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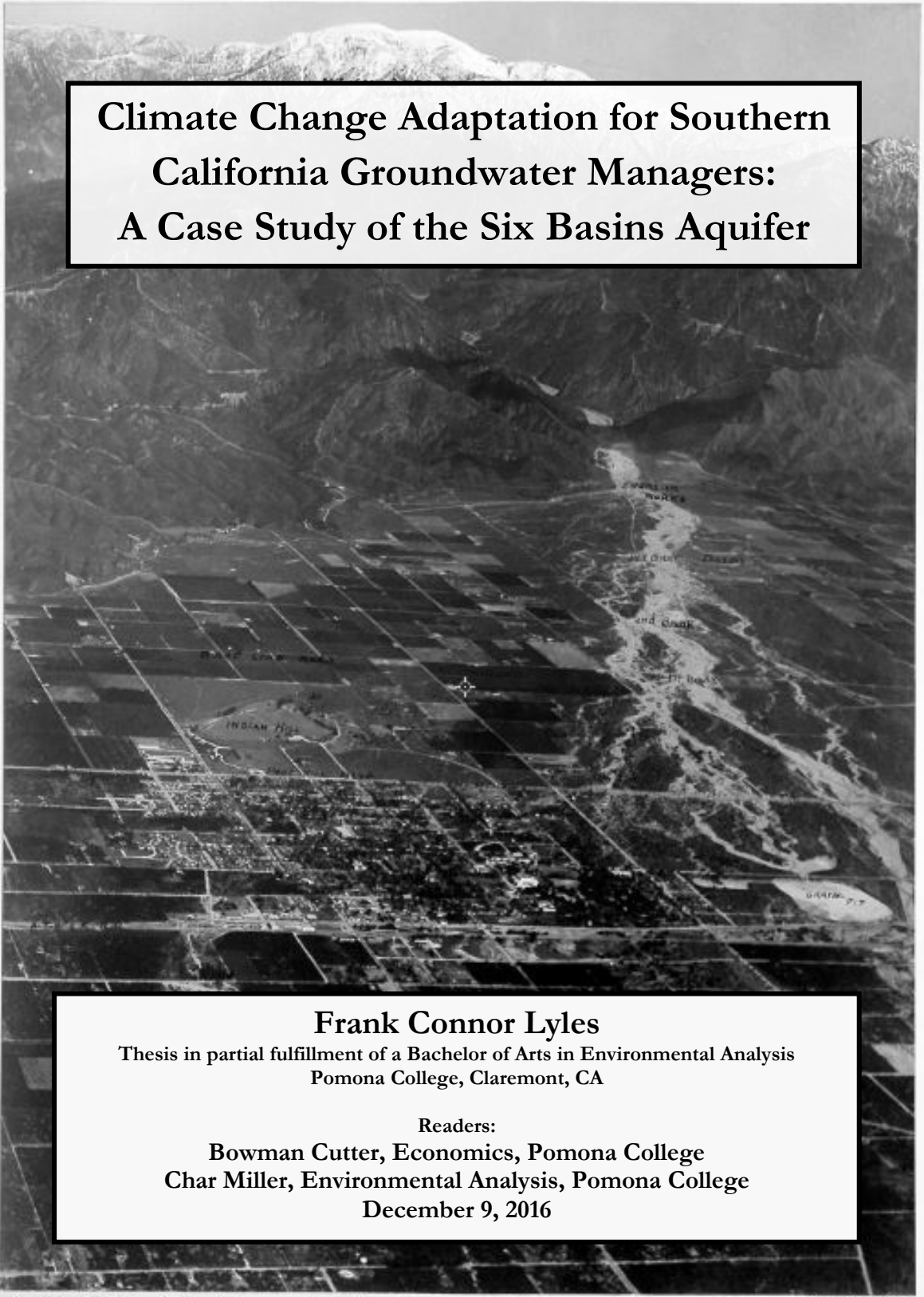
Climate Change Adaptation for Southern California Groundwater Managers: A Case Study of the Six Basins Aquifer

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Climate Change Adaptation for Southern California Groundwater Managers: A Case Study of the Six Basins Aquifer

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Thesis in partial fulfillment of a Bachelor of Arts in Environmental Analysis
Pomona College, Claremont, CA

Readers:

Bowman Cutter, Economics, Pomona College
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December 9, 2016

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Abstract

Groundwater has been very important to the economic development of Southern California, and will continue to be a crucial resource in the 21st century. However, Climate Change threatens to disrupt many of the physical and economic processes that control the flow of water in and out of aquifers. One groundwater manager, the Six Basins Watermaster in eastern Los Angeles and western San Bernardino Counties, has developed a long-term planning document called the Strategic Plan that mostly fails to address the implications of Climate Change, especially for local water supplies. This thesis presents an in-depth analysis of the Six Basin Watermaster's Strategic Plan as a case-study of how groundwater managers can improve their planning assumptions to better prepare for Climate Change. It begins with a brief history of how Southern California's environment influenced the development of the institutions that manage the Six Basins' groundwater, then provides a physical description of the aquifer itself. The current scientific literature on Climate Change's expected impacts on California water supplies are summarized, and the implications of these impacts for basin management are highlighted. The Strategic Plan's projects are evaluated and critiqued in light of these insights, including a need for the Strategic Plan to: explicitly consider Climate Change in its planning assumptions, use decision-making frameworks that account for uncertainty, and prepare for more frequent droughts and floods in the future. Climate Change will have important effects on how Southern California's groundwater is managed, and the Six Basins Strategic Plan should be revised to better account for these impacts.

Acknowledgements

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Introduction

Southern California, like many regions throughout the American Southwest, is highly dependent on groundwater to meet its water needs. This resource is particularly important in a region with highly seasonal rainfall which varies enormously year to year, often making surface water unreliable. Local groundwater can thus act as a buffer, dampening the effects of an erratic semi-arid climate, and enabling urbanization to occur where it otherwise might not. For example, the Six Basins Aquifer in eastern Los Angeles and western San Bernardino Counties has played a crucial role in the development of the cities that overlie it: Claremont and parts of Pomona, La Verne and Upland. The abundant groundwater of this basin, which was naturally recharged by streamflow from San Antonio Creek, allowed early Spanish, Mexican, and later American settlers of the area to develop numerous productive wells and a profitable citrus industry. However, by the first decades of the 20th century, over-pumping and reduced natural recharge due to land-use changes had significantly depleted the Six Basins' groundwater supply.

Faced with this unsustainable situation, major stakeholders in the region initially competed to control San Antonio Creek's valuable water resources. However, over time these groups consolidated into increasingly cooperative water-management institutions. By 1915, the Pomona Valley Protective Association (PVPA) represented almost all organizations with legal claims to the water in San Antonio Canyon, and proceeded to build extensive infrastructure to control flooding and distribute water across spreading grounds to increase infiltration and recharge of the Six Basins aquifer (Hackenberger, 2015). As Southern California's population and demand for water grew rapidly over the 20th century, beyond what could be sustainably supplied by the Six Basins, imported water from the Metropolitan Water District of Southern California (MWDSC) became increasingly important for direct uses; however, local groundwater remained a key part of local stakeholders' water portfolios, in part because it tended to be much cheaper. In 1998, the management of the aquifer was re-adjudicated and put under control of the Six Basins Watermaster (Six Basins Watermaster, 2016). This general arrangement--coordination between stakeholders to spread water from San Antonio Creek to recharge the Six Basins aquifer and thus minimize dependence on imported water--has evolved institutionally but proved relatively stable throughout the 20th century in its mission and approach to the physical problem of water scarcity. While the elevation of the water table has fluctuated over time, the Six Basins Watermaster has calculated and assigned each Party to the agreement an annual "safe yield" to ensure that discharges from wells do not dangerously over exceed recharge.

This arrangement was well-suited for the climate regime of the 20th century, with its numerous multi-year wet and dry periods scattered around a historic annual mean of 23 inches of rain per year (WEI, 2015, fig. 2–2d). However, the Six Basins Watermaster will face profound challenges in the 21st century. Demand for water will remain high, despite conservancy efforts (WEI, 2015, Chapter 3). More serious however, is the threat to water supply: California's 2011-2016 drought, already the worst on record (Diffenbaugh, Swain, & Touma, 2015), shows no signs of abating at the time of this writing (Margulis et al., 2016). The Parties to the Six Basins Watermaster have anticipated this, and developed a Strategic Plan in 2013 they hoped would

improve basin management and offer higher safe yields into the future. Their forecasting models, however, are based exclusively on historical precipitation. Climate Change is already disrupting those historic patterns and is expected to make prolonged droughts and severe floods more common in Southern California, in addition to exacerbating the already high level of variability in rainfall year to year (Diffenbaugh et al., 2015). In coming decades, temperatures and evapotranspiration are expected to rise, and rainfall will occur more variably in fewer discrete severe storm events, although mean precipitation may not decline (Cayan, 2009). These climatic changes will fundamentally disrupt the balance of recharge and discharge that Southern California's managers of groundwater, like the Six Basins Watermaster, have grown accustomed to. The Six Basins Strategic Plan, which was finalized in 2015, fails to properly anticipate the impacts Climate Change, especially on local water resources.

Given the anticipated disruptions to Southern California's climate in the 21st century, it is vital that Climate Change's impacts on groundwater are carefully considered. By synthesizing the Six Basins' Strategic Plan with Climate Change literature and a series of semi-structured interviews with key individuals, this study attempts to provide a detailed, holistic view of the challenges to sustainable management of the Six Basins Aquifer. Imperial units (acre-ft, miles, degrees F) rather than metric units are used, to be consistent with the units commonly used within the water industry.

This study begins by tracing how historic climatic and geologic factors helped shape the institutional evolution of what eventually became the Six Basins Watermaster. The next chapter provides a general physical description of the Six Basins aquifer and the infrastructure used to manage it. The third chapter evaluates the degree to which Climate Change is likely to disrupt historic precipitation patterns in the watersheds that supply the Six Basins and the fourth chapter summarizes the implications of these changes for groundwater basin management. The fifth chapter analyzes how the Strategic Plan hopes to improve basin management in the future, and whether these projects adequately anticipate and prepare for projected changes in water availability: will the proposed projects be enough to ensure reliable yields? This study concludes with policy recommendations for the Six Basins specifically, and some reflection on what these findings imply for other California groundwater managers.

Historical Background

When in the latter half of the 19th century American settlers first began settling at the foot of the San Gabriel Mountains around the mouth of San Antonio Canyon—land that would eventually become the cities of Claremont, Upland, Pomona, and La Verne—the landscape they encountered was drastically different than the heavily urbanized one visible today. The flora was dominated by sagebrush, and San Antonio Creek was a massive braided wash, with multiple channels and a propensity for destructive floods. Despite the occasional danger posed by the flood-prone wash, the area offered many features that made it attractive for development. It sat along the course of the Santa Fe Railroad and later Route 66 and featured numerous natural springs and artesian wells, which discharged water under pressure and thus eliminated the need for costly

pumps (Hackenberger, 2015, p. 26). The combination of easily available transportation and water made Claremont an ideal place for the development of a profitable citrus growing industry: “In 1889, the same year Pomona College moved to Claremont, Peter Dreher planted an orange grove in Claremont, kicking off a citrus boom that would fuel both the town’s and the colleges’ rapid growth” (Hackenberger, 2015, p. 16).

Despite the relative abundance of natural springs above what would later be called the Six Basins Aquifer, surface water in San Antonio Creek was of obvious importance as well. As the cities below the canyon mouth grew in the late 19th and early 20th centuries, competition for control of the water resources flowing from San Antonio Canyon only intensified. In the 1880s, the new cities of Pomona and Ontario consolidated their water rights and built the first dam in the canyon to allow them to measure and divide the creek’s waters (Hackenberger, 2015, p. 28).

By harvesting the water before it could reach the canyon mouth, however, the competing interests had interrupted the natural process of groundwater recharge. In 1883, geologist E.W. Hilgard “discovered the connection between the water in San Antonio Canyon and the area’s artesian wells,” namely that the former recharged the latter (Hackenberger, 2015, p. 31). If stakeholders plundered the water of the creek, their wells would quickly dry up. “By the 1890s, the water table had fallen far enough for most of the area’s artesian wells to run dry, forcing their owners to install pumps. In 1904, a study by W.C. Mendenhall confirmed that wells in the area were exceeding the capacity of the San Antonio Creek to naturally replenish them--and the situation was becoming dire” (Hackenberger, 2015, p. 31).

The same year Mendenhall published his study, geologist Willis S. Jones discovered the existence of “definite boundaries” of an natural underground reservoir—what would later be recognized as the San Jose Fault on the eastern edge of the Six Basins aquifer (Jones, 1904). Jones began a 10-year evaluation of how to control and spread floodwaters from San Antonio Creek to most effectively recharge the badly depleted groundwater. He eventually concluded it would be necessary to build a new dam at the mouth of the canyon with gates to a sluiceway, then side channels and smaller ditches to spread and infiltrate water across spreading grounds south of the dam (Hackenberger, 2015, p. 32). Around this time, he began arguing that the Pomona Valley Protective Association should guide this replenishment of groundwater. The PVPA positioned itself as the group representing the collective interests of cities west of the wash (such as Claremont and Pomona) that wanted to let water down to the mouth of the canyon and spread it to recharge the aquifer. Heeding Jones’ recommendations, the PVPA bought 650 acres of wash lands below San Antonio Dam. Simultaneously, it began aggressively litigating against San Antonio Water Company (SAWC) which wanted to hold water above the mouth of the canyon and then run it through pipes down to cities on the east side of the wash such as Upland and Ontario (Hackenberger, 2015, pp. 32–34).

In 1915, the PVPA succeeded in its litigation when a California Supreme Court decision finalized control of flood waters from San Antonio Canyon. The PVPA “won the right to have all waters except a limited amount come down to the mouth of the canyon” (Hackenberger, 2015, p. 34). That year, they began building spreading infrastructure in earnest. Soon afterwards, the

SAWC joined the PVPA, thus positioning the PVPA as the representative of nearly every important stakeholder with claims to San Antonio Creek's water (Hackenberger, 2015, p. 36).

Just as this institutional infrastructure was being finalized, in 1916 a flood overtopped the dam, destroyed the newly constructed spreading infrastructure, and threatened Pomona College on the west side of San Antonio Wash. The PVPA, of which Pomona College is a member, responded in 1917 by building a larger dam and reconstructing and expanding Jones' plan of sluiceways, dikes, dams, and reservoirs to slow debris and infiltrate water at what became known as the San Antonio Spreading Grounds (SASG). (Hackenberger, 2015, p. 35)

Even this was not enough; floods still threatened cities built along the wash. In 1936, The United States Congress finally passed the Flood Control Act as part of the New Deal, which authorized the study of creeks and their potential for flooding. Then, during a 5-day storm that reached its climax on March 2, 1938, torrential rainfall overwhelmed flood control infrastructure across Southern California, including the PVPA's dams in San Antonio Wash. Some places along the front range of the San Gabriel Mountains experienced up to 30 inches of rain during the storm;



Figure 1: Powerful floods in 1938 covered Foothill Blvd in Claremont with water and debris. (Ackerman, 1938.)

locations within the San Antonio Canyon watershed received up to 12 inches in a single 24-hour period (Burke, 1939). The debris-rich flood waters rushed down the wash, breaching dams and depositing watermelon-sized boulders on Claremont's nearly destroyed Foothill Boulevard (**Figure 1**). The flood also inundated Pomona College's campus on the west side of the wash (**Figure 2**). Throughout Claremont, the damage was at once extensive and sobering (Ackerman, 1938.).

In response to the destructive flood, which killed six people in the Pomona Valley and 81 more around Southern California (Burke, 1939), Congress amended the Flood Control Act to authorize the Army Corps of Engineers to create a flood control basin for San Antonio Creek. In 1956, the San Antonio Dam was completed, and for the first time, Claremont and its neighbors enjoyed relative safety from floods.

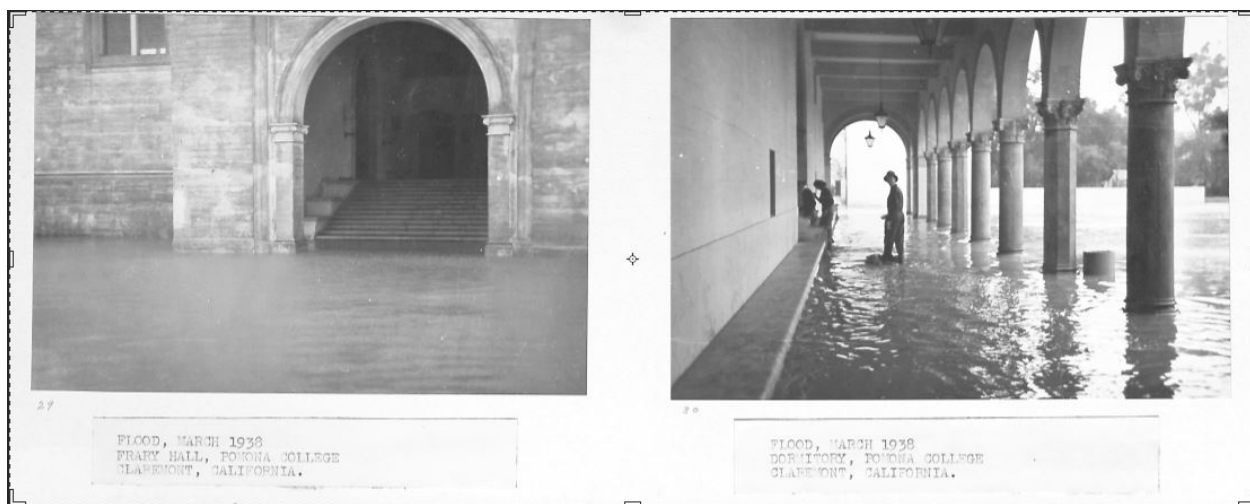


Figure 2: Pomona College, on the west side of San Antonio Wash, also experienced severe damage in the floods of 1938. (Ackerman, 1938.)

The dam, beyond simply protecting the communities already built, also triggered significant land use changes along the wash. Gravel mining expanded dramatically in the area south of the spreading grounds, on lands owned by the PVPA. Land that had once been too vulnerable to floods could now safely harbor long-term industrial activity, and gravel was in high demand in the post-World War II era due to the need for aggregate to make concrete during Los Angeles' huge road building boom. As a result of this extractive industry, San Antonio wash has now been heavily mined, with urban retail and residential development on other reclaimed wash lands filling in the gaps such that relatively little of the original sagebrush survives. What was historically (and especially geologically) a volatile, dangerous, and unpredictable landscape is now extensively controlled, managed, and urbanized (Hackenberger, 2015, p. 42).

As the San Antonio Canyon Dam has aged, however, the illusion of safety it provides for the communities built on the reclaimed wash below has grown increasingly thin. The Army Corps of Engineers has detected evidence of significant seepage through the foundation of the dam and has classified the San Antonio Dam as "Level II- urgent, Unsafe, or Potentially Unsafe" which indicates that "failure could begin during normal operations or be initiated as the consequence of

an event. The likelihood of failure from one of these occurrences, prior to remediation, is too high to assure public safety; or the combination of life or economic consequences with probability of failure is very high.” (United States Army Corps of Engineers, n.d.) This is the second most urgent designation the USACE issues, superseded only by dams that pose an imminent risk of failing during normal operations within a few years. An Issue Evaluation Study began after the Dam’s Level II classification in 2008 (United States Army Corps of Engineers, 2016), which ultimately recommended \$14m worth of repairs to the dam, to be paid for entirely by the federal government. \$1m of that was allocated in 2013, but no funds were allocated in 2014 or 2015 (United States Army Corps of Engineers, 2015). At the time of this writing, the “urgent” safety issues of the dam remain unresolved, and the extensive development that has occurred on reclaimed wash lands since the dam’s construction means that far more structures lie within the historical floodplain than in 1938.

The wash, of course, was not the only thing to be rapidly developed in the latter half of the 20th century. The entire population and economy of the region grew explosively after World War II, and despite the PVPA’s efforts to represent all interests with regard to local water needs, local water alone simply could not keep up with Southern California’s boom. City governments increasingly turned to imported water from the Sierra Nevada and Colorado River watersheds, provided by Metropolitan Water District of Southern California (MWDSC) via wholesalers like Three Valleys Municipal Water District (TVMWD). Certain rights-holding parties such as Pomona College found it more convenient to lease their pumping rights to utilities like Golden State Water Company, a for-profit corporation. With so many interconnected interests at play, the old legal framework was insufficient to guarantee proper management of the Six Basins Aquifer. In 1998 the PVPA, groundwater producers, utility providers, buyers of water in the Pomona Valley and others stakeholders entered into a “stipulated judgment” in the case *Southern California Water Company v. City of La Verne et al.* to find a physical solution to the complexities of the aquifer’s management (PVPA, 2016). The judgement established a Watermaster to oversee the physical solution: a maximum safe annual yield from the aquifer of 19,300 acre-ft/year, the allocation of production rights to individual parties, transfers between parties, carryover rights into subsequent operating years, as well as rules for many operating and management procedures (Superior Court of the State of California for the County of Los Angeles, 1998). It stipulates how unused storage space may be used by individual parties as well as how parties can expand their production rights through special projects. The judgement recognizes that, in times of unusually high precipitation when there is risk of high groundwater damaging shallow infrastructure, it may be in the Parties’ best interests to declare temporary surplus production rights above and beyond the usual Operating Safe Yield (OSY). The Six Basins Watermaster is a committee, not a person, and the PVPA remains one of the key players, along with the Cities of Claremont, La Verne, Pomona, and Upland, Golden State Water Company, Pomona College, San Antonio Water Company, Three Valleys Municipal Water District, and West End Consolidated Water Company.

By 2012, certain Six Basins Parties were still not fully satisfied with the arrangement; the Watermaster’s hydrology computer models were outdated and some Parties desired “a better

technical approach” to monitoring and managing the aquifer. The Parties decided voluntarily to further improve their management of the Six Basins by developing and implementing a Strategic Plan (WEI, 2015, sec. 1.2). Core values articulated in this new Strategic Plan, which was completed in 2015, include: increasing local supplies, storm water recharge, and water quality; managing unused groundwater storage; minimizing the cost of water; and “striv[ing] to take the long view” in planning assumptions. Although some attention is paid to future storms and droughts, and the effect of Climate Change on the price and availability of imported water is considered in basic detail, the Strategic Plan completely ignores the effects of Climate Change on local water supplies.

This brief history of the PVPA and Six Basins highlights two critical themes in the face of anticipated future Climate Change. The resource that the Six Basins Watermaster manages is highly dependent on local precipitation within the San Antonio Canyon watershed, but this watershed is a volatile environment under the best of circumstances. The institutional arrangements that evolved to manage and exploit local groundwater supplies have coped well with rainfall variability to date but they appear to be ignoring the likely effects of Climate Change in their future planning models. If the 21st century’s climate is likely to significantly deviate from historic patterns, the Six Basins may find its key source of water critically disrupted. In other words, this region has *always* experienced floods, droughts, and variable rainfall, and the success of institutions in coping with these challenges up to now may be distorting their assessment of the risk posed by the novel challenges of Climate Change in the 21st century.

Second, Climate Change carries the risk of increasing the magnitude of storm events, which have had a long and well-documented history of destructive floods along the wash. As the San Antonio Dam continues to age, the protection it can offer the now highly urbanized wash below must be seriously reevaluated. Its Level II classification indicates it may prove unable to cope with floods of 20th century magnitude, let alone the potentially larger floods to come. Given the dam’s crucial role protecting against floods, trapping sediment, and channeling water to the SASG, its resilience deserves detailed consideration.

Physical description of the Six Basins Aquifer

The Six Basins Watermaster’s Strategic Plan, released in 2015, includes a detailed description of the physical characteristics of the aquifer, including its boundaries, infrastructure, and data on the local precipitation it is so dependent upon for recharge. The following chapter draws heavily upon that report.

Fundamentally, an aquifer is any body of rock or regolith with sufficient porosity and permeability to provide water in useful quantities (Smith & Pun, 2009). Porosity is the total volume that is in pores, i.e. space not filled by rocks and thus potentially available to be filled by water. Permeability is a measure of the connectivity of those pores, and thus water’s ability to flow through porous material. In general, the best aquifers are unconsolidated sandy and gravelly sediments, similar to those found in the Six Basins. Aquifers are recharged by surface water infiltrating deeply into the soil and then percolating downward, until it reaches the level where all

pore spaces are saturated, known as the water table. The elevation of the water table in the Six Basins varies both over time, as a function of recharge and discharge rates, and spatially by location, in a loose mimicry of the land surface elevation complicated by subsurface barriers to water flow. For these reasons, ground water tends to flow from higher elevation areas of net recharge towards lower elevation areas of net discharge (Smith & Pun, 2009)—that is, from the Upper Claremont Heights Basins south toward Pomona Basin (**Figure 3, Figure 5**).

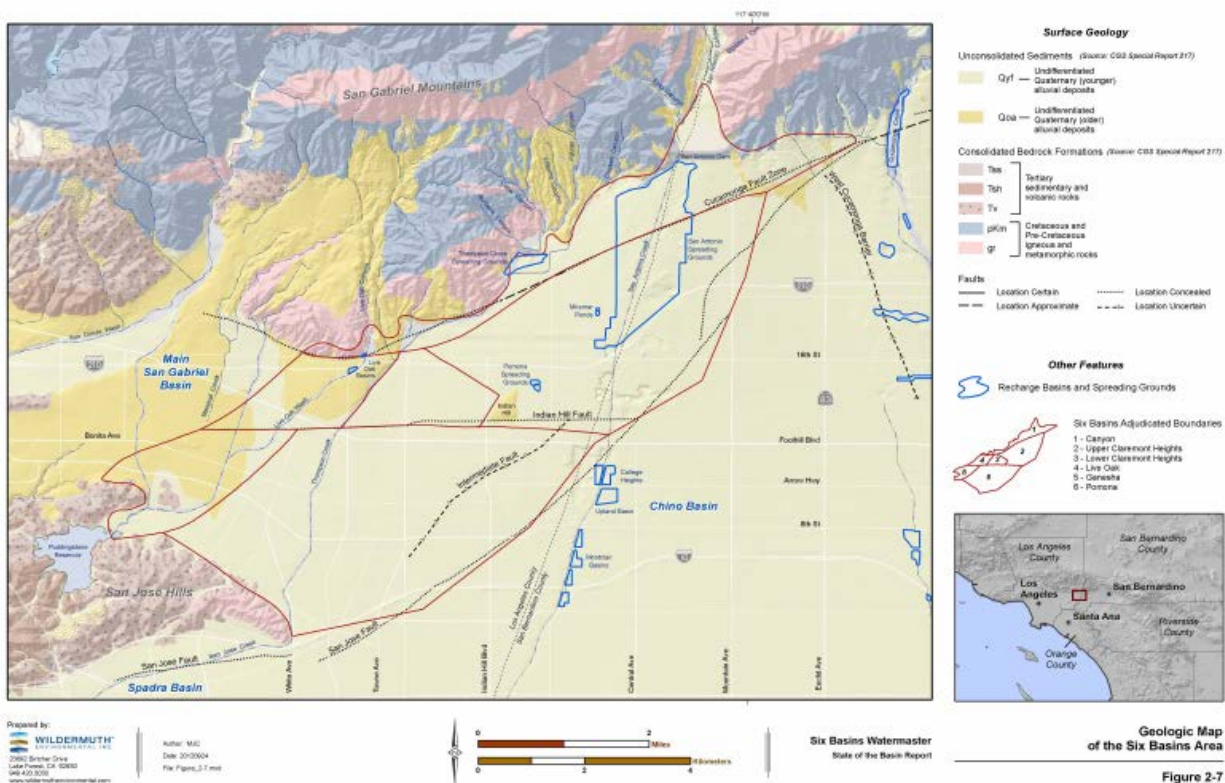


Figure 3: This map shows surface geology of the Six Basins area and the six subbasins that compose the aquifer, outlined in dark red. Spreading infrastructure is marked in blue. (WEI, 2015, figs. 2-7)

The geologic history of the Six Basins aquifer begins with the formation of the San Gabriel Mountains 5-7 million years ago, when very old crystalline basement rocks were uplifted by tectonic compression and faulting to create the Transverse Ranges of Southern California (Matti & Morton, 1993). As the mountains were rapidly uplifted and simultaneously eroded, huge quantities of sediment washed out of mountain canyons and were deposited as alluvial fans in the valley below. (This process, still very much active in the early 20th century, was the reason floodwaters were so debris-rich and destructive in the floods of 1917 and 1938.) Over millions of years, these alluvial sediment stacks grew to thicknesses of over 1000ft in places, consisting of “discontinuous layers of gravel, sand, silt, and clay,” and these sediments are where the vast majority of groundwater in the Six Basins is stored today (WEI, 2015, sec. 2.2.2.2). The water-bearing sediments can be subdivided two groups: older Pleistocene alluvium of interstratified fine-grained clay-rich layers and coarser-grained sandy and gravelly layers; these deposits are overlain by younger Holocene alluvium that is typically fresher, less weathered, and more permeable. The

older alluvium tends to be much thicker and contain most of the Six Basins' groundwater; the younger alluvium by contrast is commonly unsaturated (WEI, 2015, sec. 2.2.2.2). The entire sedimentary complex is underlain by crystalline basement rocks of very low permeability (WEI, 2015, sec. 2.2.2.1).

The Six Basins Aquifer, as Willis S. Jones first noted in 1904, has “definite boundaries” (Jones, 1904). From below, relatively impermeable basement rocks block the downward flow of water at particular depths, which vary by location but generally reflect the now buried topography of the valley prior to being filled with sediment. These basement rocks rise to the surface in the San Gabriel Mountains immediately north and San Jose Hills immediately southwest of the aquifer, again creating a definitive barrier to groundwater movement. To the southeast runs the San Jose Fault, which is not readily visible on the surface but presents a significant barrier to groundwater, as evidenced by the fact that groundwater levels “can be more than 600 feet higher in the Six Basins compared to groundwater elevations in the Chino Basin” on the other side of the fault. Even so, some relatively small (but as of 2016 still poorly quantified) amount of water discharges across the fault, especially when water levels are high. The western boundary of the Six Basins with the San Gabriel Basin corresponds to a surface water divide, but is somewhat arbitrary, because water-bearing sediments are continuous across it. During periods of low groundwater elevation, the water table sinks below the level of a subsurface bedrock ridge and the two basins become separated, and during higher water levels, water tends to mound above this ridge and flow into both basins; thus it seems unlikely that there is significant discharge from the Six Basins into the San Gabriel Basin across this divide (WEI, 2015, sec. 2.2.2.1). These physical boundaries more or less (but not exactly) match the adjudicated legal boundaries of the Six Basins, which has huge implications for groundwater management, because it means that water is mostly unable to discharge naturally out of the adjudicated boundaries of the basin.

The Six Basins also contain a number of internal features which separate the adjudicated area into subbasins, hence the name “Six Basins” (see **Figure 3**). The most important features are the Cucamonga Fault separating Canyon Basin from Upper and Lower Claremont Heights Basins, the Indian Hill fault separating Lower Claremont Heights Basin from Pomona Basin, and the Intermediate Fault within Pomona Basin. Groundwater flows across these features, but less readily than it otherwise would. Pomona Basin also has particularly complex stratigraphy with many discontinuous confining layers, which impede groundwater flow within the subbasin, and these geologic structures are still not understood in detail at the time of this writing. Because of these internal barriers and the fact that different Parties have pumping rights in different areas, it is sometimes convenient to divide the six subbasins into two groups: Live Oak and Ganesha Basins together are the Two Basins, while Canyon, Upper Claremont Heights, Lower Claremont Heights, and Pomona Basin are sometimes referred to as the Four Basins. For most purposes, however, it is reasonable to think of the entire Six Basins as functionally one groundwater aquifer.

The Six Basins is recharged via a number of pathways, some of which are natural and some of which are the result of human intervention (WEI, 2015, sec. 2.2.4.4):

- “Subsurface inflow from the saturated alluvium and fractures within the bordering bedrock hills and mountains,” which contributes an average of 28% of total recharge for the Basins.
- “Infiltration of applied and imported surface water at the spreading grounds that overlie the Six Basins” which can be extremely variable year to year, depending on precipitation, but averages around 37% of total recharge for the Basins, with 25% coming from native supplies and 12% from imported water.
- Deep infiltration of precipitation and applied water (DIPAW) including the contributions from rainfall directly onto permeable surfaces, water that flows from impermeable surfaces onto permeable surfaces, and irrigation water, which “when combined is surplus to evapotranspiration demand and soil water storage capacity.” DIPAW accounts for an average of 32% of recharge.
- Deep infiltration of septic tank discharge, around 1% of total.
- Streambed infiltration in unlined channels, also around 1% of total.

Obviously, the water of San Antonio Creek is crucial for recharge of the Six Basins Aquifer, but during most of the year, no water actually reaches the mouth of the canyon or the spreading grounds below. That is because the SAWC and the City of Pomona still retain their historic rights to the surface water of the creek. About one mile upstream of San Antonio Dam, the creek enters the Edison power house’s splitter box which collects and divides the creek’s water, allocating approximately 60% to SAWC and 40% to the City of Pomona, who pipe the water out of the canyon for potable and non-potable municipal uses (WEI, 2015, sec. 2.1.3.3). (Note that both the SAWC and the City of Pomona are parties to the 1998 adjudication of water rights in the Six Basins, and that agreement reaffirmed their right to harvest surface water for direct uses rather than allowing it to be used for groundwater recharge.) In periods of high flow in the creek, when water volumes are in excess of the Edison Box’s capacity, all water not captured by the splitter box is allowed to flow down to the mouth of the canyon and be spread by the PVPA. This means the PVPA only receives water to recharge the aquifer during the rainy season of relatively wet years: “In 28 of the last 51 years, diversions of the SASG totaled less than 1,000 acre-ft and in 11 of those years, there were no diversions” (WEI, 2015, sec. 2.1.3.3). (By contrast, the SAWC and City of Pomona have received a much more consistent and reliable quantity of surface water year to year.)

The Six Basins Aquifer, before human modifications to land use, was recharged by water naturally infiltrating into the highly permeable sediments of San Antonio Wash. The San Antonio Spreading Grounds (SASG) today, while extensively engineered, still rely on that basic principle, which is related to the fact that San Antonio Wash’s Holocene alluvium is highly permeable. After a heavy rain event, as debris-rich floodwaters run down San Antonio Canyon in excess of the capacity of the Edison splitter box, they are slowed by San Antonio Dam and most of the sediment load is deposited above the dam. The relatively clear water is then channeled through diversion gates from the dam down to the SASG, where it is divided amongst a complex system of infiltration pits, berms, and unlined infiltration channels. “There are no recent studies on the percolation rates

at the SASG, but a 1937 study showed that after initial saturation, percolation rates ranged from 0.8 cfs/acre to 6.7 cfs/acre depending on the level of improvement” (WEI, 2015, sec. 2.1.3.3). Local runoff is by far the most important source of water for recharge in the Six Basins, but a limited amount of water (typically less than 1000 acre-ft per year) comes from imported water provided by Three Valleys Municipal Water District (TVMWD).

Ideally, San Antonio Dam would be used to hold runoff temporarily in a conservation pool, and then release that water through the spillway only at the rate at which it could be safely recharged at SASG. Unfortunately, the USACE currently operates the dam exclusively for flood control, not for water conservation, so the dam’s operators are not allowed to consider water conservation criteria when deciding how quickly to release water. If a rainfall event is large, water from San Antonio Dam is often released faster than the SASG’s capacity to infiltrate it, and excess water is diverted to the concrete-lined San Antonio Creek Channel, which drains to the Santa Ana River and is lost to the Six Basins. Similarly, water that enters the SASG but does not infiltrate is returned to the San Antonio Creek Channel. In wet years or very large storms, the amount of water lost can be quite large; since water year 1961, “309,166 acre-ft of surface water, or 56% of total discharge, was diverted to the SASG for recharge; 245,203 acre-ft was not.” During extremely wet

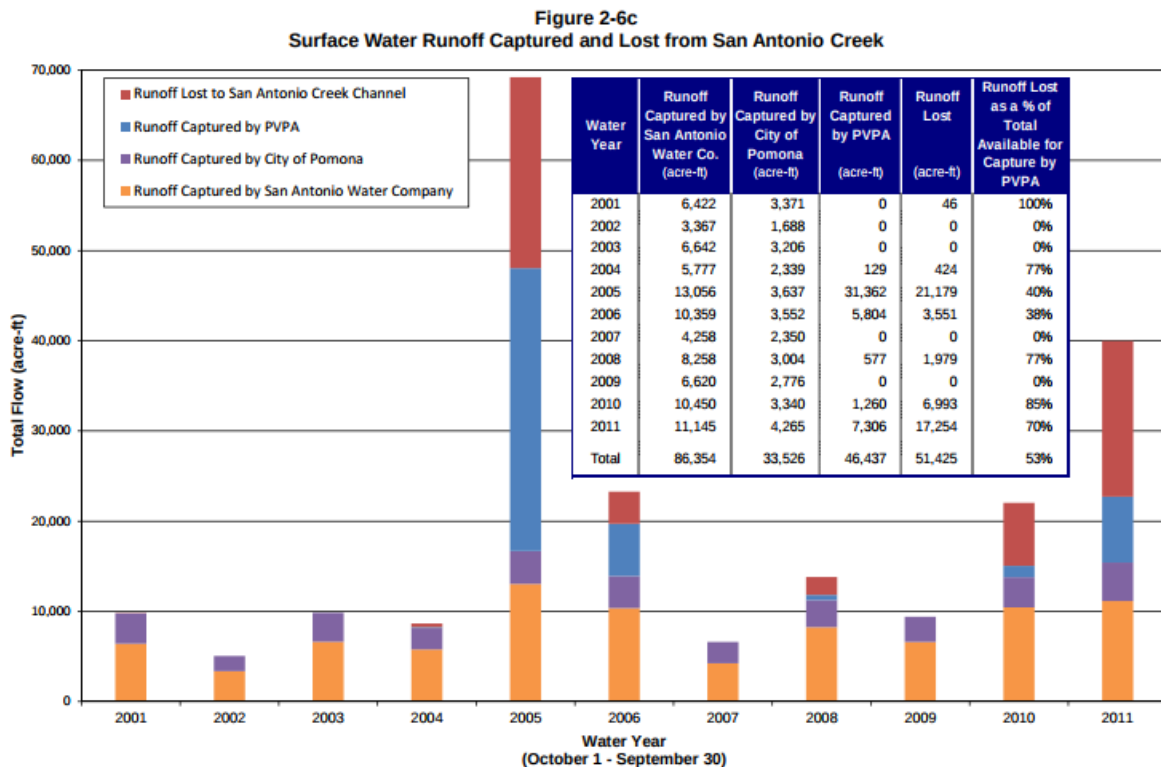


Figure 2-6c SASG Loss Analysis--Figure 2-6c
1/12/2013



Figure 4: Surface Water Runoff Captured and Lost from San Antonio Creek. Note that the total volume of water available varies enormously year-to-year. While the City of Pomona and SAWC receive a relatively consistent volume of water from the Edison Splitter Box each year, the PVPA only has water available for recharge in less than half of all years. When runoff volumes are particularly large, a high percentage of it is lost to San Antonio Creek. (WEI, 2015, figs. 2-6c)

years, the percentage of water diverted for recharge is even lower; for example, the PVPA was able to recharge only 30% of total available water in 2011 (WEI, 2015, sec. 2.1.3.3). The lack of any surface storage reservoirs intended for conservation purposes upstream of the spreading grounds is a major reason for this low efficiency (**Figure 4**).

The SASG is the main recharge facility for the Six Basins, and the one that this study focuses on primarily, but the PVPA manages two other smaller spreading grounds as well, at the mouth of Live Oak Wash and Thompson Creek. However, these two additional recharge facilities sit at the mouths of much smaller drainages that together contributed only slightly over 6% of the total water captured and infiltrated by the PVPA between 2001 and 2011. The SASG contributed almost 94% of the total captured water. Part of that disparity is due to lack of efficient infiltration at Live Oak and Thompson Creek spreading grounds; they lost 77% and 56% of the available water in their drainages, respectively, because they too struggle to quickly infiltrate sudden pulses of runoff. But even in terms of total available water, they are dwarfed by San Antonio Canyon's much larger volumes. For this reason, San Antonio Creek and the SASG are given much more attention in this study than their smaller counterparts. "All three creek systems are concrete-lined for their entire course across the Six Basins. Thus, any surface water discharge that by-passes the spreading grounds is a water resource that is lost from the Six Basins," although it can be utilized by other parties downstream (WEI, 2015, sec. 2.1.2).

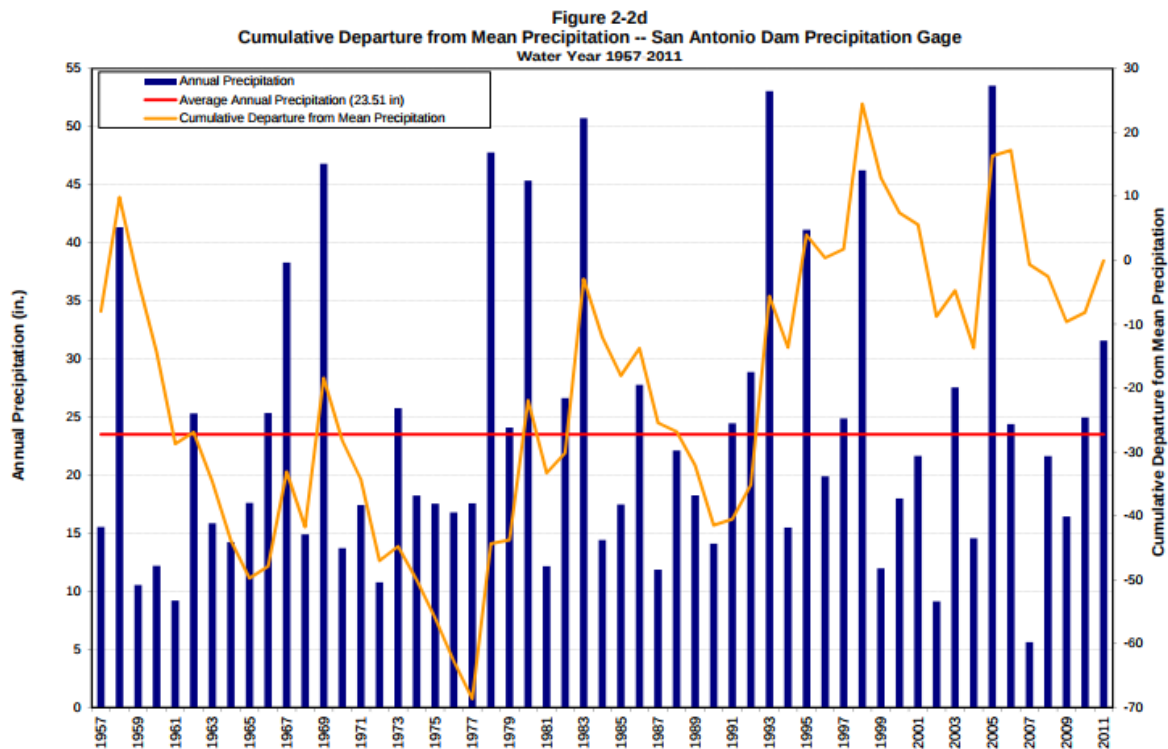


Figure 2-2d -- SanAntDam_CDFM
1/7/2013

Figure 5: Annual precipitation as measured at San Antonio Dam is extremely variable, and very rarely is there an average year. Rainfall can vary by nearly an order of magnitude from one year to the next. (WEI, 2015, figs. 2-2d)

Clearly a crucial variable in determining how much water reaches the spreading grounds and ultimately is recharged into the aquifer is local precipitation. The Six Basins specifically and Southern California in general lie within a Mediterranean Climate regime, which is characterized by hot dry summers and relatively mild wet winters, with the heaviest rainfall usually from “November through April, with the greatest monthly precipitation occurring in January and February” (WEI, 2015, sec. 2.1.1). This means that water is most needed during the hot summers when it is least available, a challenge to which the native flora and fauna have creatively adapted. Humans have attempted to adapt too, by storing water from wet winters where they can, such as in the Six Basins aquifer.

The challenge posed by highly seasonal rainfall is compounded by high variability year to year. **Figure 5** shows annual precipitation as measured at San Antonio Dam from 1957-2011. As is immediately clear, in reality there is rarely an “average year”; rainfall fluctuates enormously, and “there are generally three to five years of consecutive, below average precipitation before an average or above year occurs” (WEI, 2015, sec. 2.1.1).

The vast majority of managed recharge for the Six Basins occurs at the SASG, which overlies the Upper Claremont Heights subbasin. From there, groundwater tends to migrate south through the other subbasins, temporarily mounding at the Indian Hill Fault, and ultimately arriving in the Pomona Basin. **Figure 6** shows groundwater levels in feet above mean sea level for fall 2011, following a period of relatively heavy rainfall. Water elevations generally decline to the south, but are complicated by internal barriers to flow such as the Indian Hill Fault and Intermediate Fault. Water would naturally flow along this north-south gradient, but the process is enhanced by the fact that the land overlying the Pomona Basin has been extensively urbanized so very little natural recharge happens from surface water to that basin directly. The wells that tap the Pomona Basin are dependent on subsurface recharge for the continuing sustainability of their yields.

Water quality issues in Six Basins are complex. The legacy of agriculture and industrial activity has left many contaminants—point and nonpoint sources—in the groundwater, particularly in Pomona Basin. Chief among these are dissolved solids, nitrates from citrus farming, perchlorate, and trichloroethylene, among others. Low water quality is a major limiting factor for production of groundwater, because of the high cost of treatment and lack of treatment capacity. Poor water quality also limits the potential for recharge of recycled water, because current contaminant levels mean that groundwater does not meet the legal requirements to have “assimilative capacity” to accept more polluted water. As a result, the Six Basins can only be recharged with relatively high quality run-off from the San Gabriel Mountains or treated imported water. The cleanest, best water comes from Upper Claremont Heights Basin, because it is recharged regularly with high quality surface run-off. The worst quality is in lower-lying areas of Pomona and Ganesha Basins.

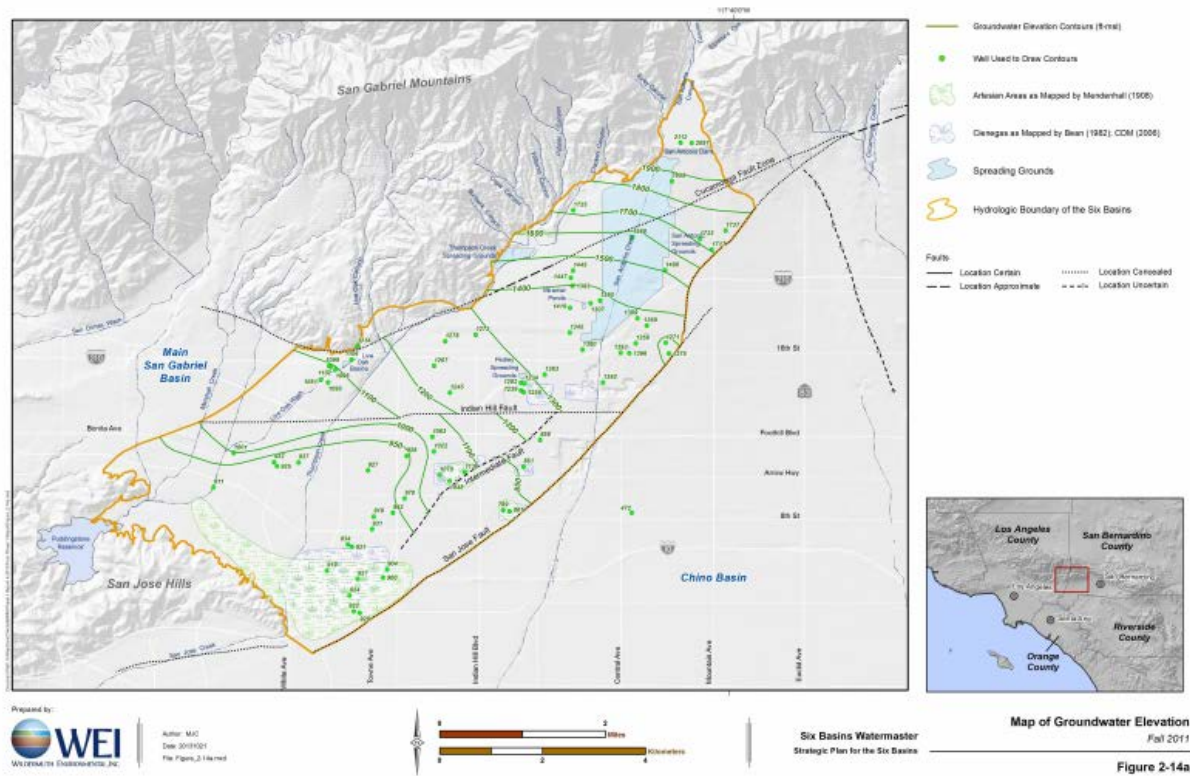


Figure 6: This map of groundwater elevation shows the general north-south gradient of the water table. Elevations are highest near SASG, and lowest at the southern end of Pomona Basin. Note also the way water mounds behind and is deflected by internal barriers to subsurface flow such as Indian Hill Fault. (WEI, 2015, figs. 2-14a)

Discharge from the Six Basin occurs in a number of ways. The largest is by pumping from commercial wells, which is done by the following parties: City of La Verne, City of Pomona, Golden State Water Company, SAWC, City of Upland, and TVMWD. The total OSY for all Parties is 19,300 acre-ft/yr.

The other major source of discharge is subsurface loss across San Jose Fault. The magnitude of this is very poorly constrained, but “rates of subsurface discharge across the San Jose Fault are likely to vary depending on groundwater elevations in the Six Basins—rates being higher during periods of high groundwater elevations when subsurface discharge can occur within the shallower, less-deformed sediments” (WEI, 2015, sec. 2.2.4.5). Discharge across the fault may average as much as about 2,700 acre-ft/yr from subbasins north of Indian Hill Fault, and about 5,300 acre-ft/yr from Pomona basin south of Indian Hill fault (WEI, 2015, sec. 3.4.1). Therefore, the Six Basins could be losing up to 8,000 acre-ft/yr to discharge across fault, and this can be reduced only by maintaining lower groundwater levels.

A third source of discharge is surface outflows from rising groundwater. This used to be much more common, as evidenced by the historical occurrence of ciegas and artesian wells throughout the Six Basins but especially at the southern tip of Pomona Basin. While surface discharges are unlikely under current management conditions, the threat of rising groundwater (less than 50 ft from surface) remains a significant concern because it can threaten shallow infrastructure and increase the risk of liquefaction in the event of an earthquake. Avoiding the risk

of rising groundwater has proven to be an important consideration in the management of the Six Basins, especially in Pomona Basin where water quality issues have limited how much parties wish to produce, and in the Upper Claremont Heights Basin, where recharge can occur very rapidly in the event of heavy rainfall.

Overall, the Six Basins aquifer shares many commonalities with other groundwater basins in California and the Western US in general, but has some important physical characteristics that are somewhat unique and deserve to be emphasized. First, it is highly dependent on local precipitation within a relatively small watershed for recharge, which has historically been very variable year-to-year. Because there is no surface water storage basin upstream of the San Antonio Spreading Grounds that can be used for water conservation, the Six Basins have little ability to use infrastructure to buffer that precipitation variability and make recharge more slow and controlled. Secondly, “The Six Basins are situated in an area that can receive and recharge large volumes of surface water, but they are a relatively small series of groundwater sub-basins with limited storage capacity” (WEI, 2015, sec. 2.2.5). In 2011, total storage for the Six Basins was about 650,000 acre-ft, but this is much smaller than the approximately 5 million acre-ft of water stored in neighboring Chino Basin, for example (Chino Basin Watermaster, 2016; WEI, 2015, sec. 2.4.3). Worse still, most recharge for the Six Basins occurs in Upper Claremont Heights and Canyon subbasins, which represent only a fraction of the Six Basins total volume. These two subbasins can fill to the point where high groundwater is a hazard, even when there is a significant amount of unused storage capacity elsewhere in the aquifer. This uneven distribution of recharge facilities further compounds the difficulty the Six Basins have in recharging large volumes of runoff quickly. The relatively small size of the groundwater basins also limits their capacity to bank water for long periods of time, especially because rates of subsurface discharge across San Jose fault are higher when water levels are high. Lastly, pumping is limited in some subbasins by poor water quality, so some of the available groundwater resources of the Six Basins sit unused. All of these attributes already affect how the Six Basins are managed, and will continue to affect management in the future.

Climate Change Forecasts

The evidence of anthropogenic Climate Change is now overwhelming. Climate Change will affect every region on the planet, even under low emission scenarios; at least some warming is already baked into the system because of historical greenhouse gas emissions regardless of whether humans reduce emissions going forward (Pachauri et al., 2014). At this point, even aggressive mitigation policies will not be sufficient to prevent some degree of Climate Change. In California, there is accumulating evidence that the 2011-2016 drought is a significant departure from past climatic patterns and may in fact represent novel conditions unprecedented in at least the past 1,200 years (Griffin & Anchukaitis, 2014). Furthermore, it appears the drought is caused not only by lack of precipitation, but also largely by elevated temperatures, which in turn increase evapotranspiration and human demand for water. Climate Change will make the co-occurrence of warm and dry conditions even more common in the future, as well as increasing the risk of destructive floods (Dettinger, 2011; Diffenbaugh et al., 2015). Given the magnitude of California’s

2011-2016 drought, and the likely relationship of the drought to Climate Change, it is crucial for the Six Basins Watermaster to assess the role drought and Climate Change will play in the future of water availability for the Parties. Local and imported supplies will be affected. Likewise, the history of San Antonio Creek's destructive floods means Climate Change's effect on storms must be carefully considered. While droughts and floods have played a significant role in the management of San Antonio Creek and the Six Basins for over a century, there is strong evidence to suggest that the 21st century will bring novel environmental conditions more severe than any yet seen by the Parties.

There is inherently some level of uncertainty whenever one attempts to predict the future, and this is certainly true of Climate Change forecasts. However, climate scientists agree on many of the basic changes that will occur in California. Cayan (2009) found that the Golden State has already gotten measurably warmer, and "the rate of warming will increase substantially over the rates we have seen in recent decades." Projections based on low emission trajectories predict "temperature increases will likely exceed 3°F" by the year 2100 compared to a 1961-1990 baseline; high emissions trajectories could produce warming in excess of 7°F. "Several of the recent climate simulations suggest that summer temperatures will increase more than those in winter," especially for areas inland of the immediate coastal zone, like the Six Basins. Climate Change is also likely to reduce air quality, increase the frequency and severity of wildfires, damage native flora and fauna, and increase the demand for electricity (Cayan, 2009).

The effect Climate Change will have on precipitation is more difficult to constrain, in part because Southern California's precipitation is determined by an unusually complex suite of factors that make downscaling from global or regional simulations to local models quite difficult (Conil & Hall, 2006). In general, the Southern California region's atmospheric variability can be characterized by three distinct wind regimes: the Common Northwesterly, which dominates in the summer months and yields stable, warm, dry conditions and mild alongshore winds; Onshore winds, most frequent in the winter months, which bring the moist air of the Pacific farther inland and contribute the "overwhelming majority" of the region's precipitation; and Santa Ana winds, when air from the high desert interior blows offshore and creates extremely hot, dry, fire-prone conditions. This three-regime situation is already substantially more complex than standard Empirical Orthogonal Function (EOF) models of atmospheric variability can capture, at least on an intra-seasonal timescale, and is further complicated by landform heterogeneity and Southern California's high topography (Conil & Hall, 2006). The important takeaway is this: the region's precipitation is notoriously difficult to model on small spatial and temporal scales—making forecasts for the San Antonio Canyon watershed in a given future season all but impossible—but the overall abundance of precipitation is critically dependent on the occurrence of onshore wind regimes.

These are, in turn, a function of larger atmospheric dynamics in the Eastern Pacific. "An eastward extension of the region of strong Pacific jet stream" appears to be "a robust feature of the large-scale simulated changes" due to Climate Change, which would mean more storms (and thus moisture) arriving at the California coast: tentatively good news (Neelin, Langenbrunner,

Meyerson, Hall, & Berg, 2013). These models have greater certainty at higher latitudes; in other words, it appears likely that the already relatively wet northern sections of the state will receive even greater precipitation during the 21st century. The models' certainty decreases for the southern portion of California, which "lies between the region anticipated to undergo increases in precipitation at mid-to-high latitudes and regions of anticipated decrease in the subtropics" (Neelin et al., 2013). Berg and Hall (2015) analyzed the results of 34 global climate models and concluded that while "models disagree on the sign of projected changes in mean precipitation" for the state, "in most models the change is very small compared to historical and simulated levels of interannual variability." California has always had high interannual variability in precipitation, but the Climate Change will amplify that, especially for the Southern portions of the state.

Thus, planners can safely expect two deviations from historical climatic patterns in the 21st century: increased temperatures, and increased interannual variability in precipitation. Berg and Hall (2015) found that extremely dry winters are not likely to increase in frequency until the latter half of the century, but extremely wet winters will "increase to around 2 times the historical frequency, which is statistically significant at the 95% level" by the year 2061. After 2061, all 34 models predict "extremely dry wet seasons [will be] roughly 1.5 to 2 times more common, and wet extremes generally triple in their historical frequency (statistically significant). Large increases in precipitation variability in most models account for the modest increases to dry extremes. Increases in the frequency of wet extremes can be ascribed to equal contributions from increased variability and increases to the mean [precipitation]" (Berg & Hall, 2015).

These forecasts indicate that increased frequency of floods is likely to be a serious impact of Climate Change. This prediction is also supported by studies that link major historical floods to "atmospheric rivers" (ARs) delivering large warm moisture-rich air to California; "In many California rivers, essentially all major historical floods have been associated with AR storms" (Dettinger, 2011). This suggests that seriously elevated flood hazards may be more common in the future: "However, for water management and operational purposes, particularly for flood frequency estimation, we will be able to quantify most Climate Changes only long after these changes have occurred." In other words, by the time climate scientists know exactly how much more frequent floods will be in the 21st century, many destructive ones probably will have already occurred. Because "flood management is overwhelmingly about preparation" (Hanak & Lund, 2012), it may be imprudent to wait until very high certainty is achieved in forecasting models before working to mitigate flood risks, especially when the flood control infrastructure is aging and potentially unsafe, as is the case at San Antonio Dam.

Although Berg and Hall (2015) do not project an increase in the frequency of extremely dry winters until after 2060, this should not be misconstrued as an indication that the frequency of droughts will not increase before then. California's 2011-16 drought is not the most severe of the last 1200 years because of low precipitation alone; low (but not anomalously low) precipitation has combined with record high temperatures to create the extreme moisture deficit (Mann & Gleick, 2015). Furthermore, The National Drought Mitigation Center notes that drought's "impacts result from the interplay between the natural event (less precipitation than expected) and

the demand people place on water supply, and human activities can exacerbate the impacts of drought. Because drought cannot be viewed solely as a physical phenomenon, it is usually defined both conceptually and operationally” (The National Drought Mitigation Center, 2016a). For example, “Socioeconomic drought occurs when the demand for an economic good exceeds supply as a result of a weather-related shortfall in water supply,” and this has certainly occurred even within the range of historical variability in Southern California’s precipitation (National Drought Mitigation Center, 2016b). Thus key three factors emerge when considering the likelihood of future droughts for the Six Basins: low precipitation, high temperatures (and thus high evapotranspiration), and increasing human demand.

The Six Basins Parties secure their water from two sources: locally, from runoff in the San Gabriel Mountains and a small amount of recycled water; and imported water from the Sierra Nevada and Colorado River, via TVMWD through the MWDSC. The 2015 Strategic Plan has emphasized that “Because imported supplies may not always be available, the Parties will work together and strive to minimize dependency on imported water and to maximize the use of local supplies when economically justified” (WEI, 2015, sec. 1.3). However, *both* local and imported supplies will face disruptions due to Climate Change, and the assumption that local supplies will be more reliable as compared to imported water is at best an under-supported assumption, and at worst a dangerous miscalculation. It is critical to evaluate how the generalized Climate Change impacts discussed above will differentially impact local and imported water supplies.

Local water supplies are currently dominated by the runoff of San Antonio Canyon, which is either directly collected at the Edison Splitter Box by the City of Pomona and SAWC or captured and spread at the SASG to recharge the Six Basins Aquifer. Runoff captured and spread at LOSG and TCSG also make small contributions (approx. 6%) to aquifer recharge. Although the Six Basins Watermaster can expect mean annual precipitation to remain relatively stable during the 21st century, the interannual variability in that precipitation will increase. Specifically, more of Southern California’s total precipitation will be concentrated into the more regular occurrence of extremely wet winters. However, as was discussed in the *Physical Description of the Six Basins Aquifer*, the spreading grounds used to recharge groundwater struggle to effectively infiltrate large pulses of water quickly. This problem is further compounded by the threat of rising groundwater during very wet periods, which can further limit the Six Basins’ ability to take full advantage of water when it is available. After 2060, extremely dry winters are projected to come more common. Increased temperatures will occur mostly in the summer, when there is little precipitation or spreading of water, so it seems plausible that increased temperatures will not be as damaging to local groundwater supplies as they would be if storage occurred primarily in surface reservoirs. To the extent that increased temperatures will be a primary driver of drought in the future, the short time water spends on the surface before being infiltrated may mean that local supplies will be relatively less exposed to increased evaporation than imported supplies.

Most Six Basins Parties purchase imported water from the Three Valleys Municipal Water District (TVMWD), while the City of Upland purchases imported water from the Inland Empire Utility Agency (IEUA). Both of these water wholesalers are in turn supplied by the Metropolitan

Water District of Southern California (MWDSC), which manages an extensive network of reservoirs, canals, and aqueducts that convey water from the Colorado River and Sierra Nevada Mountains to Southern California. For decades, these imported supplies have been crucial in allowing cities like Claremont (or Los Angeles) to grow beyond the limitations of their native water supplies, and they will continue to be crucial parts of Southern California's water portfolio in the 21st century. Therefore, Climate Change impacts on MWDSC's supplies will have a direct effect on the availability of water for the Six Basins.

The first of these two main sources of imported water is the Colorado River Basin. Models predict it will face warming-related reductions in its high altitude snowpack which currently contributes 70% of the river's runoff, which will in turn shift runoff earlier in the spring and reduce summertime flows. The high amount of reservoir storage compared to volume of runoff may help offset this effect. There is considerable uncertainty about the magnitude of temperature increases and the sign and magnitude of precipitation changes, but results suggest that even possible "precipitation increases would be offset by increased evapotranspiration, with the net effect being a reduction in runoff ranging from 8 to 20%" (Christensen, Wood, Voisin, Lettenmaier, & Palmer, 2004). Because almost all the Colorado River's runoff is consumed for human use—and upwards of 40 million people depend on these waters—any reductions in runoff will have direct and detrimental effects on the communities reliant on that water. The Six Basins Watermaster has also expressed concern that drought would increase the salinity of Colorado River supplies, thus requiring imported water be mixed with other higher quality sources in order to meet potable standards (WEI, 2015, sec. 3.1.6).

The other main source of imported water for MWDSC is runoff from the Sierra Nevada, much of which is captured by the State Water Project (SWP) at the Sacramento-San Joaquin Delta and conveyed via a series of aqueducts to farmers in the Central Valley and consumers in Southern California. However, as is the case with the Colorado River, the fate of the Sierra Nevada's water in the face of Climate Change is somewhat uncertain. There is substantial evidence that increased temperatures have already reduced the snowpack and shifted the timing of peak runoff toward earlier in spring (Belmecheri, Babst, Wahl, Stahle, & Trouet, 2016). California has extensive surface reservoir infrastructure that can help buffer the loss of the natural reservoir of the Sierra snowpack, but these alone will not be enough to cope with increased inter-annual variability in precipitation. The California Department of Water Resources predicts that "SWP deliveries will decrease by 5.6% due to Climate Change and environmental concerns in delta" if major improvements to Delta infrastructure are not pursued (Kerckhoff et al., 2013).

Conjunctive use of groundwater storage has been identified by several researchers as a key adaptation strategy for California's SWP and can offer substantial economic benefits to the state (Hanak & Lund, 2012; Pulido-Velazquez, Jenkins, & Lund, 2004). The situation appears cautiously hopeful, even with the concurrent changes to California's population and economy in the century to come. Detailed analysis of the state's water management using CALVIN simulations "point to a considerable engineering and economic ability of complex, diverse, and inter-tied systems to adapt to significant changes in climate and population. More specifically, California's

water supply system appears physically capable of adapting to significant changes in climate and population, albeit at a significant cost” (Tanaka et al., 2006). In other words, it appears that the Sierra’s water will continue to be available for use throughout the state, though at higher costs in the future (Connell-Buck, Medellín-Azuara, Lund, & Madani, 2011; Harou et al., 2010). These studies also identified some key vulnerabilities in the resilience of California’s water system, chief among these the fragile levees of the Sacramento-San Joaquin Delta which are threatened by future earthquakes and sea level rise. “The scale of potential water supply losses from a catastrophic failure of Delta levees—on the order of 6 maf per year” or 15% of the state’s developed supplies “makes finding new solutions to Delta management a top climate adaptation priority” (Hanak & Lund, 2012).

Imported supplies are thus likely to undergo significant stressors due to Climate Change, especially from increased temperatures because both the Sierra Nevada watersheds and Colorado River are fed in large part by high altitude snowpack that will be very sensitive to warming. Both sources of imported water have abundant surface and groundwater storage relative to the volumes of water supply, which will help them cope with increased inter-annual variability, and conjunctive use of groundwater storage along Colorado River Aqueduct and in California’s Central Valley will help offset the loss of snowpack, especially during droughts. Barring catastrophic failure of levees, or other earthquake damage to conveyance, there should be some imported water available through MWDSC in the future, although it may be subject to mandatory restrictions during droughts and will likely inflate in price over time.

The Six Basins Watermaster has also compiled historical data on its Parties’ demand for water and developed future projections as well. From 1999 to 2011, all parties experienced reductions in water demand, due in part to reduced demand from industrial sectors such as the end of paper production in the City of Pomona, for example (WEI, 2015, sec. 3.2.2). Several parties also reduced demand because of water-use restrictions from the State of California, but the Strategic Plan generally describes economic factors like water-intensive industries ceasing production as having a larger effect than consumer water restrictions in explaining the 1999-2011 decreases. The Parties generally predict that water demand will rise (mostly due to population increases) in the 2011-2035 period, by a range of margins depending on the party, for example:

- City of La Verne up 22%, from 6,900 af to 8,835 af.
- City of Pomona up 27%, from 22,000 af to 28,00 af.
- Golden State Water Company up 11%, from 10,800 af to 12,000 af.
- City of Upland up 12%, from 19,500 af to 22,000 af.

The Strategic Plan of the Six Basins anticipates that total water demands of the Parties (“excluding the imported water demands of the TVMWD’s member agencies outside the Six Basins”) are expected to increase from “about 67,000 acre-ft/yr in 2011 to about 77,000 acre-ft by 2035,” which is also well above 1999 levels (WEI, 2015, sec. 3.2.7). The Parties plan to meet those increases in demand “primarily with groundwater from the Six Basins and Chino Basin [where several parties also have production rights] and with recycled water,” i.e., with local supplies rather than additional imported water.

Water-conservation measures are a large part of why the Six Basins do not expect even larger increases in demand, but is unclear to what extent they have included demand-hardening in their planning assumptions. Demand-hardening is the reason why “every conservation forecast must take into account the existing stock of water-using fixtures and features for the utility area. In this sense, effective long-term conservation programs reduce the potential for further conservation.” For example, “Replacing 5 gal per flush (gpf) toilets with 1.6 gpf units severely reduces the potential for additional conservation from this source” (Howe & Goemans, 2007). For the Parties of the Six Basins which are already accustomed to some drought restrictions on water use, further demand-side reductions may prove more difficult than expected, especially as population increases in the coming decades. Dan Rodrigo of CDM Smith Consulting firm has worked with Orange County Water District on similar issues and cautioned that “price as a tool in itself is relatively inelastic,” with increases in per-unit water rates having little effect on the quantity of water demanded. To achieve further reductions in the future, he instead recommends water utilities institute an inclining rate structure or expand Southern California’s existing water rebate program (Rodrigo, 2016).

Implications of Climate Change for Basin Management

It is clear that Climate Change will impact the Six Basins in a number of key ways. Precipitation in California will become even more variable year-to-year, with precipitation concentrated into a smaller number of very wet years and very strong storms. This will put a premium on the Six Basins’ ability to capture the maximum amount of stormwater runoff during these brief deluges, but as was demonstrated in Section 2 of this thesis, the current infrastructure struggles to capture and recharge these sudden pulses of runoff; the larger the runoff, the more the PVPA typically loses. This inability to harvest high volumes of runoff will become even more of a liability in the future. A crucial adaptation strategy will be improving the ability to recharge large volumes of runoff quickly, but this is difficult because the Six Basins does not have any surface water storage facilities upstream of the spreading grounds besides San Antonio Dam, which is currently barred from considering water conservation in its operations. Unless the Watermaster gains access to some type of surface storage upstream of the spreading grounds, increased precipitation variability will almost certainly mean less recharge in the future, even if the multi-year average precipitation does not decrease.

Increased precipitation variability also means the frequency of severe floods will likely increase, but it is not yet known by how much. The USACE has indicated that San Antonio Dam, the Six Basin area’s most important piece of flood control infrastructure, may not be equipped to handle those floods. A Climate Change adaptation plan for the Six Basins will not be complete until it specifically addresses this hazard.

The effects of variable rainfall will combine with increased temperatures and evapotranspiration to fuel a higher frequency of droughts even if there is no decrease in multi-year average precipitation. Droughts, when they strike, may be multiple years in length, so the Six Basins should consider how resilient its groundwater supplies are to extended dry periods.

Unfortunately, the Six Basins is a relatively small groundwater basin, with less room to bank large amounts of water during wet years for use during dry years than some other larger groundwater basins. The Six Basins' total storage capacity was only 650,000 acre-ft in 2011 (WEI, 2015, sec. 2.4.3), while other aquifers managed by MWDSC have storage capacities on the order of many millions of acre-ft.

For these reasons, the premise that imported water will be less reliable than local groundwater supplies in the future may not be well-founded. The increase in precipitation variability year-to-year will affect SWP and Colorado River supplies as well, but unlike the Six Basins, those imported sources have access to large surface reservoir storage and much bigger groundwater basins. Temperature increases will have a particularly disruptive impact on the imported water served through MWDSC, because much of that water originates as high altitude snowpack and will be very sensitive to warming, but even with the loss of snowpack, these imported water sources may prove better prepared to cope with inter-annual variability. This is because they both have types of storage--surface and groundwater--and thus can bank water more easily year-to-year. On the other hand, key pieces of infrastructure used to convey that water to Southern California are vulnerable to natural disasters.

Regardless of which supply source is ultimately more impacted—local or imported—it is obviously in the Six Basins Parties' interest to maximize the beneficial use of local water supplies. In this respect, the Six Basins can be credited with a forward thinking attitude; they recognize that reliance on imported water should be minimized and, as the next chapter describes, have come up with a number of projects designed to maximize local supplies. This will be critically important especially in dry years, because California tends to be dry or wet as a unit so when local supplies are at their lowest, imported water will also be under high stress. During severe droughts, the state may ration imported water and place mandatory restrictions on water use (Carlton, 2016), so it is important that adaptation strategies increase local supplies and offer dry-year benefits, not just temporary benefits in wet years.

Finally, in the face of these anticipated supply challenges, the Six Basins should think carefully about how their water demand will respond to a changing climate. It seems likely that they will have relatively high residential demand during dry years, because of demand hardening effects, and so will find it difficult to reduce demand during acute droughts. Many of the best strategies for lower residential demand are already in place, so opportunities for further reductions will be harder to find. Therefore, in addition to long term programs to reduce water demand, the Six Basins Parties would be wise to consider how they might cut demand even further in the face of an acute shortage.

Institutional Responses of the Strategic Plan

The Six Basins Watermaster is the product of a long institutional evolution born from water scarcity, high climatic variability, unique environmental constraints, and an earnest attempt to manage the water resources of the San Antonio Creek and the Six Basins efficiently. For the last 100 years, it has developed the scientific understanding and management procedures necessary to

largely succeed in its goal of maintaining safe, reliable yields from the aquifer, thus minimizing dependency on imported water. By 2012, some Parties to the Six Basins Watermaster had “raised questions and concerns about current rules, regulations, agreements, and practices” or desired “a better technical approach to the management of the Six Basins” (WEI, 2015, sec. 1.2). Together, the parties began developing a Strategic Plan, which was finalized in 2015, to address those concerns and ensure continued reliability in water supplies through the year 2066. This document is the Parties’ guide to the future; it was explicitly designed as the rubric they will use to meet whatever challenges the coming decades bring. The extent to which it accurately anticipates or fails to anticipate those challenges will be key to continued water availability for the Parties and their customers in the Six Basins area. The plan is based upon the following core values (WEI, 2015, sec. 1.3):

- *Increase local supplies.* “Most water purveyors in the Six Basins will - for an underdetermined time into the future - be partly dependent on imported water for direct uses. Because imported supplies may not always be available, the parties will work together to minimize dependency on imported water and maximize the use of local supplies when economically justified.”
- *Groundwater storage.* “Unused groundwater storage capacity is a precious natural resource. The Parties will manage storage capacity to improve the water quality and reliability of the Six Basins groundwater, and minimize the cost of water. The Strategic Plan will encourage the development of conjunctive use programs.”
- *Stormwater recharge.* “The Parties will strive to increase stormwater recharge and thereby maintain and enhance the sustainable yield and water quality of the Six Basins.”
- *Water quality.* “The Parties desire to improve groundwater quality in the Six Basins and deliver water that is safe and suitable of the intended beneficial use and meets all applicable regulatory standards.”
- *Cost of water.* “The Parties wish to minimize the cost of water to their customers.”
- *Funding mechanisms.* “The Parties are committed to finding external sources (grants, etc.) to subsidize the cost to implement the Strategic Plan.”
- *The long view.* “The Parties desire a long-term, stable planning environment to develop local water-resource management projects. The Parties, independently and through [the] Watermaster, will strive to take the long view in their planning assumptions and decisions to ensure a stable and cost effective management program.”

These values are presented as being the necessary, sufficient, and desirable considerations to guide the Watermaster’s plan for basin management in the 21st century.

While these values are undoubtedly important, they contain a glaring omission: explicit planning for the local impacts of Climate Change. Despite the lip service the plan pays to the “long view”, there is strong reason to believe that the assumptions of the Strategic Plan do not adequately anticipate the impacts Climate Change will have on numerous aspects of basin management, chief among these being increased variability in the local runoff that the Six Basins are so dependent on for recharge. In the entire 288-page Strategic Plan, Climate Change is mentioned only 3 times, all

in the context of disruptions to imported supplies. No analysis of how Climate Change will affect local runoff is included, despite the abundant evidence that the 21st century will bring changes in both imported *and* local supplies. The Strategic Plan outlines specific policy responses that will help improve basin management, and many of these will also be important adaptation measures in response to Climate Change, but their importance cannot be fully understood without explicit consideration of Climate Change. This section will outline and then critique the institutional responses described by the Strategic Plan. Alternative recommendations and conclusions will be presented in the final section of this report.

The Strategic Plan anticipates future scenarios for fiscal years 2013-2066 by evaluating a Baseline Alternative—basically a business as usual continuation of the Watermaster’s current management practices—and then comparing those outcomes to those anticipated with specific interventions and improvements developed by the Strategic Plan. The report then evaluates how each proposed intervention will affect groundwater supplies, and at what costs, compared to the Baseline Alternative.

Under both scenarios, the Six Basins’ water supply will remain highly dependent on local precipitation, which the Plan models based on the historical record of precipitation for the period of 1960-2013. That historical 53-year period is simply rolled forward, such that the 53-year planning period of 2013-2066 is assumed to match the historical hydrology in a simple one-to-one pairing. The measured rainfall of 1960 was used to model 2013, 1961 for 2014, and so on to the end of planning period, with 2013 serving as the model for 2066. The report claims that “Using this historical precipitation record for the planning period is appropriate because it contains wet and dry periods of various length and intensity, and the annual average precipitation (17.82) is virtually equal to the long-term average for 1924-2012 (17.76).” (WEI, 2015, sec. 3.3.1)

That methodology is standard for many water managers, in California and beyond. To a certain extent, especially given the high uncertainty of many Climate Change models, the Strategic Plan’s precipitation assumptions seem quite reasonable; unlike inherently speculative projections, modeling future rainfall based directly on historical data requires no statistical wizardry or fuzzy error-bars. As this report already made clear, climate models often disagree even about the sign of precipitation changes, let alone magnitude. However, that does not mean that the Climate Change models provide no reliable information about future climate that could be usefully incorporated into the Six Basins Strategic Plan. The models consistently predict increased variability: the mean precipitation will probably not change significantly, but the rainfall Southern California receives will be concentrated more tightly into particularly wet years and particularly strong storms, punctuated by more frequent droughts. Before fully exploring the implications of this for the Six Basins, it is necessary to summarize the findings of the Baseline Alternative versus Strategic Plan comparison using the Plan’s arguably flawed assumptions for future precipitation.

The Baseline Alternative anticipates that over the planning period, “Many Parties plan to increase groundwater production from the Six Basins—in some cases, exceeding their share of the OSY, which requires replacement through artificial recharge of native and imported waters” (WEI, 2015, sec. 3.6). Because almost all recharge occurs at the north end of the Six Basins, these

activities will lead to higher groundwater levels around the SASG and lower levels in most other areas of the Six Basins where much of the extra pumping will occur. Water levels in Pomona Basin will decline by up to 80 ft during both dry and wet periods, as compared to their initial 2012 levels (WEI, 2015, figs. 3–10, 3–11). The steeper north-south hydraulic gradient will encourage increased flow from Upper Claremont Heights Basin to Pomona Basin which will help stabilize recharge and discharge at this new lower equilibrium. Lower water levels across most of the Six Basins will also reduce subsurface discharge across the San Jose Fault to Chino Basin. By 2066, the end of the planning period, water storage in Six Basins would decline 16% from 675,913 acre-ft to 566,531 acre-ft under the Baseline Alternative (WEI, 2015, Chapter 3). Importantly, water levels were 100-300 ft lower in the 1960s than their projected 2066 levels, indicating that the scenario is physically viable.

Water demands in excess of the production from local groundwater would be met with imported supplies. The Baseline Alternative predicts imported water will inflate in price from its 2013 level of just over \$800/acre-ft up to approximately \$2,400/acre-ft in 2040, at a rate of 4-5% increase each year (**Figure 7**). Under that assumption, the melded cost of water for the Six Basins

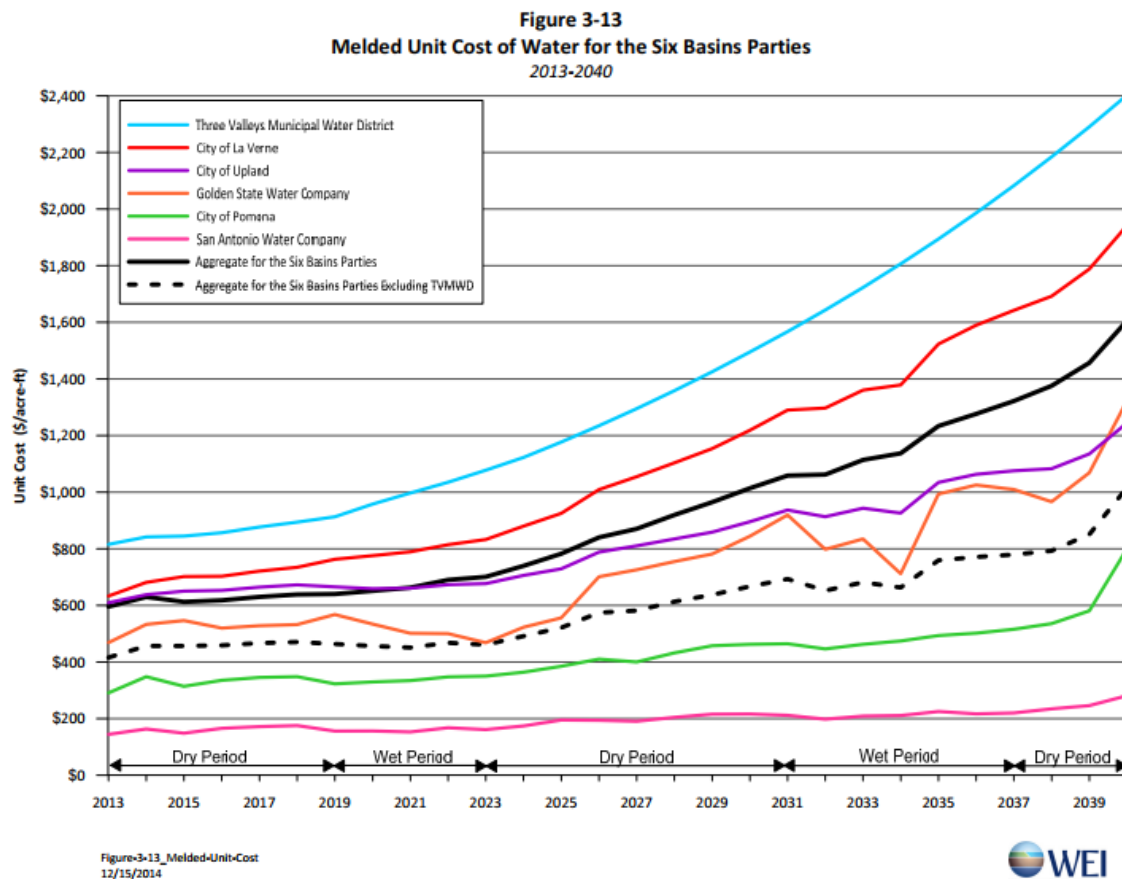


Figure 7: Melded Unit Cost of Water is a measure of how the cost of water varies between the different parties. Because each party has a different proportional mixture of relatively cheap local groundwater and relatively expensive imported water, their unit costs are quite different. SAWC has the lowest unit cost because its entire supply is local; TVMWD by contrast, has the highest unit cost because it is an imported water wholesaler with very little of its supply provided by local groundwater. (WEI, 2015, figs. 3-13)

Parties—that is their average unit cost of water mixed from all sources, both local and imported—would be approximately \$1,016/acre-ft by the year 2040 (WEI, 2015, figs. 3–13). If the annual inflation in the price of imports is as low as 2% or as high as 10%, the melded cost for the parties could be anywhere from \$818/acre-ft to \$1,861/acre-ft respectively (WEI, 2015, figs. 3–14). The individual Parties that rely least on imports are expected to see the smallest increases in melded cost. The Baseline Alternative’s price modeling only extends out to water-year 2040, but already it is clear that threats to the availability of imported supplies will have a huge effect on the overall cost of water to the Parties. However, as was emphasized before, the planning assumptions used above only consider Climate Change impacts to imported supplies, and do not include the possibility of impaired local supplies.

This uncertainty about the cost and availability of imported water is, of course, why the Parties are interested in maximizing local supplies in the first place. Under the Baseline Alternative, local groundwater is able to supply between 28% and 34% percent of the Parties total demand each year (excluding TVMWD customers outside the Six Basins). (WEI, 2015, Chapter 3)

The Strategic Plan hopes to improve upon this scenario, and begins by assessing the priorities of the Six Basins Parties, which are outlined above as the “core values” at the beginning of this section. These values in turn inform four specific goals (WEI, 2015, sec. 4.2):

- *Enhance Water Supplies* by increasing recharge, pumping more, and reducing losses in a cost effective manner, such that the Parties depend less on imported supplies.
- *Enhance Basin Management* through coordinated plans for recharge, pumping, and storage, so the available water is most effectively used.
- *Protect and Enhance Water Quality* through the cleanup of point-source contamination and control of salt and nutrient accumulation.
- *Equitably Finance the Strategic Plan* by “aggressively” pursuing other sources of funding so the consumers of Six Basins groundwater are not forced to bear the full financial burden.

The Strategic Plan attempts to take these somewhat abstract goals and translate them into more concrete actions: either changes to management of the basin or the addition of new facilities. For each action, the Parties indicated whether it was an issue for them, and thus an item worthy of further consideration in their view. For example, “Develop the ability to market basin losses” (perhaps by officially selling water to Chino Basin that is discharged across the San Jose Fault) was an issue only to GSWC and the City of Pomona. By contrast, “Capture and recharge as much stormwater as possible for the benefit of the Parties” was an issue for Claremont, the City of Pomona, Pomona College, the PVPA, SAWCo, TWMWD, and Upland. (No actions discussed by the Parties mentioned Climate Change explicitly.) In this way, a diverse set of possible approaches were considered and priorities were narrowed. The Parties then developed a list of “these goals [above], the impediments to achieving these goals, the actions required to remove the impediments, and the expected outcome or the implication of those actions” (WEI, 2015, sec. 4.3).

The result of this institutional process was a list of six project concepts (listed below) that the Six Basins Parties believe will help them to achieve the goals of the Strategic Plan. Original commentary on how Climate Change might affect these projects is also included.

1) *Increase the Use of Temporary Surplus and Increase Stormwater Recharge at the San Antonio Spreading Grounds.* The 1998 judgement already provides the Watermaster with the ability to declare a Temporary Surplus (TS) in the event of rising groundwater, so that Parties pump extra for a limited time to lower water levels. The Strategic Plan proposes that this provision be used more frequently, along with possible facility upgrades at the SASG. This would help address the impediments of lost runoff, limited recharge, the intermittent nature of spreading, high groundwater concerns, losses across San Jose Fault, the limited storage capacity of the Six Basins, declining water levels during dry periods, and water quality concerns. Right now, recharge is limited by the physical capacity for infiltration and the requirements to avoid high groundwater; this project would address both those limitations (WEI, 2015, sec. 5.2). It does not involve diverting more water from San Antonio Creek.

The Strategic Plan considered four alternative project configurations for SASG, including 4 or 7 new wells in Upper Claremont Heights Basin and minor or major improvements to SASG operations and facilities. Analysis was hamstrung by the lack of data on current infiltration rates of the SASG, so the Plan recommends installing better monitoring equipment as soon as feasible. The Strategic Plan did not analyze the effect of changing San Antonio Dam operating rules, which the USACE currently operates for flood control only, not for water conservation. Hypothetically, the dam could hold a temporary conservation pool and release it only at the rate it can be safely recharged, but this would involve re-adjudication of water rights with many downstream parties. Orange County successfully got Prado Dam to change its operation rules to include water conservation, but the process took years. The Watermaster is interested in pursuing this option but did not analyze it at this time because it “cannot likely be achieved in the next 20 years” (WEI, 2015, sec. 5.2.3).

Implementing more frequent Temporary Surpluses would allow the parties to control rising groundwater more effectively, and increase yield and recharge in particularly wet years. The Strategic Plan outlines a tiered system of exactly how much water must already have been spread at SASG in a given year for TS to be invoked. Under the same precipitation assumptions as in the Baseline Alternative, the model predicted that 4 new wells would allow the TS to be invoked in 7 out of 54 years over the planning period, for an additional 46,250 acre-ft (850 acre-ft/yr) of pumping compared to the Baseline Alternative. This would put water levels slightly lower (about 10-30ft) than the Baseline Alternative across most of the Six Basins by the end planning period, but increase the developed yield by 460 acre-ft/yr by increasing pumping and reducing subsurface outflow to Chino Basin. The unit cost of this additional supply would be \$2,050/acre-ft, which could be “substantially reduced” if the new wells were used for other pumping besides TS alone.

The construction of 7 new wells at SASG would allow the pumping of 78,500 acre-ft of water over the planning period, or an average of 1,415 acre-ft/yr. Water levels would be 5-20 ft lower than the Baseline Alternative over most of the Six Basins besides Upper Claremont Heights

and Canyon Basin, which would not experience relative declines. The annual developed yield of the Six Basins would increase by 1,300 acre-ft/yr, primarily because of increased pumping from TS and increased recharge in very wet years. The unit cost of this additional supply would be \$1,380/acre-ft, which again could be reduced if new wells were used for non TS production.

Adding monitoring and facility improvements to SASG would improve its instantaneous recharge capacity. The Parties considered just installing a better distribution and monitoring system, or making major infrastructure improvements in addition, namely new stormwater basins along the west side of the wash that could hold water temporarily when diversions to SASG exceed the maximum rate of infiltration. The latter option would ideally allow SASG to better cope with sudden large pulses of runoff. However, the currently faulty monitoring equipment in place at SASG has made it impossible to predict how recharge, pumping, groundwater levels, and yield would respond to these proposed improvements. Thus, the Strategic Plan could not estimate the unit cost of water provided by these projects, only their capital costs: \$2.7m for a better distribution and monitoring system, and \$13-52m for major improvements depending on the size of the new storage basins. Without installing the new monitoring system and using it for a number of years to calibrate and generate data, it will be impossible to know how cost-effective further facility improvements at SASG would be.

Given how difficult the PVPA has found it to recharge large sudden pulses of runoff in a short time, and the prediction that precipitation variability will only increase due to future Climate Change, these TS and SASG projects seem well suited to address a key vulnerability of the Six Basins: they would allow the Parties to take fuller advantage of very wet conditions. However, these projects will offer their greatest benefits almost entirely during wet years when imports are widely available, but that may be when recharge is needed most, to bank for dry years. The Watermaster should take very special care not to allow extra TS pumping to “steal” water for use during wet years that would otherwise be stored for a future dry year.

2) *Thompson Creek Spreading Grounds Improvements.* This project would help address many of the impediments listed above, but on a smaller scale. (Major improvements at Live Oak Spreading Grounds were determined to be cost prohibitive.) Currently, the water from Thompson Creek is diverted by the PVPA above Thompson Creek Dam into a conveyance ditch that carries water to the downstream side of the Dam, where it is diverted into 2 relatively small infiltration structures known as the Coyote Pits. If water volumes are high and the flow of Thompson Creek is too turbid and sediment-rich to be channeled through the diversion works, water is allowed to go down to the dam, where up to 217 acre-ft of runoff can pool at a time. Water in excess of this storage capacity is directed into the concrete-lined Thompson Creek channel and is lost to the Six Basins. Water that is captured behind the Dam is held until it recharges into the ground behind the dam or evaporates (WEI, 2015, sec. 2.2.3.2). Thus, water is only conveyed to the Coyote Pits of TCSG under relatively low-flow scenarios; large pulses of runoff instead go almost entirely to Thompson Creek Dam, and in times of very high flow, not all water can be captured by the dam, so much of it escapes to the concrete-lined channel and cannot be recharged. It is not currently possible to convey water directly from the dam to the infiltration pits. This means the current

infrastructure struggles to cope with large runoff volumes in wet years. From 2000-2011, “44% of the runoff from Thompson Creek watershed was captured for recharge: 556 acre-ft was diverted and recharged by the PVPA, 1,019 acre-ft was captured by Thompson Creek Dam, and 1,978 acre-ft was lost,” although 83% of the water lost was from the single very wet water year of 2005 (WEI, 2015, sec. 2.2.3.2). Even this may be overly optimistic, because the Los Angeles County Flood Control District (LACFCD) assumes negligible evaporation from the flood control reservoir behind the dam, which is probably not the case. Unfortunately, the area behind the Thompson Creek Dam is not improved for recharge, and in general “the recharge capacity and the processes that constrain it are not precisely known” (WEI, 2015, sec. 5.3).

The Strategic Plan suggests a potential project to improve the capacity for recharging runoff from Thompson Creek. The old diversion structure and Coyote Pits would be abandoned, and all stormwater would be impounded behind the dam (WEI, 2015, sec. 5.3.2). Several new, significantly larger infiltration basins would be constructed on PVPA lands below the dam, and a floating pumping station would divert water from the flood control reservoir behind the dam to the improved spreading grounds. No new wells would be required. Because of knowledge gaps and lack of data on infiltration rates, the groundwater response could not be modeled, but the Strategic Plan estimates that the improvements would increase groundwater levels slightly in the area near TCSG and increase yield by 0-1,410 acre-ft/yr, depending on the precipitation abundance of the year, with the long term average being approximately 230 acre-ft/yr more than the Baseline Alternative. “The capital cost of this project was estimated to be about \$7,170,000” plus \$10,00/yr in maintenance, so the extra water yielded would be about \$2,100 per acre-ft (WEI, 2015, sec. 5.3.7). The Strategic Plan recommends improved monitoring “regardless of whether or not improvements to the TCSG are pursued” (WEI, 2015, sec. 5.3.9).

Just like the project proposed for SASG, these proposed improvements to TCSG will help the Parties take better advantage of wet years, but offer their greatest benefits only during those few wettest years, and will sit unused much of the rest of the time. To the extent that local precipitation and regional precipitation are highly correlated, such improvements would provide improved yields only when imported water is relatively cheap but do little to reduce demand for imports when imported water is unavailable or expensive during dry years. TCSG improvements might still be cost-effective and worthwhile, but it will be hard to know until improvement monitoring is implemented and the Six Basins begins considering the year-to-year variability in the price of imported water.

3) *Supplemental Water Recharge in the Upper Claremont Heights Basin.* Basically, this project attempts to relieve the occasional “production sustainability problems at wells in the Upper Claremont Heights Basin” that result during multi-year dry periods as water in that subbasin migrates south to other parts of the Six Basins. This would help address the impediments of high groundwater and unused recycled water. The Strategic Plan proposes resolving these issues by recharging Upper Claremont Heights Basin with 3,500 acre-ft/yr of supplemental water, either locally using recycled water from Pomona Water Reclamation Plant (WRP) or from imported water from MWDSC via TVMWD or IEUA. “The intent is to increase the sustainable production

capacity in the Upper Claremont Heights Basin, and not to store large quantities of water for long periods of time” (WEI, 2015, sec. 5.4.3).

If water from Pomona WRP is used, it would require a 68,000-ft long pipeline with multiple pumping stations to convey the recycled water several miles uphill from the plant to the SASG. If water from TVMWD is used, no new facilities are required. Supplemental recharge would increase groundwater elevations in Upper Claremont heights Basin by 60 ft in the northern portion of the subbasin and decrease it by 20 ft in the southern portion of the subbasin, as compared to the Baseline Alternative. Periodic challenges from rising groundwater are expected in the northeast portion of the subbasin, but these could be mitigated by increased pumping or “reducing the amount of supplemental water recharge when high groundwater level conditions arise” (WEI, 2015, sec. 5.4.6). Using recycled water would be much more expensive because of the large capital costs needed to construct the new pipeline, with unit cost of the additional water being \$2,060/acre-ft. Using imported water would be \$684/acre-ft (WEI, 2015, sec. 5.4.7). One option considered but not analyzed would be to exchange recycled water from Pomona WRP “with IEUA for a like amount of imported water delivered through TVMWD. This would convert an underutilized asset (recycled water) into water served at high elevation in the Six Basins (the imported water) and would avoid the great expense of constructing and operating the infrastructure required to pump recycled water from Pomona WRP to the SASG for recharge” (WEI, 2015, sec. 5.4.3).

This last possibility, while mentioned almost as an afterthought in the Strategic Plan, is an excellent solution especially in the face of future Climate Change. It would be more reliable than directly purchased imports and would be cheaper than recharging recycled water via a new pipeline. These supplemental water projects are likely to be very important in Climate Change scenarios that include more frequent droughts, because wells in Upper Claremont Heights Basin struggle to produce water reliably during multi-year dry periods. Trading the currently underutilized recycled water from Pomona WTP for cheaper imported water should create substantial economic benefits for all involved.

4) *Pump and Treat Groundwater in the Pomona Basin.* The City of Pomona would pump and treat an additional 1000 acre-ft/yr in this project, which would allow the Six Basins to begin using or selling the currently underutilized groundwater resources of the highly contaminated Pomona Basin. This extra pumping would be pursued as a “Special Project” under the 1998 judgement and thus would reduce demand for imported water “regardless of the user,” so that “groundwater production developed with this project is, in a practical sense, new yield” (WEI, 2015, sec. 5.5.2). This would help address the impediments of dangerously high groundwater in Pomona Basin, subsurface losses across San Jose Fault, the limited storage capacity of the Six Basins, the limited potential for Pomona Basin in conjunctive use programs, declining water levels during dry periods, high contaminant levels limiting production, the accumulation of contaminants in Pomona Basin, and the current high cost of treatment. To achieve this, the City of Pomona’s groundwater-treatment system would be “expanded and improved to remove VOCs, perchlorate, and nitrate from the additional groundwater produced at these wells, and produce a potable water supply” (WEI, 2015, sec. 5.5.5). This would lower groundwater levels in Pomona Basin up to 140

ft below their levels in the Baseline Alternative, which may be desirable as it reduces losses across San Jose Fault and reduces the risk of rising groundwater (WEI, 2015, sec. 5.5.6). This would increase the developed yield for the Four Basins by 700 acre-ft/yr, mainly because of reduced subsurface losses, although the extra pumping would reduce the developed yield for the Two Basins by 175 acre-ft/yr. The Strategic Plan notes that groundwater levels were up to 200 ft lower in Pomona Basin the 1960's, so the project is most likely "feasible from a physical standpoint" (WEI, 2015, sec. 5.5.6). At a unit cost of \$830/acre-ft, this project is expected to be cheaper than several alternatives already discussed.

From a Climate Change perspective, this project appears to be an excellent option for a number of reasons. Firstly, by drawing down water levels, it creates new storage capacity in Pomona Basin, which is the largest subbasin within the Six Basins and the destination of most subsurface flow from the other subbasins. For both these reasons, Pomona Basin would be well-suited for multi-year storage of groundwater if it were not for its water quality issues, which currently substantially limit production from the subbasin. By pumping and treating more water from this basin, the Parties will gain what is effectively new yield, and because Pomona Basin is recharged almost entirely by subsurface flow rather than direct infiltration, groundwater supplies in this subbasin will be more insulated from inter-annual variability in precipitation than other subbasins which tend to be more quickly depleted during dry periods. The new yield from this project would be relatively low cost and available every year, both dry and wet, which makes it a very attractive project option.

5) *Conjunctive Water Management in the Six Basins.* The Strategic Plan defines conjunctive management as "the coordinated use and management of all surface water and groundwater supply sources to enhance yield and improve water-supply reliability during dry periods" (WEI, 2015, sec. 5.6). In general terms, one simple way to do this is to bank water in an aquifer year-to-year, adding extra during wet years, so that it can be withdrawn later during dry years. This would help address the impediments of high groundwater, losses across San Jose Fault, the limited ability to recharge imported water, the limited storage capacity of the Six Basins, declining water levels during dry periods, the pitfalls of using a single Operating Safe Yield (OSY) for the Four Basins, Storage and Recovery Agreements not accounting for subsurface losses, out of date computer models, contaminant levels limiting production, the accumulation of contaminants in Pomona Basin, and generally lets the Six Basins begin utilizing the current underutilized resources of the highly contaminated Pomona Basin. "Stated another way, the recharge capability at the SASG is large compared to the storage space in the basin to regulate recharge, and the location and production capacity of wells are not optimized to prevent high groundwater conditions in wet periods and maintain production during dry periods."

The Six Basins would implement a conjunctive management program by creating a "dry-year storage account" in Pomona Basin which would be added to in wet years then withdrawn from when needed. First, the project dedicates 50,000 acre-ft of groundwater already in Pomona Basin to the account. Because the imported water demands of the three largest imported water users (City of La Verne, City of Pomona, GSWC) sum to 9,000 acre-ft/yr, "a dry-year storage

account of 36,000 acre-ft is required to withstand four consecutive dry years” (WEI, 2015, sec. 5.6.2) Then given the capacity to pump and treat 9,000 acre-ft/yr from Pomona Basin, the Parties would be able to withdraw from this account to meet their demand in dry years. In years with moderate recharge, no action is taken. In wet years, water can be added to the account by pumping less than a Party’s OSY, and obtaining water from other sources instead like TS or imported water. Implementing this project would require 8 new wells, new conveyance facilities to bring raw groundwater to treatment plants, and two new treatment plants.

The Strategic Plan outlines operating rules for the conjunctive management program, including how much water must have already recharged at the spreading grounds in a given year for it to be considered wet or dry. The developed yield is expected to be about 1,500 acre-ft/yr greater with this project than the baseline scenario (WEI, 2015, sec. 5.6.6). Over the 54-year planning period simulation, water was added in 14 years for a total of 108,000 acre-ft, withdrawn in 18 years for a total of 162,000 acre-ft, and held in the account without additions or subtractions for 21 years. In that last year of the planning period, water year 2061, the storage account is depleted to zero. This translates to water levels that are 240 ft lower than in the Baseline Alternative in the southern parts of the Pomona Basin, although as mentioned previously, water levels were up to 100 ft lower than this in the 1960s so the project is likely to be physically feasible (WEI, 2015, sec. 5.6.6). However, lowering water levels by this much may increase the challenges with production sustainability in Upper Claremont Heights Basin above what is expected under the Baseline Scenario, because much lower water levels in Pomona Basin would cause water to discharge more rapidly from Upper Claremont Heights Basin.

The project would require capital costs of about \$121m to achieve an average dry-year yield increase of 3,000 acre-ft/yr. As a result, the dry-year unit cost is an extremely high \$5,430/acre-ft. “The high unit cost is due to allocating the entire project cost to the dry-year yield,” so if the new facilities this project requires were used for other purposes in wet and intermediate rainfall years also, “the unit cost of conjunctive water management could be substantially reduced” (WEI, 2015, sec. 5.6.7).

Conjunctive use programs are an inherently sound concept and have been identified by numerous scholars and policymakers as being crucial for successful adaptation to Climate Change (California Natural Resources Agency, California Department of Food & Agriculture, & California Environmental Protection Agency, 2016), so it is somewhat surprising that its cost effectiveness would look so unfavorable compared to some other projects the Strategic Plan considered. Part of the problem is likely that the Six Basins lacks a large surface-water reservoir, which is an important piece of most conjunctive use programs. Without a dam that can be used for water conservation, the only long term storage available to the Six Basins Watermaster is groundwater. It seems likely that a conjunctive use program that included a temporary conservation pool behind San Antonio Dam would perform much better than the program currently outlined. Also, as the Strategic Plan mentioned, the entire cost of the project was allocated to dry-year yields, when in fact the facilities required would probably be used “for other purposes” in normal and wet years as well. Importantly, a conjunctive use program would deliver benefits

during dry years when imported water would likely be rationed or expensive or both, so the value of the water it delivers would be higher than that of a project that delivered increased yields only in wet years.

6) *Expanded Groundwater and Surface-Water Monitoring Program.* There is much that the Six Basins Watermaster still does not know with desired precision about how water moves within its boundaries. The Strategic Plan recommends addressing this by creating a monitoring program to improve engineering knowledge and planning and to evaluate over time the performance of predictive models. This would help address the impediments of loss of runoff, limited recharge, intermittent spreading, poorly quantified losses across San Jose Fault, poorly understood hydrogeological complexities in Pomona Basin limiting effective management of the subbasin, Storage and Recovery Agreements not accounting for subsurface losses, outdated computer models, monitoring equipment currently used at SASG possibly not returning accurate and complete data, differential subsidence across San Jose Fault, contaminants already in the Six Basins, and the possibility that contaminants' point-sources may not yet be adequately addressed.

For groundwater, the program would include: generating more accurate and frequent pumping records at wells, more carefully recording changes in water levels at wells, and construction of 3 new multi-depth monitoring wells in Pomona Basin. For surface water, the program includes: working with USACE to improve data recording at San Antonio Dam, better recording of diversions to and within SASG and TCSG, updating topographic maps of SASG and TCSG, reviewing the internal hydraulics of SASG and accurately measuring recharge rates, improving monitoring of recharge rates at TCSG, creating a yearly monitoring report, and after three years creating a report to document "the existing recharge capacity and the processes that constrain it" (WEI, 2015, sec. 5.7.2.2). The Watermaster anticipates that the groundwater monitoring program will cost \$122,000 the first year it is implemented, and then \$30,000/year after that. The surface water monitoring program will be \$60,000-80,000 the first year and some unknown but likely lower cost in subsequent years.

This last project is not intended to produce new yield directly, so it cannot be compared to the other five proposed projects in terms of cost-effectiveness. Its focus is instead on providing the knowledge necessary to make informed decisions about all the other projects. Given that some uncertainties about future climate are unavoidable, it would greatly benefit the Six Basins to have as few unknown factors as possible in play with regard to their own operations. Encouragingly, the Strategic Plan indicates that this project is one of its most immediate priorities. Ultimately, however, uncertainty and knowledge gaps will be unavoidable, so in addition to improving monitoring to minimize those gaps, the Six Basins should think seriously about how to plan for the future even without all the data they would like. The final section of this report suggests some ways the Watermaster might begin to do just that.

Conclusions and Policy Recommendations

The Strategic Plan of the Six Basins, simply by existing at all, proves that the Parties are willing to think seriously about how careful foresight and planning today can improve the

management of the aquifer for decades to come. No one understands the unique circumstances of this groundwater basin better than them, and no one is more invested in ensuring the reliability of its yields. Furthermore, the current version of the Strategic Plan does not pretend to be the final one; the report concludes: “The planning assumptions in the Strategic Plan should be reviewed annually and the plan revised if the planning assumptions critical to the plan are no longer valid. At a minimum, there should be a comprehensive review of the Strategic Plan every five years” (WEI, 2015, sec. 6.4). This thesis, by highlighting some weaknesses of the Strategic Plan, hopes to assist in that process of revision.

Climate Change is real, and it will have profound impacts on many aspects of basin management, far beyond simply inflating the price of imported water, which is all the current version of the Strategic Plan considers. It will affect local hydrology, by making both floods and dry periods more common. However, just how large these impacts will be remains unknown, and will remain somewhat uncertain until those climatic changes have already happened.

This question of how to plan effectively in the face of so many unknowns is certainly not a problem unique to the Six Basins; water managers across the country are reluctant to include climate forecasts in decision making. Reasons for this include a “traditional reliance on large built infrastructure, organizational conservatism and complexity, mismatch of temporal and spatial scales of forecasts to management needs, political disincentives to innovation, and regulatory constraints” (Rayner, Lach, & Ingram, 2005). In recent years, researchers such as Polasky et al. (2011) have begun to recognize the limitations of older decision-making frameworks, and are exploring new ways to “make good decisions without full knowledge, but using fully what is known at the time.” One possibility is for planners to employ a threshold approach, which helps organize “thinking about complex problems by focusing attention on critical boundaries that have major consequences if crossed” (Polasky, Carpenter, Folke, & Keeler, 2011). For the Six Basins Watermaster, this might mean considering how many consecutive dry years the aquifer could withstand before yields drop to unacceptably low levels, or how large a flood would be required to seriously damage San Antonio Dam and PVPA spreading infrastructure. If crossing those thresholds will lead to worst-case outcomes, understanding where those thresholds are would be of great planning importance to the Watermaster.

Another potential option would be for the Watermaster to use a scenario planning approach. In this context, “scenarios are sets of plausible stories, supported with data and simulations, about how the future might unfold from current conditions under alternative human choices” (Polasky et al., 2011). Orange County Water District (OCWD) uses this framework, which does not attempt to look at every single climate model or assign probabilities to different outcomes. Rather, OCWD examines a few different plausible climate scenarios and adaptations, then looks at its water system’s sensitivity to those changes (Rodrigo, 2016). How would supplies be affected by a small change in climate? What about a larger shift? Similarly, the Six Basins Watermaster does not have to know how likely different climate scenarios are to gain useful information about how prepared the Six Basins Parties are for the future. The Strategic Plan already examined a few scenarios—but all with the very optimistic assumption that future precipitation

will be the same as historical precipitation. The hydrology models used to develop the Baseline Alternative and Strategic Plan project options could be rerun with different precipitation inputs, to simulate plausible future climates. The United States Bureau of Reclamation already has an established method for downscaling global climate models to generate different precipitation scenarios at a watershed-scale, which it has applied for planning purposes in the Pacific Northwest (Brekke, 2011; Hamlet, Salathé, & Carrasco, 2010; Risk, n.d.). The California Department of Water Resources has also begun using this approach (CDM Smith & Technical Advisory Group, 2011).

The twin challenges of droughts and floods, which were crucial factors in the history of the Six Basins, will become even more formidable as inter-annual variability increases in the future. Therefore, in addition to identifying gaps in the general planning assumptions used by the Strategic Plan, this thesis attempts to highlight five key vulnerabilities of the management and facilities of the Six Basins. Addressing these will be crucial as the Watermaster attempts to adapt to Climate Change.

- 1) **The Six Basins cannot recharge large volumes of runoff over a short period of time,** and thus lose the opportunity to capture water when it is at its most abundant. Already, this limitation has proved problematic, but, given the likelihood that Climate Change will concentrate even more of Southern California's precipitation into a few stronger storms and wetter winters, this issue takes on even more urgency.
 - a) The Six Basins must strive to take the fullest possible advantage of sudden large pulses of runoff. Temporary Surplus projects will help to address this as long as they allow extra recharge during particularly wet seasons but do not result in less water being stored for future use.
 - b) Similarly, spreading ground improvements (particularly for SASG) will help improve the ability of the Six Basins to recharge water quickly.
 - c) Both of these options, however, probably are small compared to the benefits of changing the operation rules of San Antonio Dam. Even if it does take many years to navigate the complex legal process to achieve this, it should absolutely be pursued.
- 2) **Severe multi-year droughts will likely increase in frequency** from temperature increases alone, even if there is no change in the amount or timing of precipitation. When drought strikes, it will likely impact both local and imported supplies at the same time. Therefore, the best projects the Watermaster can pursue to decrease dependency on imported water will be those that offer reliable increases in local supplies during dry years.
 - a) A very promising option is the idea of selling recycled water from Pomona WRP to parties outside the Six Basins in exchange for a like volume of imported water delivered from TVMWD, because it would increase supplies even during droughts.
 - b) Pumping and treating water from the contaminated Pomona Basin also offers a source of improved yields that would be insulated from the effects of droughts. The Strategic Plan found the conjunctive management project to offer much higher-cost

yield increases than some other projects considered, and it anticipated a complete depletion of the dry-year storage account by the end of the planning period. However, it should be possible to design a conjunctive use program that is very worth pursuing, if for no other reason than the fact that it delivers water during droughts when alternative sources will be under greatest stress. The Watermaster should continue to explore the possibility of a conjunctive use project in the Six Basins.

- c) Temperature increases, and thus evapotranspiration increases, are one of the most robust predictions for California's climate in coming decades. Because local supplies travel a relatively short distance, are stored underground, and are not as reliant on snowmelt, they should be relatively less impacted by increased temperatures and evaporation from Climate Change as compared with imported supplies. This was a core assumption of the Strategic Plan, and should continue to be reevaluated, but for now remains plausible.
 - d) In the face of future droughts, the Parties may find that demand-side conservation measures are necessary. To adequately plan for this, demand hardening should be estimated and included explicitly in the Strategic Plan's forecasts of future water needs, with a distinction made for wet and dry years. It will be helpful for all Parties to anticipate how effective rate increases or other market-based demand reduction efforts will be. It is possible that the Parties are overestimating their consumers' ability to reduce water usage further in response to price signals, especially if they have already implemented many water conservation measures.
- 3) **Severe floods will be a major Climate Change-induced hazard**, and should be explicitly planned for. Climate models predict increases in wet winters and severe storms, but even if there was no change between historical and future precipitation, it would be prudent to prepare for floods at least on the scale of the one that occurred in 1938.
- a) Worryingly, the single most important piece of flood control infrastructure for the Six Basins area, San Antonio Dam, is currently in a state of disrepair and the USACE has determined that it carries an unacceptably high risk of failure during a severe storm event.
 - b) Since the construction of the Dam, previously uninhabitable areas of San Antonio Wash have been extensively urbanized. If the Dam failed, even partially, far more lives and property would be in harm's way than in 1938.
 - c) As long as it is vulnerable to failure, specifically because of seepage in the foundations, changing the operating rules of the dam to allow for water conservation will also be highly unlikely. Thus, for both flood control and water conservation reasons, repairing San Antonio Dam should be an urgent priority, and the Six Basins Parties should use whatever political means are at their disposal to speed this process.

- 4) **The availability of imported water will vary year-to-year** based on precipitation in Northern California and the Colorado River Basin, in addition to its gradually increasing in price over time as the Strategic Plan acknowledged. Importantly, when the Six Basins Parties are most in need of imports during dry years, imported water will be more scarce and possibly also more expensive. Regardless of price, during extremely dry years, imported water will be subject to rationing and mandatory restrictions.
 - a) More sophisticated modeling of the price of imported water should be attempted in the future editions of the Strategic Plan. When evaluating the cost-effectiveness of different Strategic Plan projects, the Watermaster should also take into account whether projects will deliver their benefits in wet years, dry years, or both.
 - b) A project that delivers improved yields in dry years, thus reducing the amount of unmet demand for imported water when its availability is restricted, might in fact be more cost-effective than a seemingly cheaper project that offers benefits only in wet years.
- 5) **Much of the information needed to most effectively plan for the challenges facing the Six Basins is unavailable**, either because of poor monitoring or uncertain climate and economic forecasts. Because uncertainty is unavoidable, The Six Basins Watermaster should formally embrace decision-making frameworks designed to operate under uncertainty.
 - a) The Watermaster can also sponsor research that will resolve or reduce many current knowledge gaps. The environmental consulting firm Wildermuth Environmental Inc. (WEI) was contracted to produce the previous edition of the Strategic Plan and did an extremely thorough, clear, and professional job. The Six Basins should engage them again to produce an updated version, with the request that they include some of the suggestions presented in this thesis. They are well equipped to rerun the hydrology models used to evaluate the Strategic Plan and to consider Climate Change impacts.
 - b) In addition to contracting more studies from WEI, there is another way the Six Basins can foster research of heretofore unresolved questions about this groundwater basin's management: Pomona College. This private educational institution sits on the Watermaster committee, leases its pumping rights each year to GSWC, and generally behaves as one of the Six Basins' more passive Parties. This should change; the Six Basins would benefit from Pomona College directing its students and professors to pursue research topics related to the groundwater basin. For example, geology students could study the complex stratigraphy of Pomona Basin, while economics students attempt to model the future price dynamics of imported water in dry and wet years. There are huge educational opportunities for members of the College if they engage as a more active participant in the Six Basins, while all other Parties would in turn benefit from the expertise and engagement of the many brilliant students and faculty members at Pomona

College. In short: this thesis should be the first of many produced by Pomona College students for the benefit of the Six Basins Watermaster.

The institutions that have managed the Six Basins have a long history of successful adaptation in a challenging and volatile environment. In the coming years, those challenges will become more acute than ever as Climate Change disrupts the precipitation upon which the Six Basins rely for groundwater recharge. The full significance of these changes will only become evident as they begin to manifest themselves, but the sooner the Watermaster begins anticipating the impacts Climate Change will have on basin management, the better prepared all Parties will be to adapt. With advanced planning and forward thinking assumptions, by “taking the long view” as the Strategic Plan says, the Watermaster can help ensure that the Parties enjoy reliable yields from the Six Basins aquifer for the foreseeable future. This thesis has attempted to begin identifying specifically how that can be done.

A concluding word of hope: the Six Basins Watermaster has the physical and financial ability to adapt to Climate Change. The situation is concerning, but certainly not dire. However, effective adaptation means good planning, and good planning must include considerations of Climate Change.

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