Wastewater Treatment Facility with primary sedimentation, biofiltration, and aeration to remove solids, and secondary clarification to remove biological oxygen demand (City of Watsonville, 2010; Pajaro Valley Water Management Agency, 2016). From there, the water is sent to the on-site recycled water facilities where it undergoes tertiary treatment and disinfection (City of Watsonville, 2010; Pajaro Valley Water Management Agency, 2016). At this point, the recycled water is stored in above ground storage where it awaits distribution (Pajaro Valley Water Management Agency, 2016). It is important to note that this last stage of storage and distribution points to two of the major limiting factors in the Pajaro Valley's recycled water operations. First, the above ground storage only has the capacity to hold one million gallons of water at a time, whereas artificial recharge would not place a limit on the amount of recycled water that can be produced due to limited storage capacity (Pajaro Valley Water Management Agency, 2016). Second, distribution currently only includes agricultural irrigation customers which, as previously mentioned, can only utilize half of the potential recycled water production due to the alternating demand for irrigation water and supply of recycled water (Pajaro Valley Water Management Agency, 2014).

The level of treatment for recycled water generally depends on the type of groundwater recharge project. Water that is to be utilized for direct injection usually undergoes advanced treatment at the treatment facility (in California, this is a requirement), while water that is to be used for surface spreading can rely on soil-aquifer treatment (a natural filtration process that purifies the water) in-lieu of advanced treatment at a treatment facility (Johnson, 2009b). Table 1 details treatment requirements for direct injection and surface spreading of recycled water.

Table 1: Treatment Required for Recycled Water Recharge Projects

Water Reuse Application	Treatment Level
Groundwater Recharge – Surface Water Spreading	Preliminary, primary, secondary (sometimes advanced secondary), nutrient removal, tertiary, disinfection
Groundwater Recharge – Direct Injection	Preliminary, primary, secondary (sometimes advanced secondary), nutrient removal, tertiary, advanced, and disinfection

(Table recreated from Anderson et al., 2010)

Health and Regulatory Considerations

With any type of recycled water groundwater recharge project there are public health concerns that must be addressed. The main constituents of concern are pathogens, organic matter, trace toxic chemicals, or unregulated contaminants of emerging concern (such as endocrine disrupters, pharmaceuticals and personal care products) (Drewes et al., 2003; Asano and Cotruvo, 2004).

Although soil-aquifer treatment has been proven to be very effective, it is a process that requires a certain amount of time and travel distance for adequate treatment (Johnson, 2009b). This raises some concern as to whether the residence times of recycled water in the groundwater basin are sufficient to ensure the water is safe before it is withdrawn for potable use (Johnson, 2009b). The practice of locating projects far from potable uptake wells, both in terms of time and space, allows for a greater residence time during which soil-aquifer treatment and dilution with native groundwater takes place (Asano and Cotruvo, 2004). In California, regulations require a 500-foot distance and a minimum 6-month basin retention time before water reaches potable use uptake wells from groundwater recharge operations (Anderson et al., 2010; Johnson, 2009b).

Travel times are specific to each groundwater aquifer, dependent on the characteristics of the aquifer (Johnson, 2009b). Because these characteristics cannot be precisely predicted or calculated, new projects must find a method to demonstrate travel time (Johnson, 2009b). Tracers, which are not naturally occurring in the aquifer and are therefore easily detectable, are utilized to accurately demonstrate travel times from recharge locations to withdrawal sites (Johnson, 2009b). This method is accepted by the California Department of Public Health, and required travel times are longer if the method used does not have the same high confidence level as the tracer method (e.g., computer models which require many assumptions and have other limitations) (Johnson, 2009b). The longer required travel times provide a safety net to account for the margin of error (Johnson, 2009b).

It has been found that advanced treatment processes (e.g., nanofiltration, reverse osmosis, membrane processes, advanced oxidation) effectively reduce pharmaceutical and endocrine disrupting compound concentrations (Clara et al., 2005; Huber et al., 2003; and Snyder et al., 2007 as cited in Benotti and Snyder, 2009). Benotti and Snyder (2009) conclude that pharmaceuticals and endocrine disruptors should not be cause for dismissal of a recycled water recharge project as most compounds do not persist for long in the groundwater aquifer, and the few that do (e.g., carbamazepine and primidone, which are very persistent) can likely be treated once they are identified (Benotti and Snyder, 2009).

There are three agencies that regulate recycled water projects in California: 1) the State Water Resources Control Board (administers water rights and protects water supplies), 2) the California Department of Public Health (creates public health requirements for recycled water projects and reviews all plans), and 3) the nine regional water quality control boards (protect and enhance water supplies) (Anderson et al., 2010). Local agencies, such as water districts, can develop their own public health policies, but they must be more rigorous than the Department of Public Health's requirements (Anderson et al., 2010).

Recycled water legislation has been developing very quickly in California, with the intention of promoting recycled water projects by streamlining the permitting process. The California Water Code, California Health and Safety Code, California Code of Regulations Title 22, and the Recycled Water Policy (State Water Board Resolution 2013-0003) contain the State's regulations pertaining to recycled water (Anderson et al., 2010; State Water Resources Control Board, 2013). While discussing the details of each policy related to recycled water would be outside the scope of this project, details of Title 22 and the Recycled Water Policy, which most directly focus on recycled water utilization, will be provided for context of California's regulatory climate pertaining to recycled water.

The California Code of Regulations Title 22 includes approved uses of recycled water and pertinent requirements for implementation (Anderson et al., 2010). In 2014, Title 22 was amended by the Department of Public Health to include regulations specific to groundwater recharge with recycled water, including treatment requirements (disinfected tertiary treatment plus additional treatment), extraction well citing requirements, monitoring frequency and location parameters and other criteria to ensure that public health is protected (Anderson et al., 2010; California Department of Public Health, 2016).

Adopted in 2009, the Recycled Water Policy details permitting requirements for projects that utilize recycled water, with a goal of increasing the use of recycled municipal wastewater in California (Anderson et al., 2010; State Water Resources Control Board, 2013). This policy provides direction for the Regional Water Quality Control Boards and the public about recycled water project permitting criteria (State Water Resources Control Board, 2013). Although the criteria are designed to streamline recycled water project permitting, groundwater recharge projects still require site-specific review because there are so many variables that are unique to each basin (State Water Resources Control Board, 2013). However, this policy might speed up the process somewhat by providing general permitting criteria and information, allowing the Regional Water Quality Control Boards to focus more on location-specific issues and rely on the Recycled Water Policy for general criteria (State Water Resources Control Board, 2013). The Recycled Water Policy strongly advocates for increased recycled water use, declaring that not using available recycled water is wasteful and unreasonable (State Water Resources Control Board, 2013). This policy also notes that $1 billion in state and federal funding for projects that are pursuant to the Recycled Water Policy may be available over the next five years as a result of water industry and environmental community advocacy and support (State Water Resources Control Board, 2013). The Recycled Water Policy also states that recycled water projects are given priority in funding from the California Department of Water Resources as mandated by the State Water Resources Control Board (State Water Resources Control Board, 2013).

New regulations from both the California Department of Public Health and the State Water Resources Control Board require monitoring for constituents of emerging concern including endocrine disruptors, pharmaceuticals and personal care products, and tentatively identified compounds (Dadakis et al., 2011; State Water Resources Control Board). Because the specific contaminants of emerging concern vary between groundwater basins due to source water characteristics, treatment processes, basin hydrogeology, land use and other local concerns, the monitoring plans should be tailored to the site (Dadakis et al., 2011).

In addition to recycled water legislation, the Sustainable Groundwater Management Act of 2014 has also been a driving force in the formation of new innovative projects to sustainably manage groundwater (Association of California Water Agencies, 2014). The Sustainable Groundwater Management Act requires sustainability plans for groundwater basins and provides framework for the sustainable management of groundwater (Association of California Water Agencies, 2014).

Because it is very difficult to remediate a groundwater basin if it is contaminated, extensive measures must be taken to protect the health of the groundwater aquifer (Asano and Cotruvo, 2004). In California, regulations pertaining to recycled water projects are very stringent and account for a margin of error to ensure that public health is protected.

Why Recycled Water?

Groundwater recharge with recycled water is an attractive option for many reasons. It is more publically acceptable than direct potable reuse because of the psychological value of the environmental buffer (Amy et al., 2011). Recharge of recycled water also takes advantage of a natural storage, treatment and distribution system that is protected from evaporation, biological growth, and pollution (Asano and Cotruvo, 2004). Recycled water is reliable and drought-proof, it diversifies water portfolios allowing flexibility in water supply management, and it can improve groundwater quality issues such as salinity through dilution of the groundwater or by forming a hydraulic barrier against seawater intrusion (Amy et al., 2011; City of Tucson, 2013;

Herndon and Markus, 2014). Of particular importance to the Pajaro Valley, recycled water has the ability to match the supply of recycled water with the demand for agricultural irrigation by storing it in the groundwater basin, as opposed to surface storage, which has not had the capacity to accommodate fluctuating supply and demand (Dillon et al., 2006).

The Pajaro Valley Water Management agency considered several other new sources of water while drafting their Basin Management Plan Update, which was finalized in 2014. Importing Central Valley Project water was deemed politically unacceptable because the region is very proud of their water independence, and this option would have been expected to receive a high level of resistance from the public (Pajaro Valley Water Management Agency, 2014). Other import sources, such as nearby groundwater basins or surface water sources, were also ruled out due to low yield, expense or regulatory uncertainty (Pajaro Valley Water Management Agency, 2014). The construction of dams for winter recycled water storage reservoirs was also considered, but was found to be cost prohibitive (Pajaro Valley Water Management Agency, 2014). Desalination of seawater was the highest-yielding option with a potential of producing 7,500 acre-feet per year, but was found to be far too expensive at a cost of $228 million (Pajaro Valley Water Management Agency, 2014). Decreasing demand for groundwater by fallowing farmland is both politically and economically unacceptable (Pajaro Valley Water Management Agency, 2014). Construction of additional above ground storage was approved in the Basin Management Plan Update at a cost of between $2.8 and $6.4 million depending on project size (capacity of the final project will be between 250 and 750 acre-feet per year) (Pajaro Valley Water Management Agency, 2014). The Pajaro Valley Water Management Agency also considered artificial recharge for their Basin Management Plan Update, but decided to focus on other options such as surface water capture and recharge for the time being, with the thought that artificial recharge could be reconsidered in coming years (Pajaro Valley Water Management Agency, 2014). However, the drought has been persistent over the past few years, which may make recycled water recharge worth exploring sooner rather than later.

The cost of water recycling depends on the level of treatment and infrastructure required, but it generally ranges from $300 to $1,300 per acre-foot (Sheehan, 2009). This cost is higher than a few other sources of water such as stormwater capture and reuse (approximately $350 per acre-foot) or conservation and urban efficiency (approximately $210-$500 per acre-foot) (Los Angeles County Economic Development Corporation et al., 2008; Legislative Analyst's Office, 2008). However, recycled water is very cost-competitive compared to other high-yield, reliable water sources such as surface reservoir storage ($10,000 per acre-foot according to CALFED) or desalination (approximately $4,000 per acre-foot according to the Legislative Analyst's Office) (Sheehan, 2009; Legislative Analyst's Office, 2008). The cost to treat recycled to the highest level possible is approximately $1,000 per acre-foot, and the cost to store it underground is approximately $580 per acre-foot, bringing the total cost of groundwater recharge with recycled water to almost $1,600 per acre-foot (Los Angeles County Economic Development Corporation et al., 2008). These estimated costs are highly dependent on several factors, including annual yield (projects with higher annual yield generally have lower costs per acre-foot), construction costs, and level of recycled water treatment (Los Angeles County Economic Development Corporation et al., 2008). Table 2 below details the costs, pros and cons associated with various new water sources.

Table 2: Costs, Pros and Cons Associated With New Water Sources

Project Type	Cost/AF	Pros	Cons
Conservation and Urban Efficiency	$210 to $500	Reliable, Immediate Implementation, Low Risk, Environmentally Beneficial, Low Energy/GHGs	Limited Yield
Stormwater Capture/Reuse	$350	Variable Reliability (Dependent on Rain/Climate), 3-5 Years for Implementation, Contaminant Removal from Urban Runoff, Low Energy/GHGs	Limited Yield, May Divert Water From Streams/Environment
Seawater Desalination	$1,000 to $4,000	Most Reliable, Drought-Proof, Very High Yield (Limited Only by Energy and Cost)	6-10 Years for Implementation, High Energy/GHGs and Cost, Environmental Concern, Negative Public Perception (Coastal Site Selection, NIMBY, Environmental Issues)
Surface Storage	$760 to $10,000	Recreation, Takes Advantage of Stormwater Runoff	Reliability Dependent on Proper Management, 10-20 Years for Implementation, High Cost, High Energy/GHGs (to Pump Water to Reservoir), High Risk (Funding Constraints or Environmental Concerns Could Cause Project Abandonment), Diverts Environmental Water
Recycled Water (Not Including Recharge Operations)	$300 to $1,300	Very Reliable (Consistent Flows, Not Dependent on Rain/Climate), High Yield, Environmentally Beneficial (Prevents Demand for Environmental Water)	6-10 Years for Implementation, Risk of Negative Public Perception of Indirect Potable Reuse, Moderate Energy/GHGs (for Treatment, Conveyance)
Groundwater Recharge of Recycled Water	$1,000 to $1,600 (Including Treatment)	3-10 Years for Implementation, High Yield, Very Reliable (Drought Proof), Environmentally Beneficial (Prevents Use of Environmental Water and Groundwater Depletion)	High Cost, Moderate Energy/GHGs (Treatment, Conveyance, Recharge Operations), Risk of Negative Public Perception (Indirect Potable Reuse)

Data Compiled From: Legislative Analyst's Office, 2008; Los Angeles County Economic Development Corporation et al., 2008; Pajaro Valley Water Management Agency, 2014; Sheehan, 2009

Current Development of Recycled Water in the Pajaro Valley

Currently, 4,000 acre-feet of recycled water is produced in the Pajaro Valley every year (although only half is utilized), and approximately 3,200 acre-feet of wastewater is not recycled and is discharged to the ocean (City of Watsonville, 2010). This represents an opportunity for future expansion of recycled water production, and large projects to utilize this water, such as artificial groundwater recharge, need to be put in place. The City of Watsonville has been working with the Pajaro Valley Water Management Agency to allocate the existing supply of recycled water, and agricultural irrigation and groundwater recharge have been decidedly the best uses of this water (City of Watsonville, 2010). However, a lot of focus in recent plans has been on capturing and recharging surface runoff (Pajaro Valley Water Managemet Agency, 2014). This may have seemed like a viable option before the recent drought, but climate change and the the importance of water reliability should be cause to reconsider recycled water as a more feasible option. Projects designed to utilize surface runoff have been operating well below capacity during the drought, which not only leads to a shortage of water compared to forecasted availability, but it causes an increase in cost per acre-foot because the expensive treatment facility and operations are not producing as much water as planned. This is an excellent example of the importance of a drought proof, resilient water supply such as recycled water. Although initial capital requirements might be high for recycled water, the output is very predictable and costs per acre-foot can be accurately predicted.

There are a few surface spreading projects in operation in the Pajaro Valley, but these projects all use surface runoff rather than recycled water for recharge (Pajaro Valley Water Management Agency, 2014). The amount of recharge from these surface flow recharge projects is very limited and dependent of weather conditions. For example, the Harkins Slough Recharge Facilities only yielded 220 acre-feet of water for recovery and irrigation delivery in 2013 (Pajaro Valley Water Management Agency, 2014). Sending recycled water to a few of the existing spreading basins was an option that was considered for the Basin Management Plan Update, but it was decided that incorporating recycled water into the spreading basins would preclude the planned upgrades of Harkins Slough for optimization of surface flow infiltration (for an increase of 500-1000 acre-feet per year of recharge), which is estimated to cost between $2.2 and $5.8 million (Pajaro Valley Water Management Agency, 2014). Direct injection was also considered in the form of winter aquifer storage and recovery, which stores recycled water during the winter when irrigation demand is low and recovers the water when demand rises again (Pajaro Valley Water Management Agency, 2014). This project, which could store an estimate 3,200 acre-feet at a cost of approximately $47 million, was considered feasible, but will not be revisited for implementation for another ten to twenty years because lower cost (surface water) projects are being explored first (Pajaro Valley Water Management Agency, 2014).

One of the best justifications for a large-scale recycled water project in the Pajaro Valley over other new water sources is the fact that recycled water is already being produced and transported (via the Coastal Distribution System) in the Pajaro Valley, so the treatment facilities and some conveyance infrastructure already exists. This reduces the required start up costs to implement a recycled water groundwater recharge project.

Two Methods of Artificial Groundwater Recharge with Recycled Water

Direct Injection

Overview

Direct injection is a method of artificial groundwater recharge that entails injecting high-quality water into a confined groundwater aquifer (Petersen and Glotzbach, 2005). The injected water can be stored in the aquifer to supplement groundwater supplies and prevent depletion. Direct injection wells can also be utilized as a seawater barrier, where injection wells are lined up along the coast at strategic points (Herndon and Markus, 2014). The injected water exerts hydraulic pressure on the incoming saltwater, preventing it from flowing inland and harming freshwater supplies (Herndon and Markus, 2014). Direct injection is ideally suited for locations where soils have inadequate permeability or are not suited for trenching (for surface recharge ponds), available land is limited, or where recharge of a lower aquifer is needed (Bouwer, 2002).

Three case studies of direct injection systems that utilize treated municipal wastewater will be discussed in this section. The first case study is Orange County, California, where the main objective is to prevent seawater intrusion through construction of a seawater barrier of direct injection wells, which makes it an excellent case study for its applicability to the Pajaro Valley. The Orange County project was also selected because it is one of the oldest direct injection projects, and after recent improvements it is the largest direct injection operation in the world (Deshmukh and Wehner, 2009). The second case study is Clearwater, Florida, which aims to prevent groundwater depletion of the Floridian Aquifer. This is also directly applicable to the

Pajaro Valley, which is experiencing devastating rates of groundwater depletion throughout the basin. The last case study is South Australia, which is also intended to prevent groundwater depletion, but this case study was selected as an example of a project where injection water is not treated to a high standard.

Case Study 1: Orange County, California

The Orange County Water District's Talbert Seawater Barrier began operation in 1976 once construction of Water Factory 21, which provided the recycled water for injection, was complete (Herndon and Markus, 2014). Water Factory 21 was the first recycled water treatment facility in California permitted to inject recycled water into an aquifer that is used for potable water supplies (Herndon and Markus, 2014). At this time, the Talbert Seawater Barrier included 109 injection wells at varying depths (Herndon and Markus, 2014). By 1990, it was determined that the barrier had to be expanded to keep up with groundwater pumping, as increased chloride concentrations were seen inland (evidence of seawater intrusion) (Herndon and Markus, 2014). Many years of planning followed, and it was determined that Water Factory 21 would have to be replaced because it would not be able to accommodate the expansion (Herndon and Markus, 2014).

The new Groundwater Replenishment System (GWRS), which was completed in 2008, is the largest recycled water groundwater injection project in the world (Deshmukh and Wehner, 2009). Figure 4 shows the layout of the Talbert Seawater Barrier, and differentiates between the older injection wells and those that are newly constructed. The GWRS still recharges the Talbert Gap Seawater Intrusion Barrier through direct injection wells, and the remainder of the recycled water is sent to surface spreading basins where it infiltrates into the groundwater basin (the surface spreading component of the GWRS will be discussed in a later section) (Dadakis et al., 2011).

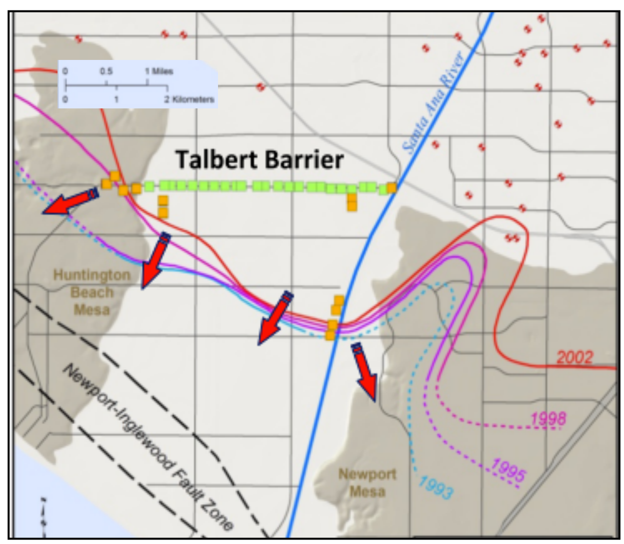

Figure 4: Layout of the Talbert Seawater Intrusion Barrier

(Herndon and Markus, 2014)

Original Injection Well
Newer Injection Well
Large-System Production Well
250mg/L Chloride Concentration

Prior to injection, the recycled water for the GWRS undergoes microfiltration, reverse osmosis, and a UV light advanced oxidation process (which kills microorganisms and oxidizes organic compounds) to ensure that the water meets or exceeds water quality standards (Fig. 5) (Dunivan et al., 2010). The California Department of Public Health and State Water Resources Control Board require that potable use wells are not within 2000 feet or a one-year travel time from injection wells (Dadakis et al., 2011). In order to ensure compliance, the Orange County Water District used groundwater flow and particle transport modeling to determine site suitability for injection wells (Dadakis et al., 2011).

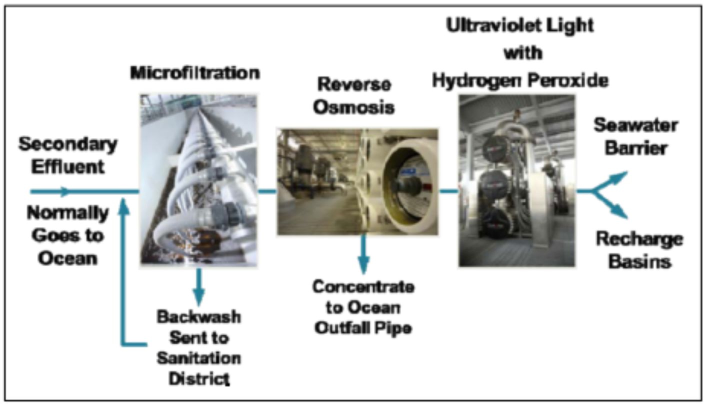

Figure 5: The GWRS Treatment Process

(Herndon and Markus, 2014)

Initially, injected water was comprised of 75% recycled water and 25% imported (purchased) fresh water (Dadakis et al., 2011). In 2009, once the Orange County Water District had proven that quality standards were met and that the recycled water posed no threat to groundwater supplies or public health, the California Department of Public Health and the Regional Water Quality Control Board approved the use of 100% recycled water for the GWRS (Dadakis et al., 2011). This was the first approval of 100% recycled water utilization by a groundwater recharge reuse project in California (Dadakis et al., 2011).

This project has been extremely successful, and as a result of this success, the Orange County Water District expanded the project in 2011 to output and utilize an additional 30 MGD of recycled water (for a total of 100 MGD) (Dadakis et al., 2011). During the expansion process, extensive studies were completed to assess the successes and areas for improvement from the original project, and to test the new facilities.

One lesson learned from the initial operation of the GWRS was that because the highly treated wastewater lacks minerals, it is corrosive and could be destructive to the pipelines and other infrastructure (Dunivan et al., 2010). Decarbonation of the water and the addition of alkaline calcium oxide (lime) has prevented such damage to the GWRS by increasing the pH of the water (Dunivan et al., 2010).

Another issue encountered was clogging of the injection wells. While testing the new wells, it was found that the pressure needed to inject the water increased after only three months, likely meaning that the injection wells were becoming clogged (Deshmukh and Wehner, 2009). The clogging was found to be caused by fine particles that were accumulating on the well filters, and because these particulates were accumulating on the filters, the staff could conclude that they were also depositing on other commonly clogged locations including the injection well screens and the gravel pack that surrounds these screens (Fig. 6) (Herndon and Markus, 2014). The clogging was suspected to be a result lime scale, but further tests were inconclusive and it was found that a reduction in lime did not reduce clogging (Deshmukh and Wehner, 2009; Dunivan et al., 2010).

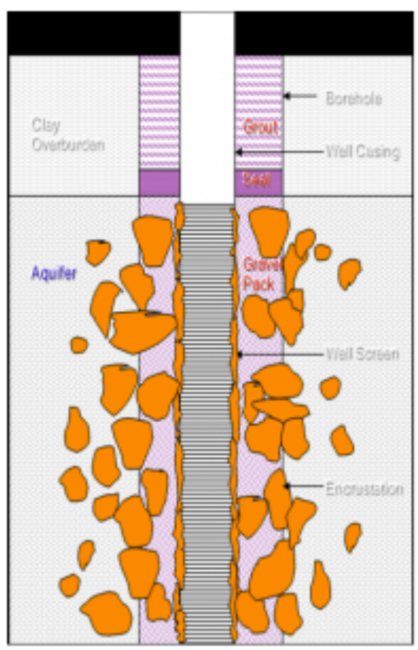

Figure 6: Schematic of the Common Clogging Mechanisms in Direct Injection Systems

(Brotcke Well & Pump, 2016)

In order to produce the additional 30 MGD of recycled water needed for the expansion of the GWRS, a new water treatment facility was needed (Dunivan et al., 2010). This treatment facility (the Steve Anderson Lift Station) featured many design improvements, including flow equalization, enhanced lime stabilization methods, more pumps and superior electronics (Dunivan et al., 2010). These improvements were based on observations and studies from operation of the initial GWRS treatment facility. The biggest advancement was the ability to accommodate fluctuating flows of incoming water (Dunivan et al., 2010). Without these flow controls the facility would have to run at a steady flow, and because the facility is going to operate 24 hours/day this would mean that flows would be set to the lowest flows (night flows dip to 25 MGD) (Dunivan et al, 2010). The flow control systems include pressure-reducing valves, flow meters, flow-control valves, and monitoring to provide data on water levels and pressure for the purpose of adjusting flow (Herndon and Markus, 2014). A large component of the flow controls lies in operation of the facility and staff training because these new processes require precise timing when it comes to turning treatment processes on and off (Dunivan et al., 2010).

The injection wells were also improved to make well redevelopment more efficient (Herndon and Markus, 2014). Well redevelopment (the disassembly and reassembly of wellhead pipes to clear them of sediments) is very costly on the original wells, so this process is only completed every other year (Herndon and Markus, 2014). However, the new wells are designed with redevelopment in mind; tubes on the well heads prevent the need for disassembly, and redevelopment can now be performed on a monthly basis and prevent serious (and costly) clogging issues (Herndon and Markus, 2014).

The Orange County Water District had incorporated expansion plans into their original GWRS design, so the original facilities were able to easily accommodate the new piping, pumps and electrical infrastructure, an incorporation was easy because all of the systems are modular (Dunivan et al., 2010). As with the original project, several design firms (in different areas, e.g., civil design, electrical) were contracted to work under one lead designer to prevent overloading of work to one firm (Dunivan et al., 2010). The designers and engineers worked closely with the project operation staff to ensure that the staff could give their input on what they had learned during the first two years of operation to help guide the design of the expansion (Dunivan et al., 2010).

The same manufacturers and suppliers were used for the expansion for the purpose of uniformity with original equipment (Dunivan et al., 2010). Because the new parts would match the old ones, two different stocks would not have to be maintained (which could result in confusion) (Dunivan et al., 2010). The original treatment equipment was also already proven to meet regulatory requirements, so using the same equipment avoided the need to test the capabilities of new equipment (Dunivan et al., 2010).

Case Study 2: Clearwater, Florida

The City of Clearwater is still in the testing phase for a recycled water direct injection project. Although this project is not fully operational, there is a lot that can be learned from this case study. The City has already completed their feasibility studies and development process, and is currently operating the pilot project. This case study provides a blueprint for feasibility analysis and planning of a direct injection project, including an excellent example of an outreach program that effectively garners community support for direct injection operations.

Approximately 57% of the potable water produced in Clearwater comes from the Upper Floridian Aquifer (Wiley et al., 2013). A high rate of withdrawal coupled with limited recharge has led to groundwater depletion in the region (Wiley et al., 2013). In addition to threatening water supplies, groundwater depletion puts the remaining groundwater at risk because the aquifer that lies directly beneath the Upper Floridian is brackish, and that saltwater will encroach upward and laterally as depletion in the upper aquifer progresses (Wiley et al., 2013).

Planning for Clearwater's groundwater replenishment project includes three stages: the preliminary feasibility study, the feasibility study, and the pilot test (City of Clearwater, 2014). The preliminary feasibility study, which began in 2009, answered the question of whether or not it was feasible to consider recharging the freshwater aquifer with recycled water (City of Clearwater, 2014). The preliminary study considered both direct injection and surface infiltration, but determined that direct injection would be more beneficial because geological characteristics in the region limit infiltration (Wiley et al., 2013). The direct injection project was considered viable, so the City continued to step two (City of Clearwater, 2014).

The feasibility study, which commenced in 2011, was a comprehensive study to assess whether wastewater could be treated to a high enough water quality standard for recharge, and if groundwater levels would improve as a result of injection (City of Clearwater, 2014). The feasibility study also yielded a preliminary design of the pilot project (City of Clearwater, 2014).

This stage was also focused on a public outreach program, an effort by the City to gain support for the groundwater replenishment project and integrate recommendations from the public into the final project (City of Clearwater, 2014). Community support for a project is a large part of project feasibility. The goal of the public outreach program was to increase knowledge in the community about why this project is necessary (by providing information about the groundwater depletion issue), how the project will be implemented, and the high water quality standards that will be attained by the project (City of Clearwater, 2014). This outreach program included a communication plan (to raise awareness and educate the public about the project and its benefits), a survey to assess public perception of the project, presentations, tours of the pilot system, and other outreach materials (e.g., brochures, website development) (City of Clearwater, 2014).

Once the City concluded that the project was feasible, they proceeded with the pilot project (City of Clearwater, 2014). Construction of the pilot project began in 2012, and it was operational by 2013 (City of Clearwater, 2014). The pilot project was designed to operate at the capacity of a full scale system that would yield 3 MGD of recycled water (City of Clearwater, 2014). The recycled water treatment facility was designed to meet or exceed drinking water standards (Wiley et al., 2013). The treatment process, which begins with treated wastewater from wastewater treatment plants, includes chemical pretreatment, membrane filtration for suspended solids removal, reverse osmosis, advanced oxidation with hydrogen peroxide and UV light, and post treatment (chemical stabilization and dissolved oxygen removal) to ensure compatibility with existing groundwater (Wiley et al., 2013).

Leggette, Brashears & Graham, Inc. (2014) completed a six-month direct injection recharge test for the City of Clearwater. For this test, one injection well and three monitoring wells were built at the wastewater treatment facility. Assessment of the aquifer's hydrogeology was an important step in this test, which included modeling for in-basin water mixing, geologic makeup of the aquifer, groundwater flow (using MODFLOW), and recharge rates (using WinFlow) (Leggette, Brashears & Graham, Inc., 2014). Aquifer dimensions, rate of flow, capacity, and confinement were also analyzed (Leggette, Brashears & Graham, Inc., 2014). Rock core samples were taken to assess harmful constituents that might leach out of the formation (arsenic was found to be a possible contaminant from the rock, as the pyrite formation can oxidize to arsenic) (Leggette, Brashears & Graham, Inc., 2014).

Leggette, Brashears & Graham, Inc. (2014) also assessed the potential effects of mixing recycled water with the existing groundwater to predict whether any precipitates would form, or if reactions might cause dissolution of the rock formation. They used software called Geochemist Workbench to model the water mixing, testing various ratios of recharge water to groundwater so that the model reflected different points in time as the aquifer becomes more saturated with recycled water (Leggette, Brashears & Graham, Inc., 2014). Oxidation of pyrite to form arsenic was a major concern, but they found that because the aquifer conditions were anoxic, the pyrite would not oxidize if the dissolved oxygen content of recycled water is similar to that of the existing groundwater (Leggette, Brashears & Graham, Inc., 2014).

The first 20 feet of the wells were 12 inches in diameter, followed by 210 feet of PVC casing that was 8 inches in diameter (Leggette, Brashears & Graham, Inc., 2014). The remainder of the borehole (to a depth of 320 feet) had no casing and was 6 inches in diameter (Leggette, Brashears & Graham, Inc., 2014). The lack of casing for the final 110 feet and the presence of arsenic in the rock meant that extra attention had to be given to monitor arsenic concentrations in the water (Leggette, Brashears & Graham, Inc., 2014).

During operation of the test system, groundwater levels were closely monitored both at the injection well and at the monitoring wells (Leggette, Brashears & Graham, Inc., 2014). Water quality samples were also analyzed weekly and compared to samples of water taken prior to the pilot test (Leggette, Brashears & Graham, Inc., 2014). This study used MODPATH (particle transport modeling) and Orange County's required six month travel time from injection wells to potable use wells to determine where injection wells should be placed (Wiley et al., 2013). Fluoride was injected into the well as a tracer to evaluate contaminant transport and assess the success of well placement; the tracer was not observed at any of the monitoring wells during the study, which was the outcome expected and supported by the WinFlow (groundwater flow) and MODPATH (particle transport) models that estimated travel time from the injection well to a monitoring well to be 5-6 months (Leggette, Brashears & Graham, Inc., 2014).

Pilot testing was successful, and Leggette, Brashears & Graham, Inc. (2014) was able to conclude that the Upper Floridian aquifer is suitable for groundwater recharge with recycled water. Their main recommendation was to conduct stringent monitoring of groundwater quality to ensure that arsenic concentrations do not increase (Leggette, Brashears & Graham, Inc., 2014). The testing also allowed the City to determine how many injection wells would be needed, and the rate and pressure of injection required, to meet their goal of 3 MGD of recycled water injection (Wiley et al., 2013). After the pilot study, the City began analyzing the results and finalizing the design and construction of the final project (Wiley et al., 2013).

Case Study 3: South Australia

The clay soils that are characteristic of South Australia restrict natural recharge of the groundwater aquifer, making artificial recharge necessary to prevent groundwater depletion (Barnett et al., 2000). The region was already utilizing recycled water for irrigation; the Virginia Pipeline Scheme transports water from the Bolivar Wastewater Treatment Plant to agricultural fields (Barnett et al., 2000). However, they found a gap between supply of recycled water and demand; water was only needed in the dry months (8 months of the year), so storage was needed during the winter months (Barnett et al., 2000). Several direct injection projects for the purpose of aquifer storage and recovery began in the 1990s, and continue to expand (Barnett et al., 2000).

Water is only injected into the lower aquifer in South Australia (the upper aquifer is the potable water source), so wastewater is only treated to irrigation quality standards prior to injection (Dillon et al., 2006). The water is pre-treated in artificial wetlands to meet these quality standards and to prevent injection well systems from becoming clogged with sediments (Barnett et al., 2000). At one recharge site (Andrew Farm in the Northern Adelaide Plains irrigation region) where the water passes through several artificial wetlands before it is injected to the confined aquifer, clogging did occur, but was remedied with the addition of a filter at the pump intake site and regular reversal of the water flow to flush out suspended solids (Barnett et al., 2000).

The Bolivar aquifer storage and recovery study, which began operation in 1996, examined the correlation between the treatment level of recycled water and well clogging (Dillon et al., 2006). The recycled water is injected into a confined limestone aquifer, and monitoring wells and pressure monitors were constructed around the injection well to monitor the recharge progress (Dillon et al., 2006). One of the monitoring wells was placed in the upper aquifer (potable supply) to ensure that no contamination occurred (Dillon et al., 2006). Clogging was predicted and observed as a result of the solids that remain in the water due the minimal treatment standards (Dillon et al., 2006). The study concluded that even if the end use of the injected water does not require thorough treatment (i.e., the water will not enter potable use supplies), additional treatment is necessary to prevent clogging of the injection wells (Dillon et al., 2006).

Direct Injection Case Study Comparison

Table 3 below provides a summary of the project objectives, successes, issues and solutions encountered in each of the three direct injection case studies.

Table 3: Comparison of Direct Injection Case Studies

Case Study	Objectives & Successes	Issues	Solutions & Implications
Orange County	-Addresses Saltwater Intrusion with Seawater Barrier -Indirect Potable Reuse -Dual Project (Excess Water Sent to Spreading Basins) -Designed for Expansion and Maintenance (Modular System for Easy Expansion, Easy Access Wells for Cleaning)	-Clogging of Injection Wells	-New Wells Designed to Make Cleaning More Efficient (Accessibility to Clogging Locations; Less Costly So Cleaning Can Be Performed More Often)
Clearwater	-Addresses Groundwater Depletion; Still In Pilot Phase -Effective Planning Process, Public Outreach Program and Pilot Model -Provides a Blueprint for Feasibility Analysis and Project Planning	-Arsenic in Rock -Public Perception	-Extensive Monitoring -Extensive Communication Plan, Public Meetings, Outreach Materials, Surveys and Tours
South Australia	-Addresses Groundwater Depletion of Lower (Non-Potable) Aquifer -Low Treatment Requirements (Irrigation Purposes Only); Uses Wetland Pretreatment -Addresses Supply/Demand Gap for Irrigation Water by Providing Winter Storage	-Clogging	-Additional Treatment Would Prevent Some Clogging -Installed Filter at Intake Pump -Regular Intervals of Backwashing to Remove Suspended Solids

(Data Compiled From: Herndon and Markus, 2014; Dadakis et al., 2011; Deshmukh and Wehner, 2009; Dunivan et al., 2010; City of Clearwater, 2014; Leggette, Brashears & Graham, Inc., 2014; Barnett et al., 2000; Dillon et al., 2006)

Common Issues and Solutions

Although soil aquifer treatment occurs as the water migrates through the aquifer's soil, injection water is generally treated to attain very high quality standards (i.e., drinking water quality) prior to injection to address public health concerns regarding contamination of the groundwater aquifer, and to prevent clogging of the injection well system (Bouwer, 2002). At a minimum, injection water should receive tertiary treatment (disinfection) to remove suspected solids and bacteria prior to injection (Bouwer, 2002). Further treatment, such as microfiltration and reverse osmosis to remove additional pathogens, nutrients and chemicals, has proven to be beneficial (Bouwer, 2002).

Unfortunately, clogging is still one of the most commonly encountered issues with direct injection, even if the highest level of treatment has been performed. Clogging can occur at various locations in the direct injection system depending on the type of clogging, but most commonly it occurs in the system filters, well screens and gravel pack surrounding the injection well (Fig. 5) (Herndon and Markus, 2014).

Clogging leads to costly repairs and lost flow capacity limiting the volume of water that can be recharged (Martin, 2013b). If the pressure heads in the aquifer are preset, which is common, the water will be prevented from flowing altogether (Martin, 2013b). Clogging could even lead to fracturing of the aquifer or confining layer as a result the required increase in pressure to keep the wells pumping (Martin, 2013b).

A study completed by Bouwer (2002) provides tools to estimate the clogging potential of recharge water that is to be injected. There are three tests that Bouwer (2002) found to be accurate in analyzing clogging parameters to predict clogging issues that may arise in the system. These tests should be run during operation of the system to act as a monitor for clogging and warn operators before a serious issue arises. The membrane filtration index looks at suspended solids in the water (Bouwer, 2002). In the parallel filter index, the recycled water is sent through columns of a replica aquifer, but at a much higher flow rate so that the replica columns clog more quickly than the actual system, acting as a warning before clogging occurs in the operational well (Bouwer, 2002). This allows for remediation before the wells are damaged (i.e., the operators would increase the backwashing time to prevent damage) (Bouwer, 2002). The assimilable organic carbon (AOC) content test involves incubation of an injection water sample to monitor bacterial growth, and assimilation of the bacterial growth to the carbon concentration that would produce the same bacterial growth (Bouwer, 2002). According to Bouwer (2002), the AOC should be under 10 micrograms/L to avoid clogging if chlorine is not going to be added to the water to prevent bacterial growth. Biodegradable organic carbon can also be assessed (which is easier), but it is better suited for waters with very high organic carbon concentrations (it is not very accurate in monitoring small concentrations) (Bouwer, 2002).

There are four types of clogging associated with direct injection of recycled water: 1) chemical (chemical reactions that form precipitates or cause dissolution), 2) physical (e.g., suspended solids, interstitial fines or aquifer fracturing), 3) biological (e.g., algae or bacteria), and 4) mechanical (e.g., gas binding) (Martin, 2013b).

To avoid chemical clogging, injection water should be in chemical equilibrium with existing groundwater water and the aquifer (Martin, 2013b). For example, as evidenced by the Orange County case study, highly treated wastewater can be corrosive because it lacks minerals, but increasing the pH of the injection water by the removal of carbon and addition of calcium oxide can prevent corrosion (Dunivan et al., 2010). Scale formation is also a very common cause of chemical clogging, but the solution depends on the type of scale (Martin, 2013b). For example, carbonate can be dissolved with the addition of acid, but sulfate requires mechanical intervention, which is more complicated (Martin, 2013b).

Physical clogging results in the build up of sediment in the injection well systems (Martin, 2013b). Operators may see the need to increase the pressure at which the water is injected, but this only increases the rate at which the system clogs due to compression of the sediments and the increased rate at which sediments pass through the well (Bouwer, 2002). Physical clogging can be prevented by treating recycled to a very high level to remove as much of the suspended solid material as possible (Martin, 2013b).

Clay soils in an aquifer can cause a combination of chemical and physical clogging. This is especially true in an aquifer with high chloride content because the polar injection water eliminates the stabilization that the saltwater (Na^+ ions) provide to the negatively charged clay particles (Martin, 2013b). Clay soils are water soluble, which increases the likelihood of dissolution (chemical clogging) (Martin, 2013b). When the particles dissolve, the fines mobilize and occupy pores which leads to physical clogging (Martin, 2013b). Gradual introduction of freshwater is helpful and has been proven to help, as has management of pH or the addition of cations (e.g., Ca+) (Martin, 2013b). This is likely to be a problem in the Pajaro Valley, which has a high content of clay in the soil and high chloride levels (due to saltwater intrusion).

Biological clogging can be predicted by carbon and nutrient concentrations, which promote biological growth (Martin, 2013b). Martin (2013b) notes that this growth usually concentrates near the well filters because this is also where suspended particles accumulate, and the compacted particles provide an ideal substrate for biological growth (as cited in Pyne, 2005). This results in a biofilm on the filter and subsequent clogging (Martin, 2013b).

Mechanical clogging can be addressed by proper system controls. For example, if gas binding is the cause of mechanical clogging, air can be removed from water with the addition of carbon dioxide or dissolved oxygen scrubbers (Martin, 2013a). The system should also be designed to prevent air from entering and becoming trapped (Martin, 2013a).

Martin (2013b) concludes that, in order to minimize damage and costs, a recycled water direct injection system should be designed with the idea in mind that clogging will occur so that methods can be established early on to best manage the clogging. Further, he states that there are remediation measures available to address all clogging issues, so they should not make a project infeasible. Proper planning is key to identify ahead of time what types of clogging issues are most likely to happen in a specific setting and how to best address them (e.g., higher level of treatment, proper backwashing intervals, compatible materials) (Martin, 2013a).

While sufficient treatment of the water prior to injection and ensuring that the system is compatible with the hydrogeology of the aquifer are very important, backwashing has been shown to be the most effective measure to address clogging once the system is in operation (Bouwer, 2002). Bouwer (2002) cites that a direct injection study in Phoenix, Arizona experienced no clogging during the first three years of operation (up to the point that the study was completed) by backwashing at regular intervals (30 minutes, 3 times per day). Bouwer (2002) notes that this interval may vary based on setting, but in general a backwashing interval of 15 minutes, 1 to 3 times per day is recommended. This backwashing technique may also eliminate the need for membrane filtration, and this reduction in treatment translates to reduced energy consumption and costs (Bouwer, 2002).

Although there are measures available to address all clogging issues, Martin (2013b) recommends highly adaptable system designs that allow operators to address unforeseen causes of clogging. Observation wells are an important piece of this last recommendation, as close monitoring for changes in hydraulics, pressure or recharge rates can alert operators to these unforeseen clogging issues (Martin, 2013b).

Aside from clogging, one criticism of the utilization of direct injection is that some of the injected fresh water flows towards the ocean (Abarca et al., 2006). Water does move away from the well radially, with the rate and direction of flow dependent on the gradient and hydraulic conductivity of the aquifer (Petersen and Glotzbach, 2005). However, a model by Abarca et al. (2006) showed that direct injection seawater barriers are still very effective in preventing seawater intrusion, even when accounting for the water that is lost to the sea.

Public perception is another very important issue faced with direct injection projects. There is the potential for a high level of public disapproval of a direct injection project, which could delay or prevent a project. The community needs to be very involved and informed throughout the project development process. The City of Clearwater implemented a very thorough and detailed public involvement program, which ensured that the public felt comfortable with the design of the system and were assured that the project would not negatively impact the health of their potable water supplies (City of Clearwater, 2014). The City of Clearwater also ensured that citizen and stakeholder concerns were heard and addressed (City of Clearwater, 2014). The public outreach completed by the City of Clearwater is exemplary, and should be initiated very early into the planning process to avoid setbacks and gain community support for a direct injection project.

Surface Spreading

Overview

Surface spreading is a method of artificial recharge where recycled water is conveyed to large spreading basins (National Research Council, 1994 as cited in Schroeder and Anders, 2002). The water then infiltrates the unsaturated zone, which is layer of soil and rock above the groundwater table, and recharges the saturated zone for groundwater replenishment, augmentation of potable water supplies, and storage (U.S. Geological Survey, 2013; National Research Council, 1994 as cited in Schroeder and Anders, 2002). Figure 7 below depicts the interaction between a spreading basin and the groundwater aquifer. The spreading basin is located on the unconfined portion of the aquifer so that the water can effectively infiltrate the soil to recharge the aquifer, and the water then flows down gradient into the confined aquifer (Johnson, 2009a).

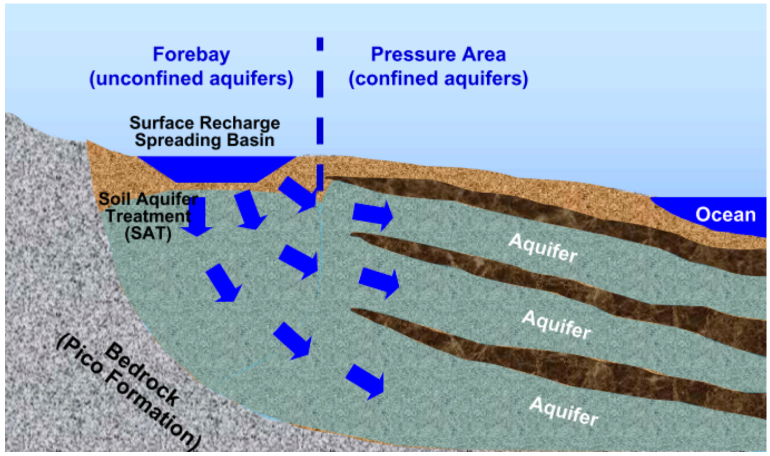

Figure 7: Interaction of a Spreading Basin and the Underlying Aquifer(s)

(Johnson, 2009a)

Recycled water for surface infiltration undergoes tertiary treatment, just as it does for direct injection (Johnson, 2009b). The difference in the treatment process between direct injection and surface spreading is that recycled water for direct injection typically undergoes advanced treatment due to public health requirements (e.g., microfiltration, reverse osmosis and in some cases UV light and/or hydrogen peroxide oxidation), while surface spreading can rely on soil aquifer treatment in place of advanced treatment (although some surface spreading projects still employ advanced treatment) (Johnson, 2009b). Soil aquifer treatment is a natural treatment process that addresses physical, biological and chemical constituents (Johnson, 2009b). Physical treatment occurs as water filters through the aquifer's soil during infiltration and while moving laterally through the aquifer, effectively removing particles in the water (Johnson, 2009b and Anderson et al., 2010). Biological treatment occurs as any organic material remaining in the recycled water is broken down by microorganisms in the soil (Johnson, 2009b). Chemical reactions (neutralization and redox reactions) that take place in the aquifer have the potential to address chemical pollutants, although this depends on the specific contaminants present in the water (Johnson, 2009b).

Once the water has reached the saturated zone (groundwater table), the recharge water mixes with native groundwater as it flows through the aquifer (Johnson, 2009b). The water is sufficiently treated and diluted before it reaches any potable use wells (Johnson, 2009b). Soil aquifer treatment is a very dependable and sustainable method of recycled water advanced treatment, and no diminishment in the level of treatment over time has been observed (Johnson, 2009b).

Two case studies of recycled water surface infiltration will be discussed in this section. The first is the Montebello Forebay Spreading Grounds in Los Angeles, California, which were established in 1962 and comprise the oldest recycled water surface spreading operation in California and one of the largest and most studied surface spreading projects the United States (Gasca and Hartling, 2012). The purpose of the Montebello Forebay Spreading Grounds is to prevent groundwater overdraft and supplement potable water supplies to reduce reliance on costly and overburdened imported water supplies (Gasca and Hartling, 2012). The second case study looks at the Sweetwater Recharge Facilities in Tucson, Arizona, which began development in 1984 (City of Tucson, 2013). This project includes several innovative processes such as post-recovery treatment (secondary treated wastewater undergoes soil aquifer treatment and then is pumped back to the wastewater treatment plant for final treatment and distribution) and artificial wetlands, which provide on-site natural treatment for backwash water while providing an amenity to the community and environment (City of Tucson, 2013). The Sweetwater Recharge Facilities were created in an effort to prevent groundwater overdraft through sustainable management of water resources (City of Tucson, 2013). While most surface spreading projects, including the Montebello Forebay, focus on underground storage and maintenance of higher groundwater levels, Tucson's overdraft protection strategy utilizes surface spreading as part of the water treatment process, and most of the water that artificially infiltrates the groundwater aquifer is then pumped back out for distribution to supplement other potable water supplies (Megdal et al., 2014). Although there are many other surface spreading operations throughout the world, these two case studies were selected because of their long duration, large scale, innovative strategies, and because they have been the focus of numerous research studies over the years.

Case Study 1: Montebello Forebay, Los Angeles, California

The Montebello Forebay Groundwater Recharge Project began in 1962 in response to groundwater overdraft and seawater intrusion from population growth in the 1950s and unregulated groundwater pumping (Gasca and Hartling, 2012). Three agencies are responsible for the management and funding of this project: 1) the Water Replenishment District of Southern California, which manages the basin, 2) the Los Angeles County Department of Public Works, which operates the system, and 3) the Los Angeles County Sanitation Districts, which provide the recycled water (Gasca and Hartling, 2012). The Montebello Forebay Groundwater Recharge Project recharges the Central Groundwater Basin (Fig. 8), which accounts for 40% of Los Angeles County's water supply (Gasca and Hartling, 2012). Sources of water for the spreading basins include imported water (from the Colorado River and the State Water Project), stormwater runoff and recycled water (Gasca and Hartling, 2012). Relative percentages of each of these water sources depend on the amount of available stormwater runoff and imported water, and regulations limit the proportion of recycled water to no more than 50% per year or 35% over a five-year period (Schroeder and Anders, 2002; Gasca and Hartling, 2012).

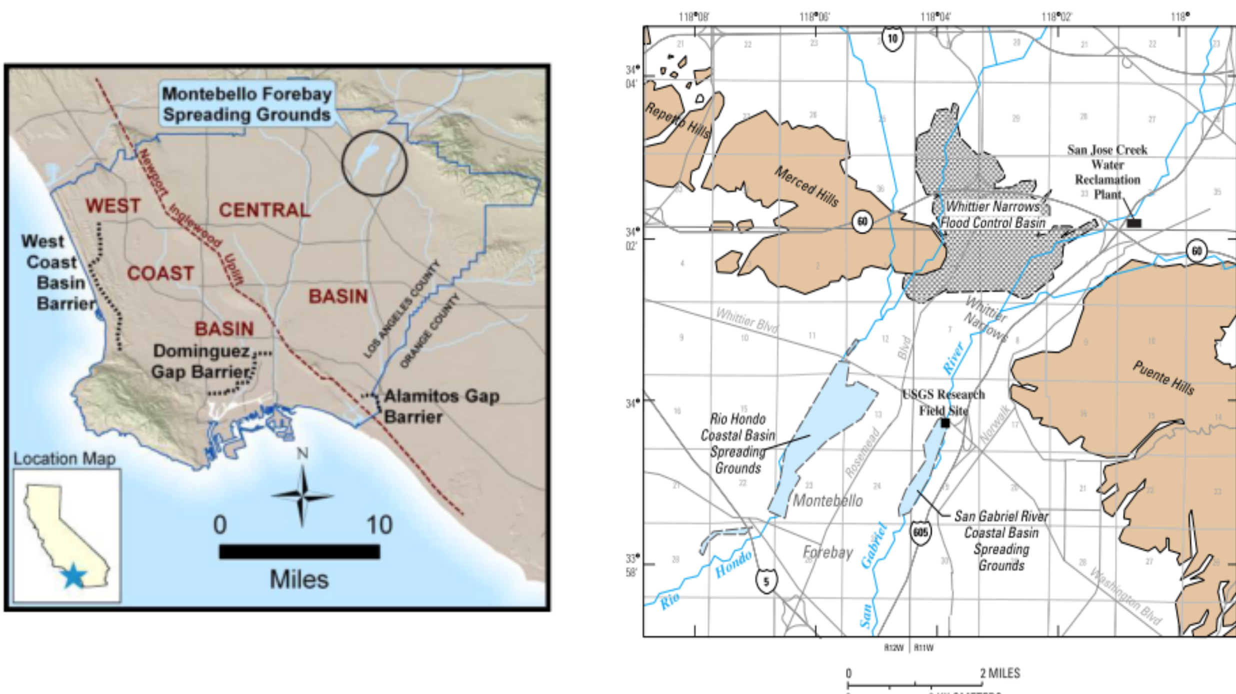

Figure 8: Location and Layout of the Montebello Forebay Spreading Grounds

(Left: Johnson, 2009b; Right: Anders et al., 2004)

The Montebello Forebay Spreading Grounds consist of two separate spreading basins (Figs. 8 and 9), the Rio Hondo Coastal Spreading Grounds (approximately 570 acres) and the San Gabriel Coastal Spreading Grounds (approximately 128 acres of constructed basin plus 308 acres of the San Gabriel Riverbed) (Gasca and Hartling, 2012). Each spreading ground is made up of a system of smaller basins (Fig. 9) (Hartling and Nellor, 1998 as cited in Anderson et al., 2010). These smaller basins are alternately filled and dried to allow maintenance in the dry basins while the other basins are in use (Hartling and Nellor, 1998 as cited in Anderson et al., 2010). Periodic maintenance of the basins allows infiltration rates to be restored, and the drying cycle also suppresses the development of vectors (Hartling and Nellor, 1998 as cited in Anderson et al., 2010). The soil above the groundwater aquifer is very permeable, consisting of moderately sorted, medium and coarse-grained sand and gravel, as well as some fine grains (Anders et al., 2004).

Figure 9: Rio Hondo (top) and San Gabriel (bottom) Spreading Grounds
(Johnson, 2009a)

For research purposes, there is a test basin with two monitoring wells next to the Montebello Forebay Spreading Grounds, which has allowed this project to become the focus of many studies and has yielded valuable information for researchers and water managers (Anders et al., 2004). Since the early 1990s, the U.S. Geological Survey has been utilizing the test basin to study the transport and fate of contaminants as the travel from the Montebello Forebay to drinking water uptake sites to ensure compliance with water quality regulations (National Research Council, 1994 as cited in Schroeder and Anders, 2002).

In 1962, at the commencement of the Montebello Forebay project, the Whittier Narrows Water Reclamation Plant was constructed, and the success of this plant led to the construction of the San Jose Creek and Pomona water reclamation plants in the 1970s (Gasca and Hartling, 2012). These water reclamation plants have undergone a series of upgrades over the years. In 1977, tertiary treatment processes were added to the water reclamation plants to increase virus removal (Anderson et al., 2010). Nitrogen removal processes were added in the early 2000s, followed by sequential chlorination in the late 2000s, and in 2011 UV disinfection was added (Gasca and Hartling, 2012). To ensure groundwater quality and compliance with public health regulations, monitoring is conducted at three points: 1) at the water reclamation plants, 2) at the entry point to the spreading basins, and 3) in the groundwater aquifer (Gasca and Hartling, 2012). Water treatment prior to infiltration at the Montebello Forebay Spreading Grounds has been proven to be sufficient by the numerous water quality studies that have been conducted on-site over the years, and none of these studies have determined that this project poses a threat to public health (Gasca and Hartling, 2012).

In the beginning (1962), the Montebello Forebay Spreading Grounds were permitted to utilize up to 32,700 acre-feet per year of recycled water (Gasca and Hartling, 2012). In 1987, after proven success and upholding of water quality standards, this permit was increased to 50,000 acre-feet per year (Gasca and Hartling, 2012). In 1991 it was increased to again 60,000 acre-feet per year in an effort to make up for years of increased stormwater runoff, which impeded complete utilization of the recycled water in the years prior (Gasca and Hartling, 2012). In 2009, the Regional Water Quality Control Board and the California Department of Public Health replaced the quantity-based limits with a percentage limit, wherein recharge water could be made up of 50% recycled water per year and 35% recycled water over a five year average (Gasca and Hartling, 2012). This was estimated to be equivalent to 65,000-67,000 acre-feet per year, and once combined with surface and imported water, the recharge water meets the demands of approximately 250,000 people every year (Gasca and Hartling, 2012).

Table 4: Progression of Permitted Recycled Water at the Montebello Forebay

Year	Recycled Water Permit
1962	32,700 acre-feet/year
1987	50,000 acre-feet/year
1991	60,000 acre-feet/year
2009	50% per year / 35% 5-year average

(Gasca and Hartling, 2012)

Using recycled water for surface spreading has proven very economical in Los Angeles due to a combination of factors (Gasca and Hartling, 2012). The wastewater reclamation plants were already using tertiary treatment (this treatment level is required because the receiving water body is a river), so the cost of wastewater treatment did not increase (Gasca and Hartling, 2012). Water is conveyed to the spreading basins with gravity rather than pumping, so transportation costs are very low (Gasca and Hartling, 2012). The water transport system also made use of an existing water conveyance system that previously transported wastewater to the river, so construction costs were saved (Gasca and Hartling, 2012). Because this conveyance system was pre-existing, surface spreading was more economical than other applications of recycled water, such as irrigation, which would require new construction of conveyance systems (Gasca and Hartling, 2012). The only downside to using this conveyance system to transport water to the surface spreading basins is that it precludes the transport of water to the San Gabriel River and the Rio Hondo River where it would provide ecosystem benefits (i.e., fish habitat).

It was determined that this water conveyance system should only be used to transport recycled water to the spreading basins rather than serving as a dual distribution system that delivers recycled water to non-potable users along the way (Gasca and Hartling, 2012). If this had been a dual conveyance system, all of the water would have to undergo additional treatment (due to the lack of soil aquifer treatment prior to use), and the spreading basins would end up receiving costly, over-treated water (Gasca and Hartling, 2012). The low price of water produced by the Montebello Forebay Groundwater Recharge Project makes it more acceptable by water consumers in Los Angeles, and allows for recycled water treatment (through sewer use fees) and water quality monitoring (through replenishment fees chargers to groundwater pumpers) to be funded by consumers (Gasca and Hartling, 2012).

In planning for groundwater recharge projects, water managers in Los Angeles concluded that the ability of a surface spreading project to accommodate fluctuating amounts of water at any time of day made it a very attractive option compared to other projects such as irrigation which have a limited demand that does not always match recycled water supply (Gasca and Hartling, 2012). Surface spreading and recharge takes advantage of existing natural storage, making it more economically viable than surface storage options, which are often prohibitively expensive (Gasca and Hartling, 2012).

Case Study 2: Sweetwater Recharge Facilities, Tucson, Arizona

The Arizona Groundwater Management Act of 1980 requires that by 2025, municipalities have renewable water supplies in place so that groundwater aquifers are protected from overdraft and the basins operate at safe-yield, meaning that a long-term balance of withdrawal and recharge is maintained (Megdal and Forrest, 2015; City of Tucson, 2013). In response, the City of Tucson developed several recycled water projects. The Reclaimed Water System, which has now been in operation for over three decades, provides landscape and golf course irrigation water, but irrigation does not utilize all of the recycled water so much of it is discharged into the Santa Cruz River (City of Tucson, 2013). The Sweetwater Recharge Facilities and the Agua Nueva Wastewater Reclamation Facility take advantage of this unused recycled water (City of Tucson, 2013). The combination of a recycled water irrigation system and a recycled water groundwater recharge project allow for the accommodation of variations in irrigation demand throughout the year, as the recycled water is almost fully utilized for irrigation in the summer while most of it is available for recharge and recovery in the winter (City of Tucson, 2013). These recharge facilities aim to prevent groundwater depletion by providing a new water source and decreasing the demand for groundwater (City of Tucson, 2013).

The Sweetwater Recharge Facilities and the Agua Nueva Wastewater Reclamation Facility operate together as a recharge and recovery project (Kmiec et al., 2005). This means that the infiltration basins are essentially utilized as a treatment system (Megdal et al., 2014). Wastewater is sent to the spreading grounds where it undergoes soil-aquifer treatment and then the water is pumped back out of the groundwater aquifer (recovered) and sent to the wastewater reclamation facility for final treatment and distribution (Kmiec et al., 2005). Excess infiltration water (left over after recovered water demand has been met) remains in the groundwater aquifer for storage to prevent overdraft and to be saved for future use (i.e., drought mitigation) (City of Tucson, 2013).

Early in the process, the City of Tucson sought input and ideas from other agencies that had successfully implemented recycled water projects, including the Orange County Water District, the West Basin Municipal Water District (Los Angeles County), and the Los Angeles Department of Water and Power (City of Tucson, 2013). After visiting other successful projects, the City of Tucson (2013) decided to begin their public outreach program very early in the process to foster community support. The public outreach program stressed the importance of a sustainable water supply and the value of unused wastewater, and aimed to educate the public about the project through meetings, presentations, social media, printed materials and through tours of a demonstration project (City of Tucson, 2013). In a survey conducted in 2013, 50% of water customers were comfortable with the idea of using recycled water for drinking water, and 66% were interested in touring the demonstration facility (Megdal and Forrest, 2015).

Construction of the Sweetwater Recharge Facilities was completed in stages. Planning began in 1983, and the demonstration phase lasted from 1984 to 1989 (Kmiec et al., 2005). The demonstration phase utilized four small test basins (3/4 acre each), ten monitoring wells, and two extraction wells to assess infiltration rates and the effectiveness of soil-aquifer treatment under the operating and hydrogeologic conditions (City of Tucson, 2013; Kmiec et al., 2005). The demonstration project was designed with three pipelines; one for potable water, one for reclaimed wastewater (only tertiary treated wastewater was permitted at this point), and one to deliver the recovered water back to the treatment plant (Kmiec et al., 2005). Potable water was used during the first few years of the demonstration until soil-aquifer treatment could be proven to be sufficient for wastewater (City of Tucson, 2013). Infiltration rates at the demonstration project were approximately one foot per day, and the only significant ground water quality change that was observed was an increase in total dissolved solids (Kmiec et al., 2005). The increase in total dissolved solids was determined to be the result of vadose zone salts leaching during infiltration, which was not considered problematic (Kmiec et al., 2005). Valuable operational and maintenance experience was also gained during this phase (Kmiec et al., 2005).

The demonstration was a success, so in 1989 the project entered the development phase (Kmiec et al., 2005). The preliminary design for the project was based on results from the demonstration phase, and included four large recharge basins (Kmiec et al., 2005). The first basin, which was completed in 1989, required excavation of the first 10-15 feet of soil to expose more permeable soil and increase infiltration rates (Kmiec et al., 2005). Two more extraction wells and additional monitoring wells were added (Kmiec et al., 2005). The basins were operated with alternating wet and dry periods (Kmiec et al., 2005). Wetting cycles were initially 10-13 days, but algae flocculation was observed, which prevents infiltration, so wetting cycles were decreased to less than one week and the drying period was increased to induce drying and cracking of the algae and sediment layer (Kmiec et al., 2005). By 1990, two more basins were complete and chlorination was introduced to reduce algae growth (Kmiec et al., 2005). The fourth basin was in operation by 1991 (Kmiec et al., 2005). Infiltration rates were continually monitored and were observed to decrease over time (Kmiec et al., 2005). Operators began "ripping" the basins, a process where equipment is used to turn over the soil to a depth of 1-3 feet in order to break up the clogging layer (Kmiec et al., 2005). The project was still receiving tertiary treated wastewater up until 1994 when Tucson Water decided it was safe to use secondary treated water (Kmiec et al., 2005). At this point, the Aquifer Protection Permit allowed for up to 3,200 acre-feet/year of secondary treated wastewater to be recharged into the aquifer (City of Tucson, 2013).

The development phase was complete in 1997, and the project commenced the full-scale phase (Kmiec et al., 2005). Four additional basins were added to the project as well as the Sweetwater Wetlands (Fig. 10), which would be used to treat backwash water from the filtration process at the treatment plant (the filters are backwashed to remove accumulated solids that have been filtered out of the water) (Kmiec et al., 2005; City of Tucson, 2013). The wetlands were designed with two flow channels, each with two settling basins and one polishing basin (Kmiec et al., 2005). Backwash water is mixed with tertiary treated wastewater prior to being discharged into the wetlands (City of Tucson, 2013). Water then flows out of the wetlands, combines with secondary treated wastewater, and enters the four newest recharge basins (the four basins adjacent to the wetlands; see Figure 10) (Kmiec et al., 2005). In addition to providing a function to the recharge operations, the wetlands are an amenity to the community and the environment as they provide wildlife habitat, walking paths, bird watching opportunities, and an outdoor classroom (City of Tucson, 2013).

With the additional basins and the construction of the wetlands, the Aquifer Protection Permit was revised to allow for 6,500 acre-feet per year to be conveyed to the recharge facilities (Kmiec et al., 2005). Operation of the project has been adjusted based on the demonstration and developmental phases. The basins are filled to 1-2 feet for 3 days, and then the flow is shut off allowing water to infiltrate until the basin is dry (Kmiec et al., 2005). The dry cycle lasts until the basin is completely dry and cracked (this usually takes a couple of days) (Kmiec et al., 2005). These dry periods are extended to approximately one month in the summer to take advantage of the heat for better drying, and this is the only time the basins can be ripped because the surface will compact and reduce infiltration if the basin surface is not sufficiently dry (dry to a depth of at least 15 inches) (Kmiec et al., 2005). With the operational and design improvements made, infiltration rates have increased to an average of 2.3 feet per day (Tucson Water, 2005 as cited in Kmiec et al., 2005).

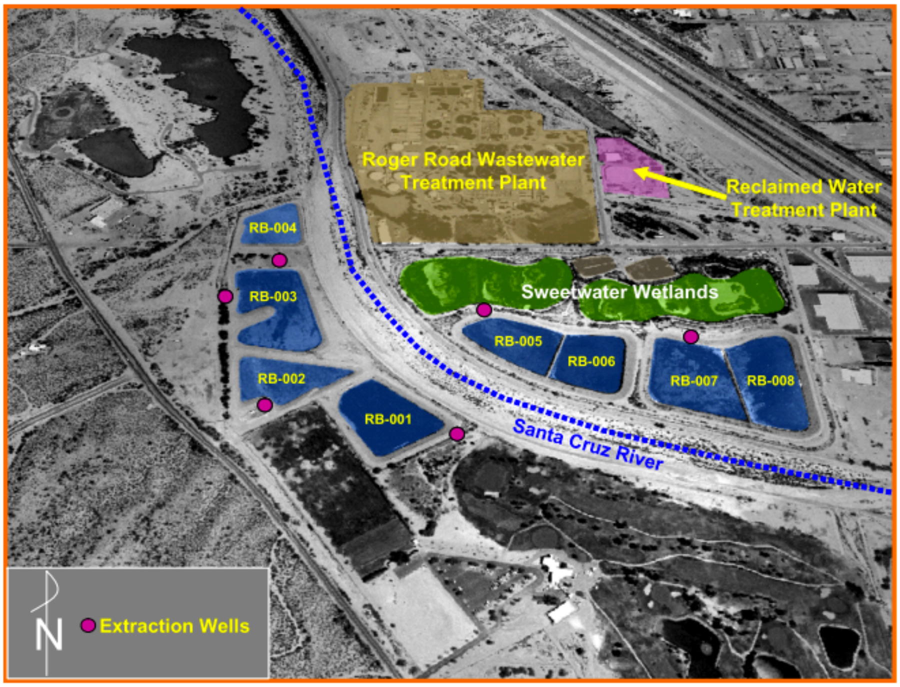

Figure 10: Layout of the Sweetwater Recharge Facilities
(Kmiec et al., 2005)

Although the public was aware of the need for sustainable water supplies, the City of Tucson understood that water quality is a key concern and that protection of public health is critical in building trust in the community (City of Tucson, 2013). In selecting a treatment process that would ensure the highest quality drinking water while remaining cost-effective, the City looked at both pre-recharge and post-recovery treatment options and found that post-recovery would be more economical and energy efficient (City of Tucson, 2013). Pre-recharge treatment would require treatment facilities to have the ability to accommodate varying amounts of wastewater, which is a expensive type of facility to build and operate (City of Tucson, 2013). Alternatively, when the wastewater is recharged into the aquifer prior to treatment, the aquifer can mitigate fluctuations (when wastewater flow is high, the excess is stored in the aquifer and can be pumped out during times of lower wastewater flow), and the reclamation post-recovery treatment facility can operate at a steady flow (City of Tucson, 2013). This allows for a much smaller, more efficient facility because it does not have to be designed to handle the highest foreseeable flows (City of Tucson, 2013). Post-recovery treatment also takes full advantage of soil aquifer treatment, which effectively replaces the filtration process that would normally occur prior to membrane treatment and therefore reduces treatment costs (City of Tucson, 2013). Once water is recovered and treated at the wastewater reclamation facility, it is mixed with Colorado River water and delivered as a blended potable water supply (City of Tucson, 2013).

Surface Spreading Case Study Comparison

Table 5 below provides a summary of the project objectives, successes, issues and solutions encountered in each of the surface spreading case studies.

Table 5: Comparison of Surface Spreading Case Studies

Case Study	Objectives & Successes	Issues	Solutions & Implications
Montebello Forebay, Los Angeles	-Prevents Overdraft -Supplements Potable Supply to Avoid Import Water	Clogging of Basin Surface	Basin System to Allow for Alternate Wet/Dry Periods for Continual Operation and Maintenance/Scraping
Sweetwater Recharge Facilities, Tucson	-Aquifer Storage and Recovery with Post-Recovery Treatment -Natural Storage for Recycled Water	-Clogging of Basin Surface -Public Perception	-Ripping/Scraping to Break Clogging Layer -Public Involvement, Recreation Opportunity in Wetlands, Demonstration Project

(Data Compiled From: Gasca and Hartling, 2012; City of Tucson, 2013; Megdal et al., 2014; Hartling and Nellor, 1998 as cited in Anderson et al., 2010; Kmiec et al., 2005)

Common Issues and Solutions

As with direct injection, the most common and serious issue encountered with surface spreading is clogging, although clogging of infiltration basins is generally not as detrimental or difficult to remedy as it is with direct injection because the clogging is easy to access and there is no expensive equipment to repair (Martin, 2013b). Clogging in surface spreading operations occurs when solids accumulate on the basin surface (e.g., sediments, sludge), biological material grows on the basin surface or in the soil, salts precipitate (e.g., calcium carbonate), and/or gas gets trapped in the soil (often as a result of other types of clogging) which blocks pore space (Bouwer, 2002; Martin, 2013b). The clogging layer is typically very thin, ranging from a few millimeters to approximately four centimeters (Hutchison et al., 2013). Water treatment to remove suspended solids, nutrients and organic carbon does prevent clogging (Bouwer, 2002;

Martin, 2013b). Unfortunately, even with the highest level of treatment, clogging will occur due to microbial growth as demonstrated by surface infiltration studies that were conducted using tap water (Bouwer and Rice, 2001 as cited in Bouwer, 2002).

There are three ways to mitigate clogging: 1) by design, 2) with proactive removal, and 3) through reactive removal (Hutchinson, 2013). Infiltration basins should be designed to prevent clogging by ensuring that they are protected against erosion that may occur during basin filling or with other water movement (Hutchinson, 2013). Basins should also be shallow to reduce compaction that can occur when too much water (weight) sits in the basin and to allow for faster draining (Hutchinson, 2013). A system of basins rather than one large basin is recommended to allow for intermittent operation (alternating wet and dry periods for maintenance purposes) (Hutchinson, 2013).

Proactive removal means treating water for suspended solids and nutrients. This requires extra removal at the treatment facility or through desilting basins, such as those constructed in the Sweetwater Wetlands (Hutchinson, 2013; Kmiec et al., 2005). Artificial wetlands are also very effective for the removal of nutrients, especially nitrate (Hutchinson, 2013).

Reactive removal means removal of the clogging layer after it has formed (Hutchinson, 2013). If the basin is going to be in use during maintenance (i.e., if there is only one basin and it was not designed for drying), the clogging layer can be vacuumed, leaving only the clean underlayer (Hutchinson, 2013). The preferred method of reactive removal is the alternation of wet periods with dry periods in which the basin is allowed to dry and crack, and at certain intervals, the subsequent removal of the clogging materials (Bouwer, 2002). This method has been proven to be very successful in restoring infiltration capacity (Bouwer, 2002). Additionally, intermittent wetting and drying reverses biological clogging by forcing biomaterial to degrade (Houston et al., 1999; Magesan et al., 1999; and Duryear, 1996 as cited in Hutchison et al., 2013). If algae growth remains problematic even when wet/dry cycling is practiced, herbicides or algal feeders (e.g., fish) may be necessary (Hutchison et al., 2013). The wet/dry cycling technique was found to be very effective for both the Montebello Forebay and the Sweetwater Recharge projects. However, effectiveness of this remediation technique varies depending on the depth of the clogging layer (Hutchison et al., 2013). A clogging layer near the surface is easy to address with drying and maintenance, but if the clogging material is too deep, infiltration rates may not be recoverable (Hutchison et al., 2013). Reactive removal should generally be performed when infiltration rates decrease to 30% of the initial rate, as determined by cost/benefit analysis (Hutchinson, 2013). If reactive removal is performed too often, recharge water becomes too expensive, although this cost varies widely depending on location and the maintenance schedule should be set accordingly (Hutchinson, 2013).

Another issue pertaining to surface spreading is that it requires a large amount of land, and the soil has to be permeable, so selection of a suitable site can be challenging (Bouwer, 2002). When the soil is more permeable, less land will be required to meet the same infiltration goals, so this should be considered when selecting a site (Bouwer, 2002). The vadose zone should not have layers of fine grains (such as clay) because they prevent flow, both downward and laterally (Bouwer, 2002). More permeable soil typically exists further down into the ground, and in some cases it may be necessary to dig the basin to the depth of the more permeable layer (Bouwer, 2002).

There are a few methods for selecting a suitable surface spreading site. Pilot testing can determine site suitability, but these tests are very expensive, time consuming and spatially limited, so they are better suited for further study after a site has been selected (Russo et al., 2015). Computer modeling can be very effective in selecting a suitable site for a surface spreading operation, they can be applied regionally, and they allow for the testing of various conditions (e.g. hydrologic parameters, management scenarios, economics, climate, or water demand) (Russo et al., 2015; Phillips, 2002). The parameters of importance specific to the groundwater basin are determined by the managers (Phillips, 2002). When GIS is combined with computer models, parameters pertaining to the basin surface, such as elevation and slope, land use, soil infiltration capacity, and geology, can be integrated (Russo et al., 2015). Subsurface parameters such as vadose zone composition, the presence of confining layers, aquifer thickness, stratification, and hydraulic conductivity should also be integrated into the model (Russo et al., 2015). Groundwater flow models can assess hydrologic feasibility for a site by predicting infiltration rates and the speed and direction of groundwater flow (Megdal et al., 2014). Modeling can also predict the effects of recharge on groundwater levels (Russo et al., 2015).

Surface spreading does cause some concern over public health. Unlike direct injection, which requires 1) reverse osmosis or 2) membrane treatment (microfiltration) and nanofiltration, surface spreading only requires tertiary treated wastewater and relies on soil-aquifer treatment for further filtration (Drewes et al., 2003). The worry is that pathogens and organic material might pass through the soil if the soil and aquifer do not have the ability or capacity to adequately treat the water (Drewes et al., 2003). In cases where the water is recovered and treated post-recovery, such as the Sweetwater Recharge Facility in Tucson, this does not pose a risk to public health. It is only when recycled water is used to recharge a basin containing potable use wells that there is concern.

Soil-aquifer treatment has been proven to be very effective at removing pathogens and nutrients, especially nitrate, but it is a process that requires a certain residence time in the groundwater basin to ensure that the water is safe before it is pumped out for potable use (Schmidt et al., 2011; Johnson, 2009b). According to the California Department of Public Health, the residence time must be at least six months to be certain that no viruses are present in the water (Johnson, 2009b). This means that it must take the water six months to travel from the injection site to the withdrawal location (Johnson, 2009b). Tracer tests are the most effective method of demonstrating travel times (Johnson, 2009b). Other methods, such as computer modeling, can also be used, but the lower confidence level of these tests (due to assumptions and limitations) would require that a twelve month travel time be demonstrated (Johnson, 2009b).

The issues of clogging, land requirements, suitable site selection and public health all need to be carefully considered and planned for when developing a surface spreading project. These challenges are inevitable, but effective solutions exist for each of them. Although some of the special requirements for surface spreading, such as the large land requirements, might serve as a deterrent for a project, the benefits of surface spreading compared to direct injection include less complicated engineering requirements (no injection wells) and lower operating costs (i.e., less water treatment and maintenance required) (Russo et al., 2015).

Dual Projects

Orange County's Groundwater Replenishment System is an excellent example of a project that effectively combines direct injection, including a seawater intrusion barrier, and surface spreading for optimal groundwater replenishment and seawater intrusion prevention (Dadakis et al., 2011). Recycled water is sent to the Talbert Gap Seawater Intrusion Barrier for direct injection as a first priority (Dadkis et al., 2011). Once the Talbert Gap Seawater Intrusion Barrier has met its injection capacity, the remaining recycled water is conveyed inland (via 14 miles of pipeline) to a series of surface spreading basins (Dadkis et al., 2011; Dunivan et al., 2010). Figure 11 below provides a map of the Groundwater Replenishment System, which stretches from the Fountain Valley/Costa Mesa area along the coast to Orange and Anaheim inland (Dunivan et al., 2010).

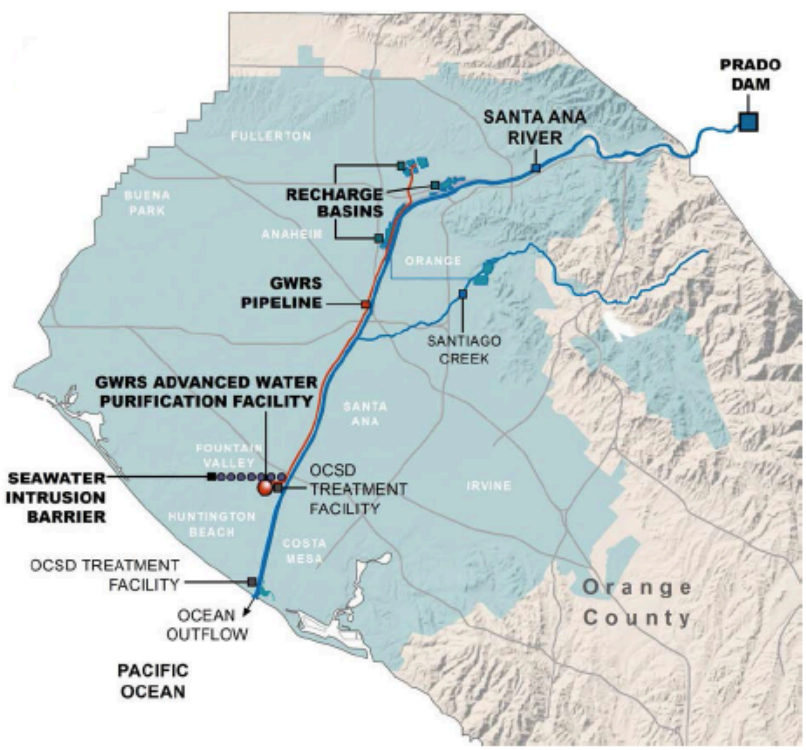

Figure 11: Map of the Groundwater Replenishment System's Seawater Intrusion Barrier, Treatment Facilities, Conveyance Pipelines, and Inland Recharge Basins

(Woodside et al., 2015)

Because seawater intrusion was a primary concern in Orange County, the seawater barrier was the first phase of the Groundwater Replenishment System and continues to be the primary focus. The success of the Groundwater Replenishment System and its continued expansion has allowed Orange County to develop new ways to utilize excess recycled water through surface spreading (City of Tucson, 2013). Integration of surface spreading basins into the Groundwater Replenishment System occurred in stages. During the major expansion of the Groundwater Replenishment System in 2008, two spreading basins (Kraemer Basin and Miller Basin) were put into use (Burris, 2015). In 2012, a third basin (Miraloma Basin) was added (Burris, 2015).

The Kraemer and Miller spreading basins were not constructed specifically for the Groundwater Replenishment System; they were pre-existing basins originally constructed to hold stormwater and excess imported water (Burris, 2015). These other water sources were initially utilized to meet the dilution requirements for recycled water as the basins were only permitted to accept 75% recycled water (Burris, 2015). The Miraloma Basin is a new basin that was constructed in 2012 for the purpose of recharging recycled water, so it was designed to prevent any clogging that may occur with recycled water (clogging may become an issue with the older spreading basins) (Burris, 2015; Woodside et al., 2015). As of 2014, all of the basins are permitted to receive 100% recycled water, but the basins continue to receive surface and imported water (Burris, 2015). In 2014, approximately 65,000 acre-feet of water were conveyed to the three basins combined, of which approximately 33,000 acre-feet was recycled water (Burris, 2015). The Miraloma Basin received the vast majority of this recycled water, while Kraemer Basin only received a very limited amount of recycled water (Fig. 12) (Burris, 2015).

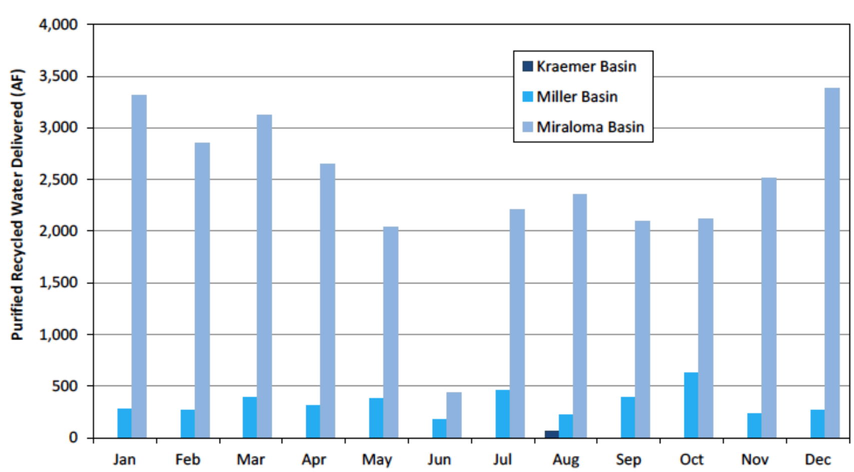

Figure 12: Recycled Water at Kraemer, Miller and Miraloma Basins

(Burris, 2015)

A major benefit of a dual project is the ability to accommodate a fluctuating production of recycled water (Herndon and Markus, 2014). This fluctuation is caused by higher secondary effluent availability during the day and lower availability at night (Herndon and Markus, 2014). It is typically very difficult to regulate flows with injection wells (they are very touchy, and it is hard to control and operate the flow meters) so they should be kept at a constant flow rate (Herndon and Markus, 2014). Dual projects allow for this by simply conveying the excess recycled water to the spreading basins, which can easily accommodate fluctuating volumes of water (Herndon and Markus, 2014).

Abarca et al. (2006) used computer modeling to simulate the effects of a dual project consisting of a direct injection seawater barrier and inland recharge ponds and found that the water that is trapped inland by the seawater barrier would be gradually desalinized by the recharge water. This study also found that surface spreading basins are less efficient than direct injection and it should be used in combination with other measures for maximum efficiency (Abarca et al., 2006). However, surface spreading does have several advantages over direct injection, such as lower cost and less complicated engineering and maintenance, making it a practical method of recharge (Russo et al., 2015). Abarca et al. (2006) concluded that dual projects are ideal for improving groundwater quality in locations that are faced with an already-contaminated groundwater aquifer prior to project implementation, such as the Pajaro Valley Groundwater Basin, because of the efficacy of desalination from a dual project. Desalination of the groundwater is an added benefit of a dual project (in addition to addressing groundwater depletion and preventing seawater intrusion), which increases the projects value and factors favorably into the cost-benefit analysis because existing groundwater supplies are made available for use.

While there are many benefits to a dual project, there are a couple of downsides worth analyzing. In most cases, all of the recycled water is treated to a very high level (i.e., microfiltration, reverse osmosis and UV-light advanced oxidation), even though only the direct injection portion of the system requires this level of water treatment(Dadakis et al., 2011). However, the surface spreading basins receive this high quality recycled water as well because they are accepting the water left over after direct injection. This means that the surface spreading water is more expensive and energy intensive than is required. However, it would not be practical to separate the surface spreading basins into an entirely different project with less-treated recycled water because this would eliminate the benefit of accommodating fluctuations in recycled water output and would necessitate additional treatment facilities and other infrastructure.

Another issue with dual projects is that they make spatial planning more complicated (Dadakis et al., 2011). For example, in Orange County a six-month or 500 foot buffer is required from surface spreading sites to the closest potable use well, but a one-year or 2,000 foot buffer is required for direct injection sites (Dadakis et al., 2011).

Based on the Pajaro Valley's similarity to Orange County in terms of the issues it is facing with seawater intrusion and groundwater depletion, and the results of Abarca et al. (2006), I believe that the Pajaro Valley would greatly benefit from a dual groundwater replenishment project. The Orange County Groundwater Replenishment System serves as an ideal model for implementation of a dual project.

Comparative Analysis of Direct Injection and Surface Spreading

There are many benefits to both direct injection and surface spreading projects. Direct injection is a more direct and effective method of preventing seawater intrusion through operation of a seawater intrusion barrier, and it requires much less land than surface spreading (direct injection only requires a site for the injection well, while surface spreading could require hundreds of acres of land for large projects) (Gasca and Hartling, 2012). Direct injection is also ideally suited for locations where soil permeability is too low for surface spreading, or where recharge of a lower aquifer is needed.

There are also many advantages to surface spreading over direct injection that make surface spreading well-worth implementing in combination with direct injection (Russo et al., 2015). Surface spreading requires less engineering and has lower operating costs than direct injection (Table 6) (Russo et al., 2015). Surface spreading basins are also easier to maintain than direct injection, and clogging issues are much less serious or costly, as evidenced by the case studies previously discussed. One of the biggest benefits of surface spreading is the ability to accommodate fluctuating flow, unlike direct injection wells, which cannot be easily adjusted according to flow due to complicated engineering and operational procedures.

If no action is taken, alternatives such as fallowing of farmland or importing water may eventually be necessary. While surface spreading, direct injection or a dual project would cost between $1,000 and $1,600 per acre-foot, this cost is much less expensive than fallowing farmland to reduce demand for water ($2,845 to $21,444 per acre-foot), and comparable to importing water ($1,500 to $1,800 per acre-foot) (Table 6) (Pajaro Valley Water Management Agency, 2014; Lin et al., 2013; Hanson and Lockwood, 2015; Los Angeles County Economic Development Corporation et al., 2008; Sheehan, 2009).

In addition to the unique benefits of these projects, each project also comes with specific issues, solutions and costs. All of these parameters are described in Table 6 below, along with the implications and costs of a no action alternative.

Table 6: Comparison of Recycled Water Recharge Projects & The No Action Alternative

Project Type	Successes	Issues	Solutions	Est. Cost (per acre-foot)
Direct Injection	- Seawater Barrier - Suitable Where Permeability Is Low - Can Recharge Lower Aquifer -Storage for Later Use	- Clogging -Public Perception -Requires Steady Flow	- More treatment, design wells for cleaning, monitor to identify clogging early, backwash several times per day - Community outreach & involvement -Operate at steady flow and send excess to spreading basins or irrigation	$1,600
Surface Spreading	- Supplements Potable Supply - Accommodates Fluctuating Flow -Provides Natural Advanced (Soil) Treatment; Less Treatment Required at Facility -Opportunity for Public Amenity -Storage for Later Use -Less Engineering	- Clogging - Public Perception -Large Land Requirements - Requires Suitable Site Parameters -Public Health (If Water Receives Less Treatment)	- More treatment, basin system to allow alternate wet/dry and maintenance, scraping/ripping of clogging layer, prevent erosion, shallow basins (reduce weight & compaction) -Provide public amenity & recreation, community involvement & outreach -Use GIS and modeling to identify sites (more permeable land = less land required for same recharge volume) - Use high confidence tracer test to show adequate travel times from recharge to uptake wells	$1,000 to $1,600
Dual Project	-Supplements Potable Supply -Accommodates Fluctuating Flow -Desalination of Water Trapped Inland by Seawater Barrier (Even More Water Available for Use)	-All Water Treated With Advanced Process (Only Required for Direct Injection) -More Complicated Spatial Planning	-Separate conveyance to direct injection to allow lower treatment for other uses -Use GIS and modeling to identify sites that are required distance from wells; use tracer tests	$1,000 to $1,600
No Action	-No Costs Incurred for Recycled Water Recharge Projects	-Continued Intrusion of Seawater and Depletion of Basin -May Necessitate Decrease in Demand	-May require importing water -May require fallowing of farmland (note: data compiled for two most common crops in Pajaro Valley: strawberries and vegetable rows: 1 acre-foot irrigates 0.42 acres of strawberries (worth $51,058/acre) or 0.37 acres of vegetables (worth $7,690/acre)	$1,500 to $1,800 (For CVP Import $21,444 (Strawberries) $2,845 (Vegetables)

(Data Compiled From: Herndon and Markus, 2014; Bouwer, 2002; Martin, 2013b; City of Watsonville, 2010; Hutchinson, 2013; City of Tucson, 2013; Gasca and Hartling, 2012; Megdal et al., 2014; Hartling and Nellor, 1998 as cited in Anderson et al., 2010; Russo et al., 2015; Phillips, 2002; Johnson, 2009b; Abarca et al., 2006; Dadakis et al., 2011; Pajaro Valley Water Management Agency, 2014; Lin et al., 2013; Hanson and Lockwood, 2015; Hanson et al., 2014a; Levy and Christian-Smith, 2011; Los Angeles County Economic Development Corporation et al., 2008; Sheehan, 2009)

Implications and Management Recommendations for Pajaro Valley

Technical Feasibility, Basin Parameters and Site Selection

Basin characteristics (e.g., hydrogeology, land use, location of potable use wells) and the availability of suitable sites determine whether surface spreading or direct injection is feasible for a particular basin. The Pajaro Valley Groundwater Basin has characteristics that make site selection difficult, but the basin is conducive to artificial recharge with careful selection of project location and implementation methods.

Basin modeling and GIS (for soil type, land use, and other map layers) allow for efficient and effective site selection for recharge projects (Balance Hydrologics Inc., 2014). For example, the U.S. Geological Survey's MODFLOW with Farm Process modeling software allows for simulation of recharge projects in a specific region so that the effects of a project at a certain site can be predicted and evaluated, and it has been successfully utilized in the Pajaro Valley (Hanson et al., 2008). The Integrated Hydrologic Model of the Pajaro Valley region created by Hanson et al. (2014b) provides information necessary to predict groundwater demand, availability, flow pattern and other geohydrologic factors, allowing for the most efficient implementation of a groundwater recharge project (Hanson et al., 2014b). This model can determine whether groundwater is able to flow vertically between soil layers or horizontally away from recharge operations (Hanson et al., 2014b; Bouwer, 2002). The Pajaro Valley Integrated Ground and Surface Water Model uses the simulation of groundwater conditions (e.g., hydrology, geology, pumping rates and locations) to model sustainable yield (where recharge meets demand and seawater intrusion is prevented) (California Department of Water Resources Central Coast Hydrologic Region, 2006). The results of this model showed that the current sustainable yield is only 24,000 acre-feet per year (compared to the 70,000 acre-feet of demand), but that the sustainable yield could be increased to 48,000 acre-feet per year if pumping adjacent to the coast was eliminated because the hydrostatic barrier would be strengthened (California Department of Water Resources Central Coast Hydrologic Region, 2006). A direct injection barrier would similarly strenthen the hydrostatic barrier.

The Pajaro Valley Basin can be roughly divided into the upper aquifer system (the alluvial deposits and Upper Aromas Sand formation) and the lower aquifer system (the Purisima and Lower Aromas Sand formations) (Fig. 13) (Hanson et al., 2003). Seawater intrusion occurs mainly in the upper aquifer system, although the lower aquifer system shows signs of intrusion at the mouth of the Pajaro Valley where a slight increase in chloride levels have been measured (Johnson, 1982 as cited in Hanson et al., 2003). A seawater intrusion barrier made up of direct injection wells could address seawater intrusion in both the upper and lower aquifer systems, as wells could be drilled to varying depths based on site specific levels of intrusion.

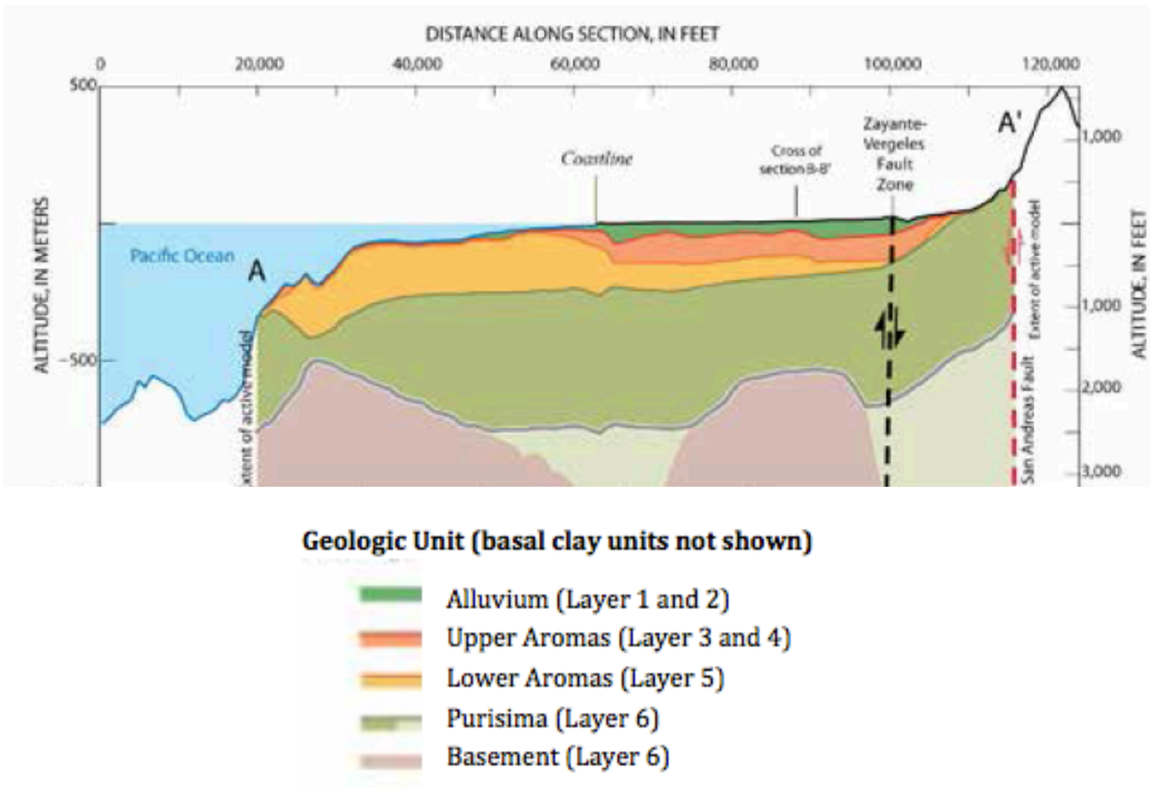

Figure 13: Cross Section of Pajaro Valley Geologic Formations

(Pajaro Valley Water Management Agency, 2014)

Although much of the Pajaro Valley is made up of relatively impermeable clay soils, especially the in the sloughs, the terraces adjacent to the sloughs are largely made up of sandy, permeable soils (Balance Hydrologics Inc., 2014). The existing surface spreading basin (for surface water) lies on the sandy terrace of Harkins Slough, for example (Balance Hydrologics Inc., 2014). These sandy terraces and other sandy sites, which occur along the coast, may provide suitable sites for additional surface spreading basins for recycled water (Balance Hydrologics Inc., 2014). Recharge is also possible in parts of the basin that are made up of clay soils, so long as the clay layers are discontinuous, as is common in the eastern part of the basin (California Department of Water Resources Central Coast Hydrologic Region, 2006). The clay layers also become thinner towards the eastern part of the basin (California Department of Water Resources Central Coast Hydrologic Region, 2006).

Several studies have been completed in the Pajaro Valley to assess basin hydrology and recharge operations, especially at Harkins Slough. Racz et al. (2012) studied infiltration rates of surface water at Harkins Slough to assess variability over time and spatially across the recharge basin. This study found that infiltration rates started at 1 meter per day and remained high for the next 40 days, but dropped to as low as 0.1 meters per day by the end of the study (Racz et al., 2012). This decreased rate of infiltration is evidence of clogging, which was also seen in the recycled water surface spreading case studies and can be easily remedied with scraping and maintenance. Currently, scraping of the spreading basin at Harkins Slough only occurs at the end of the recharge season (Racz et al., 2012). However, if this basin were divided into smaller basins, it would allow for maintenance and scraping during the recharge operations by alternating the recharge and drying cycles, and infiltration rates could be maintained.

Economic Considerations

Aside from the basin characteristics and site availability, which determine whether an artificial recharge project will be effective, costs and economic considerations are a significant aspect of project feasibility. The Pajaro Valley Water Management Agency has been the recipient of many considerable grants to implement sustainability projects. For example, in 2007 the Agency was awarded a grant of $25 million by the Department of Water Resources to implement projects such as the Coastal Distribution System and the Recycled Water Facility (Bartlett, Pringle & Wolf LLP, 2013). The Recycled Water Facility was built at a cost of $32 million, of which multiple grants have funded $12.3 million (Bartlett, Pringle & Wolf LLP, 2013). So, while it would not be wise to count potential grants as guaranteed funds when assessing the economic feasibility of an artificial recharge project, it is likely that a significant portion of the project could be funded by grants, especially because the Pajaro Valley's agricultural output is extremely valuable to the State's economy and new regulations have earmarked grants for groundwater sustainability projects. For example, the Recycled Water Policy states that over the next five years, $1 billion in grants will be available for recycled water projects (State Water Resources Control Board, 2013).

Initial costs to build treatment and distribution infrastructure or injection wells represent the majority of the costs associated with artificial recharge projects (Sheehan, 2009). However, the Pajaro Valley already has several components of the required infrastructure for artificial groundwater recharge with recycled water, most importantly the Recycled Water Facility. However, the treatment process at the Recycled Water Facility would need to be upgraded because it currently produces disinfected tertiary water that is mixed with surface water, which is suitable for irrigation and surface spreading but not for direct injection (Pajaro Valley Water Management Agency, 2011; Anderson et al., 2010). Direct injection would require that the Recycled Water Facility include advanced treatment, such as reverse osmosis, but perhaps the grant funds allocated to the Recycled Water Facility could aid in these costs (Anderson et al., 2010; Levy and Christian-Smith, 2011; Bartlett, Pringle & Wolf LLP, 2013). The Pajaro Valley Water Management Agency (2014) has estimated the cost of this facility upgrade to be approximately $50 million. The economic feasibility (cost per acre-foot) of this upgrade depends on the annual yield and the scale of the project.

Surface spreading would be very economically feasible in the Pajaro Valley. The existing spreading basin adjacent to Harkins Slough provides a site for the pilot stage of a surface spreading project, preventing costs associated with construction of a pilot project for testing and optimizing project design and operation. Aquifer storage and recovery is practiced at Harkins Slough, where excess surface water is pumped to an adjacent infiltration basin for storage, and then the water pumped out of the basin for distribution by the Coastal Distribution System when there is sufficient demand (Hanson and Lockwood, 2015). This surface spreading site could readily accept recycled water, although a conveyance pipeline would be required to transport water from the treatment facility to Harkins Slough, and it would be beneficial to divide the basin into smaller ponds for maintenance purposes (to alternate wet/dry cycles). Surface water could also be accepted at the basin in conjunction with recycled water, but this would require proper management to ensure the surface spreading basins do not become too full which could increase compaction and reduce infiltration rates (Hutchinson, 2013).

Although an artificial recharge project will be expensive ($1,000 to $1,600 per acre-foot), the costs of groundwater depletion, seawater intrusion, or loss of farmland must also be considered (Los Angeles County Economic Development Corporation et al., 2008; Sheehan, 2009). If no action is taken, costly alternatives such as fallowing of farmland will be necessary.

Strawberries are the number one crop in the Pajaro Valley, accounting for 25% of the regions crops, followed by vegetables rows, which account for 22% of the farmland (Lin et al., 2013). One acre-foot of water irrigates 0.42 acres of strawberries (worth $51,058 per acre) or 0.37 acres of vegetables (worth $7,690 per acre), so fallowing these crops would cost between $2,845 (vegetables) and $21,444 (strawberries) per acre-foot of water (Table 6) (Lin et al., 2013; Hanson and Lockwood, 2015). Groundwater depletion could also result in increased pumping costs if groundwater levels fall and deeper wells are needed, which would require construction expenses and increased energy for pumping (Takahiro, 2015). Similarly, if the basin becomes too impaired from saltwater intrusion, remediation may not even be possible or it would require very expensive desalination or importation of water. Implementation of large-scale projects to proactively address groundwater depletion and saltwater intrusion avoids the future costs of remediating the basin, finding new sources of water, or fallowing farmland.

Public Perception

Public perception is a large part of project feasibility. In the Pajaro Valley, negative public perception is not expected to be as much of an issue as in other locations because recycled water has already been in use for several years (although, it has been for non-potable uses). The Pajaro Valley Water Management Agency has a proven ability to provide high-quality recycled water, and recycled water has not caused any adverse public health issues in the Pajaro Valley. The Agency has established their reputation and the trust in the community, which should make passage of an indirect potable reuse project more feasible. The Pajaro Valley residents also take pride in locally sourced water (the Agency has expressed that they would expect a strong opposition to imported water from the Central Valley Project, for example) (Pajaro Valley Water Management Agency, 2014). Recycled water provides a sustainable, local source of water.

Designing surface spreading operations as a public amenity and an opportunity for recreation, as was done with in Tucson at the Sweetwater Wetlands, is another way to improve public perception of a project. If the community is able to interact with the project, see it first-hand, and use it as a recreational space, it could be viewed as a positive amenity. For example, walking paths or areas for bird watching could be integrated into the design for the recharge facilities.

Recommendations for Project Implementation

Implementation of a project to recharge groundwater with recycled water must begin with a feasibility study to identify major roadblocks so that they can be avoided or remedied (Bouwer, 2002). This feasibility study would address technical feasibility (e.g., geologic and hydrologic parameters) through computer models and GIS, which have already been developed for the basin. Economic considerations will also need to be included as part of the feasibility study.

Public health and water quality considerations will need to be addressed to ensure compliance with regulations. This will require careful monitoring of recycled water quality, computer modeling, and tracer tests to ensure that treatment levels and travel times to potable uptake wells are sufficient to protect public health. Recycled water compatibility with the groundwater aquifer must also be assessed to be sure that the recycled water, which lacks minerals, does not have a corrosive effect on the groundwater basin (Dunivan et al., 2010).

Public perception is another important issue that must be addressed very early in the planning process. A communication plan similar to the one implemented in Clearwater, Florida, is recommended. This plan should include public meetings, outreach materials (e.g., website, brochures), surveys, and potentially tours of the facility (City of Clearwater, 2014). Using the surface spreading basins as a recreational opportunity and community amenity, as was done at the Sweetwater Recharge Facilities in Tucson, Arizona, would be an ideal way to increase public support and involvement in the project.

A pilot test should follow the feasibility study to test operation of the project and refine the design for the full-scale project. Harkins Slough would be an excellent site to begin the first stage of the surface spreading operations because it is already in use as a recharge basin (for surface water), and would prevent construction of a new pilot facility. Harkins Slough would likely be large enough to fulfill recycled water infiltration capacity of the Pajaro Valley if the site is only to be used for recycled water infiltration. However, the ultimate goal is to maximize water supply and groundwater levels in the region, so precluding the infiltration of surface runoff would not be ideal. It would be feasible to continue accepting excess surface runoff in conjunction with recycled water, but additional recharge facilities may be required to accommodate the combination of recycled water and surface runoff.

The Pajaro Valley Basin is ideally suited for a dual project, with direct injection along the coast to act as a seawater intrusion barrier and surface spreading basins inland. The Pajaro

Valley would greatly benefit from a dual project's ability to handle fluctuations in supply and demand. Direct injection projects alone require a steady flow of recycled water, as it is very difficult to adjust flows, but surface spreading basins can easily accept varying flows (Dunivan et al., 2010; Herndon and Markus, 2014). The dual project would be designed so that the direct injection wells receive a constant stream of recycled water, and any excess treated water can be sent to spreading basins or utilized for irrigation.

Inland surface spreading is an important aspect of this artificial recharge operation, as it prevents inland withdrawals from pulling water away from the seawater barrier (Hanson et al., 2014a). The water that is recharged by inland spreading basins is also effectively trapped by the direct injection barrier, which allows it to be gradually desalinized by the continual introduction of low-chloride recharge water (Abarca et al., 2006). This is another reason that the Pajaro Valley, which is already impaired by high chloride levels, is ideally suited for a combination of direct injection and surface spreading.

A direct injection barrier would strengthen the hydrostatic barrier along the coast, and models have demonstrated that a strengthened hydrostatic barrier would double the sustainable yield (the amount that can be withdrawn without causing intrusion or depletion) of the groundwater basin (California Department of Water Resources Central Coast Hydrologic Region, 2006). The current sustainable yield of the Pajaro Valley Groundwater Basin is 24,000 acre-feet per year, but with the hydrostatic barrier this could be increased to as much as 48,000 per year (the model was developed based on elimination of coastal pumping to strenthen the hydrostatic barrier, but a seawater intrusion barrier would have a similar effect) (California Department of Water Resources Central Coast Hydrologic Region, 2006). The annual groundwater demand in the basin is approximately 70,000 acre-feet, so there would still be a discrepancy between demand and sustainable yield of at least 22,000 acre-feet per year (California Department of Water Resources Central Coast Hydrologic Region, 2006; City of Watsonville, 2010).

According to the City of Watsonville (which operates the recycled water facility) there is a total of 7,232 acre-feet of wastewater available every year (as of 2015) (City of Watsonville, 2010). The current recycled water treatment facility's 4,000 acre-foot per year capacity is limited mainly by storage availability, so I will assume that the remaining 3,232 acre-feet of secondary treated wastewater (which is currently discharged to the ocean) is available for recycled water treatment (City of Watsonville, 2010; Pajaro Valley Water Management Agency, 2014; Levy and Christian-Smith, 2011). If the current irrigation deliveries of approximately 2,000 acre-feet per year continue, there would still be 5,200 acre-feet available (a number that is increasing every year) for direct injection and surface spreading (Pajaro Valley Water Management Agency, 2014; City of Watsonville, 2010). It might also be feasible to obtain wastewater from neighboring regions (for a fee) to increase the amount of recycled water available.

While the 5,200 acre feet of recycled water recharge may seem like a small amount compared to the basin demand of 70,000 acre-feet per year, it is an important step towards achieving sustainable yield, especially by strengthening the hydrostatic seawater barrier. Recycled water recharge projects should be implemented in conjunction with other water supply and demand projects that are currently in progress in the Pajaro Valley, including 1) the Coastal Distribution System, which delivers almost 2,000 acre-feet of recycled water for irrigation every year, 2) conservation, which is expected to yield 5,000 acre-feet per year, and 3) increased surface runoff capture, which could yield as much as 4,600 acre-feet per year (Pajaro Valley Water Management Agency, 2014). Combined with recycled water recharge, these projects would provide almost 17,000 acre-feet per year, which is significant when compared to the discrepancy between sustainable yield and demand (22,000 acre-feet per year, assuming a strengthened hydrostatic barrier) (California Department of Water Resources Central Coast Hydrologic Region, 2006).

Conclusions

Groundwater recharge with recycled water would be an effective and feasible way to address the rapid groundwater depletion and saltwater intrusion in the Pajaro Valley. Recycled water is a sustainable and reliable source of local water that should be viewed as a valuable resource. Groundwater recharge is an excellent utilization of recycled water as it provides natural storage (which allows for drought mitigation or withdrawal when demand for water increases), soil-treatment (with surface spreading), and it can be used to directly prevent seawater intrusion (with a direct injection barrier).

Lessons learned from surface spreading and direct injection case studies can guide feasibility analysis and implementation of a recycled water recharge project in the Pajaro Valley. Direct injection case studies showed that clogging of injection wells is inevitable and can be costly if not planned for or addressed in a timely matter. However, when a project is constructed with clogging in mind and wells are accessible for cleaning, these costs can be minimized. Clogging was also the main technical issue encountered in the surface spreading case studies. Clogging of infiltration basins, which involves accumulation of solids on the basin surface and leads to a decrease in infiltration rates, can be remedied relatively easily through regular maintenance (i.e., basin drying and scraping). Other considerations and lessons learned from the case studies were the importance of public perception, which requires community involvement to address, and implementation measures, including how to carry out a feasibility study and ensure compliance with water quality regulations.

A dual project of direct injection and surface spreading is recommended for the Pajaro Valley. This would allow for a direct injection barrier along the coastal intrusion zone, with surface spreading inland to supplement agricultural and municipal supplies. The dual project would accommodate varying amounts of water, depending on the seasonal irrigation demand. While a constant flow of water would be sent to the injection barrier (for operational purposes), the excess would either be used for irrigation or for surface spreading, depending on demand.

The Pajaro Valley Water Management Agency has decided to focus on measures such as surface water capture, conservation and above ground storage for the time being, and will reconsider artificial recharge in the future (around the year 2025) if the current projects do not bring the basin into sustainable yield (Pajaro Valley Water Management Agency, 2014). The Pajaro Valley Water Management Agency prioritized these lower cost projects above more complicated and expensive projects such as recycled water recharge (Pajaro Valley Water Management Agency, 2014). However, the recent drought may be cause to re-think a few of the strategies laid out in the Basin Management Plan Update, as surface water supplies cannot be seen as reliable sources with a predictable output. Additionally, a simple assessment of the currently proposed projects (surface water capture, conservation and above ground storage) shows that these projects are expected to yield just over 10,000 acre-feet, which will clearly not fulfill the sustainable yield discrepancy of 22,000 to 46,000 acre-feet (dependent on various factors) (Pajaro Valley Water Management Agency, 2014; City of Watsonville, 2010). Recycled water recharge would bring the basin much closer to sustainable yield, with the potential of increasing basin recharge by approximately 5,000 acre-feet per year and strengthening the hydrostatic seawater barrier, which further increases sustainable yield. Groundwater recharge with recycled water is a local, sustainable, drought-proof water supply that could address seawater intrusion and groundwater depletion in the Pajaro Valley. However, recycled water recharge projects can take up to ten years to plan and permit and require additional time to build and implement (Sanitation Districts of Los Angeles County, 2011). This means that the time to start planning for groundwater recharge with recycled water is now.

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