An Economic Analysis of the Institutional, Spatial and Temporal Dimensions of the Central Arizona Groundwater Replenishment District: Implications for Arizona's Water Future

by

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LIST OF ACRONYMS

ACC	Arizona Corporation Commission
ADEQ	Arizona Department of Environmental Quality
ADWR	Arizona Department of Water Resources
AF	acre-feet
AFY	acre-feet per year
AMA	Active Management Area
ARS	Arizona Revised Statutes
AWBA	Arizona Water Banking Authority
AWS	Assured and Adequate Water Supply
BOR	Bureau of Reclamation
CAGRD	Central Arizona Groundwater Replenishment District
CAP	Central Arizona Project
CAWCD	Central Arizona Water Conservation District
CC&N	Certificate of Convenience and Necessity
CWCGV	Community Water Company of Green Valley
GIS	Geographic Information System(s)
GMA	Groundwater Management Act
GRD	Groundwater Replenishment District
GSF	Groundwater Savings Facility
M&I	Municipal and industrial
MAF	million acre-feet
SCVWD	Santa Cruz Valley Water District
USF	Underground Storage Facility

ABSTRACT

Created by Arizona's development community, the Central Arizona Groundwater Replenishment District exists to facilitate compliance with the Assured Water Supply rules by replenishing excess groundwater pumped by its members. Currently, Arizona law does not require groundwater replenishment to take place within the area of hydrologic impact, and the enormous growth of CAGRD's replenishment obligation in recent years has caused some to question the sustainability of pumping in one location and replenishing in another. This thesis attempts to explain both the formation and the potential future of CAGRD using economic principles. The analysis of CAGRD's formation uses Nash's model of a cooperative negotiation with bargaining power to provide insight into the political economy behind the creation of the District. CAGRD's potential future is also studied, with particular attention paid to the economics of how CAGRD affects and is affected by the geographic distribution of water supplies in an Active Management Area. The spatial (GIS-based) economic model developed for this analysis allows for the prediction of the timing of any water utility's transition from groundwater pumping (and possible CAGRD replenishment) to direct delivery of a renewable water supply. While today CAGRD provides water providers and developers with an incentive to spatially disconnect their pumping and replenishment, the model presented in this thesis demonstrates that in the long run CAGRD will likely encourage these entities to stop mining groundwater and to import renewable water supplies. As this paper's model makes clear, the key factors controlling this decision include the water utility's distance from renewable water supplies, water demand, and degree of reliance on CAGRD for replenishment, as well as the CAGRD replenishment rate and the ADWR water level decline standard for recovery wells.

1. INTRODUCTION

Water is a resource of exceptional environmental, political, emotional, and economic significance. In no other place is this more palpable than in the semi-arid state of Arizona: like the august Grand Canyon in the northern part of the state, Arizona's human history cannot be fully appreciated without an understanding of the role of water.

The 20th century was a period of dramatic transition in Arizona. Significant advances in groundwater pumping and conveyance technologies in the 1930s effectively reversed mankind's basic relationship with water supplies, and for the first time in history, water could be made available virtually anywhere across the desert landscape. Today, central Arizona's largest river is a man-made aqueduct that brings Colorado River water from Parker Dam to Tucson—an uphill journey 336 miles long. This $4 billion aqueduct—the Central Arizona Project—serves the needs of millions of people and thousands of acres of farmland each year.

Over the next fifty years, as Arizona's population increases from six to over twelve million, Arizona must grapple with meeting its growing water demand (ADES 2006). In some ways, where this new development occurs relative to the present location of renewable water supplies is simply a matter of developing the infrastructure necessary to ensure that each new home and office building has a water supply equal to its demand. In other ways, the location of this new development may be more consequential than one might anticipate. If the trend of building groundwater-dependent satellite communities continues, how long will local groundwater supplies last? How much will it cost to deliver renewable water supplies to dry-well communities, when will this delivery occur, and who will pay for it? In the meantime, will anyone pay to mitigate the environmental consequences of dewatered aquifers?

This Master's thesis explores the economic implications of the institutional, spatial, and temporal dimensions of one of Arizona's more controversial water institutions: the Central Arizona Groundwater Replenishment District ("CAGRD"). To illuminate the economics behind these often opaque dimensions of water policy, two economic models will be used: the first, a Nash cooperative bargaining model, will address the formation of CAGRD; and the second, a spatially-explicit model of long-term water costs, will attempt to reveal the potential long-term economic implications of CAGRD by predicting its affect on the spatial balance of water supplies in an Active Management Area. Ultimately, the most important goal of this study is to engender a deeper understanding of CAGRD and its implications for the state of Arizona.

To introduce and begin to build context for the problem at hand, however, a brief overview of pertinent details regarding Arizona's complex system of water management will first be presented.

1.1. A Brief History of Arizona Water Management, 1912-1968

Water has profoundly shaped the history of Arizona (August, Jr. and Gammage, Jr. 2006). The task of obtaining and managing water resources has been an enduring challenge to Arizonans since well before the state of Arizona entered the Union in 1912. Early American settlers, like the Hohokam centuries before them, developed extensive irrigation and flood control systems to manage surface water for agricultural and urban uses. Encouraged by the Reclamation Act of 1902 to "make the desert bloom," farmers expanded their irrigated lands into the desert, with the help of large water storage and delivery projects (Jacobs and Worden 2004).

The introduction of new pumping technology in the 1930s and 1940s enabled Arizona farmers to irrigate farmland that was once too far from surface water supplies to be considered irrigable. Arizona quickly entered a new era of agricultural production. In the period from 1940 to 1953, irrigated crop production in Arizona expanded from 500,000 acres to over 1.3 million acres, causing irrigated water demand in Arizona to rise from approximately 1.5 million acre-feet[1] (MAF) to 4.8 MAF (Kelso, Martin and Mack 1973; Glennon 1991). Arizona's population similarly grew over the same period, nearly doubling its population with the addition of over 400,000 new residents.

A consequence of such rapid growth, however, was that the rate of groundwater pumping grew to be far in excess of natural recharge rates in many areas. The "Ice Age" waters in Arizona's aquifers, deposited in an era when Arizona's climate was significantly wetter than it is today, were now being rapidly depleted by the state's numerous agricultural production wells.

With the groundwater and surface waters of the state's interior managed largely by irrigation districts, Arizona leaders soon turned to the Colorado River as the critical "next bucket" of water to serve the state's agricultural and municipal water needs. Years of bitter political wrangling had produced the Colorado River Compact in 1922, which divided the Colorado into Upper and Lower basins and allocated rights to the river's presumed average flow among the seven states. The Compact reserved Arizona the right to divert 2.8 MAF of the 7.5 MAF allocated to the Lower Basin states each year. Yet with much of the state's water demand located hundreds of miles from the river, Arizona had not been able to put much of its entitlement to beneficial use. Instead, the majority of Arizona's apportionment was being beneficially used by irrigation districts in California, or else flowing into Mexico as surplus to the international agreement guaranteeing Mexico 1.5 MAF annually.

Despite the legal security of their right, Arizona leaders became fearful that the politically powerful state of California would see their use of Arizona's entitlement as grounds for

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[1] An acre-foot of water is defined as an acre of water one foot deep, or 325,821 gallons.

revisiting the Colorado River Compact and its allocation among the basin states. Clearly, this scenario would not bode well for Arizona. Having no infrastructure in place to put its allocation to beneficial use, Arizona leaders, led by U.S. Senator Carl Hayden, recognized that revisions to the Compact would not be favorable to Arizona’s entitlement. A consensus soon emerged that held that the best solution to the dual problem of groundwater overdraft and unused Colorado River water would be to augment the state’s water supply by importing Colorado River that was not being used by mainstem farmers and Indian tribes. Achieving this goal was a long, costly process. Initiated by Senator Hayden during the Second World War, the project to deliver Colorado River water to central Arizona would take half a century and no shortage of ingenious political and financial maneuvers. In truth, nearly all water policies developed in Arizona over the last half-century have been shaped by the fear that Arizona may lose part of its entitlement to the Colorado River.

1.2. The Central Arizona Project

To bring the water from the Colorado River into central Arizona, an aqueduct was proposed by Arizona Senator Carl Hayden in 1944. The system, known as the Central Arizona Project (CAP), was authorized twenty-four years later by the Colorado River Basin Project Act of 1968, after a long legal battle with California. The Act supported Arizona’s right to divert water through the CAP but declared the right junior to all other existing rights on the River. Believing the loss in priority to be worth the exchange, Arizona accepted the terms and began engineering the CAP in 1973. In October of 1979, progress was halted by a threat made by the Secretary of the Interior Cecil Andrus that unless Arizona adopted a statewide groundwater management code, the federal government would not allow Arizona to divert Colorado River water for the CAP.[2] The Arizona state legislature responded to Andrus' threat by passing the Groundwater Management Act nine months later in June of 1980, and construction continued on the 336-mile system of canals, pumping stations, and secondary distribution systems comprising the CAP aqueduct (Needham 2005).

Financing the Central Arizona Project was an enormous undertaking. At over $4 billion, the full cost of the CAP was too much for Arizona to bear, particularly for the farmers for whom much of the water was intended. With some negotiation, the federal government agreed to front the cost of the project, and Arizona agreed to repay roughly half of the cost. For this purpose, Arizona established a special taxing district called the Central Arizona Water Conservation District (CAWCD) to oversee both the operations of the project and the repayment of the federal loan, which was to commence upon declaration of substantial completion of the CAP aqueduct. A particularly important clause in the loan's contract was that the interest charged on the portion of the project dedicated to delivery of municipal and industrial water would be approximately 3.3 percent, while deliveries of agricultural water would be interest free (Governor's CAP Advisory Committee Report 1993, p. 80).

Prior to construction of the CAP, expectations were that non-Indian agriculture would buy approximately 60 to 80 percent of the CAP supply for the first few decades of operation (Wilson 1992). It was also believed that as central Arizona urbanized and developed the infrastructure to be able to accept CAP water for residential use, non-Indian agriculture's share of the CAP allocation would diminish due to agriculture's lower priority right. But economic

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[2] This was the public perception of how the threat transpired. Andrus has since revealed that it was in fact Arizona Governor Bruce Babbitt who asked Andrus to make this threat. Babbitt perceived the danger of bringing in renewable supplies without addressing the problem of groundwater overdraft and was frustrated by a conservative Arizona legislature unwilling to address the problem. Therefore, he secretly implored Secretary Andrus to require the establishment of a groundwater code as a prerequisite to obtaining an allocation of Colorado River water for the CAP from the Department of the Interior (Andrus 2005). Andrus agreed.

realities prevented the realization of these expectations (Wilson 1997). Half of the eligible agricultural landowners in the CAP service area (Maricopa, Pinal, and Pima Counties) declined to contract for CAP water when it became available because it was too expensive. For those districts that did contract for CAP supplies, the availability of lower cost water supplies (e.g. groundwater, surface water, and effluent) reduced demand for CAP water, and as a result, water deliveries to non-Indian agriculture declined by 48 percent between 1989 and 1991 (Wilson 1992).

Unable to force CAP water upon farmers and irrigation districts, Arizona began to craft water policies and programs to encourage agricultural water users to accept CAP water. Among these programs have been the agricultural pool program and the groundwater savings program (Megdal and Shipman 2008). Other policies and programs have been developed to maximize the use of CAP water by the municipal sector. These include the Arizona Water Banking Authority, the Assured Water Supply Rules, and the Central Arizona Groundwater Replenishment District. The authority of these programs, however, stems from the Groundwater Management Act of 1980.

1.3. The Groundwater Management Act of 1980

Arizona's Groundwater Management Act (GMA)—widely regarded as a progressive groundwater code when it was enacted into law in 1980—truly marked the beginning of a new era of water management in Arizona. It created the Arizona Department of Water Resources (ADWR) to manage the state's water resources, and established four Active Management Areas in central Arizona, delineated by natural hydrologic boundaries, to allow for greater local management of the state's water resources. Each Active Management Area (AMA) is required to create five management plans, each ten years in duration. To gradually bring the problem of groundwater overdraft under control, the management plans are designed to become more restrictive with time. The GMA also mandated a number of conservation practices from the municipal and industrial (M&I) sectors and prohibited agriculture from irrigating land in the AMAs that did not have an Irrigation Grandfathered Right (IGFR).

The GMA enabling legislation also established a single, guiding management goal for each AMA to direct the water management activity within the AMA throughout the five management periods. The Phoenix, Tucson, and Prescott AMAs were created with the management goal of achieving safe yield by 2025, "safe yield" meaning "to achieve and thereafter maintain a long-term balance between the annual amount of groundwater withdrawn in an active management area and the annual amount of natural and artificial groundwater recharge in the active management area" (Arizona Revised Statutes §45-562; §45-561). Because safe yield is measured over the entire AMA, the water table may be declining in some areas of the AMA as long as these areas are offset by rising water levels elsewhere in the AMA. By contrast, the management goal for the heavily agricultural Pinal AMA was to "allow development of non-irrigation uses, preserve the agricultural economies for as long as feasible, and preserve water for future non-irrigation uses" (ARS §45-562). This management goal, once termed "planned depletion," and was designed to preserve the agricultural economy of the Pinal AMA for as long as is economically feasible. A fifth Active Management Area, the Santa Cruz AMA, split off from the southeastern portion of the Tucson AMA in 1994 to allow greater focus on the area's unique hydrology and international issues (Colby and Jacobs 2006). The Santa Cruz AMA's management goal is "to maintain a safe-yield condition in the active management area and to prevent local water tables from experiencing long-term declines" (ARS §45-562).

1.4. The Assured and Adequate Water Supply Rules

From a water conservation perspective, one of the most important provisions of the Groundwater Management Act was simply a reinforcement of a 1973 state law regarding water supply adequacy for subdivisions. Under this law, developers were required to obtain a determination from the state regarding the availability of water supplies prior to the sale of new subdivision lots (ARS §45-108). Developers demonstrating "inadequate" water supplies for a subdivision were required to disclose this information to potential buyers, but were nevertheless allowed to sell lots to willing buyers. The 1980 GMA supersedes this law in the AMAs by prohibiting the sale or lease of subdivided land in an AMA for which an Assured Water Supply has not been demonstrated.

According to Arizona law, not all developments are subdivisions. The definition of a subdivision in the GMA is linked to the real estate section of the Arizona Revised Statutes, which defines a subdivision as having six or more lots and containing at least one parcel of less than 36 acres (ARS §32-2101). If a development does not fit the definition of a subdivision under this statute, it is not required to obtain an Assured Water Supply determination from ADWR, but, like all lot sales outside the AMAs, it is still subject to the 1973 Water Adequacy Statute. All subdivisions within the AMAs not served by a designated water provider must obtain a Certificate of Assured Water Supply from ADWR under the GMA. The demonstrated water supply requirements for areas both inside and outside AMA boundaries are collectively known as the Assured and Adequate Water Supply Rules.

To obtain a Certificate of Assured Water Supply, a subdivision must demonstrate that: (1) the water supply is physically, legally, and continuously available for 100 years; (2) the water meets water quality standards or is of sufficient quality; (3) the proposed water use is consistent with the management goal of the AMA; (4) the proposed water use is consistent with the current management plan of the AMA; and (5) the developer has the financial capability to construct any necessary water storage, treatment, and delivery systems.[3]

While the GMA established these basic criteria for demonstrating an Assured Water Supply, it did not provide ADWR with clear instructions regarding how to enforce compliance with the management goals of the AMAs. To this end, ADWR drafted a more rigorous set of Assured Water Supply Rules in November 1988 to require new development in the safe yield AMAs to demonstrate that the assured water supply is primarily renewable.[4] The Draft Rules, as they are called, met with strong resistance from the Arizona development community, and even drew criticism from agriculture (Avery, et al 2007; Glennon 1991). Of particular offense to developers was the provision of the draft rules that limited exactly how much groundwater could be used to demonstrate an Assured Water Supply. Since the allowable groundwater was to be measured on an acre-foot per acre basis, the number of residences per acre for new developments would be limited in the AMAs. Furthermore, the allowable groundwater supply was restricted even if the groundwater right was an agricultural Irrigation Grandfathered Right, effectively reducing the value of agricultural land and weakening the incentive for conversion from agricultural to residential land use (Glennon 1991). Recognizing the political power of the opponents of the Draft Rules, ADWR quickly yielded and established a committee to evaluate the potential economic impacts of the draft rules.

Several years of public process, mainly between the development community and the Department of Water Resources, followed the failure of the 1988 draft rules. Short of not

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[3] See A.C.C. R12-15-703 to 707 for a more detailed description of each AWS criteria.
[4] See R12-15-722 for more details about the 1988 AWS Draft Rules.

developing, development interests had several ways to comply with the Draft Rules' proposed limitation on groundwater pumping, including purchasing CAP water, utilizing existing water farms outside AMAs (prior to 1991), obtaining a water service agreement from a municipal water provider with a CAP allocation or other surface water rights, or obtaining rights to use effluent (Glennon 1991). In reality, however, economic and legal difficulties rendered many of these options impractical, at best, for many subdivisions (Avery et al 2007).

With time, different ideas for addressing the need for new growth to rely on renewable water supplies surfaced. One popular idea led to the authorization of single-county replenishment districts in 1990, eventually leading to the formation of the Phoenix Groundwater Replenishment District and the Santa Cruz Valley Water District. The Phoenix Groundwater Replenishment District, taking the approach of making membership mandatory for the entire Phoenix AMA, failed to garner the support of the City of Phoenix, which was not comfortable with the district's proposed governance and tax structure (Buschatzke 2007). The Santa Cruz Valley Water District (SCVWD) was created as a temporary entity to "facilitate water resource management" in the Tucson AMA, and more specifically, to augment the renewable water supply of the AMA and perform replenishment on behalf of its members (ARS §48-4802; SCVWD 1993). The SCVWD was therefore given a variety of powers and duties, including the construction of recharge projects; cooperation with government entities; issuance of revenue bonds; and the ability to adopt groundwater replenishment responsibilities (SCVWD 1993). While the District reported a "significant" level of interest in its services during the planning period, it performed limited activities in the Tucson AMA related to water augmentation, recharge site identification, and policy coordination from 1991 to 1993, and was later eclipsed by a more permanent and convenient replenishment authority: the Central Arizona Groundwater

Replenishment District. While the statutes giving replenishment authority to the Phoenix GRD and the SCVWD still exist, these local replenishment authorities are not likely to be revived (Buschatzke 2007; Megdal 2007).

1.5. The Central Arizona Groundwater Replenishment District

In 1993, the development community proposed a compromise with the Arizona Department of Water Resources in the form of a replenishment authority under the auspices of CAWCD. This replenishment authority is known as the Central Arizona Groundwater Replenishment District (CAGRD). CAGRD was created to give the development community an efficient and practical means of complying with the criterion of the Assured Water Supply (AWS) rules that new growth in the Active Management Areas rely primarily on renewable water supplies. Unlike the previously authorized replenishment districts, CAGRD was authorized as a multi-county replenishment authority to operate in the Phoenix, Pinal, and Tucson AMAs to serve members who voluntarily join the District. CAGRD members are classified as either Member Service Areas (water providers), or Member Lands (subdivisions).

1.5.1. Member Service Areas

A “water provider” is defined in the Arizona Revised Statutes as a “city, town, private water company or irrigation district that supplies water for non-irrigation use” (ARS §45-561). A water provider seeking to comply with Criterion 3 of the Assured Water Supply Rules (which relates to the consistency of the demonstrated water supply with the management goal of the AMA) may join CAGRD as a Member Service Area (MSA) (ARS §48-3780). Membership in CAGRD automatically fulfills Criterion 3 (CAGRD Executive Summary). Still, to obtain a

Designation of Assured Water Supply, the MSA must demonstrate that the proposed water supply meets the four other criteria of the AWS rules. Membership in CAGRD legally transfers the replenishment obligation from the MSA to CAGRD. CAGRD then has up to three full calendar years from the year that the groundwater replenishment obligation is incurred to fulfill its replenishment obligation (ARS §48-3771). The cost of replenishment is fully paid by the MSA on a per acre-foot basis.

1.5.2. Member Lands

The other type of CAGRD member is the subdivision, or Member Land (ML). The Assured Water Supply rules state that a developer must obtain a Certificate of Assured Water Supply for a proposed subdivision to enable plat approval and authorization of sale or lease from the Department of Real Estate (ADWR 2001). The developer may meet the requirement that the proposed water supply must be primarily renewable by legally and physically obtaining renewable supplies to serve the subdivision, or by enrolling the subdivision as a CAGRD Member Land (ML); as with MSAs, membership in the CAGRD automatically satisfies Criterion 3 of the AWS rules. To enroll, the applicant must define the boundaries of the property, specify the number of individual units to be built, agree to provide the CAGRD with water use data for the purposes of calculating the annual replenishment obligation, and pay an Enrollment Fee per housing unit. Member Lands not containing a golf course are classified as Category 1 Member Lands; those MLs with a golf course are classified as Category 2 Member Lands. Category 1 MLs pay annual replenishment reserve charges and replenishment reserve fees, pursuant to ARS §48-3772(E); Category 2 MLs, that is, subdivisions with a golf course, are exempt from these charges and fees, pursuant to ARS §48-3774.01(C). The Enrollment Fee is annually established by CAGRD, and is $23 per home for the year 2007-08. In addition to the Enrollment Fee, the ML is also required to pay an Activation Fee prior to the issuance of a public report for the subdivision, pursuant to ARS §48-3772(A). The Activation Fee is also established annually by CAGRD, and is $63 per home in 2007-08. The difference between the Enrollment Fee and the Activation Fee is that the developer must pay the Enrollment Fee to enroll the subdivision as a Member Land in the CAGRD, but does not have to pay the Activation Fee until just prior to construction. The impact of the CAGRD fee schedule on the CAGRD's ability to fulfill its legal obligations is discussed in Chapter 2, Section 2.3.4; the broader economic implications of the fee schedule are discussed in Chapter 5, Section 5.2.2.

A subdivision served by a water provider with a designation of Assured Water Supply does not need to apply to ADWR for a Certificate of Assured Water Supply; the developer need only obtain a written commitment of service from the designated provider to demonstrate compliance with the AWS rules (ARS §45-576(A, F)).

1.5.3. Location of CAGRD Replenishment

The basic requirement for the location of replenishment is that it must occur within the same AMA as the excess groundwater pumping. But in the Phoenix AMA, the CAGRD has the additional statutory requirement that, "to the extent reasonably feasible," groundwater pumped out of the east portion of the AMA must be replenished in the east subbasin of the Salt River Valley, and similarly for pumping and replenishment in the west portion of the AMA (ARS §48-3772(G); §48-3772(I)). In the Pinal and Tucson Active Management Areas, the CAGRD is not required by statute to replenish in the same subbasin as the excess groundwater pumping. Nevertheless, the CAGRD does make an effort to replenish excess groundwater as close to the site of pumping as possible: in the Tucson AMA, the CAGRD replenishes excess groundwater pumped in the northern part of the AMA at recharge facilities in Marana and Avra Valley when feasible; likewise, the preferred recharge site for pumping from the southern portion of the Tucson AMA is the Pima Mine Road Underground Storage Facility (Neal 2007). (A map of the Tucson AMA is provided in Appendix A-1.)

1.5.4. CAGRD Replenishment Costs

The CAGRD replenishment rate consists of four parts: a water and replenishment component, an administrative component, an infrastructure and water rights component, and a replenishment reserve charge (see Table 1.1 in Appendix B). The water and replenishment component includes all costs of purchasing and transporting water supplies, and is computed separately for each AMA. The administrative component covers the administrative costs of CAGRD replenishment, and is the same for all AMAs. The infrastructure and water rights component is designed to cover the costs of securing rights to long-term water supplies, and is computed separately for each AMA. (In practice, this component is considered inadequate for its intended purpose.) The replenishment reserve charge is paid by MSAs and Category 1 MLs, and covers the cost to the CAGRD of establishing and maintaining a replenishment reserve of long-term storage credits for each AMA, per ARS §48-3780.01. Because the replenishment rates are designed to cover the previous year's replenishment obligation, much of the revenue that supports CAGRD's statutory obligations is lagged by at least one year.

1.5.5. Governance, Operations, and Planning

The Central Arizona Groundwater Replenishment District is not a district in the sense of being an autonomous entity; it is simply an expansion of the authorities of the CAWCD to include groundwater replenishment. As such, the CAGRD is managed by CAWCD staff and governed by the Board of Directors of CAWCD.

Water providers serving CAGRD Member Lands must annually report to CAGRD and ADWR the volume of groundwater and the volume of excess groundwater delivered to each parcel within the Member Land (ARS §48-3775a). Similarly, water providers serving CAGRD Member Service Areas must annually report to CAGRD and ADWR the total volume of groundwater and the total volume of excess groundwater delivered within the service area. In the Phoenix and Tucson AMAs, the volume of excess groundwater is then multiplied by an annually increasing "minimum reporting factor" to calculate the volume of replenishment CAGRD must do on behalf of each member (see Table 1.2 in Appendix B). The minimum factor is multiplied by the member's groundwater use to determine the volume of excess groundwater to be reported. The factor depends on the nature of the member (Member Land or Member Service Area), the date of enrollment, and the AMA. For example, if Rancho Sahuarita Water Company pumped 1,100 AF of groundwater in 2007, ADWR would first determine the portion of this pumping that is considered "excess" groundwater, then Rancho Sahuarita would multiply this volume of excess groundwater by CAGRD's excess groundwater reporting factor for a Member Service Area in the Tucson AMA for 2007—that is, 9/30ths, or 0.3. ADWR's determination of the volume of excess groundwater is based upon the water provider's share of the basin's natural recharge, among other things specifically related to the water provider. If the volume of excess groundwater is 1,000 AF for Rancho Sahuarita, then the replenishment obligation for Rancho Sahuarita would be 300 AF (1,000 x 0.3) in 2007. The excess groundwater replenishment factor increases through time. The purpose of the replenishment factor is to ease the transition for CAGRD members into paying the relatively high cost of CAGRD replenishment.

Pursuant to ARS §48-3775, CAGRD must submit a Conservation District Annual Report to ADWR by August 31 of each year showing the groundwater replenishment obligations incurred and satisfied in the previous calendar year. The CAGRD must replenish each AMA's aggregate replenishment obligation within three calendar years. Water providers serving MSAs pay the CAGRD for the replenishment of the entire service area's annual excess groundwater consumption, and recover the cost in their rates. With Member Lands, individual parcels are charged for the replenishment CAGRD performs on their behalf in the form of an assessment on their property tax.

To demonstrate that its activities are in compliance with the management goals of the AMAs, the CAGRD must submit a Plan of Operation to the Director of the Arizona Department of Water Resources every ten years describing the activities for each active management area that the CAGRD proposes to undertake during the following one hundred calendar years (ARS §45-576.02C). The plan must include the following information for each of the three AMAs:

- Cumulative groundwater replenishment obligations and the extent to which those obligations have been met in the 10 years preceding submittal of the plan;

- An estimate of the CAGRD's current and projected groundwater replenishment obligations for current members for the 20 calendar years following the submission of the plan;

- An estimate of the CAGRD's projected groundwater replenishment obligations for the 100 years following the submission of the plan for current members and potential members based on reasonable projections of real property and service areas that could qualify for membership in the 10 years following the submission of the plan;

- A description of the water resources that the CAGRD plans to use for replenishment purposes during the 20 calendar years following submission of the plan and water resources potentially available for groundwater replenishment purposes during the subsequent 80 calendar years;
- A description of the CAGRD's current replenishment reserve activities in each AMA for the 10 years preceding the current plan and planned replenishment reserve activities for the ensuing 10 years to be undertaken pursuant to ARS §48-3772E;
- A description of any facilities and projects to be used for replenishment and the replenishment capacity available to the district during the 20 calendar years following submission of the plan;
- An analysis of potential storage facilities that may be used for replenishment purposes;
- A description of the CAGRD's capability to meet the current and projected groundwater replenishment obligations for the 20 years following the submission of the plan; and
- Any other information that the director may require.

One of the key requirements of the Plan of Operation is the demonstration that the CAGRD's water portfolio is reliable and secure. However, the standards for this demonstration are different from the AWS standards for individual water providers and developers. While the CAGRD must provide a description of water it "plans" to use to fulfill 20 years of replenishment obligation and water "potentially available" for the remaining 80 years of the standard 100-year AWS demonstration, other entities must acquire firm water supplies for 100 years. No statute requires the CAGRD to possess secure water supplies to meet its obligations for 100 years, as is the requirement for non-CAGRD members.

The temporary nature of CAGRD's water supply portfolio may be justified, however. Since the CAGRD replenishes water after it has been pumped, it may logically follow to allow the CAGRD some flexibility in obtaining water supplies to meet its obligation. Also, because water providers must demonstrate the physical availability of groundwater, the reliability of the customer's water supply is physically unaffected by the CAGRD's ability to demonstrate the future availability of water supplies. Another reason is that the risk of losing one particular water source demonstrated on paper is reduced by allowing the CAGRD to assemble a diverse water supply portfolio, which is more difficult to do with more economically scarce long-term water supplies. CAGRD appears to be a good candidate for cobbling together the "left over" water supplies that would not otherwise be used to demonstrate 100 years of water (Holway, Newell, and Rossi 2006).

In the short-term, CAGRD will continue to rely year-to-year on "excess" CAP water—unused CAP entitlements, un-contracted CAP supplies, and surplus Colorado River supplies—to fulfill its replenishment obligation. But excess CAP water is only a temporary resource; as demand for CAP allocations increases, the "low-hanging fruit" of excess CAP supplies will be removed from the market. As stated in the 2001 Report of the Governor's Water Management Commission, "a permanent demand has been created on temporary supplies" (Governor's Water Management Commission 2001). In time, CAGRD will be forced to enter the water supply market and compete for limited and increasingly expensive water supplies. While replenishment dues are relatively inexpensive for CAGRD members today, future replenishment costs are likely to be significantly higher than current rates. (Future water supplies may include Indian leases, mainstream Colorado River allocations, or effluent supplies.)

To protect the customers of the CAGRD from having to pay the highest market price for increasingly scarce water supplies, and to avoid having a crisis of water supply availability, the 2001 GWMC recommended that legislation be drafted to require the CAGRD to establish a "replenishment reserve" of up to 20% of CAGRD's 100-year replenishment obligation. The replenishment reserve, instituted in 2004, consists of long-term storage credits that are stored on behalf of the members of the CAGRD for each AMA. The Replenishment Reserve Fees must be paid by new members as of 2004 and are based on the AMA's Replenishment Reserve Charge and the volume of each member's projected built-out replenishment obligation (Ferris, Megdal, and Eden 2006). The benefit of the replenishment reserve is that it does not force CAGRD to purchase 100-year firm supplies and therefore compete with water providers, many of them CAGRD members themselves. It also allows CAGRD the flexibility to take advantage of short-term water supplies at reasonable cost as they become available.

1.5.5.1.Water Availability Status

In 1999, an additional responsibility was added to CAGRD's already unenviable list of obligations with the passage of House Bill 2262, the Water Sufficiency and Availability Act. The statute allows any city, town, or private water company that qualifies as a CAGRD Member Service Area to meet the physically available water supply criterion of the Assured Water Supply rules by entering into a contract to have CAGRD deliver water where it is physically accessible. In effect, water providers unable to receive a designation of AWS or renew their designated status due to physical constraints may contract with CAGRD to receive up to 20,000 acre-feet of water per year for recharge in the location of recovery or for direct delivery. Upon approval of CAGRD's application to grant "Water Availability Status" to the water provider, CAGRD and the water provider are free to contract for *ex ante* deliveries (ARS §45-576.07B). Rates for water deliveries per a Water Availability Status contract do not include a replenishment reserve component. As of December of 2007, the City of Scottsdale is the only MSA that has executed a Water Availability Status contract with CAGRD, at a maximum of 3,460 acre-feet per year.

Essentially, the Water Availability Status provision extends the responsibilities of the CAGRD from helping all members demonstrate the availability of a renewable water supply to helping some members with the more basic requirement of showing that water is physically available to begin with.

1.6. Underground Storage, Savings, and Replenishment Programs

For entities possessing a CAP subcontract, there are several alternatives to the CAGRD that facilitate compliance with the AWS rules. The Underground Storage, Savings, and Replenishment Program was originally authorized in 1986, and later expanded in 1994. The program was developed to help achieve Arizona's goal of fully utilizing (and thereby protecting) its entitlement to the Colorado River by facilitating replenishment of CAP water.

1.6.1. Groundwater Savings

The groundwater savings program is one of the pillars of the Underground Storage, Savings, and Replenishment Program. It is essentially a partnership between irrigation districts looking for low-cost water supplies and cities looking to make use of available renewable supplies, including CAP water and, to a lesser extent, effluent. Per the Assured Water Supply rules, a municipal water provider must offset all pumped groundwater that is deemed "excess." Participation in the Groundwater Savings program helps accomplish this by allowing the municipal provider to purchase CAP water and resell it to the partnering irrigation district (or individual farmer in some cases) at a cost that competes with the district's cost of pumping groundwater. The district therefore uses CAP water "in lieu" of the groundwater it would have pumped, and the municipal provider earns storage credit for the "saved" groundwater.

To participate as a Groundwater Savings Facility, an irrigation district must receive a permit from ADWR to register as a GSF. To receive a permit, a district must demonstrate legal and physical ability to pump groundwater, and prove to ADWR that the CAP water to be subsidized by the water provider would be substituted on a gallon-for-gallon basis for the groundwater that would have been pumped by the district (ARS §45-812.01(B)). A farmer whose land lies within an irrigation district that holds a valid GSF permit automatically qualifies to receive CAP water through the Groundwater Savings Program.

To partner with a particular GSF, a municipal water provider must obtain a Water Storage Permit from ADWR (ARS §45-831.01(A)). Water stored at a GSF by a permitted water provider may be recovered at any time. However, if the water provider wishes to recover some of the water stored at a GSF after the end of the calendar year, it must obtain a long-term storage account with ADWR to be able to keep a record of its generated storage credits. For example, if 100 AF are stored at a GSF in August and are not recovered until the following January, then the stored water is added to the utility's long-term storage account. Since the water was not recovered within the same calendar year as it was stored, the long-term storage credits available to the utility are 95 percent (95 AF in this case) of the original volume stored; the remaining five percent (5 AF) are a non-recoverable "cut to the aquifer" for the simple purpose of aquifer replenishment. Only water providers with a Designation of Assured Water Supply from ADWR may earn long-term storage credits.

To illustrate how the groundwater savings program works, consider an example "Water Company X" in Tucson. Possessing a CAP allocation but unable to deliver it directly, the Company may use its CAP allocation indirectly through participation in the groundwater savings program. After obtaining a Water Storage Permit, Water Company X may coordinate with

"Irrigation District Y" to deliver its subcontracted CAP water to Irrigation District Y for a price that competes with other water sources the District would have used. Once the delivery has occurred, Water Company X may then recover none, part or all of the resulting groundwater savings credits anywhere within the AMA at any time.

1.6.2. Underground Storage

The underground storage program differs from groundwater savings in that it physically adds water to the aquifer by directly recharging surface water using injection wells, streambeds, or constructed spreading basins. Any water supply that meets the standards of the Arizona Department of Environmental Quality may be directly recharged; effluent treated to high quality standards (ADEQ Class A) is often recharged through streambeds. As with indirect recharge, the stored water retains its legal character upon recovery. For example, groundwater that is recovered using water storage credits generated with CAP water is legally considered CAP water upon recovery, though it may be chemically dissimilar from CAP water and recovered many miles from the location of storage. Effluent is considered to be its own category of water—neither groundwater nor surface water; upon recovery, it is still simply "effluent."

As with groundwater savings, water stored at an Underground Storage Facility (USF) may be recovered directly by installing pumping wells near the recharge site and wheeling the water on the CAP aqueduct or other distribution system, or indirectly by pumping groundwater in another location and extinguishing storage credits from the storer's long term storage account. In addition, water recovered after the end of the calendar year in which the storage occurred is considered recovery of long term storage credits and is subject to the five percent "cut to the aquifer" (ARS §45-852.01).

1.7. Emergence of ‘Paper Water’ Management

Arizona’s storage and recovery programs are truly innovative water management practices in the sense that they have maximized the use of renewable supplies, achieved the full use of Arizona’s Colorado River entitlement, successfully stored large volumes of water to mitigate the impact of future drought, and moved Arizona closer to offsetting gross overdrafts in some of the state’s most unbalanced aquifers (Colby and Jacobs 2006). Yet part of the reason these programs are considered innovative is that they gained wide support from disparate interests to achieve these policy objectives. This process naturally required some compromises, often in the form of policies and provisions that may be considered less desirable from a long-term water management perspective.

One result of these provisions often debated in the Arizona water community is the “paper water” system as a disincentive for water users to correct local aquifer drawdowns. Paper water refers to “the accounting methods used to track the amount of water added to and removed from underground aquifers in the AMA and for water that passes into and out of the boundaries of the AMA” (Schwarz 2006). The paper water system was developed in the 1980s as a critical step toward managing the groundwater resources of the AMAs. It provides a legal accounting procedure for monitoring water users’ groundwater pumping and replenishment. However, the paper water system is criticized for monitoring groundwater pumping and replenishment at the AMA level rather than a more local level. The AMA-level accounting stance effectively treats the AMA like a giant bathtub, where the water level quickly equalizes in the tub regardless of the locations of inputs and outputs. Critics of this system point out that because aquifers do not behave like bathtubs, reliance on a system that allows groundwater to be replenished far from the area of pumping enables localized water level drawdowns to continue. Thus, the paper water system enables a water utility to be in full compliance with the AWS rules on paper while dewatering a portion of an aquifer that is far from the location of existing renewable water supplies. This is seen as a problem for two reasons: (1) the water utility does not have to pay for any environmental damages from dewatering the aquifer; and (2) renewable supplies will eventually have to be imported to provide the residents of the community served by the water utility with a stable supply of wet water.

The paper water system was developed to allow urban and suburban growth to continue in the AMAs by delaying the cost of physically transporting renewable water supplies. Built upon and taking full advantage of the paper water system is the Central Arizona Groundwater Replenishment District. The enormous popularity of the CAGRD has engendered concern that the paper water system is enabling growth to occur without regard for the future cost of that growth on future residents. As the cost of replenishment increases, homeowners in CAGRD member subdivisions will be forced to pay these higher costs. In addition, some of these communities may need to invest in the physical infrastructure to directly deliver CAP supplies as their wet water supplies dwindle. To date, the potential implications of paper water reliance have not been explicitly analyzed.

1.8. Research Objectives and Hypotheses

This research effort is has two primary objectives. The first objective is to use the language and conceptual models of economics to explain how CAGRD formed, and link some of its current issues to the process of its formation. The second objective is to use a spatially explicit economic model to (a) show how CAGRD (together with the "paper water" system) affects the regional distribution of physical water supplies in an Active Management Area, and (b) predict the long-term economic impact of CAGRD. Once developed, this model should serve to reveal the factors that control the duration of CAGRD dependence for a given water provider and make explicit the economic significance of this dependence.

The two hypotheses regarding CAGRD's formation and long-term impact that this study will attempt to test are:

(1) As a powerful regulated interest, Arizona's development community changed its opportunity set by affecting the institutions governing water use by new developments;

(2) The duration and degree of dependency upon the CAGRD to comply with the Assured Water Supply rules vary widely among its members, depending primarily on the location and size of the CAGRD member.

Subsequent chapters will discuss the theory and analytical framework used to test these two hypotheses. Chapter 2 explains the economic theory underpinning the analyses used to test the hypotheses, discussing both the political economic theory of a cooperative negotiation with bargaining power (for *Hypothesis 1*), and the mathematics and microeconomic theory of the optimal depletion of an exhaustible resource (for *Hypothesis 2*). Chapter 3 discusses the evaluation methods for deriving the data for the political economic analysis, and the results of this analysis. Chapter 4 develops an economic model with a strong spatial component to analyze the long-term economic impacts of the CAGRD with respect to *Hypothesis 2*. Finally, Chapter 5 concludes the results of this research effort and discusses policy implications and potential improvements and extensions.

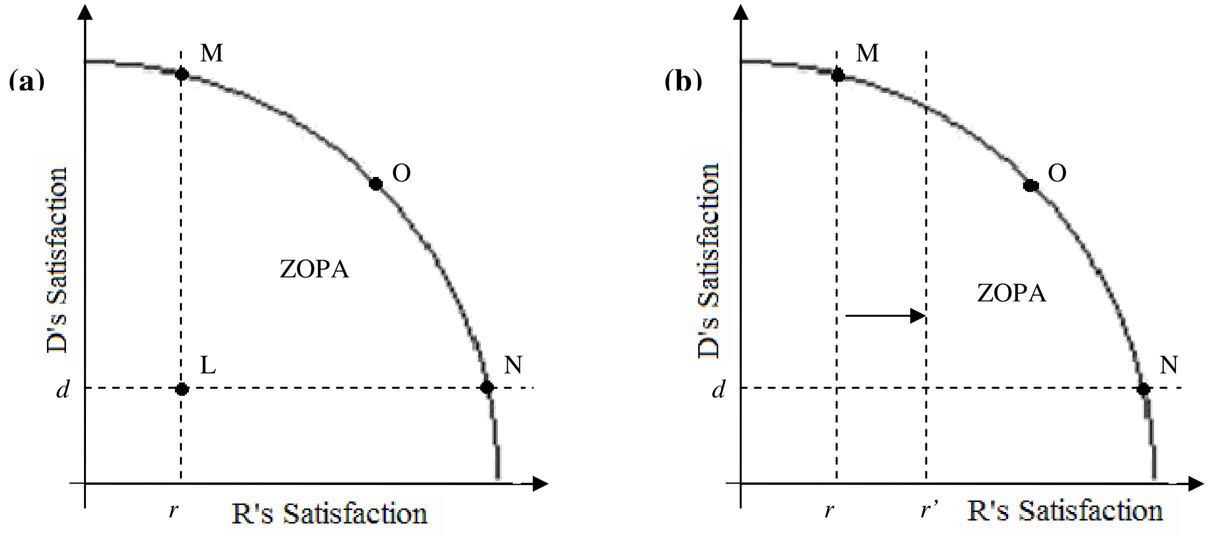
2. CONCEPTUAL MODELS

Understanding the formulation and long-term implications of the Central Arizona Groundwater Replenishment District requires two conceptual models. The first conceptual framework uses a Nash cooperative bargaining model to understand the political economy of the CAGRD's formulation. The second conceptual model blends elements of optimal control theory, the economics of exhaustible resource consumption, and spatial analysis to examine the CAGRD's possible long-term economic impacts.

2.1. Nash's Cooperative Bargaining Model

The economic theory of cooperative bargaining, an extension of what is known as the mutual gains model, is a useful framework for understanding the political economy of the CAGRD's formation. The mutual gains model is an analytical framework for negotiated agreements predicated on the assumptions that negotiating parties understand each other's interests, and agreements yield net gains for all parties. Figure 2.1 illustrates the principles of the mutual gains model. Each axis represents the satisfaction (or gains) index of the negotiating parties: player D's satisfaction increases northward along the y axis; player R's satisfaction increases eastward along the x axis. Each player has a reservation value with respect to the negotiation, a "best alternative to negotiated agreement" (BATNA), depicted as lines d and r in Figure 2.1. Negotiation occurs only when both parties expect to be better off by negotiating; therefore, for each party, the expected return must be greater than the BATNA. The marginal point of negotiation is the intersection of the BATNAs for the two parties—point L in Figure 2.1a, a sort of worst-case scenario for negotiation. To the northeast of L lies the zone of potential agreement (ZOPA). The ZOPA is bounded by the negotiation possibilities frontier (NPF), which represents the set of efficient agreements yielding the maximum possible gains from negotiation. Some points along the NPF favor player D (as in point M); other points favor player R (point N).

Figure 2.1: *The Mutual Gains Model*

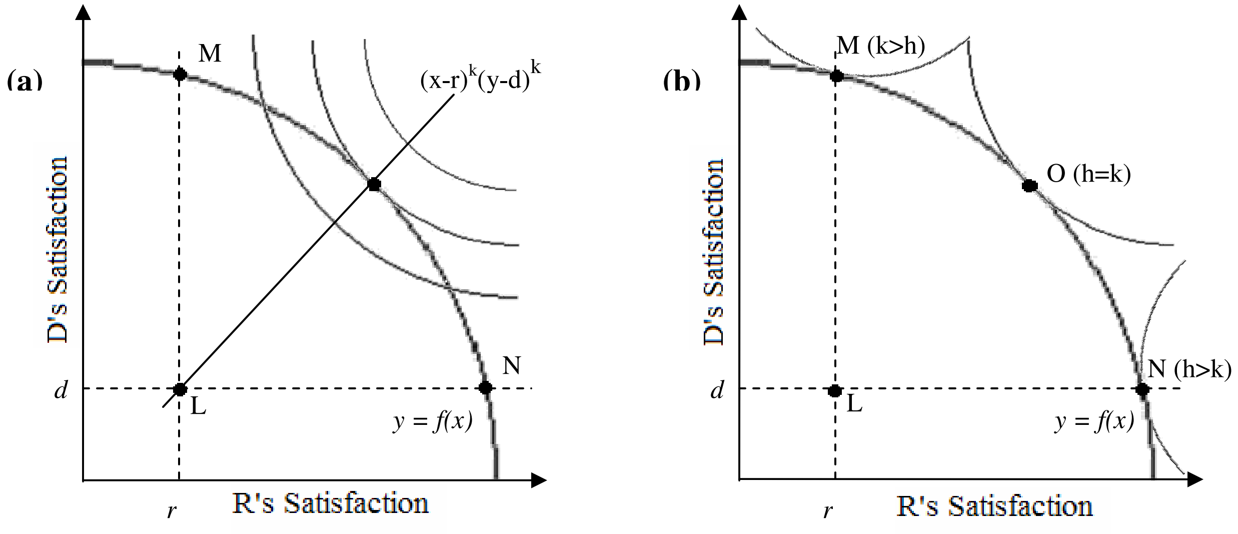


During a negotiation, a party may increase the position of their own BATNA or decrease the position of the opposing party's BATNA by using information advantage, threats, or better negotiating skills to influence the opposing party's perception of the negotiation. Figure 2.1b illustrates a situation where R is able to increase its position from *r* to *r'* during negotiation. R's maneuver raises the level of satisfaction required to entice R to negotiate, and eliminates from the set of efficient agreements those that were previously most favorable to D. Each party should therefore work to strengthen their BATNA relative to their opponent's BATNA prior to and during negotiation.

John Nash extended the mutual gains model to develop the economic theory of bargaining power in a negotiated agreement (Dixit and Skeath). The Nash bargaining model further requires that (1) the negotiated outcomes are invariant if two parties' payoffs increase proportionally; (2) efficient outcomes are achieved; and (3) irrelevant (non-efficient) alternative outcomes are ignored.

Figure 2.2 graphically illustrates Nash's cooperative solution to a negotiated agreement with bargaining power. D's BATNA is to accept a rule prescribed by R, at a cost of *d.* In other words, if negotiations fail, D cannot expect a better outcome from R's prescribed rule than *d.*

Figure 2.2: *Nash's Cooperative Solution*



Now let R's gains from negotiation be designated as x and D's gains be designated as y. The set of efficient agreements forming the negotiation possibilities frontier (NPF) will therefore take the functional form of $y = f(x)$. Any negotiated agreement will result in the following gains for the two parties:

R receives a total payoff of x-r;

D receives a total payoff of $y-d$.

Let the division of gains received by each of the bargaining parties be designated such that R receives an h-proportion of the surplus, D receives a k-proportion, and h and k sum to one. Maximizing

$$(x-r)^h(y-d)^k \text{ subject to } y = f(x) \tag{2.1}$$

Gives the unique Nash cooperative solution:

$$(x-r)/h = (y-d)/k \tag{2.2}$$

The bargaining power parameters h and k are critical to the final negotiated outcome. First, because the proportions of bargaining power affect the shape of the objective function, a range of efficient, optimal solutions to negotiation is possible. Each optimal solution in this range lies along the NPF, and all are possible Nash solutions to the cooperative agreement. If one party's bargaining power increases, they are able to influence the objective function such that the set of available contract curves—and, therefore, the set of optimal solutions—is moved in their favor. An increase in h corresponds to an increase in ($x-r$) and a decrease in k and in ($y-b$). An increase in h also tips the balance of favorable outcomes toward R and away from D. When h equals k, the negotiated agreement reaches point O, and the gains from negotiation are evenly distributed between R and D; when h equals 1, R possesses all the bargaining power in the negotiation, and an agreement is reached with outcome N, favoring R exclusively; conversely, when D holds all the bargaining power, an agreement is reached with outcome M, favoring D exclusively. Any range of outcomes is possible when the bargaining power is shared between R and D—that is, h and k are such that $0<h,k<1$.

The Nash cooperative agreement demonstrates that agreements or rules formulated in the mutual gains framework will depend upon the balance of bargaining power between the negotiating parties. Bargaining power comes in many forms. Superior negotiating skills naturally improve bargaining power. Threats (to walk away from the negotiation, for example) may also shift the balance of bargaining power in a negotiation. Information advantages may also translate into bargaining power, if used to alter the content of the body of data under contemplation, to shape options and perceptions of reality, or to alter the order or valuation of possible outcomes (Bartlett 1973). With the outcome so contingent upon the balance of bargaining power, each negotiating party will seek to improve its own BATNA in negotiation by changing the other party's perception of the negotiation, decreasing the BATNA of the opposing party, and/or increasing its own proportion of bargaining power.

2.2. Optimal Depletion of an Exhaustible Resource

The second conceptual model attempts to elucidate the long-term economics of the CAGRD using optimal control theory, as it relates to the economic theory of exhaustible resource consumption. Provided some basic policies are met, water utilities in Arizona's AMAs will continue to pump groundwater until it is economically efficient for them to import renewable water supplies from the CAP aqueduct. Optimal control theory and the economic theory of exhaustible resource consumption provide the conceptual framework for how we might estimate the likely durations of time that water providers will continue to pump and replenish groundwater (and thus rely upon the CAGRD to meet the Assured Water Supply rules). In Chapter 4, spatial analysis will be used as a tool for generating and analyzing key pieces of economic data for this analysis.

2.2.1. Optimal Control Theory

Following Holland and Moore (2003), let $W(t)$ represent the quantity of groundwater utilized by the water provider at time t and $U_t(W(t))$ be the gross surplus gained from this water at time t where $U_t' > 0$ and $U_t'' < 0$. The water provider has two possible sources of water: local wells under their control or imported water from another source. Let I be the quantity of water that could be imported.[5] However, I can be imported only after the construction of a pipeline, connecting the two water distribution systems. Let P be the pipeline construction costs and $C_I I$ be the operating costs (including water price) of importing I acre-feet of water after the pipeline is constructed.

Currently, the groundwater is replenished by precipitation (R) and the percolation of W at a rate $0 \leq \alpha \leq 1$. Total recharge is $R + \alpha W(t)$. The quantity of groundwater pumped at t is $g(t)$. The overdraft is $g(t) - R - \alpha W(t)$. The growing difference between $g(t)$ and total recharge can stimulate regulatory action against the water provider by the water authority.

The state variable

$$\int_0^t g(\tau) - R - \alpha W(t)\, d(\tau) \tag{2.3}$$

is the cumulative groundwater overdraft. Pumping cost is an increasing function of the cumulative overdraft because pumping cost at time t depends on the pumping lift. As a result, let $c(S(t))g(t)$ be the cost of pumping $g(t)$ acre-feet of groundwater, where $c' > 0$. Pumping costs increase over time as the groundwater stock is depleted.

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[5] A fundamental assumption of this analysis is that water utilities will be able to obtain any volume of CAP water necessary to meet their future demand.

The water provider must choose the optimal time (*T*) to build the pipeline so as to maximize the present value of gross surplus less costs, where *r* is the discount rate. The water provider's challenge is

$$\max_{g(t),T} \int_0^T e^{-rt}[U_t(W) - c(s)g]\,dt - e^{-rt}P + \int_T^\infty e^{-rt}[U_t(W) - c_I I]\,dt \tag{2.4}$$

The first integral is the water provider's discounted net surplus before the pipeline has been built. The second term in the objective represents the present value of the pipeline construction costs. The second integral represents the net surplus after the pipeline has been built and importation has begun. We assume that no groundwater is pumped following the importation of renewable water supplies.

The equation of motion and the initial condition of the stock variable are

$$\dot{S}(t) = g(t) - R - \alpha W(t)$$

$$S(0) = 0$$

In the steady state, groundwater mining will cease, i.e. $S = 0$. If it is efficient to build the pipeline and utilize it at capacity (implies shutting down all wells), steady-state water usage is $W^{ss} = I$.

To compute the efficient time for a water provider to construct a pipeline, first define the superscripts (-) and (+) to indicate paths before and after *T*, the optimal time to construct the pipeline and begin delivering water sourced from outside the water provider's service area (Hartwick, Kemp and van Long 1985). The first-order condition for optimal project timing, $H^- + rP = H^+$, is

$$e^{-rt}[U(W^-) - c(s)g^- - \lambda(T)(g^- - R - \alpha W^-)] + re^{-rt}P - \{e^{-rt}[U(W^+) - c_I I]\} = 0$$

(2.5)

This equation is derived by constraining Equation (2.4) with the equation of motion of the stock and differentiating with respect to *T*. This first first-order condition can be written as

$$U(W^-) + \alpha\lambda(T)W^- - (c(s) + \lambda(T))g^- = U(W^+) + \alpha\lambda(T)W^+ - c_I I - rP$$

(2.6)

The first three terms on the left-hand side of Equation (2.6) represent the gross benefit gained from water usage and recharge less the costs of pumping groundwater. The right-hand side is the net benefit of importing water via pipeline. So Equation (2.6) implies that the optimal time (*T*) to build the project is when the net benefit of importing water exceeds the net benefit of pumping groundwater.

2.3. Microeconomic Principles of Exhaustible Resources

Optimal control theory provides a formal mathematical treatment of the relatively straightforward microeconomic principles dealing with exhaustible resource consumption. Groundwater is considered an exhaustible resource in central Arizona because the rate of extraction exceeds the rate of natural recharge in most circumstances. Arizona law acknowledges that groundwater mining will occur and allows some mining in the AMAs and almost all mining outside of AMAs.[6] Mining is limited in the AMAs by ADWR's groundwater decline standard of a maximum of four feet per year decline (Bodenchuk 2008). Groundwater mining is also alleviated by artificial recharge, wherein renewable supplies are brought in and allowed to recharge an area of the aquifer. Yet for the purposes of water management,

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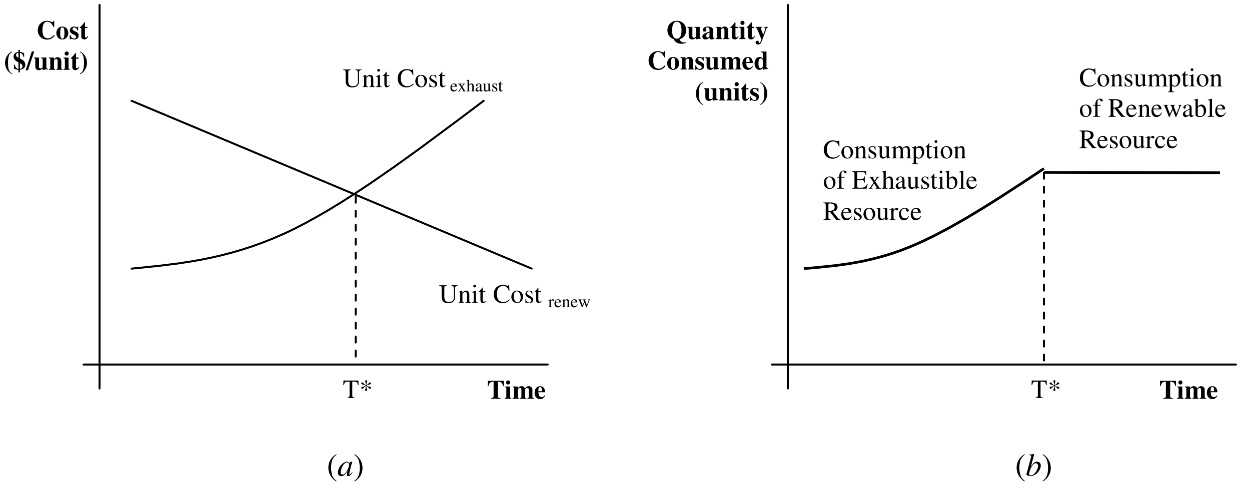
[6] If a developer seeking to build a subdivision outside of the AMAs, the current Assured and Adequate Water Supply rules do not require the developer to demonstrate that the water supply is renewable; the water supply need only be of adequate quality and legally, physically, and continuously available for 100 years. See ADWR's summary of the AWS program, <*http://www.azwater.gov/dwr/WaterManagement/Content/Forms/WADSumm.pdf*>

recharging in a well field's cone of depression is basically equivalent to a transition to renewable supplies. Most communities in Arizona are currently relying on the provision that allows recovery of stored water outside the area of hydrologic impact. Under these conditions, the physical supply of groundwater is in fact an exhaustible resource.

Hotelling (1931) is widely credited with developing the foundations for the modern economic theory of exhaustible natural resources (Devarajan and Fisher 1981). Hotelling recognized that a resource owner's profits depend not only on the rate of extraction but also on the stock remaining in the ground, for the simple reason that extraction costs increase with cumulative production. A century earlier, David Ricardo similarly reasoned that a resource of heterogeneous units is consumed starting with the units that have the lowest marginal cost of extraction. This is true for groundwater in two ways: (1) water tables fall as the cumulative extracted stock increases, requiring higher energy and treatment costs to extract and use the resource; and (2) as local water supplies dwindle it may become necessary to seek out more distant supplies, which are inherently more expensive than the cost of pumping in the initial time period due to the cost of importing the alternative supply. In other words, by pumping groundwater in period t, a groundwater user affects the cost at which they and other water users obtain their water supplies in period $t + 1$. Water is thus withdrawn too quickly because a groundwater user is not fully compensated for reducing its rate of pumping to the socially efficient rate in period t (Provencher and Burt 1993).

The rate of depletion of an exhaustible resource is affected by the presence of a backstop renewable supply. If a renewable substitute is available to replace the exhaustible resource, depletion is more rapid and continues until the marginal extraction cost rises to a "switch price," equal to the average cost of importing the renewable substitute. As the optimal control model presented in the previous section makes clear, the resource user will stop mining the exhaustible resource and import the renewable substitute when the marginal extraction cost for the exhaustible resource rises to the switch price. In particular, consumption tends to move to a steady-state determined by the social rate of time preference and either the marginal rate of supply for the backstop resource or the marginal cost at which the backstop supply becomes available (Krautkraemer 1998). It is possible (though not modeled in this study) that under certain conditions the resource user will choose to employ both resources simultaneously (see, for example, Tsur and Zemel 2003). But to enable a positive resource flow, and possibly to mitigate environmental damages resulting from continued resource extraction, a renewable supply will be required to augment or supplant the diminishing stock. The expected form of such a transition can be seen graphically in Figure 2.3. Panel (*a*) graphically shows that while the unit cost of importing the renewable supply decreases with water demand and other factors, the unit cost of continuing to pump groundwater increases with water demand and similar factors. At any point in time, the utility will choose to use the supply that is available at lowest

Figure 2.3: *The Transition to a Renewable Resource: Cost (a) and Quantity (b) Profiles*



cost. Initially, groundwater is available at lowest cost, so the utility pumps groundwater. At point *T**, however, the unit cost of pumping becomes equal to the cost of importing a renewable supply, prompting the utility to make the economically rational decision to stop mining groundwater and instead import renewable water supplies to meet water demand.[7]

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[7] The consumption of the exhaustible resource may continue after T* at the rate of stock replenishment, *r*. For many exhaustible resources, such as mineral deposits, *r* is zero, and only improvements in technology may allow for additional use of the exhaustible resource. In the case of groundwater, however, there is often some small amount of recharge to the system that is small enough to consider the resource exhaustible, yet large enough to accommodate some level of sustainable resource consumption.

3. THE POLITICAL ECONOMY OF THE CAGRD

Understanding the political economic context in which the CAGRD formed is imperative to testing the first hypothesis of this study, and a critical first step in evaluating the CAGRD's long-term economic impact. Often, the issues surrounding a particular policy can be traced back to the political economy of its formation, development, and governance. This chapter outlines a framework for analyzing the political economy of the CAGRD's formation, and discusses the relationship between the CAGRD's political economic context and some of its key initial and secondary effects.

3.1. Analytical Approach

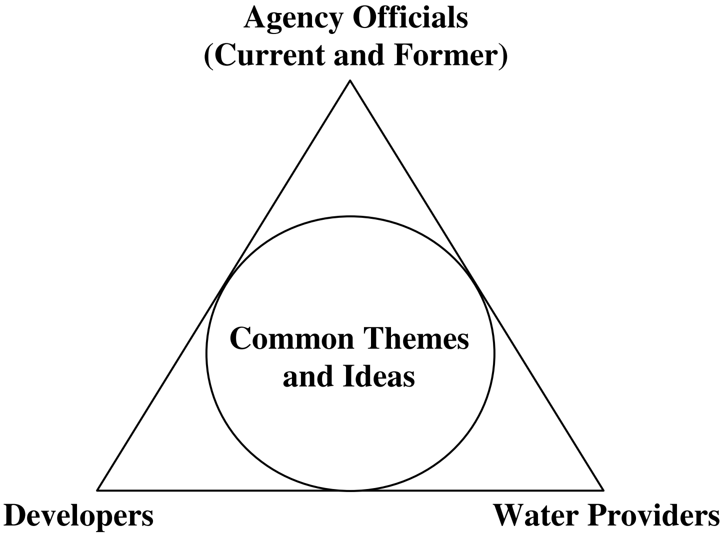
Accurate, reliable information is the foundation of effective policy analysis. Depending on the research question and the particular policy being examined, this information may be quantitative or qualitative in nature. Often economists analyze policies using only quantitative data. They do so at their own peril. Some of the most important policy questions require an endeavor into the world of qualitative evaluation, and to ignore these questions is to risk producing an ultimately ineffectual analysis. Quantitative measures, though widely accepted as the standard for evaluation, often do not adequately capture the complexities of the issue at hand. As we will see later in this study, understanding a policy's political, social, and emotional context may yield economic insights that would not be gleaned from quantitative data analysis.

One established qualitative method of policy evaluation is *triangulation*. The term triangulation refers to the idea promoted by Donald Campbell that "every method has its limitations, and multiple methods are usually needed" (Patton 2002). As in geometric triangulation, where the surveyor uses multiple points to calculate his position, triangulation in policy evaluation involves the use of multiple evaluation methods or data sources, including both quantitative and qualitative approaches (Patton 2002). Denzin (1978) identified four different types of triangulation. Of these, two are used in this study: methodological triangulation and data triangulation.

Methodological triangulation is the use of multiple methods to study a single problem. It is used in this study to analyze the CAGRD and the paper water system using both qualitative and quantitative methods. The qualitative method used in this study forms the basis for the analysis of the political economy of the CAGRD and its formation: standardized, open-ended interviews of individuals who are knowledgeable about the research topic. The goal of these interviews is to gain multiple perspectives and thus maximize the accuracy and relevance of the study. The interviews were geared primarily toward the analysis of the political economy of the CAGRD's formation. Indeed, attempting to elucidate the political economy of the CAGRD without seeking multiple perspectives on its formation and impacts would have resulted in a rather myopic and incomplete analysis. (This chapter describes the interview process and discusses the results of the findings of the interviews.) The quantitative method used in this study, developed in Chapter 4, is a spatial economic model to analyze the possible long-term economic impact of the CAGRD. The benefit of using both qualitative and quantitative methods in this study is that it builds checks and balances into the analysis.

Data triangulation is the use of a variety of data sources in a study, and is used here in gathering qualitative data in the interview process. Interviewee candidates were selected based on their affiliation with a particular target group that presumably would have a unique perspective on the CAGRD and its formation: current and former government agency officials, water providers, and members of the development community. Figure 3.1 illustrates the principle behind data triangulation. Qualitative data gathered from multiple perspectives allows the researcher to compare among these perspectives and discern common themes and ideas in what he hears and observes. These common themes and ideas form the basis for the development of a coherent, reliable explication of the CAGRD's formation and effects.

Figure 3.1: *Triangulation of Multiple Perspectives Improves Accuracy, Relevance*



3.2. Data

Interviews were conducted in June and July of 2007 to gather information from 20 individuals considered knowledgeable about the CAGRD. Roughly equal numbers of interview candidates were selected for each interview target group: water utility officials; developers and development interests; and current and former government agency officials, including CAGRD staff. (See Appendix D for a list of interviewees.) For about half of the interviews, two people served as interviewers, both taking notes that were later compared. A standard, open-ended interview protocol was used to guide the discussion. The basic interview protocol consisted of the following questions:

- Why did the CAGRD form? Describe the events leading to its formation.
- To what extent would it be feasible to require subdivisions to comply with the AWS rules without joining the CAGRD?
- From your perspective, has the existence of the CAGRD affected development (numerically or geographically) in the Phoenix, Pinal, or Tucson AMAs? If so, how?
- How would developers cope with CAGRD capping membership outright?
- Describe the ideal solution to the growing enrollment problem, from your perspective.
- Does the location of replenishment within an AMA matter? Why or why not?

While a protocol was used to guide the discussion, often additional questions were asked in order to expand upon issues important to the interviewee. In closing, interviewees were allowed to share any additional comments or concerns regarding the Central Arizona Groundwater Replenishment District that he or she felt had been omitted from the discussion.

After all the interviews were conducted, the interview responses were studied to identify areas of agreement and disagreement from the different perspectives regarding the CAGRD's formation, its private and social costs and benefits, and possible solutions to some of the issues surrounding it.

3.3. Results

3.3.1. The CAGRD's Formation

The Central Arizona Groundwater Replenishment District formed in response to a number of legal and political pressures. The first and most immediate pressure was the need to empower the safe-yield Active Management Areas to achieve safe-yield by 2025. While the Arizona Groundwater Management Act of 1980 originally outlined what would become the Assured and Adequate Water Supply (AWS) rules in 1995, the language in the GMA enabling ADWR to adopt the AWS rules was unclear, and as of 1993 they had not yet been adopted. In fact, ADWR had attempted to introduce AWS "Draft Rules" in 1988, but a strong negative reaction to the Draft Rules from Arizona's residential developers and homebuilder associations caused them to be quickly suspended. Essentially, the Draft Rules failed because they lacked an "institutional mechanism to help developers comply" with the progressive statutes. The relative ease with which the Draft Rules were repealed stands as a testimony to the development community's power over the details of its own regulation. It also strongly suggested to ADWR that the support of the development community would be crucial to the survival of subsequent AWS rules. Eventually, negotiations between ADWR and key members of Arizona's development community would pave the way for the adoption of an agreeable "institutional mechanism" in form of the Central Arizona Groundwater Replenishment District.

Another source of pressure leading to the formation of the CAGRD was Arizona's desire to maximize the use of its Colorado River entitlement. One reason behind this desire was the depletion of the aquifers in central Arizona. A more pressing motivation, however, was the fear among Arizona water managers that the use of Arizona's unclaimed apportionment by California and Mexico would enable Congress to revisit the River's allocation to permanently reduce Arizona's entitlement. Decades earlier, this same fear initiated and sustained Arizona's rally behind the authorization, funding, and construction of the CAP aqueduct. Now, it appeared that constructing the aqueduct was not enough to put CAP water to beneficial use; though substantially complete by 1993, its annual conveyance capacity was disappointingly underutilized by over one million acre-feet (CAP 2005). As predicted by William Martin and Robert Young during the design phases of the CAP, the price of CAP water was not competitive with the cost of groundwater. Hence, irrigation districts that signed take-or-pay contracts for CAP water were left in the position of having to pay for water that its member farmers were not taking or paying for. Since agriculture was unable to afford the water deliveries the CAP was designed to facilitate, Arizona's Colorado River entitlement remained underutilized and, perhaps, available for the taking. Short of forcing the agricultural and municipal sectors to directly use more CAP water, CAP identified artificial recharge as a quick and relatively inexpensive means of putting the rest of the entitlement to use.

In the face of these two major pressures, the CAGRD came as a unique solution to two of the state's biggest water management problems: the depletion of groundwater supplies and the inadequate use of Arizona's Colorado River entitlement. Notwithstanding the failure of the Phoenix Groundwater Replenishment District, the development community felt that interest in an entity offering replenishment services remained significant, particularly in the private sector, and that a voluntary-membership approach might be more widely supported. So, in 1992, representatives from a large developer of master-planned communities met with the Director of ADWR to present the idea of a voluntary-enrollment replenishment entity. The Director, recognizing the opportunity to gain the development community's support for the AWS rules by giving them a mechanism of compliance, supported the idea. The contingent of developers then spoke with members of the CAP board, who supported the idea as a means of using more CAP water and agreed to provide oversight of the replenishment authority should it succeed. In short, as Avery, Consoli, Glennon, and Megdal (2007) aptly put it, "a deal was struck." Within months, Fennemore Craig law firm was retained by the small group of developers to draft the legislation, and on April 22, 1993, the Groundwater Replenishment District Act became law.

Applying Nash's cooperative bargaining model may help to clarify and deepen our understanding of the political economy surrounding the CAGRD's formation. In the early 1990s, ADWR was attempting to regulate the use of groundwater to support new development by adopting the Assured Water Supply rules in the Active Management Areas. The three central AMAs of Phoenix, Pinal, and Tucson were experiencing rapid population growth, and residential development was a significant source of revenue for the state of Arizona. As such, Arizona's political leaders were generally in support of population growth. Arizona's development community, in turn, depended upon the openness of Arizona's water policies toward new connections—particularly those using groundwater. Accordingly, water policies that would potentially restrict Arizona's rate of population growth were seen as a threat to Arizona's economy in general and the development community in particular.

As insisted upon by numerous sources (including one of the individuals who spearheaded the creation of the CAGRD on behalf of his development firm), the CAGRD was the result of a cooperative negotiation. Several parties played some part in advancing the negotiation, but ADWR and the development community were the two most important players. Applying Nash's bargaining model, ADWR plays the role of the regulator and the development community represents the regulated interest. As was demonstrated in Chapter 3, the negotiated outcome strongly depends upon the balance of bargaining power in the negotiation. During the negotiations that led to the formation of the CAGRD, the balance of power was skewed toward the development community—that is, in Equations (2.1) and (2.2) of Chapter 2, the development community (player D) had more bargaining power ($k>h$) than ADWR (player R). The primary source of the development community's bargaining power was the swift revocation of the AWS Draft Rules in 1988, which demonstrated the development community's power to control its own regulation, and effectively served as a warning to ADWR that the development community had the power to prevent the AWS rules from being adopted unless ADWR somehow helped the development community comply with the rules. Many of the individuals interviewed for this study believed that the development community's bargaining power was so strong that the AWS rules would never have been passed without some conciliatory measure like the CAGRD. In other words, the development community's best alternative to negotiated agreement (BATNA) was simply the status quo, where new homes could rely upon groundwater without having to offset the pumping with replenishment. But ADWR's leaders could not afford to allow the Groundwater Management Act to remain ineffectual with respect to municipal groundwater consumption; rather, these leaders knew that they had a responsibility to get the AWS rules passed and get the safe-yield AMAs on track to meeting their statutory management goal of achieving safe-yield by 2025. Put another way, ADWR's BATNA was the failure of the AWS rules and the loss of safe-yield as an achievable objective for the AMAs. With so much to lose, ADWR recognized that negotiating with the development community was the only way forward.

The development community was able to leverage its bargaining power in the cooperative negotiation with ADWR and capture a large share of the gains from the negotiation in the form of a developer-friendly replenishment district. Several provisions of the CAGRD testify to the power of the development community in shaping the CAGRD's enabling legislation: (1) the cost of enrolling in the CAGRD ($23 per home) is not only far below the cost of delivering renewable supplies directly but is also below the typical development impact fee for new residential water connections in most cities (Tucson Water currently charges $1,940 per home) (Tucson Water website 2008); (2) the cost of replenishment is passed entirely to the homeowner (ARS §48-3778); and (3) CAWCD does not have the legal authority to limit CAGRD enrollment. These provisions significantly reduced the impact of the AWS rules on the development community by minimizing the cost of compliance by instituting a low enrollment fee, passing the financial responsibility to the homeowner, and legally guaranteeing a simple means of AWS rule compliance for years to come. As a result of the CAGRD's generous provisions, the AWS rules had little effect on the magnitude or pattern of urban development in central Arizona. Virtually all the interviewees—water providers, water agency officials, and developers alike—agreed with this basic conclusion.

3.3.2. Initial Effects of the CAGRD

The creation of the Central Arizona Groundwater Replenishment District as an authority of the Central Arizona Water Conservation District paved the way for the adoption of the Assured Water Supply rules in February, 1995. The two policies are inextricably linked; nearly all of the individuals interviewed for this study argued that without the CAGRD, the AWS rules would never have been adopted because the development community would have used their political influence to prevent it. To illustrate the interconnectedness of the AWS rules and the CAGRD, several of the interviewees considered my question regarding whether it would be feasible to force developers to comply with the AWS rules without the CAGRD to be simply "naïve." "It would never have happened" was a common response to this question, and from the firm resolve of the interviewees representing the development community, it appears likely that developers would never have allowed a situation in which they were required to demonstrate use of renewable supplies without something resembling the current CAGRD—and never will.

The CAGRD provided a simple means for developers to comply with the AWS rules, and therefore allowed developments to continue to rely on groundwater as they had before. After the AWS rules were passed, subdivisions continued to rely on groundwater for their physical water supply as they had before the rules were passed. The only difference between before and after the AWS rules is that owners of homes platted after 1995 that are not in the area of a designated water provider and are legally considered part of a subdivision are now paying higher property taxes to have the CAGRD bring CAP water into their AMA to replenish the groundwater they have used. On an Active Management Area level, this is a big step. The AWS rules have been successful in terms of bringing the water budgets of the Phoenix and Pinal AMAs closer to safe yield. In some ways, the state has the CAGRD to thank for allowing that to happen. But neither the AWS rules nor the CAGRD address the problem of "dry members" continuing to pump groundwater in areas that are suffering from severe groundwater declines. So in effect, the CAGRD has been a benefit to the AMAs in that it has enabled physical water supplies to be brought into the AMAs per the AWS rules; however, it has also been a curse in that it has enabled development to occur regardless of the location of renewable water supplies. Furthermore, it is the conviction of several individuals interviewed for this study that the CAGRD has decoupled land use and water planning and has thus made it more difficult not only to avoid pumping groundwater in areas of severe overdraft, but also more difficult to develop the integrated physical infrastructure necessary to efficiently deliver renewable water supplies to these problem areas.

3.3.3. Secondary Effects of the CAGRD

It is the secondary effects of the CAGRD that have attracted the most criticism: the rapid rate of enrollment in the CAGRD, and the location of CAGRD members relative to the location of the renewable water supplies that are replenished on behalf of the members.

3.3.3.1.Enrollment

Preeminent among the issues faced by the CAGRD is the fact that its membership has exceeded nearly all expectations since its initial Plan of Operation was approved in 1995. Initial projections estimated that CAGRD's replenishment obligation in 2014 would be about 37,000 acre-feet; by 2004, the estimate had been revised upward to 97,700 acre-feet (Avery et al 2006). Enrollment of Member Land homes in the CAGRD through the end of 2006 exceeded the projections of the 2004 CAGRD Plan of Operations by nearly 47,000 units—more than 25 percent over projections (CAWCD July 2007).[8]

The high rate of enrollment in the CAGRD reflects the simplicity of the decision to enroll. Little is required of developers or water providers wishing to enroll as Member Lands or Member Service Areas. Developers enrolling subdivisions must pay a simple enrollment fee of $23 per home; water providers pay no fee, but simply enter into a contract to have the CAGRD replenish their excess groundwater pumping. The CAGRD enrollment process essentially eliminates the cost of complying with the criterion of the AWS rules demanding use of renewable supplies, as well as the risk of someday violating this criterion. Even MSAs that are not able to meet the physical availability criterion of the AWS rules may contract with the CAGRD to have wet water delivered to their service area, per the Water Availability Status

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[8] A summary of the CAGRD's member enrollment since 1995 is given in Figure 3.2 (Appendix C). Correspondingly, CAGRD's replenishment obligation through the same period is given in Figure 3.3 (Appendix C).

provision added in 1999.[9] Furthermore, many water providers with CAP allocations and access to indirect methods of using their CAP allocations (i.e. groundwater savings and underground storage facilities) have still joined the CAGRD because it is an easy way (and sometimes the only realistic way) to demonstrate the availability of 100 years of renewable water supplies to meet their future demand. Thus, for most developments and for some cities, the CAGRD is easily the lowest cost means of complying with the AWS rules.

There is also evidence to suggest that developers are enrolling homes earlier than necessary. Construction of ML homes through 2006 lagged Plan projections by nearly 17,000 units, or 18 percent below projections. Accordingly, actual replenishment obligations resulting from member pumping in 2006 were about 11,500 acre-feet, almost 23 percent below projections (CAWCD July 2007). CAWCD staff suspects that some of these homes may be registered decades before they are actually constructed (CAWCD July 2007). One obvious explanation for the early enrollment phenomenon is that developers are hedging against the risk that complying with the AWS rules may not be so cheap and easy in the future. In a sense these developers are buying an option: while the CAGRD door is wide open to new members today, it is unlikely to remain that way for long, as the CAGRD's cheap primary water supply—excess CAP water—disappears with rising demand for CAP and Colorado River supplies. The high enrollment in the CAGRD is a direct result of the low cost of enrollment.

The water agency officials and the water provider staff interviewed for this study tended to speak differently about the enrollment problem than the interviewees representing the development community. Individuals in the former group tended to frame the growing

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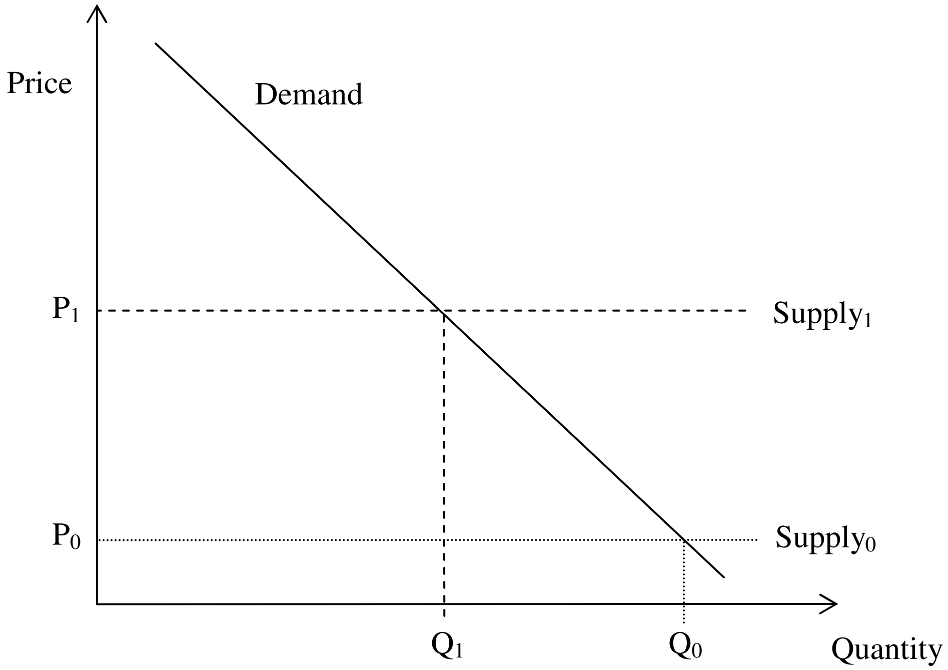
[9] The Water Sufficiency and Availability Act (Arizona House Bill 2262) was enacted in 1999. It allows any city, town, or private water company that qualifies as a CAGRD Member Service Area to meet the physically available water supply criterion of the Assured Water Supply Rules by entering into a contract to have CAGRD deliver water where it is physically accessible. See Section 1.5.5.1 for more details.

enrollment problem as a lack of regulatory control, wherein CAGRD needs the explicit authority to limit enrollment before acting on the issue, but would never be able to obtain this authority because development community would not allow it. Individuals in the latter group, while affirming the observation that the development community would not stand for CAGRD capping enrollment, discussed the issue as a matter of money. Interviewees representing the development community conveyed the sense that developers would be willing to pay much more to ensure compliance with the AWS rules than they are currently paying through membership in the CAGRD. This is a salient point. While CAGRD does not have the legal authority to deny or otherwise limit enrollment, it does have the authority to change its enrollment fee. Nearly all of the interviewees in the development community group felt that CAGRD, instead of focusing on what it cannot do to control enrollment, should focus on what it can do: change the price. A simple graph of supply and demand (Figure 3.2) shows that this is an economically sound suggestion. Since CAGRD membership is supplied at a quantity that is invariant with changes in the enrollment fee, the supply curve for membership is drawn perpendicular to the price (y) axis. At a low enrollment fee of P_0, more developers will choose to enroll their subdivisions in the CAGRD, at a quantity of Q_0. Raising the price to P_1, fewer subdivisions (Q_1) will be enrolled.

Accurately predicting the response to price changes is difficult, however. The CAGRD has never changed the enrollment fees for new Member Lands and the price elasticity of demand for CAGRD enrollment is unknown. Nevertheless, higher enrollment fees would encourage potential CAGRD members to consider other ways to comply with the AWS rules rather than joining the CAGRD by default. Some alternative methods of compliance suggested by the individuals interviewed for this study include the establishment of a private replenishment cooperative, a higher degree of effluent reuse for non-potable and replenishment purposes, direct delivery of CAP supplies, purchase of extinguishment credits, and construction within the service area of a designated water provider. If CAGRD is concerned that its membership has grown beyond its ability to provide replenishment services, it ought to consider increasing its enrollment fee to decrease the rate of enrollment to reasonable levels. CAGRD is not the only available option for developers seeking to comply with the AWS rules, but with exceedingly low enrollment fees it appears that CAGRD membership is basically the only option being considered by developers. Increasing the fee may help to reduce enrollment, increase conservation of groundwater in some areas, provide CAGRD with the financial resources to acquire the water supplies to meet its replenishment obligation, and increase the incentive for cooperation among water utilities seeking to use renewable supplies directly.

Figure 3.2: *Demand and Supply for CAGRD Membership*



3.3.3.2.Location of Replenishment

Another secondary effect of the CAGRD is that it has allowed development to occur far from the CAP canal and existing artificial recharge projects, contributing to the reliance upon "paper" water to comply with the Assured Water Supply rules. Per the AWS rules, the basic spatial requirement for CAGRD's replenishment is that it must be within the same AMA as the excess groundwater pumping (i.e. if groundwater is pumped in the Tucson AMA, it must be replenished in the Tucson AMA). While CAGRD replenishes in USFs and GSFs that are close to the CAP aqueduct to minimize costs for its members, most of its members are pumping groundwater many miles from the location of replenishment. Over time, the hydrologic disconnect between pumping and replenishment may have serious consequences for some members. Avery, Consoli, Glennon, and Megdal (2007) framed this problem in terms of "wet" members and "dry" members:

> "Wet" members are located in close proximity to CAGRD's recharge and delivery infrastructure, so that the member service area or the water provider serving an ML is pumping groundwater in reasonable proximity to the site of replenishment. In such areas, groundwater levels are likely to remain stable. In other instances, the site of pumping is located far from the CAP delivery system and storage sites that CAGRD has used, thus far, to meet its replenishment obligations. In these "dry" areas, the hydrologic impacts of pumping are not mitigated by replenishment. (p. 351)

The existence of "dry" members is a source of concern for many people in Arizona's water community, including those interviewed for this study. In an issue statement drafted in 2000 regarding the CAGRD, the Tucson AMA Safe-Yield Task Force opined that this imbalance may lead to physical availability problems for some CAGRD members (Tucson AMA Safe-Yield Task Force, 2000). In order to maintain the physical water supply of these "dry" members, infrastructure will need to be constructed to directly deliver CAP supplies to their service areas. For such members, reliance upon the CAGRD is likely to be a "bridge" to comply with the AWS rules until it is necessary or efficient to deliver renewable supplies directly. Yet for other members who are within the area of hydrologic impact of replenishment or have stable groundwater supplies for other reasons, it may prove to be more cost-effective to continue to pump groundwater and pay the CAGRD for its replenishment services.

Therefore, any policy seeking to adjust the apparent imbalance of physical water supplies is faced with a complex and delicate matter. Each municipal water provider or private water company faces a unique set of conditions related to physical water availability, water quality, water demand, distance to renewable supplies, and so on. Requiring all water providers to immediately transition to direct delivery of renewable supplies would not even be plausible, let alone efficient. Instead, the comparative economics of groundwater pumping and infrastructure development will likely guide each AMA's physical water supplies into equilibrium in the long run. The question is, how long will it take? And what will it cost? And who will pay for it?

4. THE SPATIAL AND TEMPORAL DIMENSIONS OF WATER RESOURCE ECONOMICS: IMPLICATIONS FOR CAGRD RELIANCE AND LONG-TERM IMPACT

In the final analysis, the utility of the Central Arizona Groundwater Replenishment District will be judged by its impact on the ability of the Phoenix, Pinal, and Tucson Active Management Areas to achieve safe yield.[10] As Chapter 3 makes clear, Arizona would not have had the Assured Water Supply rules without the CAGRD or a CAGRD-like mechanism. Without the AWS rules, it would have been nearly impossible for these AMAs to achieve safe yield by 2025. (Even with the AWS rules, most experts would agree that it is unlikely that the so-called "safe-yield AMAs" will be able to accomplish this.) Since the ability of these AMAs to achieve safe yield was the big concern that precipitated ADWR's push for the adoption of the AWS rules, it is only reasonable to ask whether the CAGRD as we know it today was worth the compromise to pass the AWS rules. Or more precisely, does the CAGRD move these AMAs in the direction of safe yield or away from it?

In answering these important questions, we today have the benefit of hindsight—at least in part. Identifying in retrospect the problems associated with the CAGRD is relatively easy; the District has been publicly criticized in recent years for its out-of-control membership enrollment, its swelling replenishment obligation on tenuous supplies, and its perverse incentive structure (Tenney 2007; Vincent 2007). These are noteworthy observations and obviously grounds for careful policy changes. Nevertheless, attempting to discern the CAGRD's impact on the AMAs' ability to achieve safe yield requires a larger spatial and temporal perspective than a simple look at the recent past. Since the achievement of safe yield hinges upon the degree to which renewable water supplies are substituted for groundwater, the spatial economic analysis

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[10] While historically the Pinal AMA has eschewed the management goal of achieving safe yield, it has begun to move in that direction by revising its Assured Water Supply rules in 2006.

developed in this chapter analyzes the CAGRD's impact on this substitution process in the long term.[11] From this spatially and temporally broad vantage point, we should be in a better position to assess the ultimate utility of the CAGRD and the "paper water" system on which it depends.

4.1. Analytical Approach

In Chapter 3, it was shown that it is possible to predict the efficient switch point between groundwater and direct delivery of CAP water by comparing their respective costs through time. The costs to consider in calculating the switch point are simply the parameters in Equation (2.6). Some of these parameters are relatively straightforward to estimate. However, a water utility's location strongly influences many of the key cost parameters in the evaluation of its switch point, most notably the distance CAP water must be transported to serve the water utility and the physical conditions of the utility's groundwater supply. Since these cost parameters are inherently spatial, the tools of geography and spatial analysis are uniquely fitted for deriving them. Geographic information systems (GIS), the modern geographer's tool of choice, are widely used in geographic analysis to capture, manage, manipulate, analyze, model, and display spatially-referenced data. The tools of GIS are particularly useful in this application because they provide the means to estimate both the cost of groundwater pumping and the cost of importing CAP water for one or many water utilities. Thus, a "spatial economic" model was developed using the tools of GIS to produce estimates of these location-based parameters. For other parameters, GIS were not necessarily used.

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[11] Focusing on the long term, this study does not consider indirect use of renewable water supplies (i.e. recharging CAP water outside the area of hydrologic impact) to count as use of renewable water supplies.

4.1.1. Predicting the Cost of Groundwater Pumping

The unit cost of groundwater pumping is equal to the sum of the direct costs incurred from pumping and treating the groundwater, and in some circumstances replenishing this groundwater in accordance with statute.[12] A simple equation for estimating the average unit cost ($ per acre-foot) of groundwater pumping (*AC*) is given by

$$AC = \Sigma\ (CL + CT + CC + CR) \qquad (4.1)$$

where *CL* is the cost to lift groundwater to the land surface; *CT* is the cost to treat the water; *CC* is the capital cost of improving and replacing wells; and *CR* is the cost of replenishment (in Active Management Areas, if necessary).

The cost of lifting groundwater to the surface (*CL*) can be estimated by the equation

$$CL = \frac{KLP}{E} \qquad (4.2)$$

where *K* is a (unitless) constant determined by the density of the fluid (1.024 for groundwater); *L* is the vertical lift from the water level in the well to the land surface in feet (ft); *P* is the unit cost of energy per kilowatt-hour ($/kwh); and *E* is the well efficiency, which is usually 70 percent for municipal pumping wells (U.S. EPA 2000). Therefore, the pumping cost is directly proportional to the depth to the groundwater and the energy rate.

Water treatment is usually a small percentage (about 5%) of the total costs of water service. Treatment cost depends on water quality, but since groundwater quality can vary significantly from one location to another (and even within the same vertical profile at a particular location) it is inherently difficult to predict the cost of water treatment for a given area without collecting a significant amount of data first-hand. In general, though, we can expect

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[12] A more complete definition of the cost of groundwater pumping would include the opportunity cost of not replenishing within the area of hydrologic impact. Quantifying this cost, however, is beyond the scope of this Master's thesis.

water treatment to increase with depth because the total dissolved solids (TDS) in groundwater generally increase with depth as warmer ambient temperatures enable higher solution rates for minerals. An estimate of the depth-treatment cost function may be obtained empirically by examining the typical water treatment costs of various water providers in the Tucson area. In all likelihood, however, treatment cost will not significantly affect the efficient timeline of groundwater use for any water provider because it is a relatively minor expense.

The cost of replenishment, however, may be the largest expense for a water provider. Replenishment cost is a direct cost to the water provider, but also represents an opportunity cost because the water provider pays the cost of replenishment but foregoes the hydrologic benefits of storage. A water provider must replenish its reported excess groundwater pumping through the CAGRD. In the Tucson AMA, the cost of CAGRD replenishment is currently \$282/af—3.24 times the CAP M&I rate of \$87/af. According to Equation (4.2), if a water provider is pumping from a depth of 475 feet, CAGRD replenishment will increase the cost of pumping groundwater by about 50%. For some water providers, the only way to keep from paying the CAGRD for replenishment is to build a pipeline to import CAP water directly.

Further complicating our estimate of the cost of groundwater pumping is the fact that water levels are spatially and temporally dynamic. Predicting the direction and magnitude of these changes across space and through time is a serious challenge, even for expert hydrologists with large budgets of money and time. Micha Gisser, an economist at the University of New Mexico, used a simple equation in estimating water level changes,

$$AS\,\frac{\Delta h}{\Delta t} = R + (\alpha - 1)W \tag{4.3}$$

where A is the area of the aquifer; S is the aquifer storativity value (dimensionless); $\Delta h/\Delta t$ is the change in head (i.e. water level) with respect to time; R is the natural recharge to the aquifer; α is the return flow coefficient; and W is the volume of water pumped from the aquifer. We can further simplify the equation by setting R and α equal to zero, since R is often negligible in those parts of the basin that are not affected by stream baseflow and artificial recharge. Thus, water level changes are directly proportional to groundwater pumping, and inversely proportional to the aquifer's area and storativity. While the latter variables may be easily attained with maps and hydrogeologic investigations, the intensity of future groundwater pumping is only as good as the population projections they are based upon. Therefore, multiple pumping scenarios should be considered in the model.

Another possible way to predict water level changes is to observe historical trends in water levels and use these rates to estimate the water level surface for future years. A key assumption required for this method, however, is that changes in water levels will be constant over time. Demands on groundwater resources are not constant over time, but may be increasing because of population pressures, or may become stable if artificial recharge is introduced or if a neighboring well field stops pumping. Such scenarios are difficult to predict but a model must use the best available data to incorporate as many expectations as possible into the model. For this reason, Gisser's simple equation to predict water table changes is probably the more desirable of the two techniques to estimate future water levels.

4.1.2. Estimating the Cost of Importing Renewable Supplies

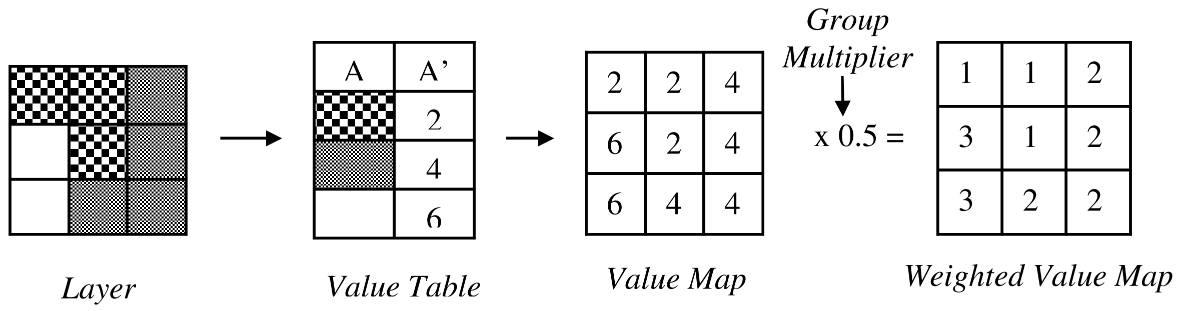
To estimate the cost of importing renewable supplies, a geographic information system is absolutely essential. Drawing a straight line from the CAP aqueduct (the supply node) to a water provider (the demand node) would be an erroneous and simplistic method of determining the cost of the pipeline. Between each supply and demand node is actually a landscape of physical, economic, and political obstacles that must be avoided: steep slopes, roads, utility lines, landfills, buildings, etc. In reality, the least-cost distance between the two nodes is not a straight line, but a line that is straight when possible and meandering whenever it is in fact cheapest to do so. GIS provides a framework for building such obstacles into a predictive model to determine the least cost pathway for the water pipeline—a good and necessary foundation for estimating its cost.

4.1.2.1.Siting Pipelines Using a Suitability Surface

Pipeline route selection is an exercise in constrained optimization, wherein the objective is to minimize the length of the pipeline subject to land suitability constraints. Often, infrastructure projects incorporate both pecuniary and non-pecuniary constraints into the optimization problem. Pecuniary measures include access to rights-of-way, overall pipeline length, land value, and geologic material. Non-pecuniary measures may include distance from natural amenities, distance from potential mining areas, and alignment along future infrastructure corridors. Each measure may be incorporated into a GIS as its own map layer, which may be manipulated and integrated with other layers. By weighting and overlaying each of these layers in a GIS, it is possible to create a "suitability surface" for the pipeline and use this surface for finding the shortest pipeline route across the aggregated suitability surface. The pathway or corridor identified by the model is the one that minimizes the cost of the pipeline. This process is known formally as *corridor analysis*. Corridor analysis is rooted in locational analysis, a subfield of geography, and has been applied to problems of siting oil and natural gas pipelines (e.g. Delavar and Naghibi 2003), highways (e.g. Grossardt, Bailey and Brumm 2001; Jha and Schonfeld 2004), wildlife migration patterns (e.g. Singleton and Lehmkuhl 2001), and other linear features.

Huber and Church (1985) describe the basic methodology for siting transmission corridors using computerized corridor location systems. A suitability surface is a raster-based (i.e. square grid system) surface created in a GIS. The surface is the aggregate of several input layers. Each input layer may contain one or many elements (a cemetery contains one element, the cemetery itself; a soil map contains many elements, one for each soil type). Each element is assigned a suitability score based on its suitability for the construction and/or presence of a pipeline. Figure 4.1 shows the procedure for developing a suitability surface.

Figure 4.1: *Procedure for creating a cost input layer for an aggregate suitability surface*



To illustrate the procedure for developing a suitability surface, consider surface geology as an input layer, with three elements: course gravels, weathered limestone, and granite (depicted as checkered, grey, and white in Figure 4.1). Since it would be easiest to build a pipeline through course gravels, more difficult for weathered limestone, and exceedingly difficult for granite, these elements are assigned suitability values of 2, 4, and 6 to reflect their suitability for pipeline construction ("Value Table" in Figure 4.1). This assignment or reclassification yields a value map, which may be considered a suitability surface for this particular input layer ("Value Map" in Figure 4.1). These layers are aggregated to form the total suitability surface. Prior to aggregating the input layers, we may group the layers into categories and assign each category a different weight in the computation of the suitability surface, to better reflect the priorities of different layers or groups of layers in the site selection process. In the example in Figure 4.1, geology has been given a weight of 50% in the calculation of the suitability surface. For example, regulatory layers may be more important than physical layers, so we may weight these groups accordingly. Huber and Church (1985) use the equation

$$SS_j = \frac{\sum_{l=1}^{n} w_l V_{lj}}{\sum_{l=1}^{n} w_l} \tag{4.4}$$

to calculate the final suitability scores for each cell in the grid, where SS_j is the suitability score for cell j (lower values are more suitable); l is an index of input layers (e.g. railroads); n is the total number of input layers; w_l is the weight for layer l; and V_{il} is the value of cell j in layer l.

The aggregate suitability surface is analogous to a topographic surface, with peaks of relatively high cost and valleys of relatively low cost. Adjusting the relative weights of the elements in the input layers will change the form of the suitability surface and the identified pipeline corridor alignment. Therefore, several weighting systems should be examined. Once an agreeable suitability surface has been developed, a shortest path algorithm (e.g. Dijkstra’s algorithm, 1959) is used to identify the optimal corridor between the origin and destination points such that the “cost” of the corridor, as defined by the cumulative cost of traversing each of the cells along the corridor, is minimized.

4.1.2.2.Estimating Pipeline Construction Cost

The "real-world" cost of constructing the pipeline along the corridor identified in the GIS model may be estimated using standard engineering cost estimates for materials, labor, right-of-way, and miscellaneous engineering and administrative costs. It is a complex undertaking, and pipeline cost estimates are only expected to be within 30% of the eventual as-built cost. In light of the complexities associated with estimating the cost of constructing pipelines, it is sufficient for our purposes to use simplified rules of thumb developed in previous studies and apply sensitivity analysis to produce a range of possible costs for each pipeline. Dean Trammel, a pipeline engineer working with Tucson Water, assembled planning estimates for the unit cost of installing pipes of various diameters for use in this study. The planning estimates include all costs of pipeline construction—including materials, rights-of-way, engineering, and contingencies—and are assumed to be within +50% and -30% of the actual as-built cost (Trammel 2008).

4.1.3. Evaluation and Uncertainty

Earlier in this chapter, it was shown that the optimal point of transition to renewable water supplies requires that the marginal costs of the exhaustible and renewable resources are equal. By estimating the marginal cost of groundwater pumping through time, and by converting the capital cost of the pipeline into a marginal cost per acre-foot of delivered water, it is possible to produce an estimate of each water provider's most efficient transition to accepting direct deliveries of CAP water.

Many of the parameters in the proposed model are unknown. Therefore, multiple scenarios will be used to show how the results of the model change when different assumptions are used. Pumping energy rate, CAGRD replenishment cost, and the water provider's demand for CAGRD replenishment are all parameters that are expected to significantly affect the model's results. Therefore, the results presented in Chapter 5 will include calculations of the sensitivity of the model to many of the parameters but will focus on these three in particular.

4.2. Data

Numerous sources and approaches were utilized in collecting the data for the spatial economic model. Appendix B-3 tabulates the sources or methods behind each of the model's inputs. Some data are inherently spatial and were collected using GIS, while others were obtained from official documents or reports.

The first task of the analysis is to predict the cost of groundwater pumping for a given water utility—a function of the depth to groundwater and the costs of energy, treatment, replenishment, and well maintenance and installation. Current depth to groundwater was obtained from ADWR's Groundwater Well Sweep Inventory (GWSI) dataset; future depth to groundwater was calculated using Gisser's equation for water level drawdown (Equation 4.3). In Gisser's drawdown equation, aquifer area (A) was assumed to be the area of a circle with a radius of 1.5 miles. Aquifer storativity (S) was obtained from a map of observed storativity values in the Tucson basin assembled by ADWR. Recharge (R) is taken to be a relatively small value—in the range of 100 to 500 AF per year. Return flow was set equal to zero, since most water utilities do not recharge their effluent locally. Water demand (W) was taken from CAP's *Outlook 2003* water demand projections.

Given the water level and water demand in a given year, the groundwater pumping cost may then be determined from the costs of energy, water treatment, CAGRD replenishment, and well maintenance and installation. The cost of pumping due to energy was calculated from Equation (4.2); pumping energy rates used in the model are based on Tucson Electric Power's Municipal Water Pumping Rate No. 43.[13] Since treatment cost depends strongly on water quality, it was difficult settle on a generic equation for water treatment related only to depth. In reality, however, treatment represents only about 3-6% of a typical water bill. Therefore, an empirical formula will suffice for the purposes of this model.[14] This model's equation assumes that the cost of water treatment (*TC*) is \$8/af at land surface, \$16/af at 1,000' bls, and increases linearly with depth in the following form:

$$TC = 0.008*\text{Depth} + 8 \qquad (4.6)$$

The CAGRD replenishment rate (*CR*) was projected using the current trend in the replenishment rate. Historically, the CAGRD replenishment rate in the Tucson AMA has been between 300 and 325% of the CAP M&I subcontract rate. A range of 300-350% was used in this model. The CAGRD replenishment rate has the potential to be the largest portion of a CAGRD member's groundwater pumping cost. Any excess groundwater pumping that is not able to be offset by other means (groundwater savings, underground storage, effluent recharge, etc.) is discounted by CAGRD's excess groundwater reporting factor (see Appendix B-2) to determine the actual volume of groundwater to be replenished by the CAGRD; the member then pays the CAGRD for replenishing this proportion of its actual excess groundwater pumping. After 2015, however, the minimum reporting factor goes away for all MSAs and for MLs enrolled prior to 2004. The appropriate minimum reporting factor is therefore included in the calculation of each member's CAGRD replenishment cost. Yet since the proportion of each member's groundwater pumping

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[13] For a rate schedule, see http://www.tucsonelectric.com/Docs/Rate43.pdf.

[14] In most cases, groundwater is not really "treated" like effluent is treated. It is simply pumped out of the ground and chlorinated before delivery. For example, Vail Water Company only chlorinates its groundwater, at an average cost of about \$6 per AF (with depth to water being around 475') (Volpe 2008). Therefore, this model probably overestimates the water provider's actual groundwater treatment cost.

being offset by the CAGRD is unknown, several scenarios must be used. If the model calculates that the member's water levels are declining by more than 4 ft/yr, then the model assumes that 100% of the member's groundwater is being replenished by the CAGRD, in accordance with ADWR rules regarding water level declines.

One final cost of groundwater pumping considered in the model is the cost of maintaining and replacing existing wells and installing new ones to meet additional demand (*CC*). Wells depreciate with use and eventually need to be replaced. The per-acre-foot annual cost of well depreciation is estimated in the University of Arizona Agricultural Extension's Pump Water Budgets to be approximately $36 per acre-foot. This fixed cost is simply added to the cost of groundwater pumping. When water demand rises, additional wells must be installed to serve the additional demand. A new well with an annual pumping capacity of 1,000 AF per year costs approximately $350,000 and lasts about 20 years (U.S. Bureau of Reclamation 2007; Malcolm Pirnie 1998). Thus, for every 1,000 AF of additional water demand, the fixed cost of an additional well is added to the cost of groundwater pumping.[15]

Having predicted the approximate cost of pumping one acre-foot of groundwater in a given year, the next task of the analysis was to calculate the approximate cost of importing one acre-foot of CAP water to the water provider's service area in the same year—in other words, to calculate the cost of transitioning to renewable supplies in that year.

The cost of importing CAP water depends on the pipeline's length and unit cost. To predict pipeline length, a suitability surface was created in ArcMap. Suitability layers were selected based on information provided in the Tucson Water Design Standards Manual and on advice given by pipeline engineers at the U.S. Bureau of Reclamation. The Manual states that

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[15] The fixed cost is first annualized over 30 years and then converted to an average per-acre-foot cost by dividing the annual cost by total water demand.

pipelines should be located “in existing rights-of-way or… in a dedicated utility corridor where possible.” The Manual also includes a list of considerations for siting pipelines, which include: paving moratoriums; utility congestion; geotechnical data; native plant vegetation and undisturbed areas; environmental clearance (archaeology and endangered species); constructability; and future development (Tucson Water Design Standard No. 8-08). Reclamation engineers recommended similar factors, and further emphasized that existing rights-of-way for utilities are followed as often as possible when new transmission mains are installed.

Most of the pipeline location factors listed in Tucson Water's Design Standards Manual can be captured in a GIS model by four layers: street network; railroads; major pipelines; and major power transmission mains. If a pipeline follows these features but avoids crossing them, it will automatically follow existing rights-of-way, minimize traffic disturbance, avoid disturbing undisturbed land, and avoid archaeological sites and endangered species habitats. For this reason, these four layers were selected for the suitability surface. The layers were downloaded from the GIS Server of the Pima County Department of Transportation (DOT).

The suitability surface was created by forming suitability layers from each of the four input layers and adding them together to form an aggregated suitability surface. To get the suitability surface to follow the linear features yet minimize crossings of those features, a buffer was created around each layer’s linear feature (i.e. the actual road or pipeline). The buffer was then assigned a low suitability score (1) relative to the linear feature itself (10). The remaining open space on the layer was assigned a high suitability score (100) to ensure that the pipeline corridor would avoid crossing portions of the landscape that had not been previously disturbed or did not have a right-of-way easement. Table 4.1 shows the suitability scores applied to the different cell values (linear feature, buffer, and open space) of each layer in the model.

Table 4.1: *Suitability Scores Assigned to the Suitability Layers*

Layer	Feature	Buffer	Open Space
Street	10	1	100
Railroads	10	1	100
Pipelines	10	1	100
Powerlines	10	1	100

In aggregating the suitability layers to form the suitability surface, it is possible to weight each suitability layers differently to account for the relative importance of each layer. For example, if following existing pipelines is determined to be the most important factor in choosing a pipeline alignment, then the existing pipelines layer should be weighted more heavily in the calculation. For simplicity, two weighting systems were used in this model. Weighting system A treats each layer equally; weighting system B favors pipelines and powerlines as the first and second most important factors, respectively, and does not differentiate between streets and railroads. Table 4.2 shows the specific weights assigned in each of the weighting systems.

Table 4.2: *Weighting Systems for Calculation of the Suitability Surface*

Layer	Weight A	Weight B
Streets	1	2
Railroads	1	2
Pipelines	1	5
Powerlines	1	3

The total cost of the pipeline ($) is equal to its total length (linear feet, given by the GIS model) multiplied by the unit cost ($/linear foot) of installing the pipeline. Estimates of the unit cost of pipeline were obtained from pipeline engineer Dean Trammel, of Tucson Water's Systems Planning Department. These estimates are used for planning purposes only, and are assumed to be within +50% to -30% of the actual as-built cost of the pipeline. As shown in Figure 4.2, the unit cost depends on the diameter of the pipe, and exhibits decreasing returns to scale with respect to pipeline diameter. Tucson Water's estimates include materials, labor, rights-of-way, and miscellaneous expenses, plus 15% for engineering and 15% for contingency.[16]

Pipe diameter was calculated such that (a) the maximum velocity of water in the pipe does not exceed 5 feet per second; (b) the peak flow rate is double the total annual water demand; and (c) the pipe accommodates not just this year's peak flow demand but also the anticipated peak flow demand thirty years from now. Since the area of the pipe is πr^2, and discharge is equal to the product of area and velocity (5 ft/s), it is possible to determine the pipe diameter such that the pipeline can accommodate the future expected peak flow rate. Once the pipeline diameter is established, the total cost of the pipe is determined by simply multiplying the pipe unit cost (dollars per linear foot, \$/lf) by the total length of the pipeline (feet).

The total capital cost of the pipeline is then converted into an annual per acre-foot cost over the life of the pipeline. The total capital cost is first converted into an annual payment amount by dividing the total cost by the appropriate annuity factor. The annuity factor depends on the interest rate and the life of the project. A range of interest rates—4%, 6%, and 8%—are used in the model. The typical life of a water transmission pipeline project is about 30 years (BOR 2000). Each year's annual payment amount is then divided by the projected water demand in acre-feet in that year, thereby giving the cost per acre-foot of importing the CAP water. The

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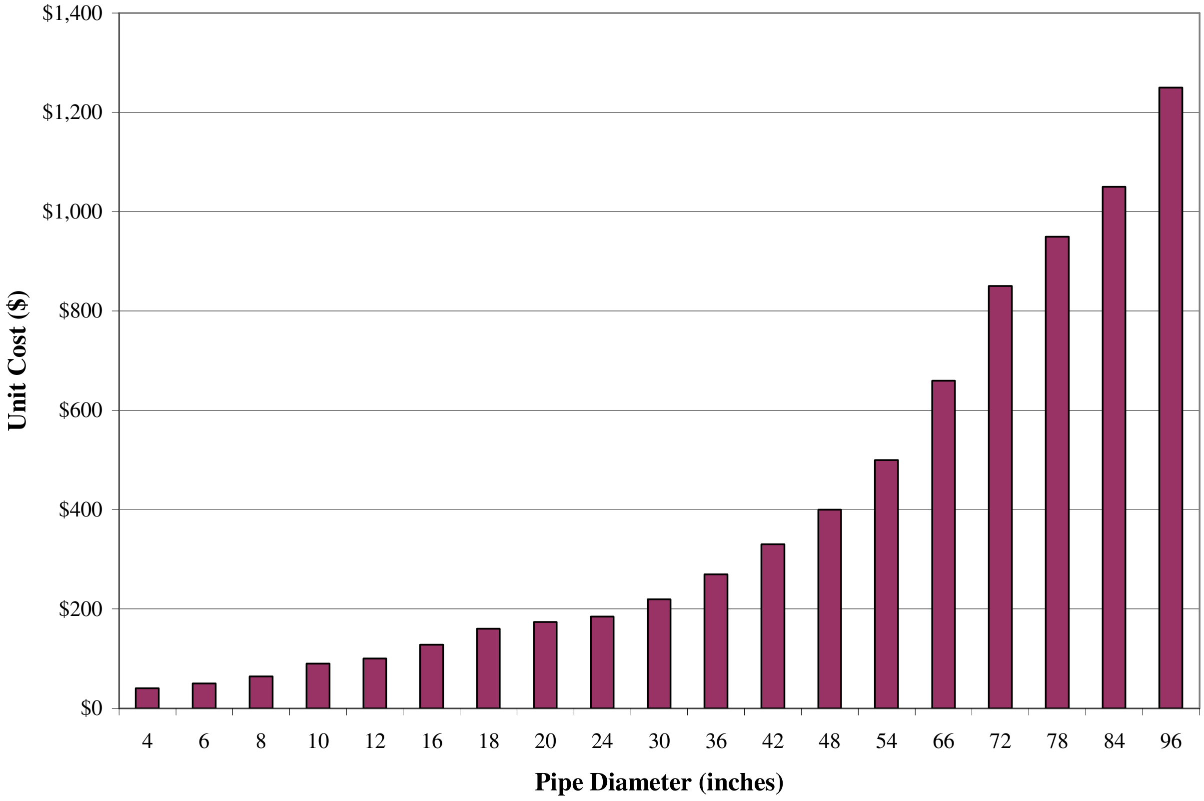
[16] Trammel's unit cost estimates track closely with the results of a pipeline cost model developed by McCoy and Rubin (2008, forthcoming) for natural gas pipelines using as-built cost information for 263 on-shore natural gas pipeline projects in the contiguous 48 states. Though natural gas pipelines differ from water pipelines in many respects, it is remarkable (and somewhat reassuring) that McCoy and Rubin's natural gas pipeline unit costs differ from Trammel's water pipeline unit costs by no more than 20%. (For some pipe diameters the estimates are within 1% of one another.)

cost of CAP water (the projected CAP M&I rate) is then added to the pipeline cost to determine the total cost per acre-foot for building a pipeline to directly deliver CAP water to the water utility.

Figure 4.2: *Conceptual Unit Cost Estimates for Pipelines of Various Diameters*



CAP water is also relatively expensive to treat. Due to the scope of this study, it was assumed that the water utilities would be delivering the CAP water to its service area and treating it for potable use, rather than recharging and recovering the CAP water. In 2007, the Bureau of Reclamation developed a range of estimated costs for treating CAP water to potable standards. The BOR estimated that treating CAP water to potable standards using conventional treatment technology would cost about $185 per acre-foot. For simplicity, this study assumes that conventional treatment will be used; however, it is possible that this treatment cost could be higher if other methods (or a combination of methods) are used to treat the incoming CAP water.

As demonstrated by the optimal control model in Chapter 2, the optimal time (T) to build the pipeline is when the net benefit of importing water exceeds the net benefit of pumping groundwater. Therefore, the final step in evaluating T is simply to compare the two unit cost curves for groundwater pumping and direct delivery of CAP water. The intersection of these two cost curves represents the water utility's point of transition from groundwater to CAP water.

4.3. Results

We are now prepared to interpret the results of two case studies for the analytical model developed in this chapter. Case Study I is Vail Water Company; Case Study II is the Community Water Company of Green Valley. Both water utilities are located in the Tucson Active Management Area. For each, the model analyzes the potential switch point between groundwater and direct delivery of CAP water, examines the impact of the CAGRD on the switch point, and applies scenario analysis to assess the robustness of the results.

4.3.1. Case Study I: Vail Water Company

Vail Water Company is located in the southeast corner of the Tucson basin, and is bisected by Interstate 10 (see Appendix A-1 and Appendix C-3). It is roughly 15.6 square miles in area and delivered 1,057 AF of water in 2006 (ADWR 2008). Vail Water Company subcontracted for 786 AF of CAP water in 1984, and will increase its allocation in 2008 to 1,857 AF. Nevertheless, its distance from the CAP canal and the physical availability of groundwater have discouraged it from directly delivering its CAP allocation (CAP 2007; Volpe 2008).

Instead, Vail has stored its CAP allocation at the Kai-Red Rock groundwater savings facility. This is a perfect illustration of “paper water” at work: Kai-Red Rock is located approximately 60 miles from Vail and is not only hydrologically downgradient but is also in a different hydrologic subbasin, according to ADWR. The renewable water supply that Vail is indirectly using at the Kai-Red Rock GSF does not benefit Vail Water Company in any physical sense; the water only provides the legal benefit of statutory compliance.

Historically, Vail has not recovered all of its 786 AF through groundwater pumping, thereby accruing long-term storage credits for this stored water. These credits are a valuable asset to Vail in terms of reducing its excess groundwater pumping, controlling its replenishment costs, and storing up supplies for future drought. (However, to continue to recover these long-term storage credits within its service boundaries, Vail must keep its water level declines to a maximum of 4 feet per year.) Vail Water Company was the very first water provider to enroll in the CAGRD as a Member Service Area, in November 1995. CAP’s *Outlook 2003* report projects that Vail Water Company’s annual water demand will continue to grow steadily at 500 AF per year out to 2035—effectively doubling demand by 2015 and tripling demand by 2025 (Appendix C-3). These projections were made during a period of exceptional population growth in Arizona, however, and may overstate the future population growth in Vail’s service area.

One final note about Vail Water Company: in 2000, Vail became the first private water company to attempt to recover its CAP-related costs from its customers. In hearing the case, the Arizona Corporation Commission ruled that the proposed CAP-related costs would represent a cost to Vail’s customers for which they were not really receiving a benefit (ACC Opinion and Order, Decision No. 62450). To the ACC, Vail should come up with a way to directly deliver its CAP allocation or else risk losing its ability to charge for the expenses it annually incurs to hold and store its CAP allocation. A reasonable target date for such a delivery system was determined by the ACC to be no later than 2015. This requirement is completely unique to Vail Water Company, and is a fascinating example of the interplay between the rules and regulatory authorities of ACC and ADWR in determining which water management practices are considered acceptable and which are not. According to ADWR, Vail Water Company has met all its requirements to remain a designated water provider, having proven (among other things) both the physical availability of 100 years of groundwater to serve its projected water demand and the use of renewable water supplies by storing CAP water at Kai Farms near Picacho Peak and recovering what is legally “CAP water” in its service area. Yet from the perspective of the ACC, the 60-mile gap between the locations of where the CAP water is stored and where (legally, not magically) it is recovered is very real, and if Vail Water Company cannot really put their CAP allocation to use then it should not be able to hold a CAP allocation. (Interestingly, this use-it-or-lose-it philosophy of water rights is what caused Arizona to push so hard for the CAP in the first place.[17]) The cost of directly delivering CAP supplies in 2015 under various assumptions is presented in the results for this case study and compared to the efficient switch point estimated by the spatial economic model.

4.3.1.1.Cost of Pumping Groundwater

ADWR’s Groundwater Well Site Inventory (GWSI) database reveals that the average depth to groundwater for wells in Vail’s service area is approximately 432 feet. As Vail’s water demand grows, the water level will continue to decline. The rate of decline depends on the

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[17] See Holland and Moore (2003) for an interesting (albeit politically naïve) analysis and discussion of the optimal timing of the construction of the CAP aqueduct. Their study found that the CAP was build approximately 86 years too early, indicating that Arizona’s lack of a truly secure property right to the Colorado River resulted in an inefficient allocation of resources in the form of a CAP aqueduct that was not really needed at the time.

values for water demand, aquifer area, and aquifer storativity used in the model. An initial cost estimate was produced with the assumptions that CAP's *Outlook 2003* demand projections are correct, that the area impacted by the wells is simply a circle with a radius of 1.5 miles (or about 7 square miles), and that ADWR's tested storativity value for the Vail area of the 0.13 is correct.

Assuming no natural or artificial recharge in the vicinity of Vail's well field, Gisser's Equation (4.2) estimates that the current rate of water level decline is 1.6 ft/yr. Due to the additional water demand, this rate increases to 4.1 ft/yr by 2020. Since this rate of decline exceeds ADWR's water level decline standard, Vail will need to begin relying on the CAGRD to offset 100% of its groundwater pumping by 2020. If CAP's *Outlook 2003* water demand projections are correct, Vail will need an additional well every 10 years to keep up with their growing demand. Figure 4.3 gives the initial projections for Vail's groundwater pumping cost out to year 2100. The solid part at the bottom of each bar in the graph represents all the groundwater pumping costs other than replenishment; the top hatched portion represents the cost of CAGRD replenishment. In 2005, the predicted pre-replenishment cost of groundwater pumping for Vail Water Company is about \$104/AF; adding CAGRD's replenishment fee of about \$253/AF would bring the total to about \$360/AF. However, since Vail is not currently using the CAGRD for replenishment, its costs are simply \$104/AF.[18] In 2020, however, the model predicts that Vail will begin to rely on the CAGRD for replenishment, thereby increasing its groundwater pumping costs to about \$500/AF.

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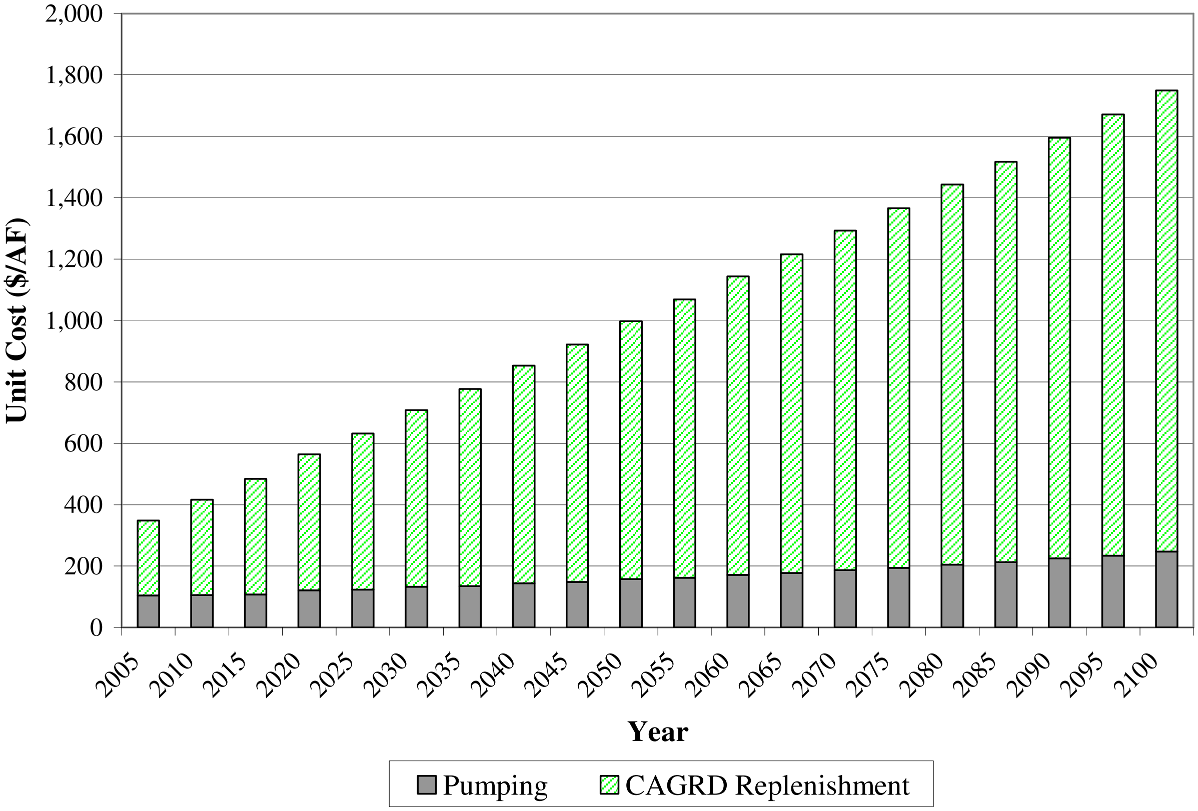
[18] In fact, Vail Water Company's cost of groundwater pumping in 2007 was \$108 per AF. The GIS model is therefore within about 4 percent of the actual cost of groundwater pumping for this case study.

Figure 4.3: *Projected Groundwater Pumping Cost for Vail Water Company, 2005-2100*



4.3.1.2.Cost of Importing Renewable Supplies

The capital cost of the pipeline depends on the pipeline's length, diameter, unit cost, and loan interest rate. The total length of the pipeline from the CAP aqueduct to the edge of Vail's service area was determined using corridor analysis. Appendices A-2 and A-3 geographically show the basic steps used to determine the likely path of the pipeline. The origin for the pipeline corridor was specified as the CAP terminus (since it is the closest point on the CAP aqueduct to Vail's service area), and the destination was selected as a central location along the far western boundary of the Vail's service area. Next, the suitability surface layers were added to the map: existing major pipelines, existing major power transmission lines, streets, and railroads. Each layer was buffered and weighted according to the methods described in the "Data" section of this chapter, then combined to form the aggregate suitability surface. The final step in the process was to compute the least cost path across the suitability "landscape" between the origin and destination points. The pipeline corridor identified by the model varied depending on the weighting of the suitability layers. Weighting the layers equally produced a northern alignment following Interstate 10, with a total length of 139,920 feet (Appendix A-4). Favoring existing pipelines and power lines, a different route emerged that tended to follow pipelines and power lines, with a total length of 143,208 feet, or about one-half mile longer than the first alignment (Appendix A-5). While a thorough comparison of the costs and benefits of the two routes is beyond the scope of this study, Appendix A-6 offers a glimpse into what that process might entail. Additional selection criteria (e.g. wildlife habitat, geologic faults, nature preserves, and land ownership) may be added to the map to aid in the selection between the two corridors. For the purposes of this model, both pipeline alignments will be considered.

To arrive at the total capital cost of building the pipeline, the total length of the pipeline determined in GIS is multiplied by the unit cost of the appropriately sized pipe. If Vail Water Company were considering building a pipeline in 2005, it would need to size the pipeline to be able to serve their expected water demand in 2035 of about 3,900 acre-feet, and thus would require a pipe diameter of 20" at an approximate unit cost of $230 per linear foot (with a suggested range of -30% to +50%, or $161 to $345/lf). The first pipeline alignment yields a total capital cost of $32.20 million. At an interest rate of 6% over 30 years, the annual payment would be $2.3 million. Divided by the water demand in 2005, the pipeline would cost $2,725 per acre-foot. Adding the CAP water treatment cost of $185/AF and the CAP M&I rate brings the total to about $2,910/AF for switching to direct delivery of CAP water in 2005. (Using the alternative southern pipeline alignment, the cost of direct delivery would be slightly higher—

around $2,970/AF.) Appendix C-4 shows the projection of the cost of delivering renewable supplies for the northern pipeline alignment. While the total cost of building the pipeline increases as the 30-year projected water demand increases, the cost per acre-foot declines through time as the annual payment of the construction cost is spread over a larger water demand.

An alternative that has been mentioned is that Tucson Water, which already delivers some CAP water to its customers, could theoretically wheel Vail's CAP allocation through its delivery system to Vail's service area. Obviously, this would significantly reduce the cost of directly delivering CAP water to Vail. It would also raise some questions regarding how Tucson Water ought to charge Vail for this service. While Vail should certainly pay the marginal cost of extending Tucson Water's delivery system out to Vail, Tucson Water would likely want to charge Vail for the *average cost* of delivering this additional volume of water from start to finish, rather than the marginal cost of delivery. The average cost would include the marginal cost of recharging and recovering the water at the Central Avra Valley Storage and Recovery Project and wheeling it to Vail, plus some negotiated portion of the fixed cost incurred by Tucson Water to put this infrastructure in place.[19]

Obtaining a rough estimate of the cost of this arrangement to Vail Water Company is achieved by changing the point of origin for the CAP supplies from the CAP terminus to the boundary of Tucson Water's service area closest to Vail's service area. Appendix A-7 shows the new origin and destination points for the CAP water, as well as the derived pipeline corridor stretching between the points (the route simply follows an existing pipeline). The total length of the new pipeline is approximately 23,000 feet or 4.4 miles. Keeping the same water demand and

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[19] In fact, Tucson Water already attempts to recover some of this fixed cost from new customers through its System Equity Fee. See Tucson Water's "Rates and Fees" webpage at *http://www.ci.tucson.as.us/water/* for more details.

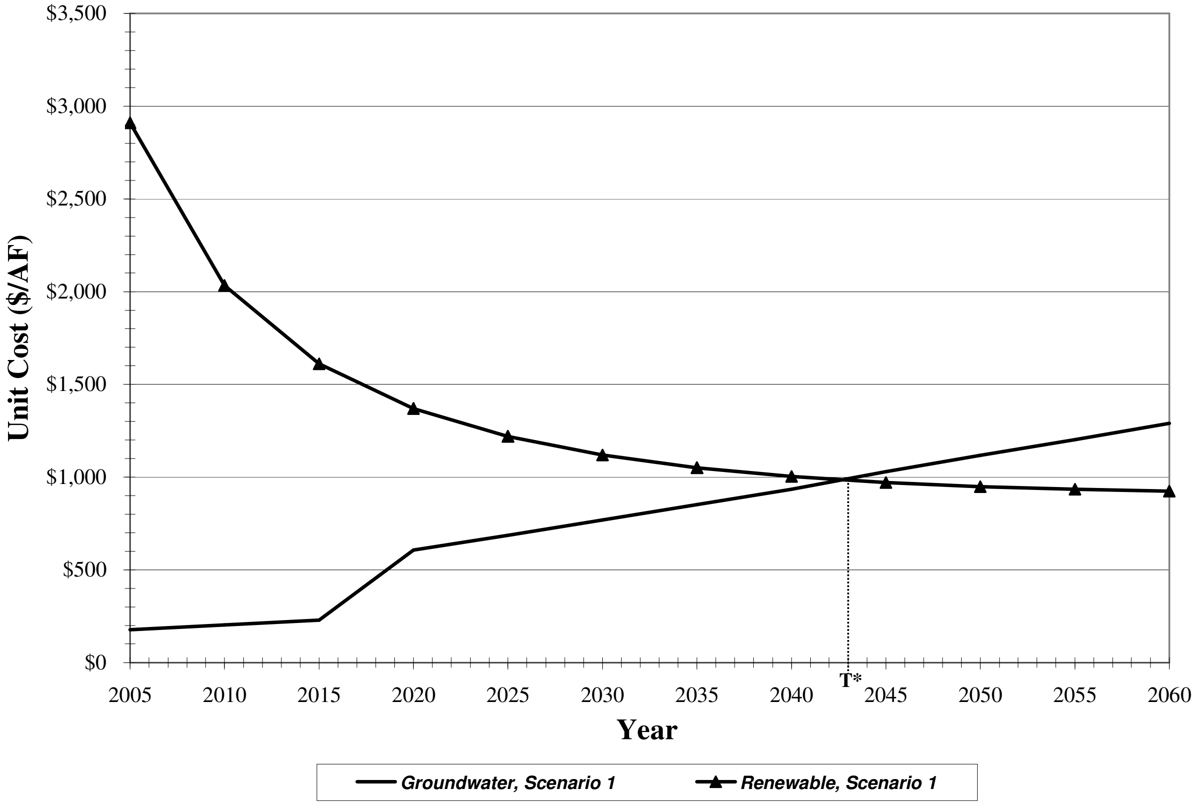
pipe unit cost parameters, the new cost estimate for direct delivery of CAP water through Tucson Water's delivery system is substantially lower than the cost of delivering CAP water from the CAP terminus--$698/AF for direct delivery in 2005, versus the $2,910/AF for the longer pipeline beginning at the CAP terminus. The two cost estimates through 2060 are compared graphically in Appendix C-5.

4.3.1.3.Evaluation of the Optimal Transition to Renewable Supplies

As demonstrated in Chapter 2, the optimal time (*T*) to build the project and switch to direct delivery of CAP water is when the net benefit of importing water exceeds the net benefit of pumping groundwater. In other words, the evaluation of *T* is made possible through a comparison of the projected costs of groundwater pumping and pipeline construction. The two cost projections are shown graphically in Figure 4.5. Under the initial conditions (i.e. northern pipeline alignment, energy rate = $0.087/kWh, CAGRD reliance = 0% in 2005, etc.), the switch point for Vail Water Company is projected to be sometime around 2040-2045.

As Figure 4.5 demonstrates, the cost of CAGRD replenishment plays a major role in determining the switch point. In Figure 4.4, the cost of CAGRD replenishment is borne sometime between 2015 and 2020, providing an economic incentive to the water provider to switch to renewable water supplies far sooner than it would if it only had to pay the cost of groundwater pumping. This piece of information provides some key insights into the costs and benefits of the CAGRD as it relates to the AWS rules.

Figure 4.4: *Comparison of the Costs of Groundwater Pumping and Direct Delivery of CAP Water via Pipeline for Vail Water Company, 2005-2060 (Scenario 1)*



I said at the beginning of this chapter that, in the end, the CAGRD would be judged based on its impact on the ability of the AMAs to achieve safe yield. In answering this question, consider four basic Policy Scenarios:

Policy Scenario A: The Assured Water Supply rules were never passed and thus do not exist.

Policy Scenario B: The Assured Water Supply rules were passed because the CAGRD was created. This is the current situation in which we find ourselves.

Policy Scenario C: The Assured Water Supply rules were passed without the creation of the CAGRD or any centralized, agency-managed replenishment district to provide a mechanism to show indirect use of CAP water. Still, the "paper water" system of using CAP water indirectly is allowed to continue.

Policy Scenario D: Same as Scenario C, except the privilege of using CAP water indirectly (i.e. the paper water system) is hypothetically revoked in 2008.

Now consider these Policy Scenarios as they relate to the graph in Figure 4.4 above (c.f. Table 4.3). Under Policy Scenario A, the cost of CAGRD replenishment would never be factored in. Instead, the cost of groundwater pumping would dictate whether water utilities would decide to transition from groundwater to direct delivery of CAP water. Appendix C-6 demonstrates the result of Policy Scenario A this scenario graphically, and indicates that Vail's switch point is certainly not before 2060, and probably not for many decades afterward.

Table 4.3: *Scenarios to Assess CAGRD's Impact on Direct Delivery of CAP Water to Vail*

Policy Scenario	***AWS Rules***	***CAGRD***	***Paper Water***	***Water Supply 2008***	***Predicted Switch Point***	***Cost/AF at Switch Point***
A	No	N/A	N/A	Groundwater	2100+	N/A
B	Yes	Yes	Yes	Groundwater	2045	$970
C	Yes	No	Yes	CAP Indirectly	2015	$1,600
D	Yes	No	No	CAP Directly	2005	$2,910

Under Policy Scenario B (the current situation), the AWS rules and the ADWR water level decline standard together require Vail to begin paying the CAGRD to replenish its excess groundwater pumping around 2020. The additional cost of CAGRD replenishment causes Vail to approach the switch point by around 2045. The per-acre-foot cost at this point would be approximately $970. Under Policy Scenario C, Vail would theoretically be required to directly deliver its CAP allocation as soon as it was not able to store enough CAP water (through long-term storage credits or annual recharge and recovery) to offset its excess groundwater pumping. How this scenario would impact the switch point is not particularly obvious. Comparing Vail's record of CAP water storage and recovery to its historical and projected water demand, it appears that this date could potentially be around 2015. Finally, consider Policy Scenario D, under which neither the CAGRD nor any other forms of indirect use of CAP water are permitted to comply with the AWS rules. Policy Scenario D would require Vail Water Company to switch from groundwater pumping to direct delivery of CAP water immediately (2008 in this example). This would cause the cost of water delivery to jump from $110/AF to about $2,910/AF—the equivalent of increasing the average customer's monthly water bill from $46 to $108, ceteris paribus.[20] However, the initially high monthly bill would decrease as the high fixed cost of constructing the pipeline were spread over more customers, and would eventually be equivalent to the average monthly bill under Policy Scenario B in 2020 (about $66).

These four scenarios give us some insight into the nature of the CAGRD's impact on the achievement of safe yield. Since we know from Chapter 3 that the existence of the CAGRD enabled the passage of the AWS rules, Policy Scenario A is the most plausible alternative to Policy Scenario B. In Policy Scenario A, groundwater pumping would continue indefinitely (or at least until the physical water supplies could no longer be obtained at a low enough cost). Policy Scenario B, the current situation, the cost of CAGRD replenishment represents a significant additional cost to any CAGRD members that rely on the CAGRD. The magnitude of this cost makes it highly influential in the timing of the transition to direct delivery of CAP water. For some CAGRD members, the CAGRD replenishment rate controls the timing of their

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[20] Assuming 7,722 gallons per month (Tucson AMA user average), and holding all other costs for administration, operations, and maintenance constant between groundwater and direct delivery of CAP water. Under this assumption, the current average monthly water bill for Vail Water Company is about $46 per month, which includes all costs of pumping, administration, operations, maintenance, etc.

transition to direct delivery of CAP water as a rudder steers a large ship. If the cost path of CAGRD replenishment is not linear, as it is modeled here, but rather quasi-concave (that is, it increases at an increasing rate through the medium term), then this is likely to cause CAGRD members that are more dependent on the CAGRD to transition to direct delivery of CAP water sooner. While the CAP board does not necessarily control the price of CAGRD replenishment with these nuances in mind, its price setting authority may be a useful policy instrument in the future if the AMA wishes to speed up the transition to direct delivery of CAP water.[21]

4.3.1.4.Scenario Analysis

Thus far we have performed the spatial economic analysis using only one set of assumptions. We must now revisit the initial parameter assumptions and discern the degree to which changes in these assumptions affect our results. Given the number of variables used in the model and the uncertainty associated with them (for example, the relationship between the CAP M&I rate and the cost of CAGRD replenishment), scenario analysis (i.e. changing many parameters at once and observing the impact) is highly favorable to sensitivity analysis (i.e. doing comparative statics by changing one variable at a time and observing the impact).

Appendix B-4 summarizes the assumptions used for Scenarios 1, 2, and 3. (Note that these scenarios are distinct from the Policy Scenarios presented above and have an altogether different purpose.) We have already examined Scenario 1, the base case parameter assumptions. Scenario 2 is designed to represent the *least* favorable conditions for importing CAP supplies; Scenario 3 is designed to represent the *most* amenable conditions for importing CAP supplies. Some of the parameters represent engineering standards, established physical relationships, or

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[21] For example, a tax could be added to the CAGRD replenishment rate for certain members that are pumping groundwater in areas that are prone to subsidence or have been shown to be environmentally sensitive.

water policies that apply to Vail Water Company; these remain constant for all three scenarios. Parameters that change across the scenarios are shaded in Appendix B-4.

Scenario 1

Table 4.4 tabulates the key results for Scenario 1. The basic prediction of the model is that direct delivery of CAP water to Vail Water Company via pipeline will become economically efficient sometime between 2040 and 2045. (The cost predictions for Scenario 1 are shown in Figure 4.3 on p. 83. This graph makes it easier to see that the more precise date of the predicted switch point is 2043). Of course, this assumes that Vail Water Company's customers will bear the entire cost of the pipeline. The possibility of partnerships with other utilities (e.g. Spanish Trail Water Company) to help spread the capital cost of the pipeline is very real. If such partnerships were established, the efficient time of transition would obviously be shortened.

Table 4.4: *Vail Water Company, Key Results for Scenario 1*

YEAR	**GROUNDWATER PUMPING COST**			**PIPELINE COST**			**DIFFERENCE**
	DRAWDOWN (dh/dt)	WATER LEVEL (ft bls)	PUMPING COST ($/AF)	CAPITAL COST ($)	UNIT PMT ($/AF)	DD COST ($/AF)	
2005	-1.60	432	$99	$32,197,691	$2,648	$2,910	**$2,734**
2010	-2.42	444	$100	$32,197,691	$1,747	$2,034	**$1,832**
2015	-3.26	460	$102	$34,233,177	$1,300	$1,611	**$1,382**
2020	-4.10	481	$606	$34,233,177	$1,035	$1,371	**$764**
2025	-4.93	506	$687	$34,233,177	$859	$1,220	**$532**
2030	-5.77	534	$776	$34,233,177	$735	$1,120	**$351**
2035	-6.60	567	$858	$34,233,177	$642	$1,051	**$200**
2040	-7.43	605	$947	$34,233,177	$570	$1,004	**$69**
2045	-8.26	646	$1,029	$34,233,177	$513	$971	**($59)**
2050	-9.10	691	$1,118	$34,233,177	$466	$948	**($170)**
2055	-9.93	741	$1,202	$40,709,724	$427	$933	**($269)**
2060	-10.77	795	$1,291	$40,709,724	$393	$925	**($366)**

Scenario 2

Scenario 2 is designed to reflect conditions that are less favorable to transitioning to renewable supplies than those in Scenario 1: the growth in water demand is half that of *Outlook 2003*'s projections; the pumping energy rate is 40% cheaper (Tucson Electric Power's interruptible rate); the CAGRD replenishment rate is only 3 times the CAP M&I rate; the pipe unit costs are 50% higher than in Scenario 1 (the high end of Tucson Water's estimated range); and the interest rate on the capital cost of pipeline construction is higher (8%). (See Appendix B-4 for the exact parameters used for Scenario 2.)

The key results for Scenario 2 are tabulated numerically in Table 4.5 and shown graphically in Appendix C-6. Because the cost of directly delivering CAP water is so high and the cost of pumping groundwater is so low under the assumptions of Scenario 2, the predicted switch point does not occur within the study period but rather sometime after 2060.

Table 4.5: *Vail Water Company, Key Results for Scenario 2*

YEAR	**GROUNDWATER PUMPING COST**			**PIPELINE COST**			**DIFFERENCE**
	DRAWDOWN (dh/dt)	WATER LEVEL (ft bls)	PUMPING COST ($/AF)	CAPITAL COST ($)	UNIT PMT ($/AF)	DD COST ($/AF)	
2005	-1.60	435	$158	$48,272,400	$4,854	$5,117	**$4,959**
2010	-2.01	445	$183	$48,272,400	$3,860	$4,147	**$3,964**
2015	-2.43	457	$208	$51,420,600	$3,197	$3,508	**$3,300**
2020	-2.85	471	$234	$51,420,600	$2,728	$3,064	**$2,830**
2025	-3.27	488	$260	$51,420,600	$2,379	$2,740	**$2,480**
2030	-3.68	506	$298	$51,420,600	$2,110	$2,494	**$2,196**
2035	-4.10	527	$771	$51,420,600	$1,895	$2,304	**$1,533**
2040	-4.52	549	$845	$51,420,600	$1,721	$2,154	**$1,309**
2045	-4.93	574	$938	$51,420,600	$1,575	$2,033	**$1,095**
2050	-5.35	601	$1,011	$51,420,600	$1,452	$1,935	**$923**
2055	-5.77	630	$1,093	$61,075,080	$1,347	$1,854	**$761**
2060	-6.18	660	$1,167	$61,075,080	$1,256	$1,788	**$621**

Scenario 3

Scenario 3, in contrast to Scenario 2, is designed to reflect conditions that are more favorable to transitioning to renewable supplies than those in Scenario 1: the growth in water demand is double that of *Outlook 2003*'s projections; the pumping energy rate is 30% more expensive; the CAGRD replenishment rate is 3.5 times the CAP M&I rate; the pipe unit costs are 30% lower than in Scenario 1 (the high end of Tucson Water's estimated range); and the interest rate on the capital cost of pipeline construction is lower (4%). (See Appendix B-4 for the exact parameters used for Scenario 3.)

The key results for Scenario 3 are tabulated numerically in Table 4.6 and shown graphically in Appendix C-7. Since Scenario 3 assumes conditions that result in a relatively low cost of direct delivery and a relatively high cost of groundwater pumping and replenishment, the predicted switch point occurs far sooner than in the first two scenarios (around 2025 for Scenario 3, versus 2043 for Scenario 1 and beyond 2060 for Scenario 2).

Table 4.6: *Vail Water Company, Key Results for Scenario 3*

YEAR	**GROUNDWATER PUMPING COST**			**PIPELINE COST**			**DIFFERENCE**
	DRAWDOWN (dh/dt)	WATER LEVEL (ft bls)	PUMPING COST ($/AF)	CAPITAL COST ($)	UNIT PMT ($/AF)	DD COST ($/AF)	
2005	-1.60	435	$191	$22,527,120	$1,475	$1,737	**$1,546**
2010	-2.67	448	$218	$22,527,120	$883	$1,170	**$952**
2015	-3.76	467	$258	$23,996,280	$628	$940	**$682**
2020	-4.84	491	$660	$23,996,280	$487	$823	**$163**
2025	-5.93	521	$749	$23,996,280	$398	$758	**$10**
2030	-7.02	556	$839	$23,996,280	$337	$721	**($117)**
2035	-8.10	597	$930	$23,996,280	$291	$701	**($229)**
2040	-9.18	643	$1,022	$23,996,280	$257	$691	**($331)**
2045	-10.27	694	$1,128	$23,996,280	$230	$688	**($440)**
2050	-11.35	751	$1,221	$23,996,280	$208	$690	**($531)**
2055	-12.43	813	$1,319	$28,501,704	$190	$697	**($622)**
2060	-13.52	880	$1,413	$28,501,704	$175	$706	**($708)**

Comparison of Scenarios

Table 4.7 tabulates the "DIFFERENCE" columns from Scenarios 1-3 (that is, the difference between the cost of directly delivering CAP water and the cost of pumping—and perhaps replenishing—for each year) and reinterprets the numbers as the "Net Benefit" of delaying the transition to direct delivery of CAP supplies. In all of the scenarios, Vail Water Company receives a positive net benefit for delaying the transition until at least 2025 (panel *a*).

Table 4.7: *Estimated Gain in Net Benefit to Vail of Wheeling CAP Water Through Tucson Water's Service Area*

(a) Origin = CAP Terminus

NET BENEFIT ($/AF)

Year	**Scenario**		
	1	**2**	**3**
2005	$2,734	$4,959	$1,546
2010	$1,832	$3,964	$952
2015	$1,382	$3,300	$682
2020	$764	$2,830	$163
2025	$532	$2,480	$10
2030	$351	$2,196	**($117)**
2035	$200	$1,533	**($229)**
2040	$69	$1,309	**($331)**
2045	**($59)**	$1,095	**($440)**
2050	**($170)**	$923	**($531)**
2055	**($269)**	$761	**($622)**
2060	**($366)**	$621	**($708)**

(b) Origin = Tucson Water

NET BENEFIT ($/AF)

Year	**Scenario**		
	1	**2**	**3**
2005	$521	$903	$314
2010	$372	$739	$214
2015	$296	$629	$157
2020	**($101)**	$551	**($244)**
2025	**($186)**	$492	**($323)**
2030	**($263)**	$434	**($399)**
2035	**($337)**	**($50)**	**($473)**
2040	**($407)**	**($129)**	**($546)**
2045	**($487)**	**($221)**	**($633)**
2050	**($559)**	**($290)**	**($705)**
2055	**($625)**	**($365)**	**($781)**
2060	**($695)**	**($429)**	**($854)**

One point that was mentioned earlier is that partnerships could reduce the cost of direct delivery, and a partnership between Vail Water Company and Tucson Water to have Vail's CAP water delivered most of the way to Vail by wheeling it through Tucson's water delivery infrastructure is one potential partnership. We may quantify the benefits of this arrangement by considering the origin of the pipeline to be the nearest edge of Tucson Water's service area

(Panel *b* in Table 4.7), then comparing the net benefit for this arrangement to the scenarios already presented in which the origin of the CAP water is the terminus of the CAP aqueduct. The switch point under this new arrangement is roughly 2015-2035, depending on the assumptions. This analysis illustrates the simple concept that the mechanism by which the CAP supply is delivered to Vail's service area has a profound effect upon the utility's switch point.

4.3.2. Case Study II: Community Water Company of Green Valley

The second case study looks at the optimal transition to direct delivery of CAP water for the CAGRD Member Lands located within the service area of the Community Water Company of Green Valley (CWCGV). Located approximately 20 miles south of Tucson in Green Valley, CWCGV delivers groundwater to some 18,000 residents in its eight-square-mile service area. Unlike Vail Water Company, CWCGV has not been designated by ADWR as having an Assured Water Supply, and as a result, developments within CWCGV's service area must obtain a Certificate of Assured Water Supply from ADWR. To get a Certificate, these developments must join the CAGRD. Therefore, while some of CWCGV's customers pay for CAGRD replenishment because their homes are located in a CAGRD Member Land, CWCGV does not face this cost and (unlike Vail Water Company) does not have an incentive to transition to delivery of renewable water supplies because of the high and rising costs of CAGRD's replenishment services.

Community Water has held a CAP allocation of 1,337 AF since 1985, and is seeking to acquire an additional 1,521 AF that has been made available through the Gila River Tribal Water Settlement. However, Community Water currently has no way to directly use its CAP allocation. As an undesignated water provider, Community Water may not earn long-term storage credits with this water; therefore, it must recover its CAP allocation within the same calendar year in which it was stored. As it stands, Community Water pays for but does not use its CAP allocation. Still, it sees its CAP allocation as a valuable asset.

CAP's *Outlook 2003* report predicts that Community Water's demand will rise at a rate of about 115 AF every five years between 2015 and 2035, or 23 AF per year. Appendix C-8 compares Community Water's rate of growth to Vail's. Although Community Water's total water demand is initially higher than Vail's, Community Water's rate of growth is far slower, according to CAP's projections.

4.3.2.1.Cost of Pumping Groundwater

In 2005, Community Water reported the water levels in its production wells to be between 237' and 417', with an average water level of 320'. Recharge to the aquifer system occurs along the mountain front to the west and as underflow and stream channel recharge in the Santa Cruz River, which bounds Community Water's service area to the east. According to a well spacing study for the Green Valley area submitted to ADWR in 2005, the 50-year regional water level decline rate is about 1.9 feet per year.

Assuming the natural recharge to the aquifer system in the vicinity of Community Water's well field to be about 10 million cubic feet (230 AF) per year, Gisser's Equation (4.2) estimates that the current rate of water level decline is 3.4 ft/yr. Given the slight increase in demand predicted by CAP's *Outlook 2003* report, this rate increases to 4.1 ft/yr by 2020. If CAP's *Outlook 2003* water demand projections are correct, Community Water's existing wells are adequate to serve its demand for many decades to come. Appendix C-9 gives the initial projections for Community Water's groundwater pumping cost out to year 2100. The solid part at the bottom of each bar in the graph represents all the groundwater pumping costs other than replenishment—that is, the cost attributable to groundwater pumping borne by Community Water; the top hatched portion, however, represents the cost of CAGRD replenishment that must be paid by water customers living in CAGRD Member Lands within Community Water's service area. The latter cost is paid as part of the customer's property tax bill. In 2005, Community Water's cost of groundwater pumping is predicted to be about $162/AF (including the cost of holding its CAP allocation, at the M&I rate of $78/AF). For Member Land homeowners, the additional replenishment fee of $253/AF would bring the total to about $415/AF. Nevertheless, this additional $253/AF is not paid directly by Community Water, but rather its customers.

4.3.2.2.Cost of Importing Renewable Supplies

According to the GIS layer used for this study, the closest point of delivery on the CAP aqueduct to Community Water Company of Green Valley is the CAP terminus. The optimal route for a pipeline from the CAP terminus to the northern edge of Community Water's service area given by the GIS model is approximately 133,438 feet (25.3 miles). Appendix A-8 shows this pipeline alignment (Alignment 1), which considers roads, railroads, major pipelines, and major power lines to be equally desirable as paths to follow across the landscape. Weighting pipelines and power lines relative to roads and railroads, a shorter pipeline alignment (Alignment 2) of 111,609 feet (21.1 miles) is specified (shown in Appendix A-9). Although Alignment 2 may be desirable for its shorter length, it cuts directly through the San Xavier Indian Reservation. Crossing the Reservation could be seen as undesirable because of the potential legal complications of siting the pipeline on the reservation. Thus, the first pipeline route might be favored because it minimizes the length of the pipeline that is located on the reservation.[22]

In reality, however, it appears that there is a delivery system in place to transport CAP water from the terminus of the CAP aqueduct to the Pima Mine Road underground storage facility near the intersection of Nogales Highway and Pima Mine Road in Sahuarita, AZ. Appendix A-10 shows the route that the model predicts from this point. The route identified by the model is identical to the pipeline alignment selected by engineers as part of a study to estimate the cost of delivering CAP water to the Green Valley area (Malcolm Pirnie 1998). The results of this case study are based upon this route, which measures 46,747 feet (or approximately 9 miles) in length.

Community Water's demand is predicted to be relatively stable over the study period of 2005-2100; a pipe diameter of 16" would be adequate to serve this projected demand. Given the total length of the pipeline, the pipe diameter, and the projected water demand, we may predict the per-acre-foot cost of directly delivering CAP water to Community Water through time.

4.3.2.3.Evaluation of the Optimal Transition to Renewable Supplies

Figure 4.3 (p. 83) compares the unit costs of pumping groundwater and directly delivering CAP water through time under the initial conditions (i.e. Scenario 1). Without a large population base over which to spread the cost of importing CAP water, the unit cost of importing CAP water is initially very high for Community Water. Furthermore, as a water provider that does not have a designation of Assured Water Supply, Community Water Company is not

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[22] Unlike the situation with Vail Water Company, Tucson Water does not have delivery infrastructure in the ground between the CAP terminus and Community Water, such that Community Water could wheel its CAP supply through Tucson Water's infrastructure. For this reason, I do not consider this as a plausible alternative scenario for the Community Water case study.

subject to the requirement of the AWS rules to demonstrate use of renewable supplies, and therefore has no reason to pay for CAGRD replenishment. Instead, Community Water's current water resource costs only consist of the cost of holding its CAP allocation and the cost of pumping groundwater. Therefore, Community Water's cost of groundwater pumping is comparatively very low (the solid portion of the columns in Appendix C-9 represents Community Water's groundwater pumping cost, while the hatched portion represents the additional cost of CAGRD replenishment that it does not have to bear). Under present conditions, the model predicts that Community Water will not find it economically efficient to transition from groundwater to direct delivery of CAP water at least through the end of the study period (2060). However, since Community Water is not a designated water provider, any customers in Community Water's service area whose homes were built after 1995 must be part of a subdivision that is enrolled as a CAGRD Member Land. These customers do in fact bear the additional cost of CAGRD replenishment. We will see in a moment how adding this cost into the calculation significantly alters the switch point for Community Water.

4.3.2.4.Scenario Analysis

The same basic structure of the three scenarios developed for the Vail Water Company case study was also applied to the Community Water Company of Green Valley case study. Major differences between the Vail Water Company and Community Water case studies are the aquifer storativity value, initial water level, natural recharge rate, pipeline diameter and length, rate of growth in the utility's water demand, and the institutional differences that come with Vail Water Company being a designated water provider and CAGRD Member Service Area and Community Water Company being an undesignated water provider serving CAGRD Member

Lands. Appendix B-8 shows the parameter assumptions for each scenario. However, the Community Water case study borrows the same pumping energy rate, CAGRD replenishment rate function, alternative water demand functions, alternative pipe unit cost functions, and interest rate as the Vail Water case study.

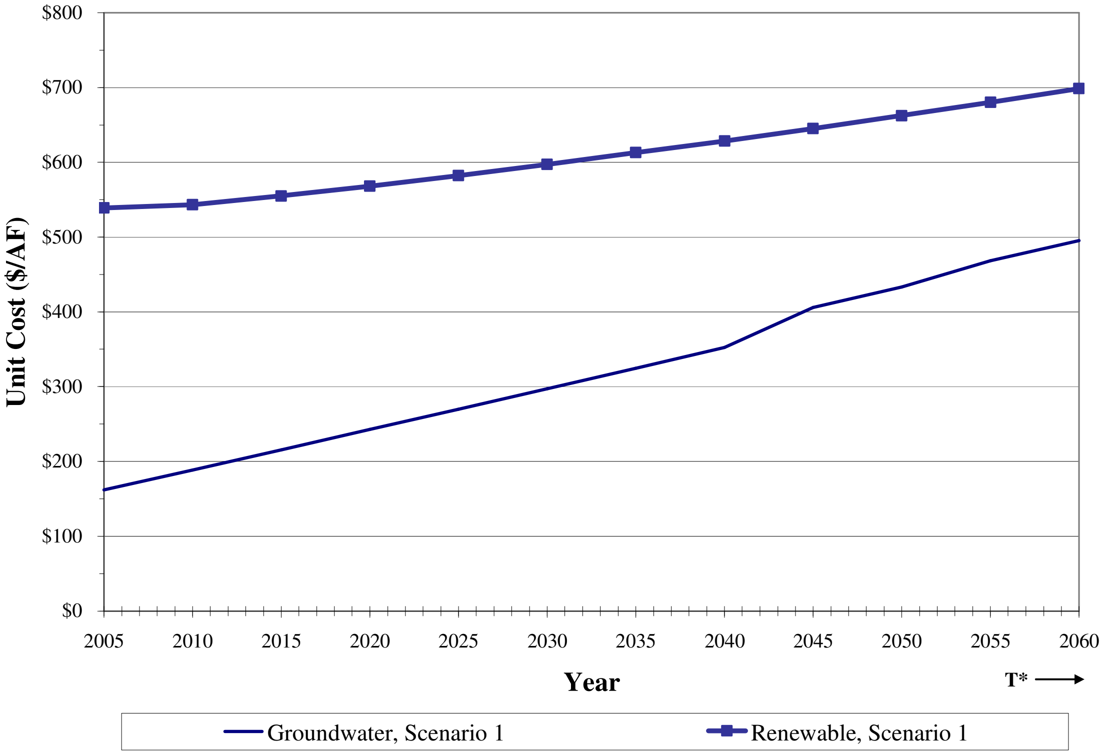
The key results of the model under the assumptions of Scenario 1 are given in Table 4.8 and shown graphically in Figure 4.5. The results from Scenarios 2 and 3 are tabulated in Appendices B-6 and B-7 and shown graphically in Appendices C-10 and C-11. The most important point to be taken from the results of this analysis is that none of the scenarios result in an efficient transition between groundwater and CAP water before 2060 for Community Water.

Table 4.8: *Community Water Company of Green Valley, Key Results for Scenario 1*

YEAR	**GROUNDWATER PUMPING COST**			**PIPELINE COST**			**DIFFERENCE**
	DRAWDOWN (dh/dt)	WATER LEVEL (ft bls)	PUMPING COST ($/AF)	CAPITAL COST ($)	UNIT PMT ($/AF)	DD COST ($/AF)	
2005	-3.41	320	$162	$7,913,332	$276	$539	**$377**
2010	-3.72	339	$189	$7,913,332	$256	$543	**$354**
2015	-3.93	358	$216	$7,913,332	$243	$555	**$339**
2020	-4.14	379	$243	$7,913,332	$232	$568	**$325**
2025	-4.35	401	$270	$7,913,332	$222	$582	**$312**
2030	-4.56	424	$297	$7,913,332	$212	$597	**$300**
2035	-4.78	447	$325	$7,913,332	$204	$613	**$288**
2040	-5.02	472	$352	$7,913,332	$195	$628	**$276**
2045	-5.24	499	$406	$7,913,332	$187	$645	**$239**
2050	-5.46	526	$433	$7,913,332	$180	$662	**$229**
2055	-5.68	554	$468	$7,913,332	$174	$680	**$212**
2060	-5.90	584	$495	$7,913,332	$168	$699	**$203**

Now let us consider a situation in which Community Water must take into account the cost of replenishing the groundwater it pumps to serve its Member Land customers. Indeed, these customers already pay this cost directly to CAGRD as part of their property tax. Appendices C-12, C-13, and C-14 show how considering this additional cost affects the timing of Community Water's transition to direct delivery of CAP water for Scenarios 1, 2, and 3, respectively. Under the conditions of Scenarios 1 and 3, the switch point would now be roughly 2020-2025 and 2040-2045, respectively. If the pipeline cost is closer to the cost assumed in Scenario 2, then the switch point would still be sometime after 2060, even if Community Water were paying the CAGRD to replenish 100% of its groundwater pumping. (However, since this analysis assumes that all of Community Water's groundwater pumping would need to be replenished through the CAGRD, the predicted switch points are probably underestimated—that is, they would probably be later in reality than the model predicts.)

Figure 4.5: *Unit Costs of Groundwater Pumping and Direct Delivery of CAP Water via Pipeline for Community Water Company of Green Valley, 2005-2060 (Scenario 1)*



A third situation to consider is if Community Water became a Designation of Assured Water Supply. As a designated water provider, Community Water would be required to demonstrate use of renewable water supplies. It could do this by storing and recovering or directly delivering its CAP allocation, or else by continuing to pump groundwater and simply paying the CAGRD to replenish its excess groundwater pumping (after enrolling as a CAGRD Member Service Area). At the present time, the least cost way for Community Water to demonstrate use of renewable supplies is by storing and recovering its CAP allocation. However, as a designated water provider, Community Water would now be subject to ADWR's 4 feet per year water level decline criteria. Violation of this standard would require Community Water to depend fully on the CAGRD in order to keep its designation. The cost paths for the three scenarios under this situation are depicted in Appendices C-15, C-16, and C-17. Initially, Community Water uses its CAP allocation indirectly to offset its groundwater pumping. But as the water level decline criteria is violated under each of the scenario assumptions, Community Water's cost of groundwater pumping increases dramatically (in years 2010, 2015, and 2030, for Scenarios 3, 1, and 2). The timing of this violation depends upon the rate of growth in Community Water's water demand (Scenario 1 is CAP's *Outlook 2003* projections for Community Water; Scenario 2 is half this growth rate; Scenario 3 is double this growth rate).

Appendices C-12 through C-17 clearly illustrate the sensitivity of the switch point to the water level decline standard, the degree of dependence upon the CAGRD, and the CAGRD replenishment rate. Another graph, Appendix C-18, demonstrates even more clearly just how sensitive the switch point may be to changes in ADWR's water level decline standard. This graph shows the switch point under the assumptions for Scenario 1 for both the existing 4 ft/yr decline standard and for a hypothetical situation in which ADWR's water level decline standard is increased to 5 ft/yr. In this case, violation of the decline standard is delayed by more than 15 years. Likewise, the utility's degree of dependence upon the CAGRD and the CAGRD replenishment rate also strongly influence the switch point. If a utility does not use the CAGRD as a replenishment mechanism, it is likely to delay the direct delivery of CAP water; however, a utility that replenishes 100% of its excess groundwater pumping through the CAGRD will have an economic incentive to transition to direct delivery of CAP water sooner than it would if it did not rely on the CAGRD. For utilities in the latter group, the rate at which the CAGRD replenishment rate rises through time will significantly affect its decision of when to transition to direct delivery of CAP water.

The results of the model provide some insights into how the CAGRD affects the AMA-wide transition to direct use of renewable water supplies. Had the CAGRD not been established, the AWS rules would not have been adopted and private and municipal water utilities would be considering only the cost of physically obtaining groundwater supplies, which would not provide an adequate incentive to transition to renewable water supplies for many decades to come and perhaps not until the physical supply of groundwater “runs out” or the cost of pumping becomes prohibitive. Fully depleting certain areas of the regional aquifer would result in some major externalities to the environment and to other groundwater users, including subsidence-related damages to the aquifer and to homes and various kinds of transportation and utility infrastructure. By paying the CAGRD to replenish excess groundwater pumping, utilities face a small but increasing incentive to transition from groundwater to direct delivery of CAP water and avoid the damages that occur when their groundwater is depleted.

Many people in Arizona are concerned about the CAGRD, and they have their reasons: the size of CAGRD’s member enrollment; the way the CAGRD eliminates the incentive for developers to seek out renewable water supplies rather than simply sink wells to serve the new development; the way CAGRD has enabled development to rely on “paper water” and sprout in "dry" areas; CAGRD's ability to obtain enough water supplies to fulfill its growing replenishment obligation; the potential for CAGRD to receive preference in the allocation of CAP water so that it *can* fulfill its replenishment obligation; and so on. This study has attempted to show that some of these issues could be resolved by some simple price changes. It is certainly true that the high rate of enrollment strains CAGRD's ability to meet its replenishment obligation in a time of growing competition for renewable water supplies. However, the high member enrollment in the CAGRD is a function of the low cost of enrollment; by raising the cost of enrollment, CAGRD will in theory cause potential members to consider other options of complying with the Assured Water Supply rules and reduce the rate of enrollment.[23] It is also true that the CAGRD has enabled the geography of urban development in Arizona to remain relatively unfazed by the AWS rules. But the practical alternative to the CAGRD would have been the failure of ADWR to institute the AWS rules. If it would have been possible to have the AWS rules and not the CAGRD, development would likely have occurred closer to existing sources of renewable water supplies to reduce the cost of importing renewable water supplies to the new homes. It is also possible under this scenario that more partnerships would have occurred between and among private and municipal water utilities to further reduce the cost of importing renewable supplies. While it is too complex to simulate what development patterns might have been under an alternate policy scenario, we can examine the potential long-term impact of the CAGRD for the development that *has* occurred. This analysis suggests that the CAGRD actually creates an incentive for a water utility to transition from groundwater to direct delivery of CAP water far sooner than if the utility were not a member of the CAGRD. In its

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[23] As mentioned in Chapter 3, the actual impact of fee changes is unknown since the price elasticity of demand for CAGRD membership is unknown. Still, since there is no reason to expect the demand curve for CAGRD membership to be upward sloping, higher fees should reduce the enrollment rate.

present form, the CAGRD encourages the use of the paper water system in the short run with a low enrollment fee, but may discourage its use in the long run with a high replenishment rate.

5. SUMMARY AND CONCLUSION

Following the passage of the Groundwater Management Act (GMA) in 1980, the Arizona Department of Water Resources (ADWR) sought ways to support the management goals of the active management areas (AMAs) established by the GMA legislation. Because the Phoenix, Tucson, and Prescott AMAs were created with the management goal of achieving safe yield by 2025, ADWR needed to institute policies to encourage the use of renewable water supplies in these areas. ADWR attempted to do this with the Assured Water Supply Draft Rules in 1988. The rejection of the Draft Rules by Arizona's development community persuaded ADWR to allow members of the development community to create a mechanism to help developers comply with the inevitable Assured Water Supply (AWS) rules. The mechanism created by the development community in 1993 is the Central Arizona Groundwater Replenishment District (CAGRD).

The CAGRD is essentially the result of a cooperative negotiation between ADWR (the regulator) and the development community (the regulated interest) which took place in the early 1990s. Possessing the majority of the bargaining power in the formation of the CAGRD, the development community captured the largest gains in this cooperative negotiation. The provisions of the CAGRD reflect the development community's gains from the cooperative negotiation, being largely pro-development.

At the time of its passage, the CAGRD was considered to be a critical policy instrument for enabling the passage of the AWS rules. Fifteen years into the existence of the CAGRD, this assertion is still the consensus in Arizona's water community. Yet it is also largely recognized that the CAGRD has enabled and perhaps encouraged the spatial distribution of physical ("wet") water supplies to remain imbalanced by encouraging the hydrologic disconnection between the locations of groundwater pumping and replenishment. While the CAGRD is not exclusively to blame for this, it has undoubtedly played a significant role in removing the incentive the AWS rules were designed to create—that is, to replace groundwater pumping with the use of renewable water supplies. Instead of renewable water being directly delivered to a new subdivision, the subdivision may enroll in the CAGRD and demonstrate use of renewable water supplies indirectly. The subdivision continues to pump groundwater locally and replenish this groundwater remotely in an area that is very unlikely to hydrologically benefit the subdivision's local groundwater resources. Therefore, while the intention of the AWS rules was to correct this imbalance of physical water supplies, the CAGRD effectively negates the ability of the AWS rules in the short to medium term.

Economic theory, however, insists that in the long run, equilibrium of physical water supplies will emerge. Groundwater users will only continue to pump groundwater until the cost of pumping is equal to the cost of importing a renewable water supply.[24] The CAGRD affects the timing of the switch point between the two resources by raising the cost of groundwater pumping with a replenishment fee. Because the cost of replenishment is very high relative to the cost of pumping groundwater, CAGRD members are likely to have earlier switch points than non-CAGRD members. This provides some insight into the long-term effects of the CAGRD. While in the short term the CAGRD enables new growth to continue to pump groundwater, thereby intensifying the spatial imbalance of physical water supplies in the three central AMAs, in the long term it appears that the CAGRD will also hasten the regional transition to direct delivery of CAP water because of the increasing cost of replenishment borne by the members. For example, Vail Water Company is able to demonstrate use of renewable water supplies for its

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[24] Assuming, of course, that the entity will have access to renewable water supplies at its switch point. It is possible that CAGRD could be the entity to acquire and deliver the renewable supplies to the member. Regardless, the member would have to pay for the importation of the renewable supplies.

new growth as a member of the CAGRD. However, the additional cost of CAGRD replenishment nearly quadruples its groundwater pumping cost. With this additional cost, this small private water company that is located over 25 miles from the CAP aqueduct may find it efficient to transition to direct delivery of CAP water decades before their demonstrated 100 years of groundwater are fully used. If Vail did not continue to pay the additional cost of CAGRD replenishment, however, it would not have an economic incentive to import CAP water and would thus continue to pump groundwater many years longer than it would if it were a CAGRD member—perhaps beyond the 100 years that they have demonstrated is feasible.

This study underscores some important policy considerations for CAGRD, and shows that CAGRD has several tools at its disposal to resolve some of the concerns surrounding the District. First, while the rate of enrollment in the CAGRD has raised concerns among many water providers, this rate may be reduced by increasing CAGRD's enrollment fee. To date, CAGRD has kept its enrollment fee very low, sending a signal to developers that CAGRD is willing and able to accommodate growth with ample water supplies. Since the growing competition for CAP supplies clearly shows that renewable water supplies are and will continue to be economically scarce, CAGRD's fee structure must signal this scarcity on the enrollment side if it wishes to ensure that it grows at a more moderate pace.

Another cause of concern is the way in which the CAGRD encourages new development to hydrologically disconnect groundwater pumping and replenishment. But as the results of this study demonstrate, the CAGRD replenishment rate is critical in determining the switch point between pumping groundwater and importing CAP water for the CAGRD members. Therefore, the CAGRD replenishment rate may be an effective policy tool, together with ADWR's water level decline standard, to control the timing of when water utilities will transition from a less sustainable water management regime (groundwater pumping) to a more sustainable one (direct use of renewable supplies).

Although the optimal control-based economic modeling developed in this study was designed for the purpose of analyzing the long-term impact of the CAGRD on the spatial balance of water supplies in the Tucson AMA, the methods and results of the study are immediately applicable to answering other important water policy questions in Arizona and perhaps in other locations. For example, the model presented in Chapter 4 is able to determine any water utility's efficient switch point from groundwater to importation of an alternative supply. The switch point is pregnant with information about the future of the water utility and the area, most notably in that it provides a glimpse into the likely duration of local groundwater pumping. Currently, there is no established method to determine the ultimate volume of groundwater to be removed from a local aquifer (to the knowledge of the author), but this study provides a framework to begin to predict this volume for a given water utility or aquifer area. If this volume is indeed estimable, then it would also be possible to use this method to study the future environmental damages to riparian areas that would occur from groundwater pumping by users that did not take account for these externalities in their pumping decisions. Likewise, if these costs could be quantified and included in a water utility's groundwater pumping cost, then this model would be able to measure how the inclusion of these heretofore ignored environmental costs would temporally affect the switch point. In addition, since this study is designed to find the *efficient* switch point between groundwater and renewable water supplies, comparison of the predicted switch point with a water utility's actual switch point may help to quantify the utility's willingness-to-pay to avoid the perceived risk (physical or legal, real or imagined) associated with continuing to pump groundwater or importing renewable supplies.

Another example of how this study helps to answer other policy questions is its ability to predict the long-term water costs that could be borne by a particular homeowner over the next few decades. Certainly it should not be surprising that some homes will continue to have cheaper water than other homes, but this study makes that fact explicit and enables the analyst to explore the significance of location, water provider, local rate of groundwater decline, population growth, Assured Water Supply and CAGRD status, intergovernmental agreements, and policy changes to the bottom line of their water bills. Finally, this methodological framework may be useful for analyzing the efficiency of proposed water service changes. For example, if a water utility wishes to import renewable supplies for the purpose of saving groundwater, the switch point estimated by this model is a useful starting place to determine what the social willingness-to-pay for groundwater conservation ought to be in order to justify importing renewable supplies to save groundwater and not simply wait until it is economically efficient.

While the economic model developed in this thesis shows promise as an analytical framework, some additional effort could certainly improve the accuracy of the model and extend its usefulness. One particular point of weakness in the model is its use of Gisser's simplistic equation for estimating the rate of water level decline. A more widely used approach to estimate drawdown in an unconfined aquifer through time is the Neumann equation, which would improve the drawdown estimates but would require more aquifer parameters than simply the aquifer storage. Another element of the model to potentially improve is the fact that the pipeline cost estimates do not explicitly consider elevation as a cost factor; instead, the elevation change is endogenous to the pipe unit cost estimates provided by Tucson Water, which implicitly assume that the pipeline project will have an "average" amount of elevation change for the Tucson basin. If the model were applied to a water provider of higher elevation, the pipeline cost would need to be increased to account for the additional facilities and operations needed to move the water uphill. Improved GIS data could also help with the accuracy of the model (for example, the accuracy of the CAP aqueduct shapefile used in the GIS analysis directly affects the accuracy of the results).

Finally, a few caveats should be acknowledged in light of the fact that this study was made possible by adopting some simplifying assumptions. One assumption of the model mentioned in footnote 24 is that water utilities will be able to obtain renewable water supplies at their switch point. In reality, some water utilities currently do not have access to enough CAP water to meet their total water demand, and would need to subcontract or lease additional CAP water to meet part or all of their future water demand. Whether these utilities will be able to obtain additional CAP water supplies is a complex uncertainty that simply cannot be modeled. A second caveat is the assumption that CAGRD will continue to be able to meet its replenishment obligation and therefore enable some of its members to retain their Designation of Assured Water Supply and continue to pay the CAGRD for replenishment. If these utilities lose their status as a designated water provider, then they will not have to pay the CAGRD for replenishment and will therefore have a weaker incentive to transition to direct delivery of CAP supplies. A final caveat to mention (although surely there are more) is that this study assumes that water utilities, at the moment they transition to direct delivery of CAP water, will still be able to demonstrate that a water supply is physically available to meet 100 years of demand. Unless adequate groundwater supplies remain at the switch point, this would probably be a significant challenge for most water utilities. Resolving this issue for each water utility is (thankfully) beyond the scope of this study. Since municipal water use is among the highest value uses of water, however, it is unlikely that municipal water utilities will not be able to obtain enough water supplies to meet their demand. In the end, it is simply a question of how much it will cost.

Future work on this project should attempt to improve the above weaknesses if possible and automate the process so that a water utility's switch point under different assumptions can be examined more quickly. After making these improvements, it would be interesting to apply the model to other case studies in the Tucson AMA to gain a truly regional perspective of the CAGRD and what it means for the transition from groundwater to direct delivery of CAP water in the coming years. Additional applications outside of the Tucson area would also be feasible. As an immediate example, it would be interesting to see what this analysis would reveal in the Phoenix and Pinal Active Management Areas.

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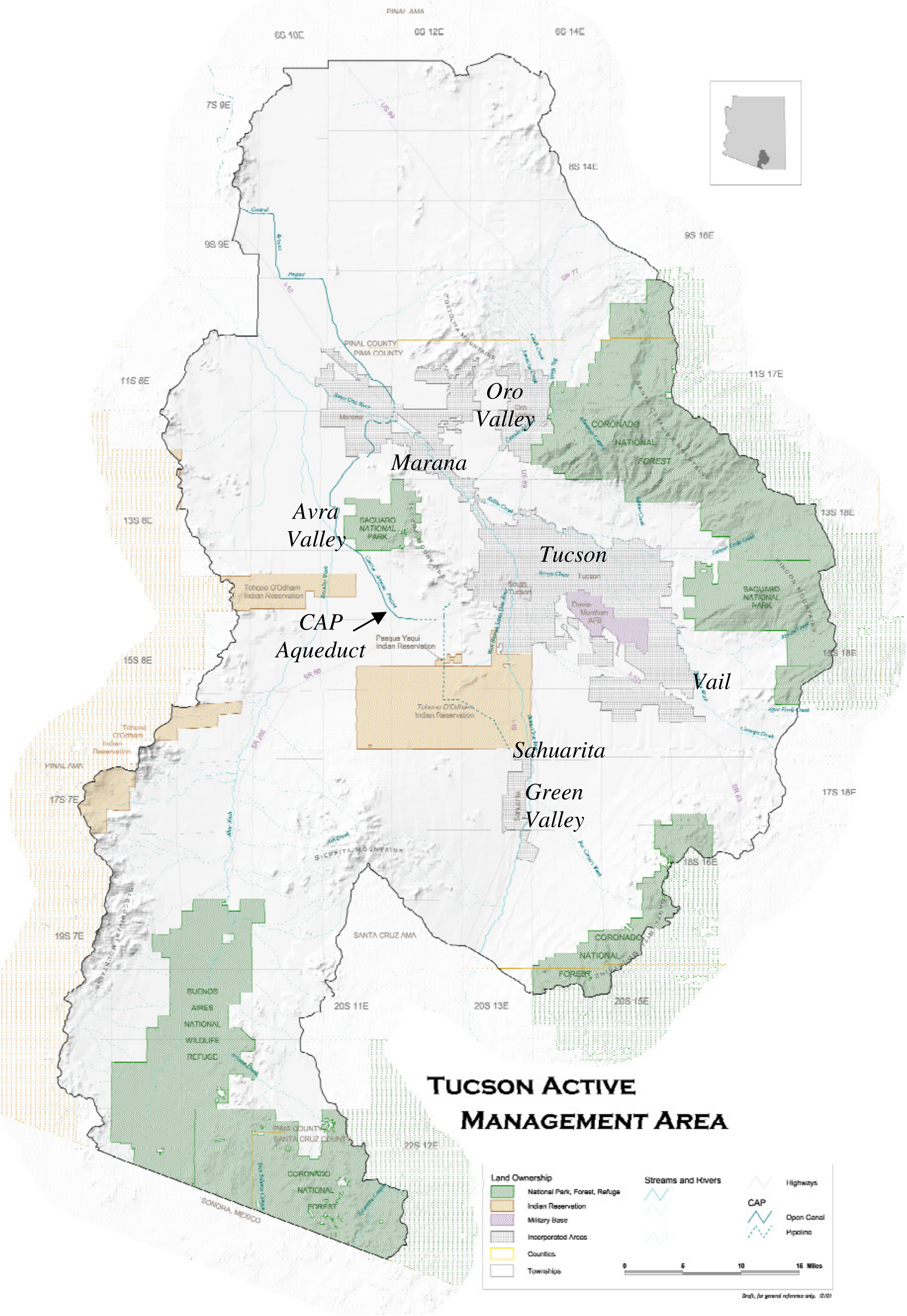
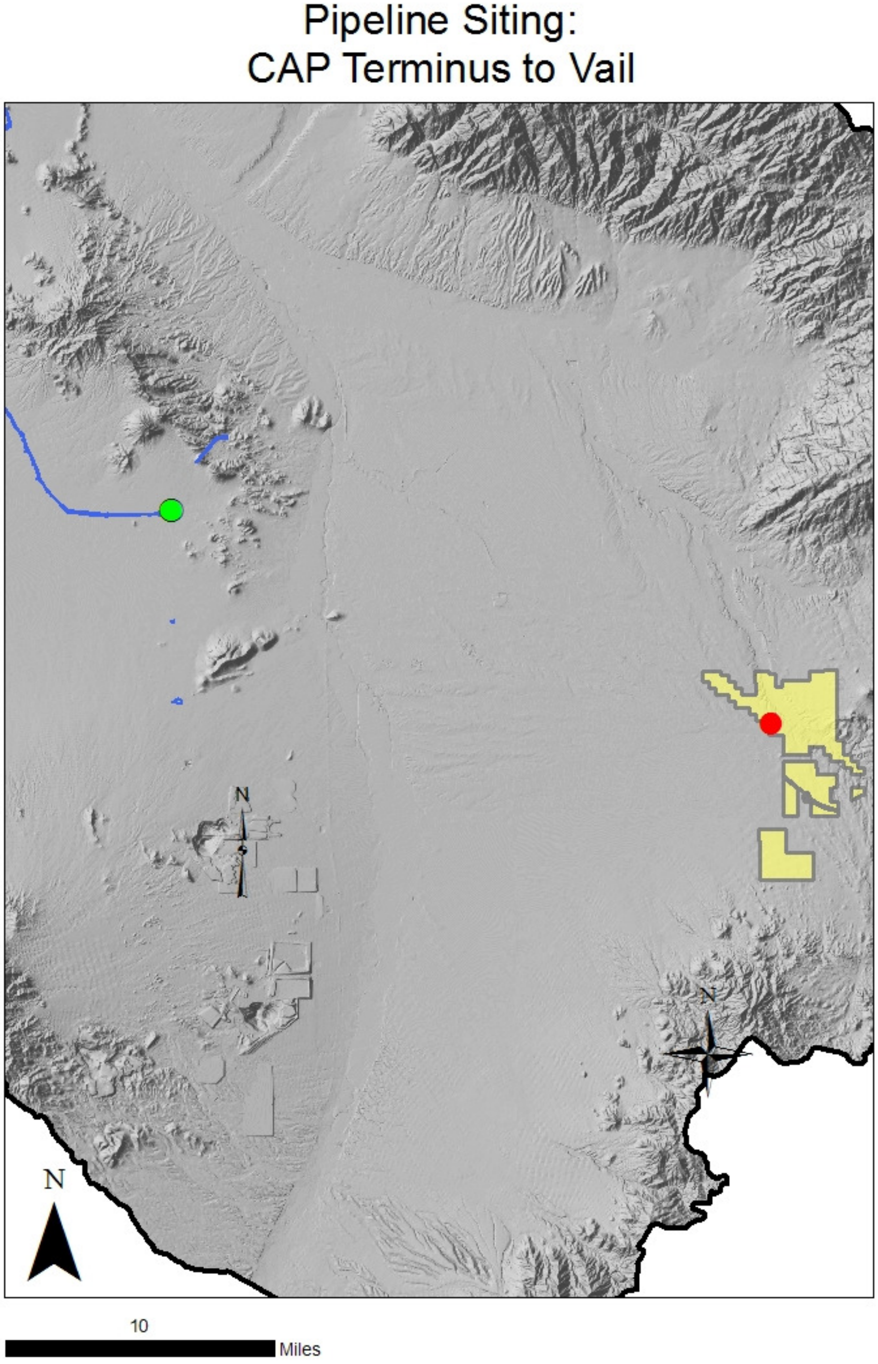
APPENDIX A:
MAPS

APPENDIX A-1: *Map of the Tucson Active Management Area*



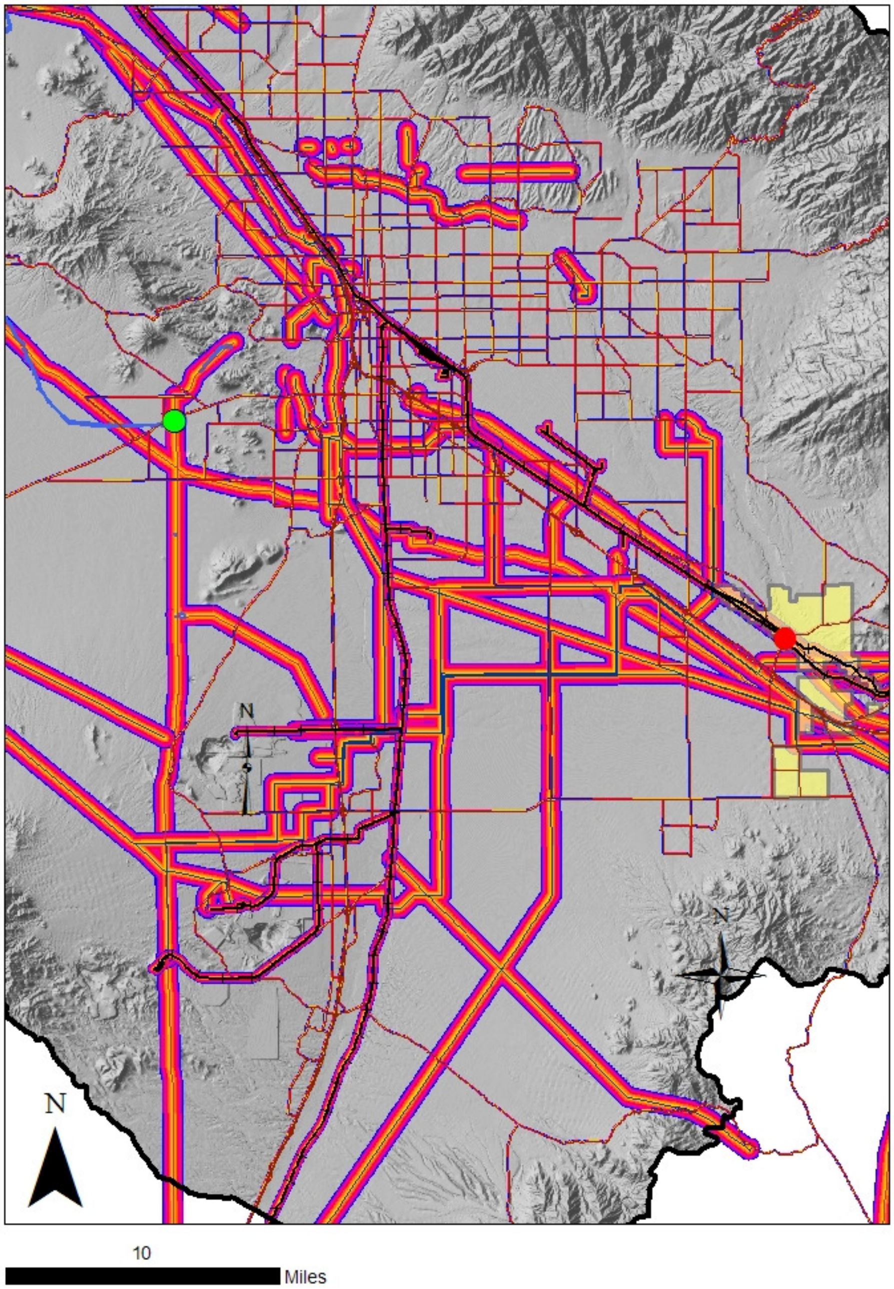
Source: Arizona Department of Water Resources, http://www.water.az.gov

APPENDIX A-2: *Corridor Analysis Model for Delivery of CAP Water to Vail, AZ*

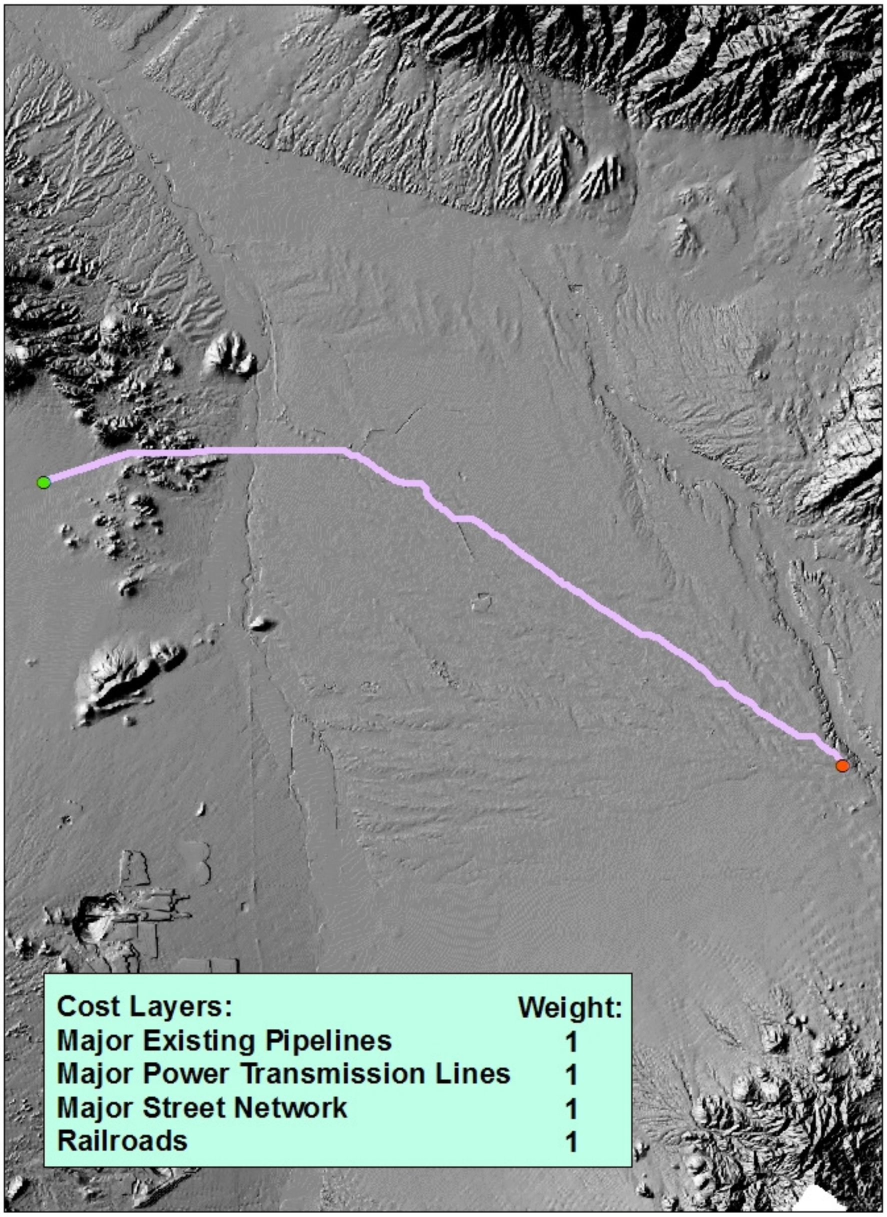


APPENDIX A-3: *Corridor Analysis Model for Delivery of CAP Water to Vail, AZ*

Pipeline Siting:
CAP Terminus to Vail

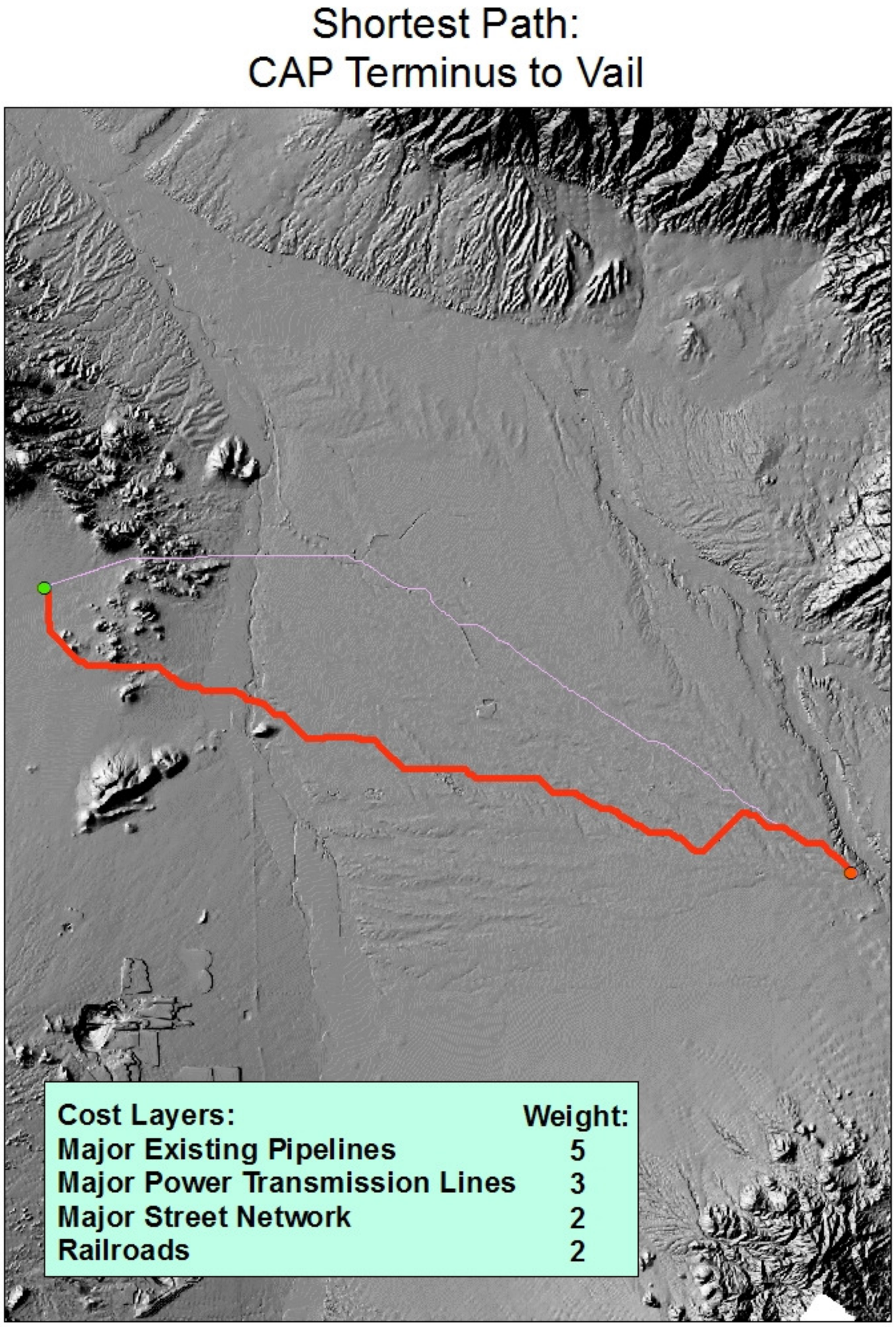


APPENDIX A-4: *Initial Pipeline Configuration from CAP Terminus to Vail, AZ, Evenly Weighting Each Suitability Layer*

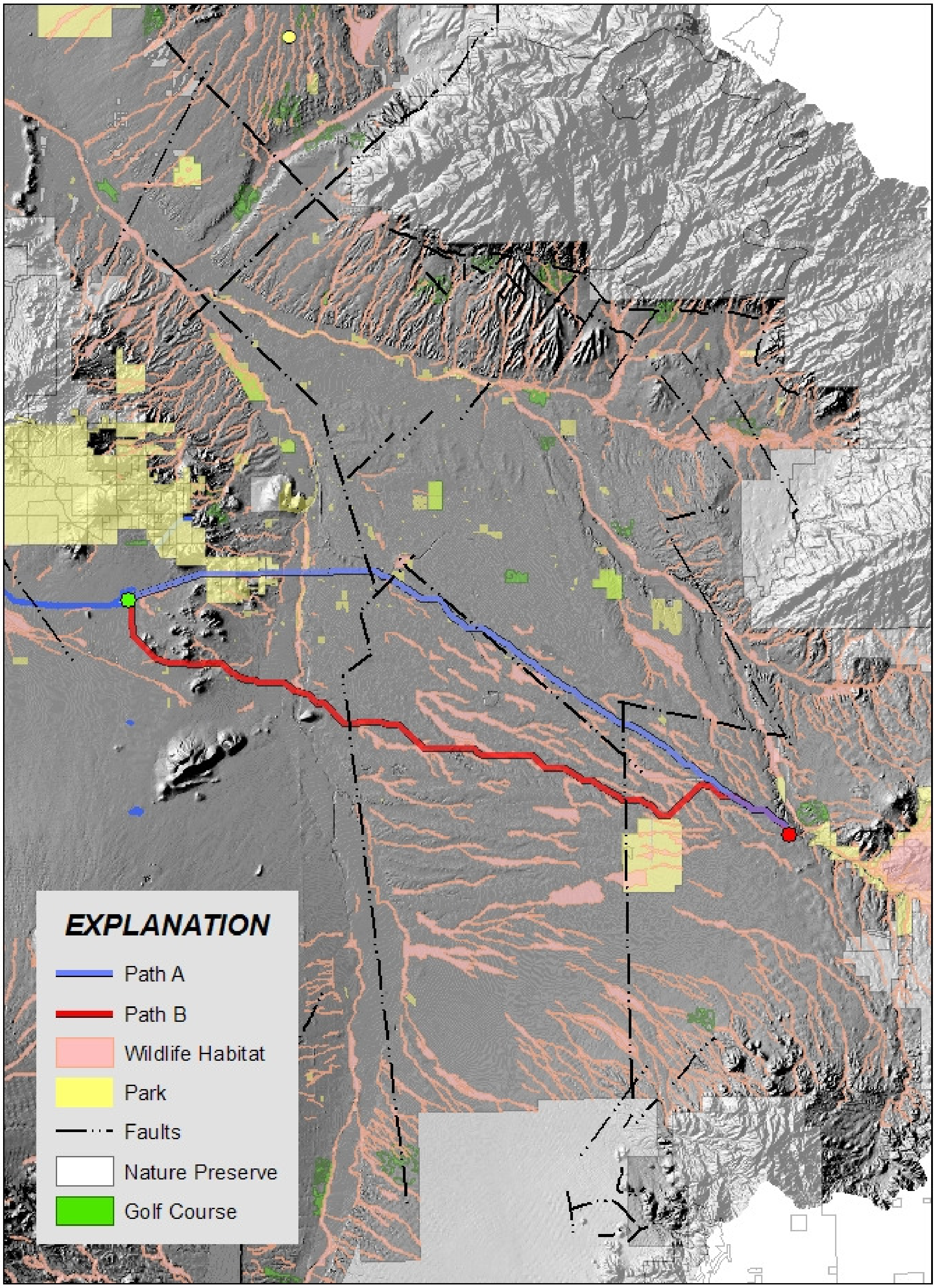


Shortest Path:
CAP Terminus to Vail

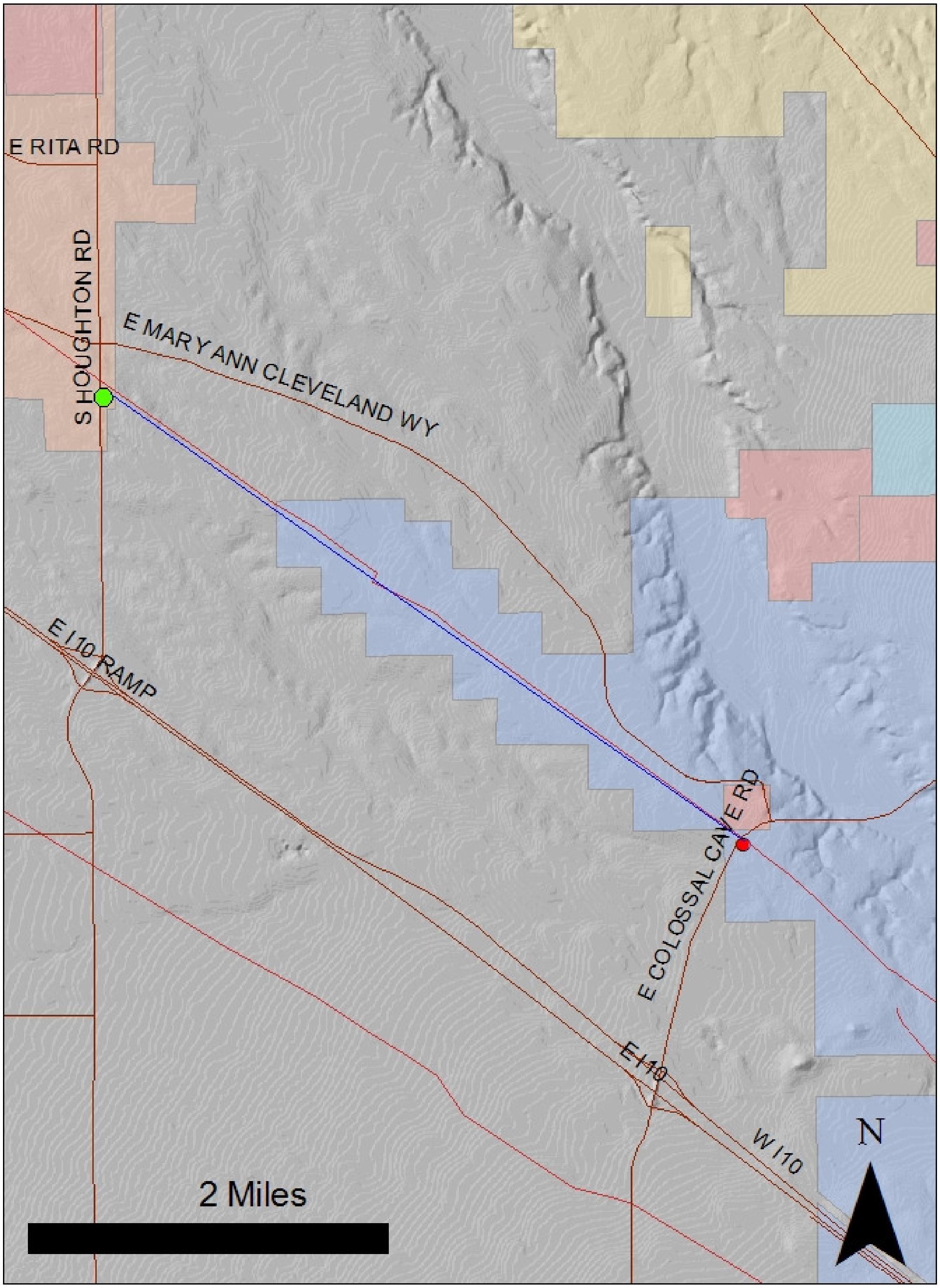
APPENDIX A-5: *Alternate Pipeline Configuration from CAP Terminus to Vail, AZ, With Preference to Existing Pipelines and Power Lines in the Weighting of the Suitability Layers*



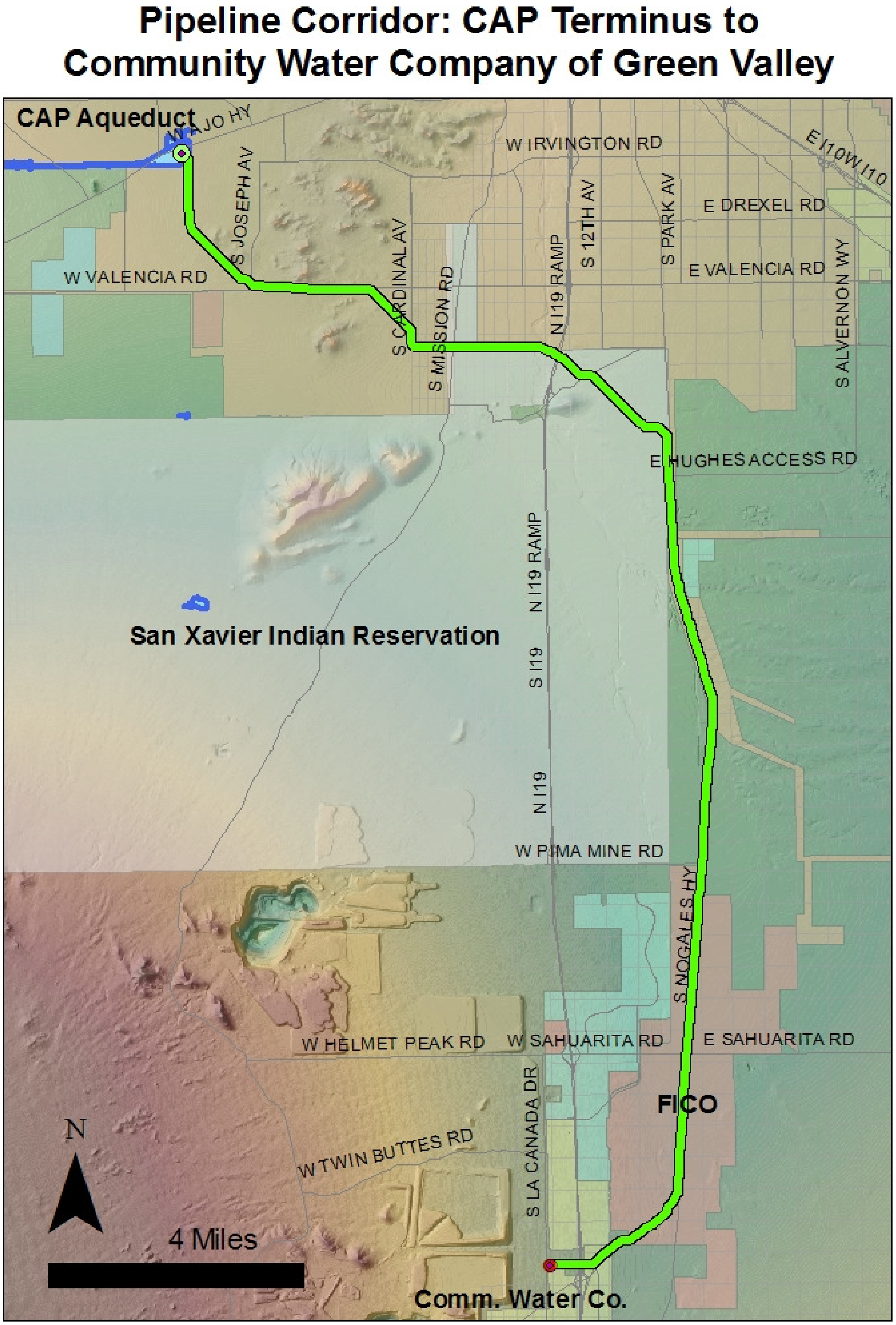
APPENDIX A-6: *Evaluation of the Two Pipeline Routes with Additional Siting Considerations*



APPENDIX A-7: *Alternative CAP Delivery Arrangement: Wheeling Through Tucson Water's Delivery Infrastructure*

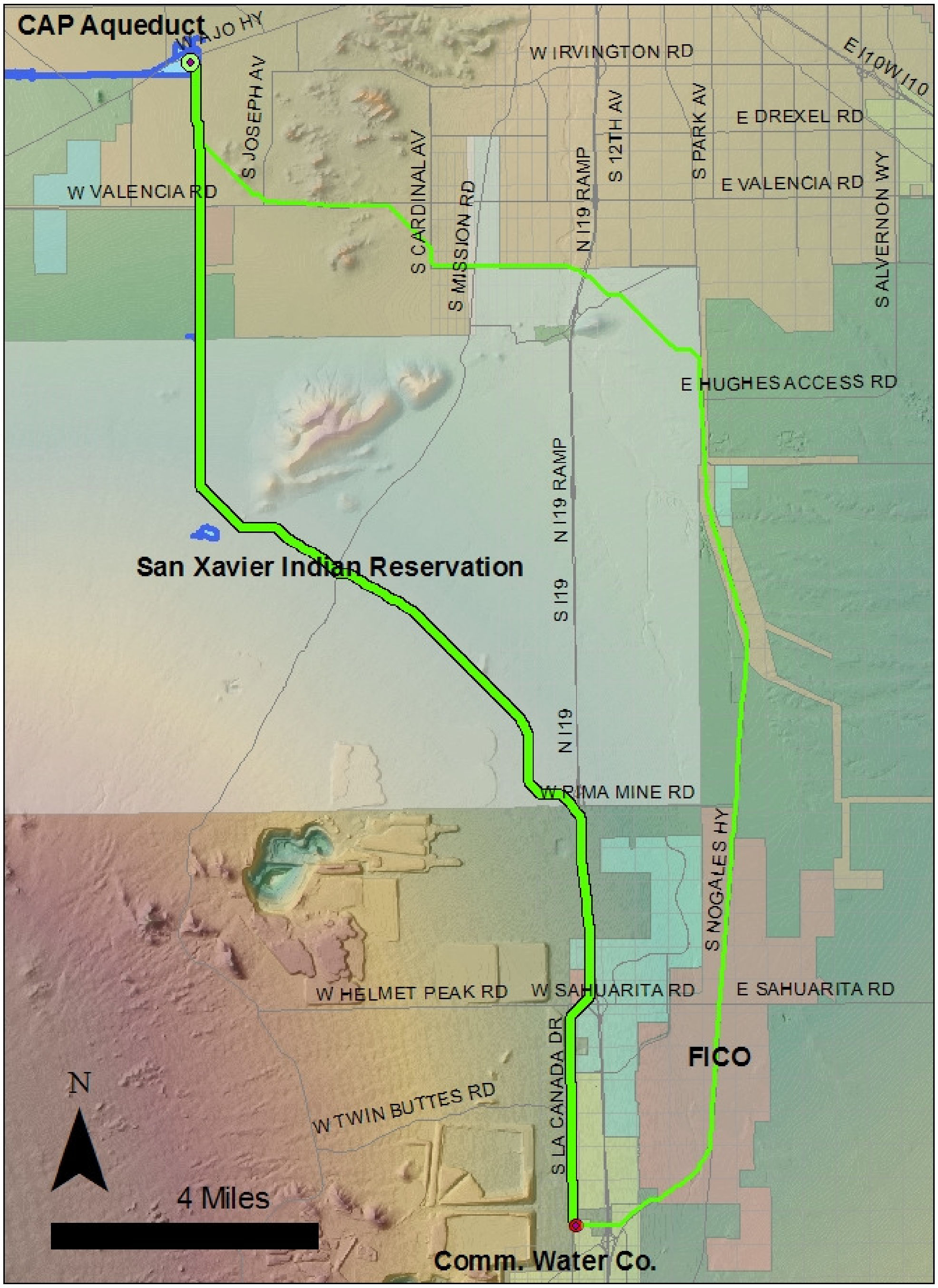


APPENDIX A-8: *Pipeline Alignment from CAP Terminus to Community Water Company of Green Valley: Even Weighting of Suitability Factors (Alignment 1)*



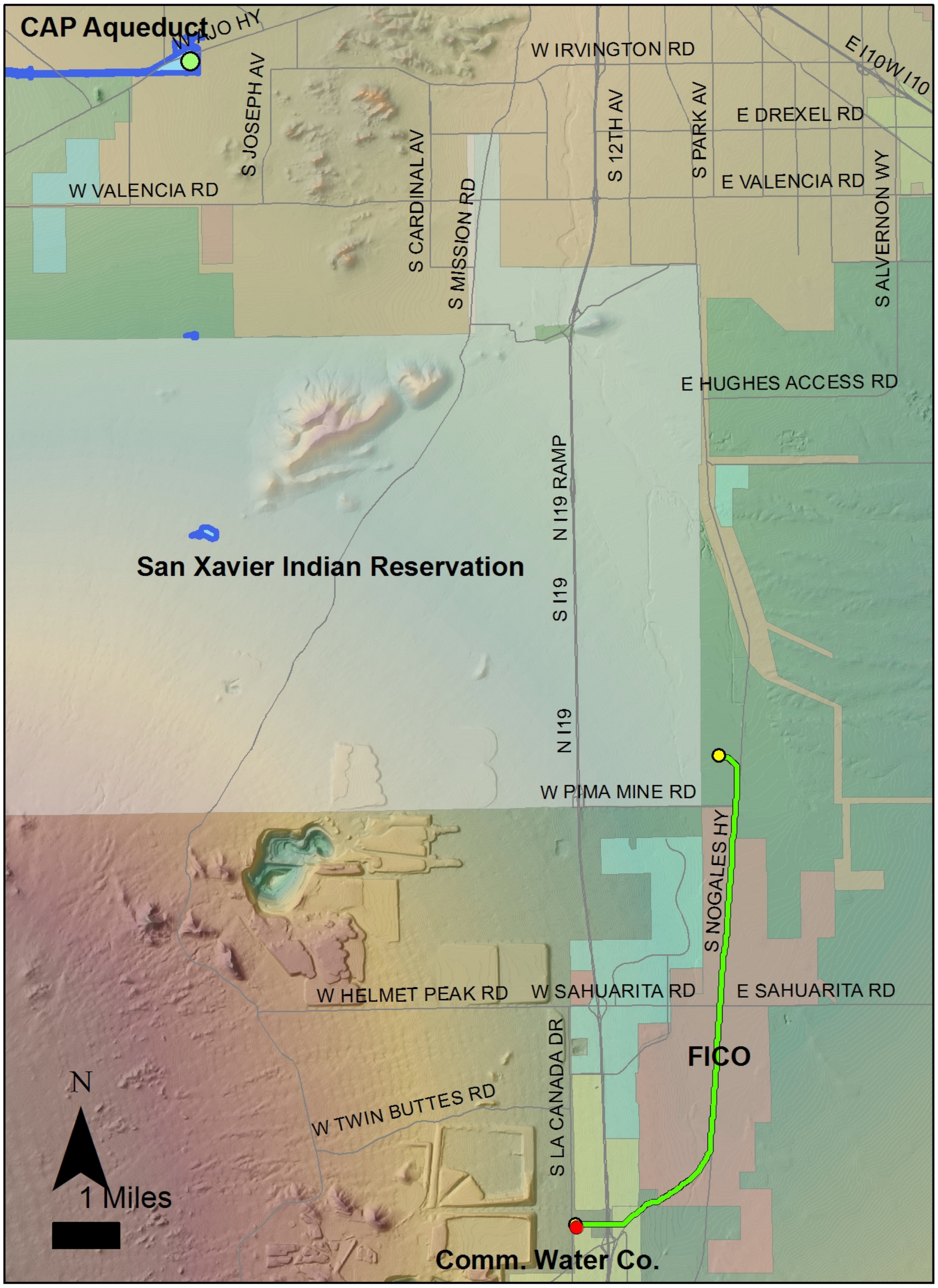
APPENDIX A-9: *Pipeline Alignment from CAP Terminus to Community Water Company of Green Valley: Weighting System Favoring Pipelines and Power Lines (Alignment 2)*

Pipeline Corridor: CAP Terminus to Community Water Company of Green Valley



APPENDIX A-10: *Pipeline Route Identified Assuming Pipeline Begins at the Pima Mine Road Underground Storage Facility (Community Water Company of Green Valley Case Study)*

Pipeline Corridor: Pima Mine Road USF to Community Water Company of Green Valley



APPENDIX B:
TABLES

APPENDIX B-1: CAGRD Replenishment Assessment Components

COMPONENT	COST BASIS	2007-08 RATE (per AF)[1]
Administrative[2]	Total cost of administering the CAGRD	$28
Infrastructure & Water Rights[2]	Costs of purchasing water rights and developing infrastructure to deliver and replenish water	$79
Water & Replenishment[3]	Cost to purchase, transport, and recharge/replenish water supplies	$112; $87; $133
Replenishment Reserve[3]	Costs to establish and maintain a replenishment reserve for each AMA	$21; $25; $25

TOTAL COST OF CAGRD REPLENISHMENT:

Phoenix AMA $28+79+112+21 = **$240**

Pinal AMA $28+79+87+25 = **$219**

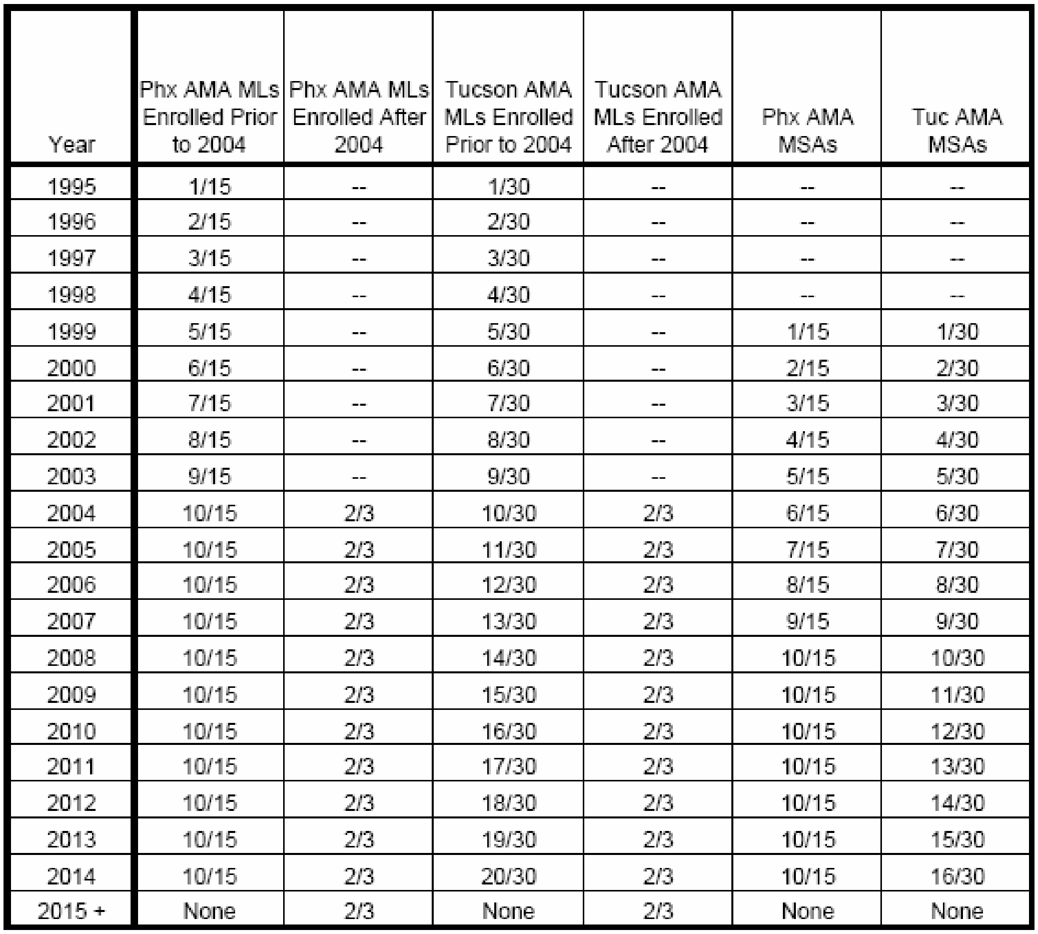
Tucson AMA $28+79+133+25 = **$265**

[1] Where appropriate, multiple rates are given for Phoenix, Pinal, and Tucson AMAs, respectively

[2] Uniform across AMAs

[3] Computed separately for each AMA

***APPENDIX B-2:** CAGRD Excess Groundwater Reporting Factor*



Year	Phx AMA MLs Enrolled Prior to 2004	Phx AMA MLs Enrolled After 2004	Tucson AMA MLs Enrolled Prior to 2004	Tucson AMA MLs Enrolled After 2004	Phx AMA MSAs	Tuc AMA MSAs
1995	1/15	--	1/30	--	--	--
1996	2/15	--	2/30	--	--	--
1997	3/15	--	3/30	--	--	--
1998	4/15	--	4/30	--	--	--
1999	5/15	--	5/30	--	1/15	1/30
2000	6/15	--	6/30	--	2/15	2/30
2001	7/15	--	7/30	--	3/15	3/30
2002	8/15	--	8/30	--	4/15	4/30
2003	9/15	--	9/30	--	5/15	5/30
2004	10/15	2/3	10/30	2/3	6/15	6/30
2005	10/15	2/3	11/30	2/3	7/15	7/30
2006	10/15	2/3	12/30	2/3	8/15	8/30
2007	10/15	2/3	13/30	2/3	9/15	9/30
2008	10/15	2/3	14/30	2/3	10/15	10/30
2009	10/15	2/3	15/30	2/3	10/15	11/30
2010	10/15	2/3	16/30	2/3	10/15	12/30
2011	10/15	2/3	17/30	2/3	10/15	13/30
2012	10/15	2/3	18/30	2/3	10/15	14/30
2013	10/15	2/3	19/30	2/3	10/15	15/30
2014	10/15	2/3	20/30	2/3	10/15	16/30
2015 +	None	2/3	None	2/3	None	None

Source: CAGRD *Plan of Operations 2004*, Appendix D, Table D-1.

APPENDIX B-3: *Data Sources for Spatial Economic Model*

Input	**Data Type**	**Source**
Aquifer area	GIS	PimaDOT GIS Server, Water Provider Service Boundaries
Aquifer storativity	GIS	ADWR, storativity map of Tucson basin
Water Demand	GIS	CAP's *Outlook 2003* report
Groundwater depth	GIS	ADWR's GWSI database
Energy rate	Document	Tucson Electric Power, municipal well rate
Treatment cost	Document	BOR, SAWRMS Report, 2000
CAGRD replenishment rate	Document	Trend taken from historical CAGRD rates
Well installation cost	Document	BOR “Sierra Vista” study
Pipeline Length	GIS	Path determined from model suitability surface
Existing pipelines	GIS	PimaDOT GIS Server
Power transmission mains	GIS	PimaDOT GIS Server
Roads	GIS	PimaDOT GIS Server
Railroads	GIS	PimaDOT GIS Server
Pipeline Diameter	Document	Determined from formula, based on Water Demand
Pipeline Unit Cost	Document	Tucson Water pipeline cost estimates (approximate)
CAP water cost	Document	Trend taken from historical CAP M&I rates
Interest rate	-	Range: 4-8%
Life of pipeline	Document	BOR, SAWRMS Report, 2000
Fixed cost of municipal well	Document	UA Ag Extension, Pima County Pump Water Budgets

APPENDIX B-4: *Vail Water Company Case Study: Parameters for Scenarios 1, 2, and 3*

	SCENARIO		
Variable	**1**	**2**	**3**
Radius of aquifer (mi)	1.5	1.5	1.5
Area of aquifer (sq ft)	196,960,896	196,960,896	196,960,896
Initial Water Level (ft bls)	435	435	435
Storativity	0.13	0.13	0.13
Natural Recharge (cf/y)	0	0	0
Return Flow (%)	0	0	0
Energy rate ($/kWh)	$0.0808138	$0.0509800	$0.1040000
Well O&M Cost ($/AF)	$36	$36	$36
Outlook 2003 Demand Factor	1	0.5	1.3
CAGRD Cost Factor	3.25	3	3.5
Water Level Decline Standard (ft/yr)	-4	-4	-4
Pipeline Length (ft)	139,920	139,920	139,920
Pipe Diameter (in)	16	16	16
Pipe Max Flow Velocity (ft/s)	5	5	5
Design Flow - Demand Factor	2	2	2
Tucson Water Pipe Unit Cost ($/lf)	$230-$291	$230-$291	$230-$291
Pipe Unit Cost Factor	1.0	1.5	0.7
Pipe Unit Cost ($/lf)	Varies by Year	Varies by Year	Varies by Year
Capital Cost ($)	See Results	See Results	See Results
CAP Treatment ($/AF)	$185	$185	$185
Interest Rate	6.0%	8.0%	4.0%
Annuity Factor	13.76483115	11.25778334	17.29203330
Annual Payment ($/yr)	Varies	Varies	Varies

APPENDIX B-5: *Community Water Company of Green Valley Case Study: Parameters for Scenarios 1, 2, and 3*

	SCENARIO		
Variable	**1**	**2**	**3**
Radius of aquifer (mi)	1.5	1.5	1.5
Area of aquifer (sq ft)	196,960,896	196,960,896	196,960,896
Initial Water Level (ft bls)	320	320	320
Storativity	0.12	0.12	0.12
Natural Recharge (cf/y)	10,000,000	10,000,000	10,000,000
Return Flow (%)	0	0	0
Energy rate ($/kWh)	$0.0808138	$0.0509800	$0.1040000
Well O&M Cost ($/AF)	$36	$36	$36
Outlook 2003 Demand Factor	1	0.5	1.3
CAGRD Cost Factor	3.25	3	3.5
Water Level Decline Standard (ft/yr)	-10	-10	-10
Pipeline Length (ft)	46,747	46,747	46,747
Pipe Diameter (in)	16	16	16
Pipe Max Flow Velocity (ft/s)	5	5	5
Design Flow - Demand Factor	2	2	2
Tucson Water Pipe Unit Cost ($/lf)	$169	$169	$169
Pipe Unit Cost Factor	1.0	1.5	0.7
Pipe Unit Cost ($/lf)	$169	$254	$118
Capital Cost ($)	$22,588,385	$33,882,577	$15,811,869
CAP Treatment ($/AF)	$185	$185	$185
Interest Rate	6.0%	8.0%	4.0%
Annuity Factor	13.76483115	11.25778334	17.29203330
Annual Payment ($/yr)	$1,641,022	$3,009,702	$914,402

APPENDIX B-6: *Community Water Company of Green Valley, Key Results for Scenario 2*

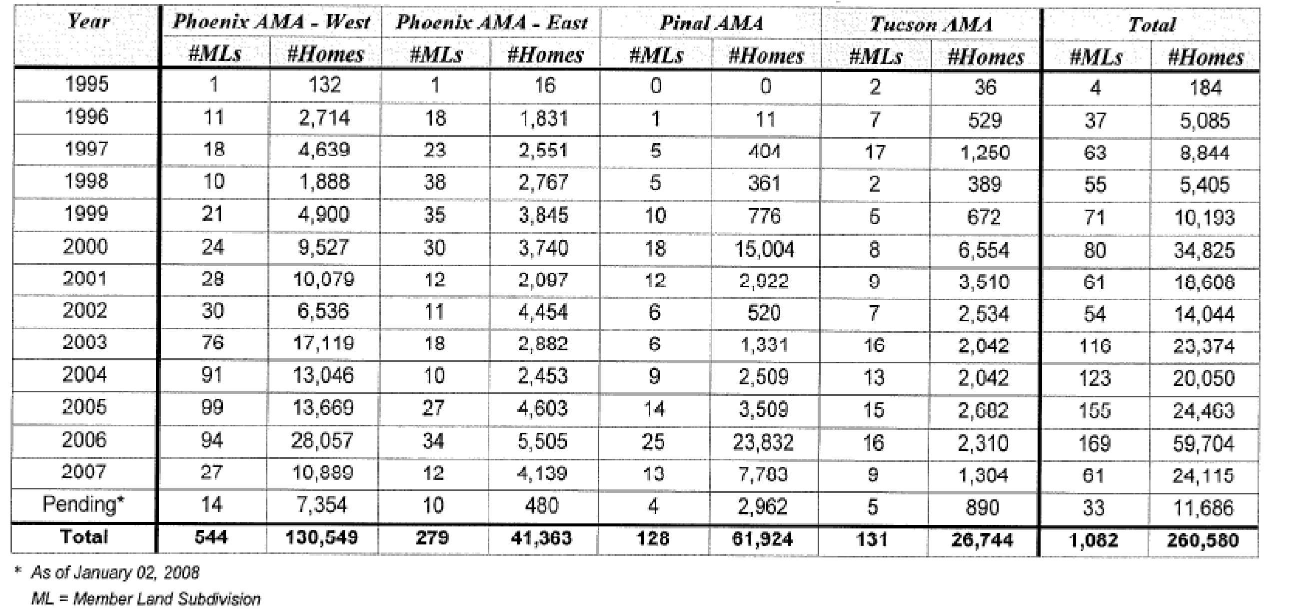
YEAR	**GROUNDWATER PUMPING COST**			**PIPELINE COST**			**DIFFERENCE**
	DRAWDOWN (dh/dt)	WATER LEVEL (ft bls)	PUMPING COST ($/AF)	CAPITAL COST ($)	UNIT PMT ($/AF)	DD COST ($/AF)	
2005	-3.41	320	$148	$11,869,998	$507	$769	**$621**
2010	-3.57	338	$174	$11,869,998	$487	$774	**$600**
2015	-3.67	356	$200	$11,869,998	$475	$786	**$586**
2020	-3.78	375	$226	$11,869,998	$463	$799	**$573**
2025	-3.88	394	$252	$11,869,998	$451	$812	**$560**
2030	-3.99	414	$278	$11,869,998	$440	$825	**$547**
2035	-4.10	435	$304	$11,869,998	$430	$839	**$535**
2040	-4.21	456	$330	$11,869,998	$419	$853	**$522**
2045	-4.33	478	$388	$11,869,998	$409	$867	**$479**
2050	-4.44	500	$413	$11,869,998	$400	$882	**$469**
2055	-4.55	523	$449	$11,869,998	$391	$898	**$449**
2060	-4.66	546	$474	$11,869,998	$382	$914	**$439**

APPENDIX B-7: *Community Water Company of Green Valley, Key Results for Scenario 3*

YEAR	**GROUNDWATER PUMPING COST**			**PIPELINE COST**			**DIFFERENCE**
	DRAWDOWN (dh/dt)	WATER LEVEL (ft bls)	PUMPING COST ($/AF)	CAPITAL COST ($)	UNIT PMT ($/AF)	DD COST ($/AF)	
2005	-3.41	320	$173	$5,539,333	$154	$417	$244
2010	-3.81	339	$200	$5,539,333	$140	$427	$226
2015	-4.08	359	$228	$5,539,333	$131	$442	$214
2020	-4.36	381	$256	$5,539,333	$123	$459	$203
2025	-4.64	404	$284	$5,539,333	$117	$477	$193
2030	-4.91	429	$312	$5,539,333	$111	$495	$183
2035	-5.19	455	$341	$5,539,333	$105	$514	$173
2040	-5.50	482	$378	$5,539,333	$100	$533	$155
2045	-5.78	511	$423	$5,539,333	$95	$553	$130
2050	-6.07	542	$451	$5,539,333	$91	$573	$122
2055	-6.36	573	$487	$5,539,333	$87	$594	$107
2060	-6.65	607	$515	$5,539,333	$83	$615	$99

APPENDIX C:
FIGURES

***APPENDIX C-1**: CAGRD Enrollment Summary, as of January 2, 2008*

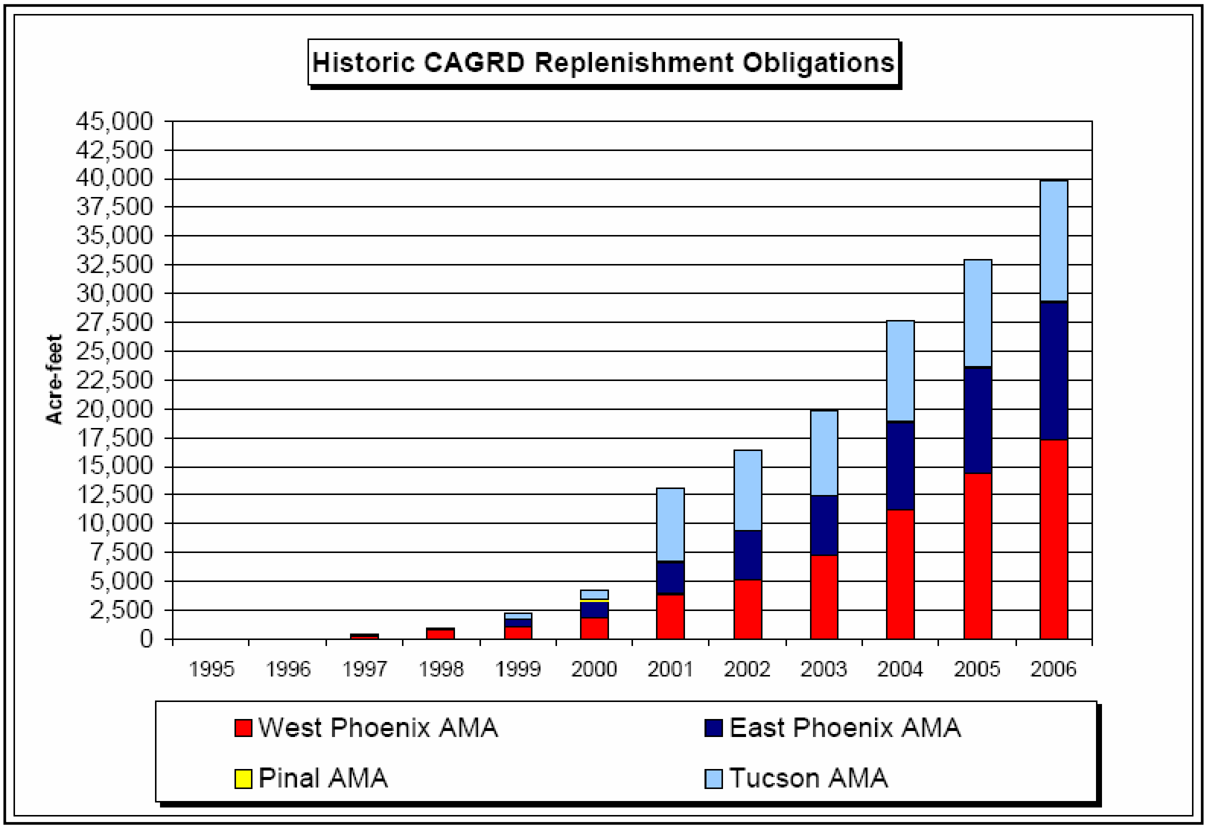


Year	*Phoenix AMA - West*		*Phoenix AMA - East*		*Pinal AMA*		*Tucson AMA*		*Total*	
	#MLs	*#Homes*	*#MLs*	*#Homes*	*#MLs*	*#Homes*	*#MLs*	*#Homes*	*#MLs*	*#Homes*
1995	1	132	1	16	0	0	2	36	4	184
1996	11	2,714	18	1,831	1	11	7	529	37	5,085
1997	18	4,639	23	2,551	5	404	17	1,250	63	8,844
1998	10	1,888	38	2,767	5	361	2	389	55	5,405
1999	21	4,900	35	3,845	10	776	5	672	71	10,193
2000	24	9,527	30	3,740	18	15,004	8	6,554	80	34,825
2001	28	10,079	12	2,097	12	2,922	9	3,510	61	18,608
2002	30	6,536	11	4,454	6	520	7	2,534	54	14,044
2003	76	17,119	18	2,882	6	1,331	16	2,042	116	23,374
2004	91	13,046	10	2,453	9	2,509	13	2,042	123	20,050
2005	99	13,669	27	4,603	14	3,509	15	2,682	155	24,463
2006	94	28,057	34	5,505	25	23,832	16	2,310	169	59,704
2007	27	10,889	12	4,139	13	7,783	9	1,304	61	24,115
Pending*	14	7,354	10	480	4	2,962	5	890	33	11,686
Total	**544**	**130,549**	**279**	**41,363**	**128**	**61,924**	**131**	**26,744**	**1,082**	**260,580**

* *As of January 02, 2008*
ML = Member Land Subdivision

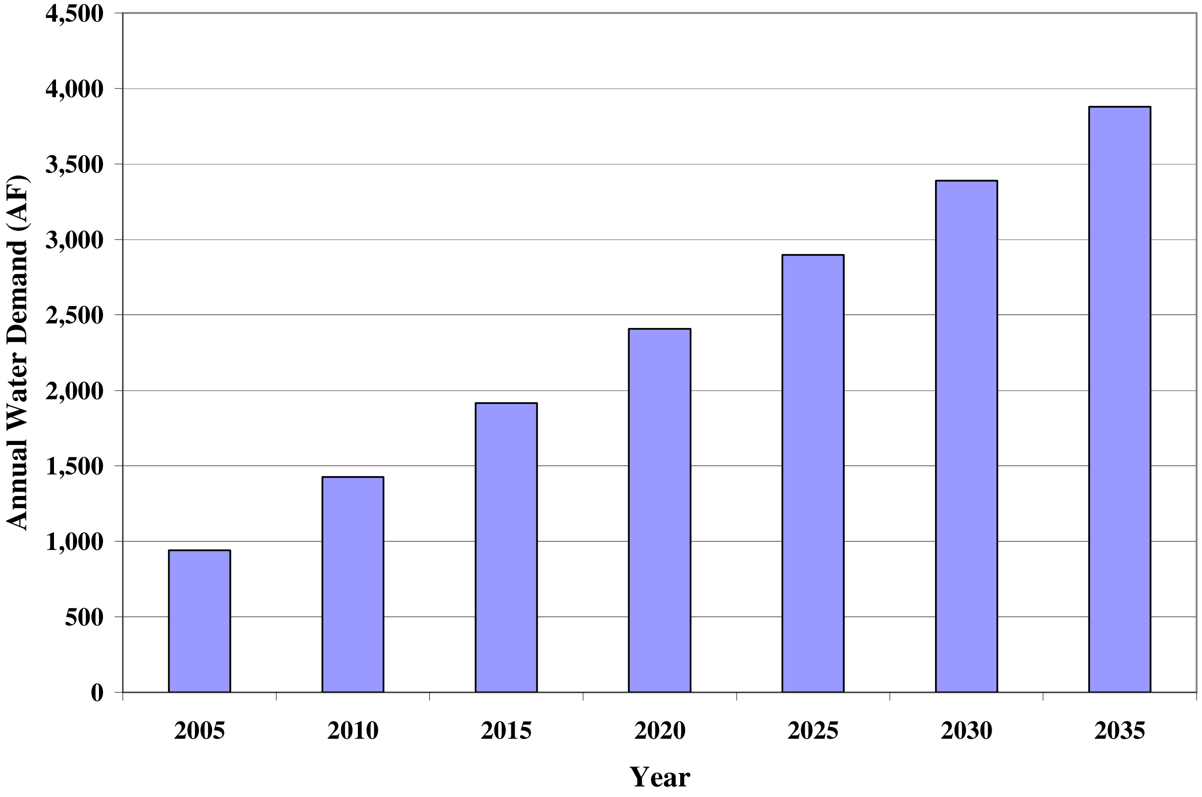
Source: CAGRD website, http://www.cagrd.com

***APPENDIX C-2**: CAGRD Replenishment Obligations, 1995-2006*

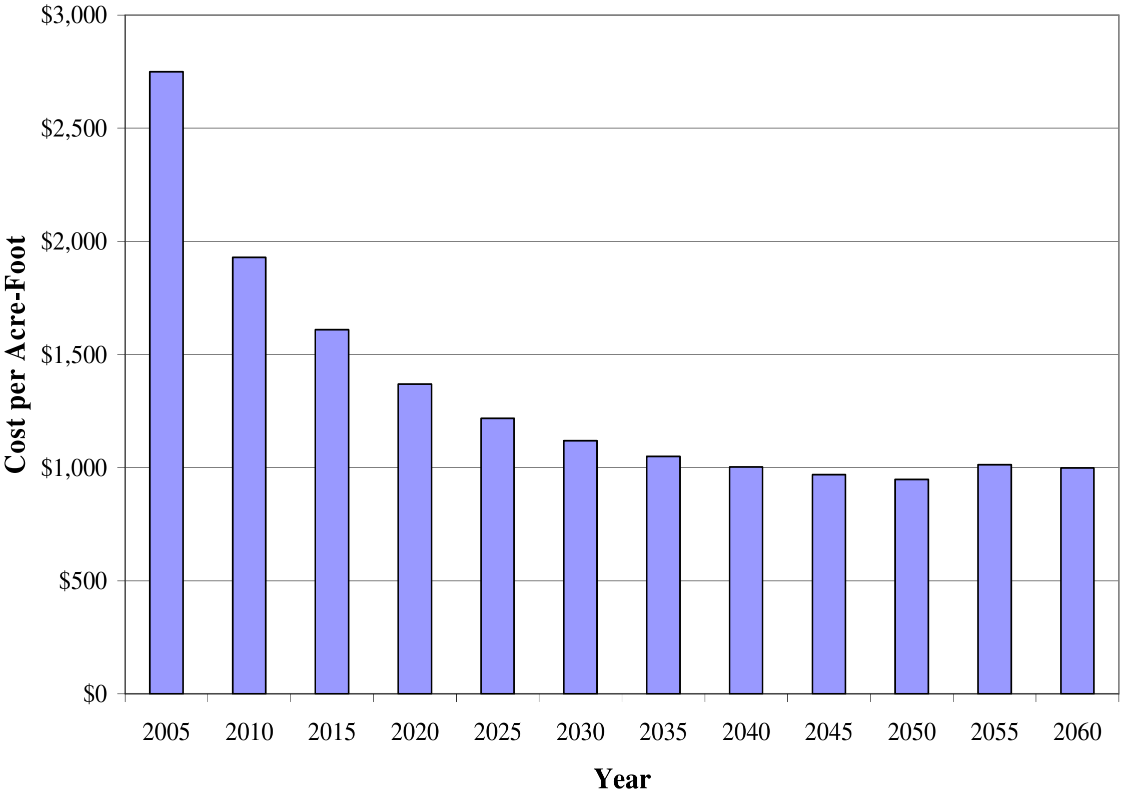


Source: CAGRD website, http://www.cagrd.com.

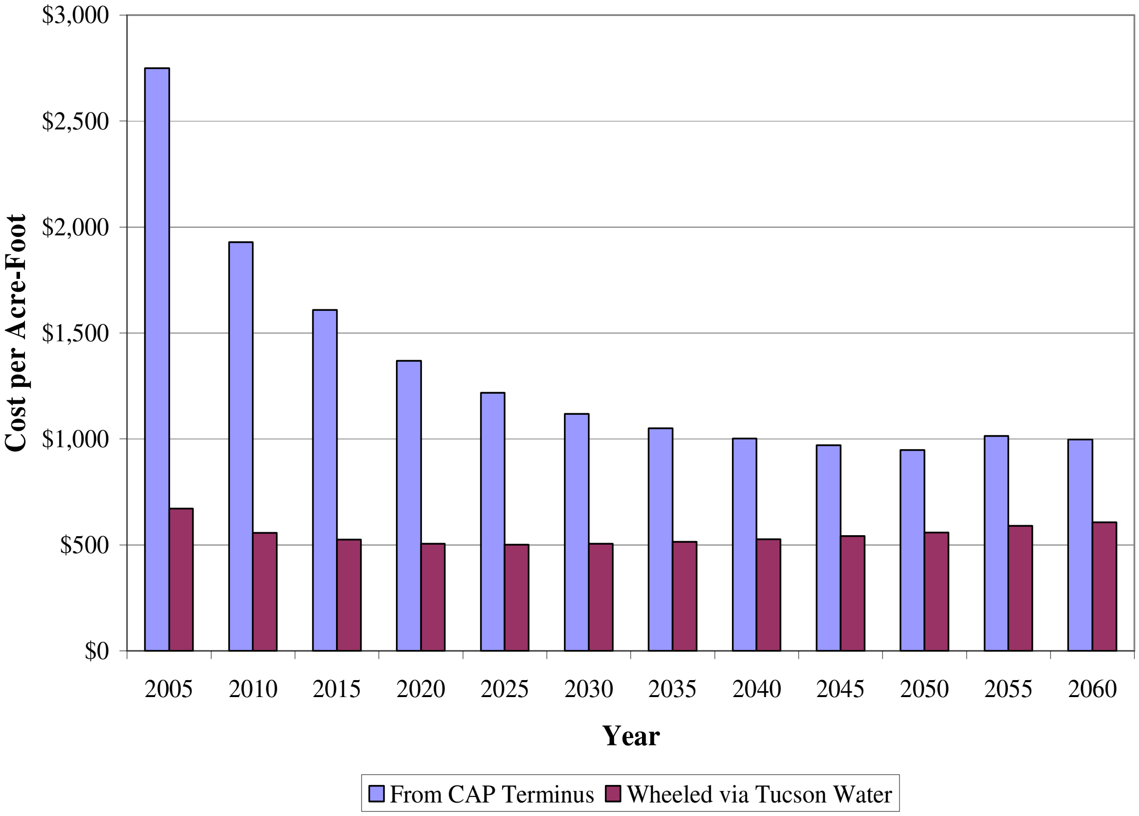
APPENDIX C-3: *Outlook 2003 Annual Water Demand Projections for Vail Water Company*



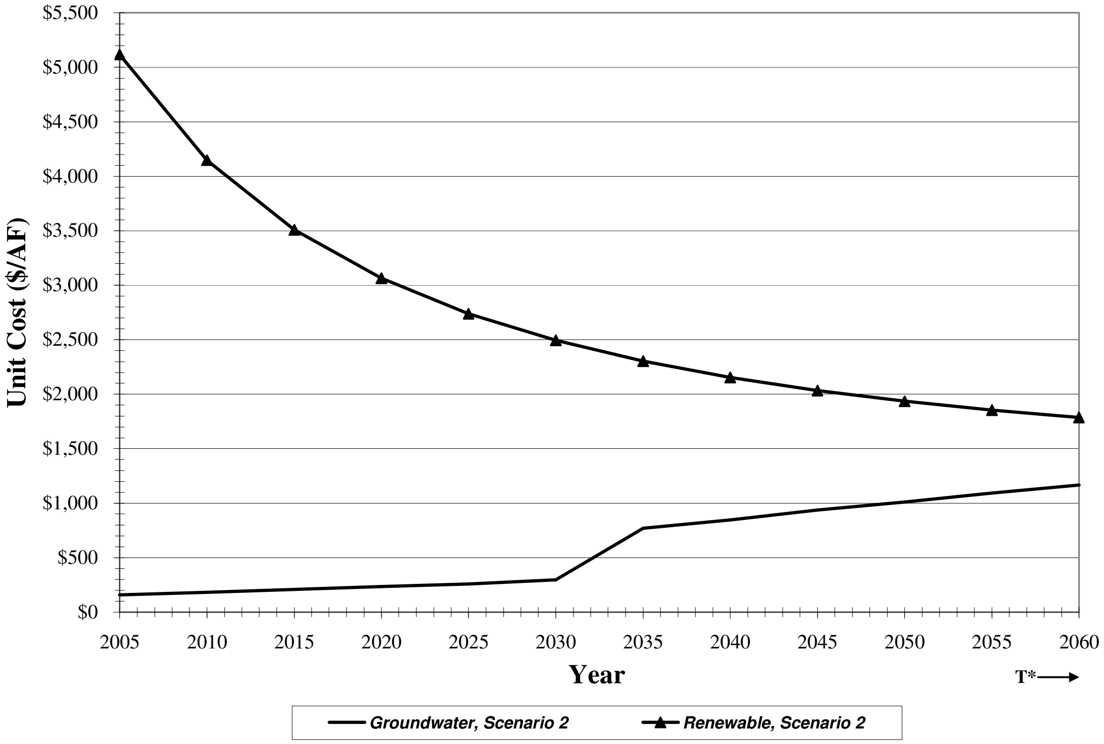
APPENDIX C-4: *Projected Unit Cost of Directly Delivering CAP Water to Vail Water Company, 2005-2060*



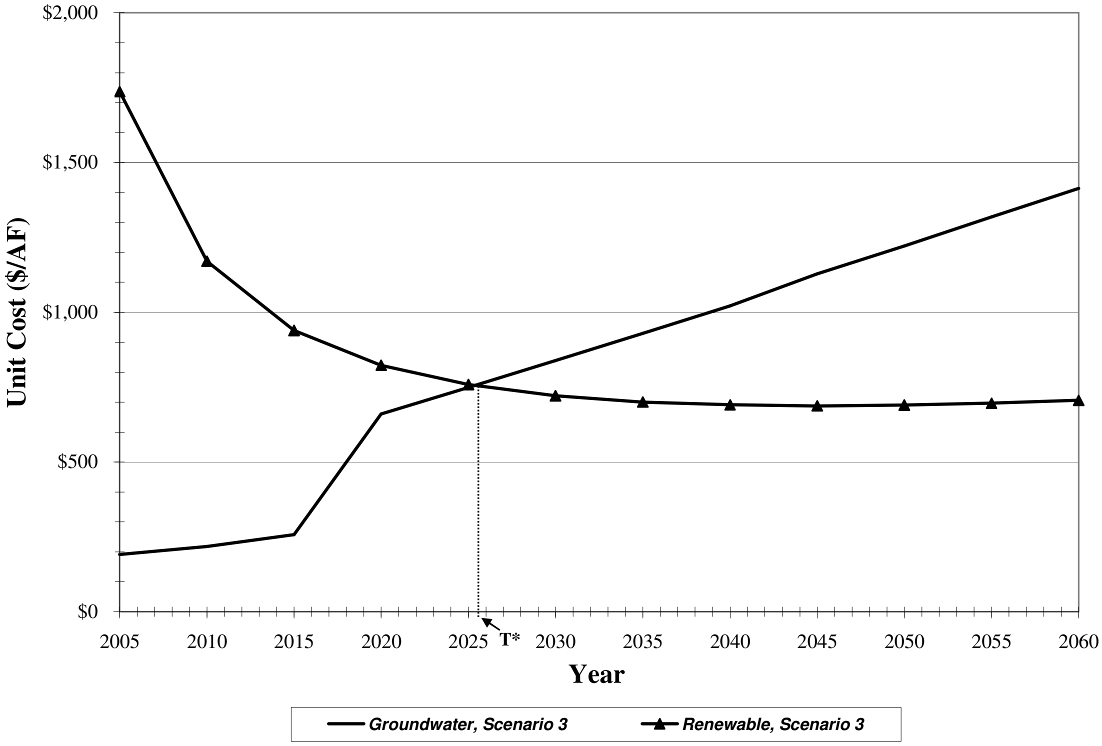
APPENDIX C-5: *Cost of Direct Delivery of CAP Water to Vail Water Company: Using Tucson Water's Delivery Infrastructure vs. Building Own Delivery Infrastructure*



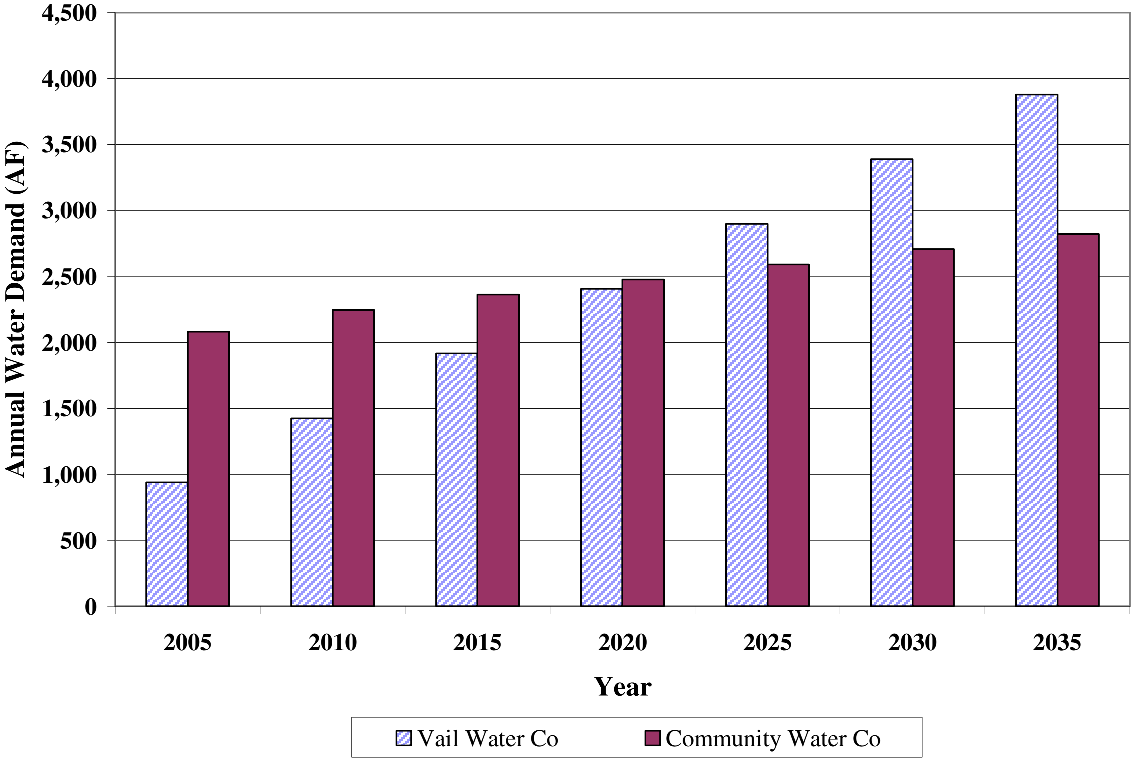
APPENDIX C-6: *Comparison of the Costs of Groundwater Pumping and Direct Delivery of CAP Water via Pipeline for Vail Water Company, 2005-2060 (Scenario 2)*



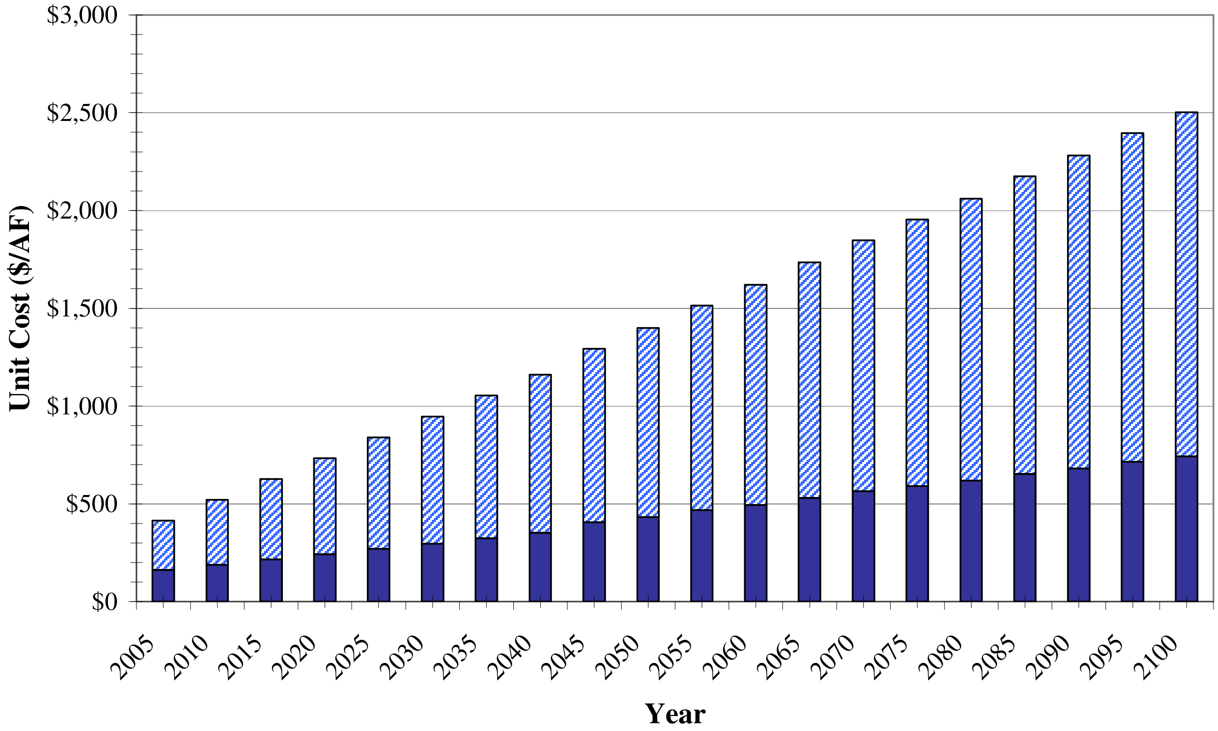
APPENDIX C-7: *Comparison of the Costs of Groundwater Pumping and Direct Delivery of CAP Water via Pipeline for Vail Water Company, 2005-2060 (Scenario 3)*



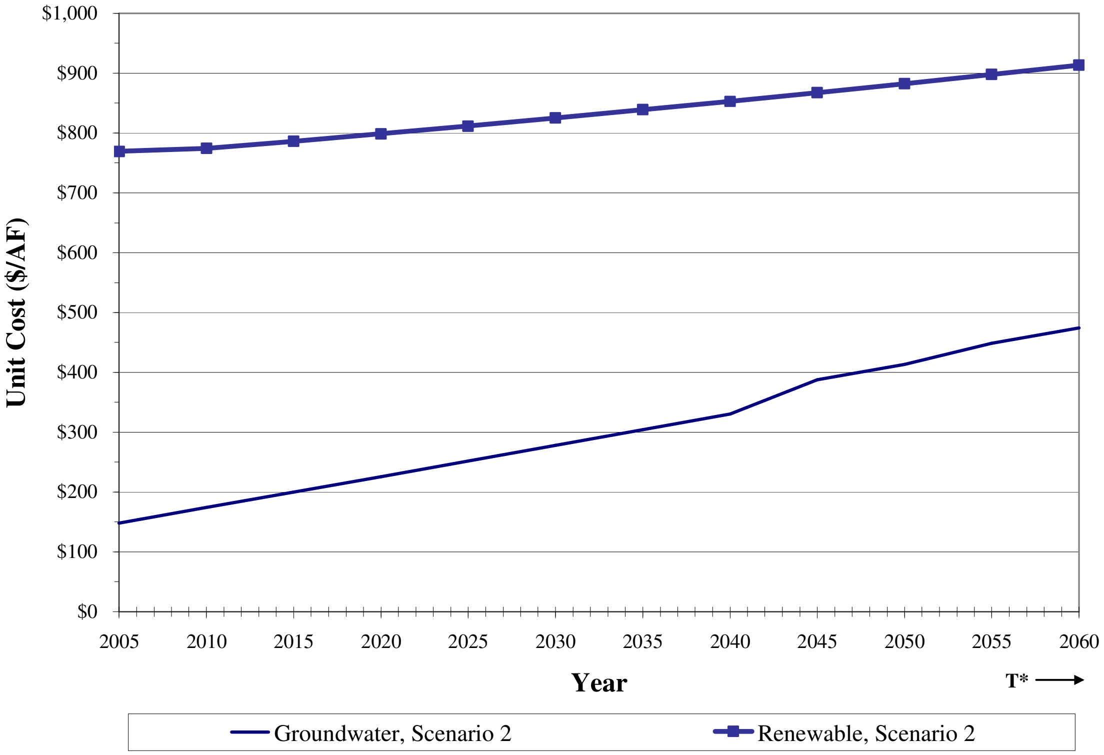
APPENDIX C-8: Outlook 2003 *Water Demand Projections: Community Water Company of Green Valley vs. Vail Water Company*



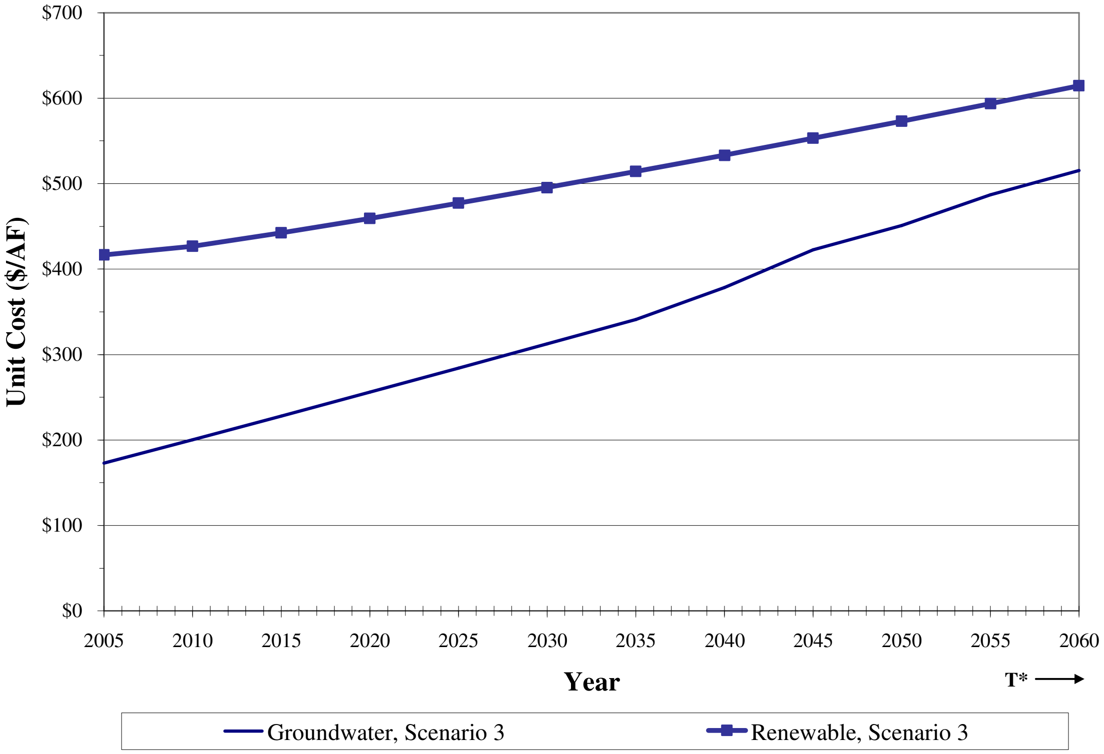
APPENDIX C-9: *Projected Groundwater Pumping Cost for Community Water Company of Green Valley, 2005-2100*



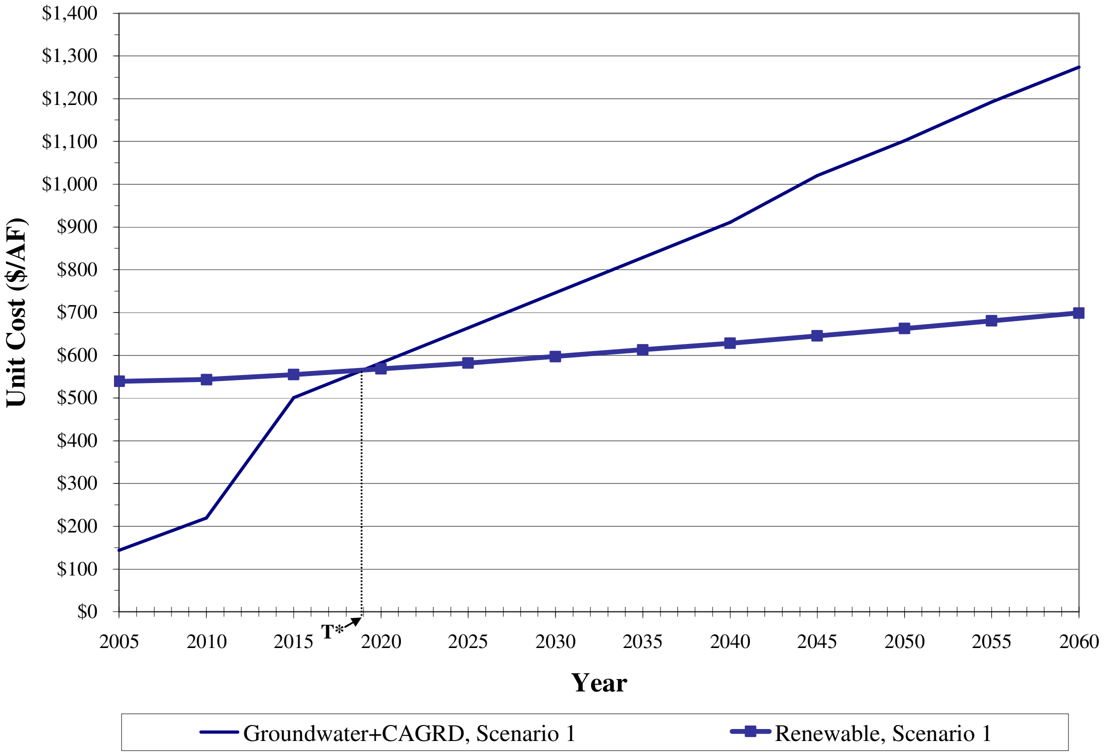
APPENDIX C-10: *Unit Costs of Groundwater Pumping and Direct Delivery of CAP Water via Pipeline for Community Water Company of Green Valley, 2005-2060 (Scenario 2)*



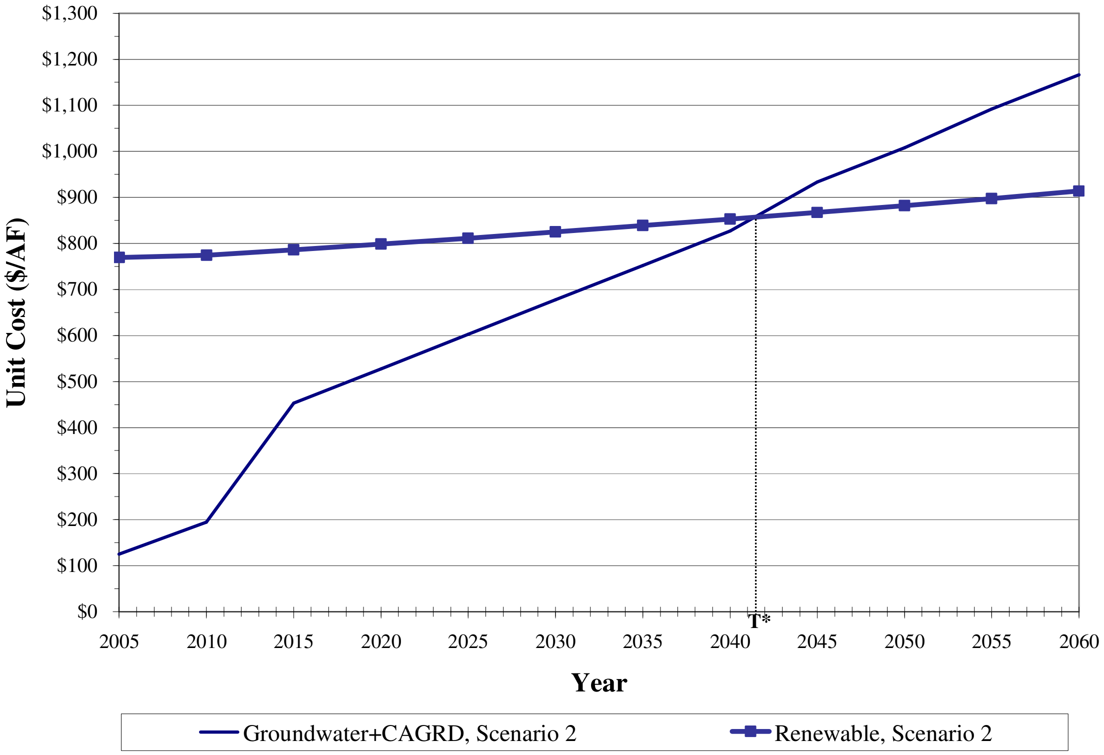
APPENDIX C-11: *Unit Costs of Groundwater Pumping and Direct Delivery of CAP Water via Pipeline for Community Water Company of Green Valley, 2005-2060 (Scenario 3)*



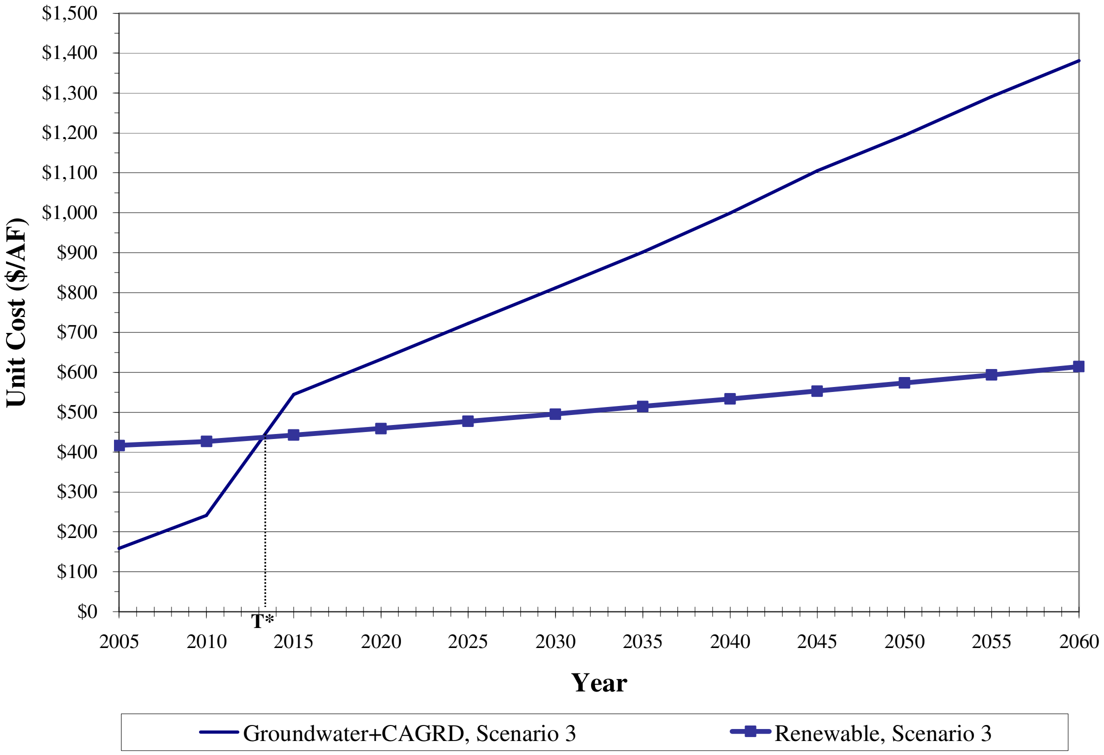
APPENDIX C-12: *Consideration of CAGRD Replenishment Cost Borne by Member Land Customers, Community Water Case Study (Scenario 1 assumptions)*



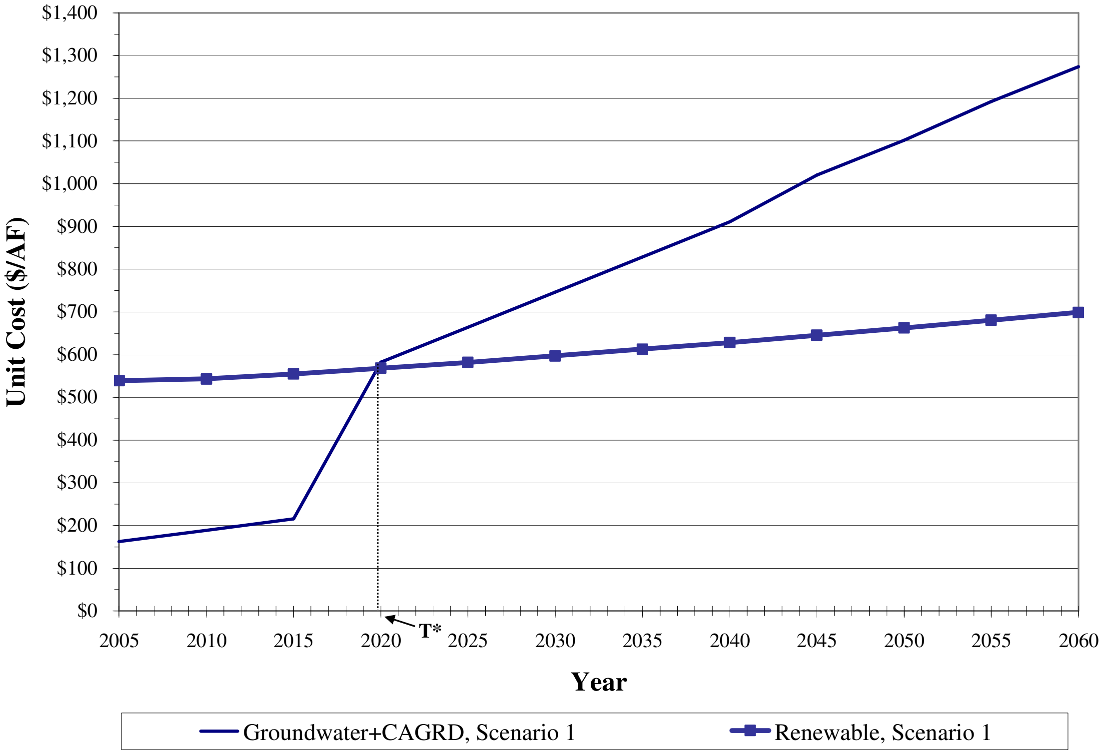
APPENDIX C-13: *Consideration of CAGRD Replenishment Cost Borne by Member Land Customers, Community Water Case Study (Scenario 2)*



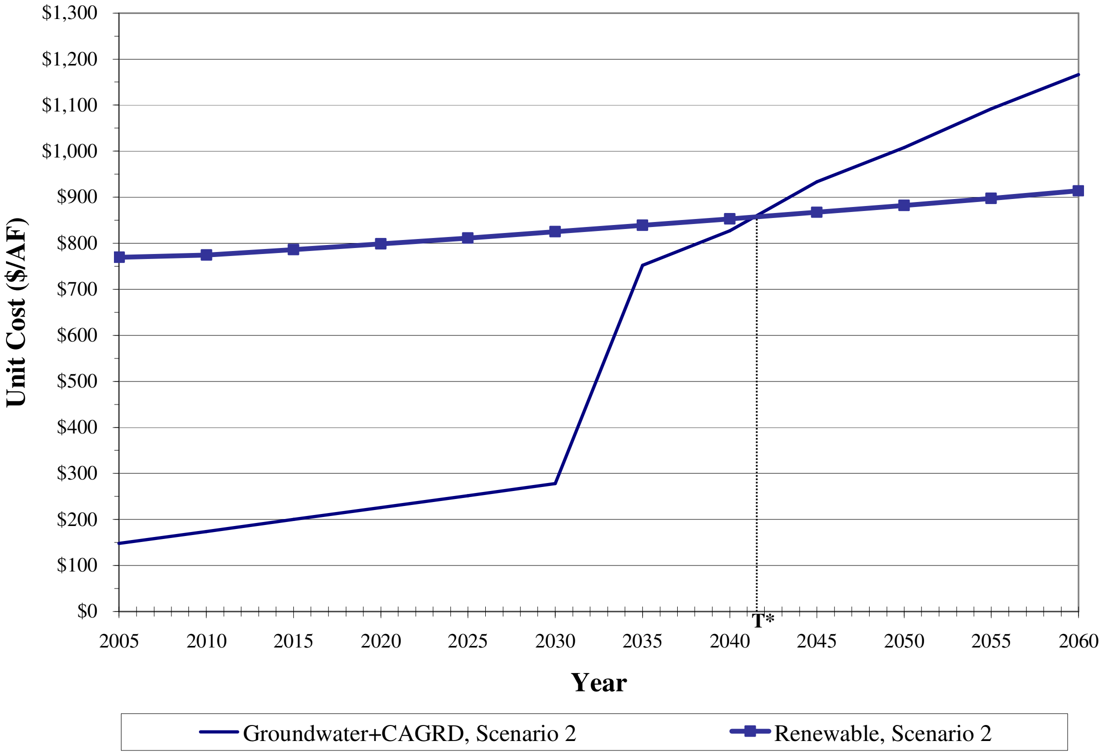
APPENDIX C-14: *Consideration of CAGRD Replenishment Cost Borne by Member Land Customers, Community Water Case Study (Scenario 3)*



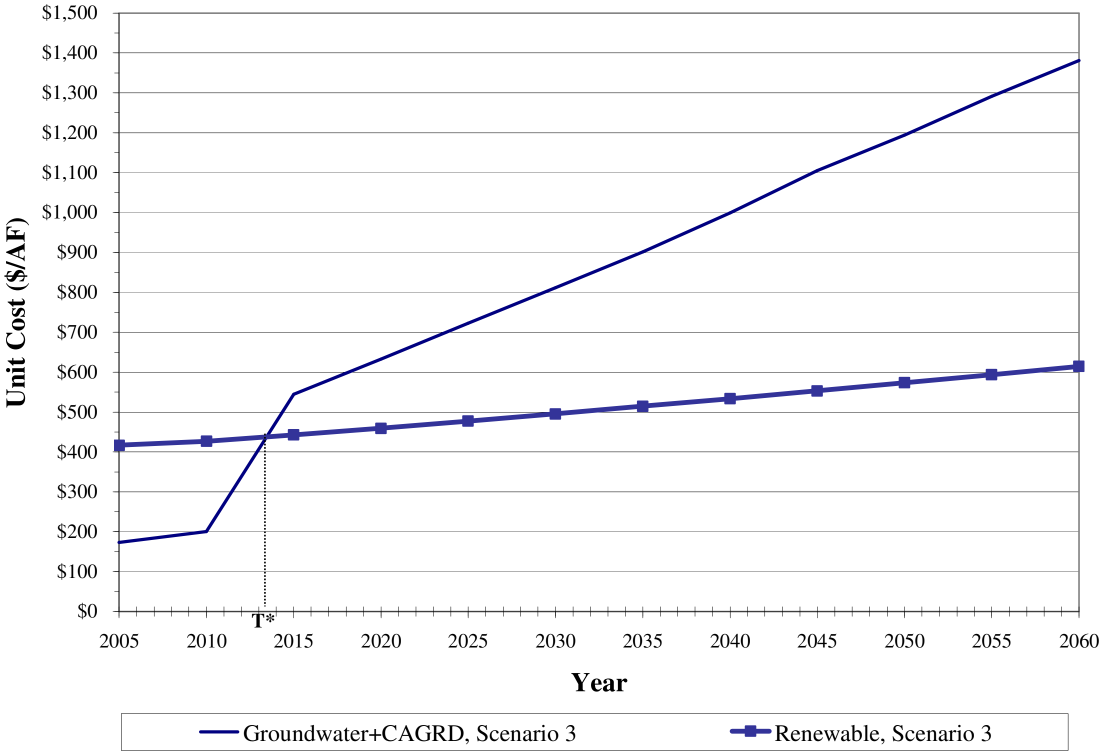
APPENDIX C-15: *Alternative Situation: Community Water Becomes Designated Water Provider and is Forced to Pay CAGRD for Replenishment Upon Violation of ADWR's Water Level Decline Standard (Scenario 1 assumptions)*



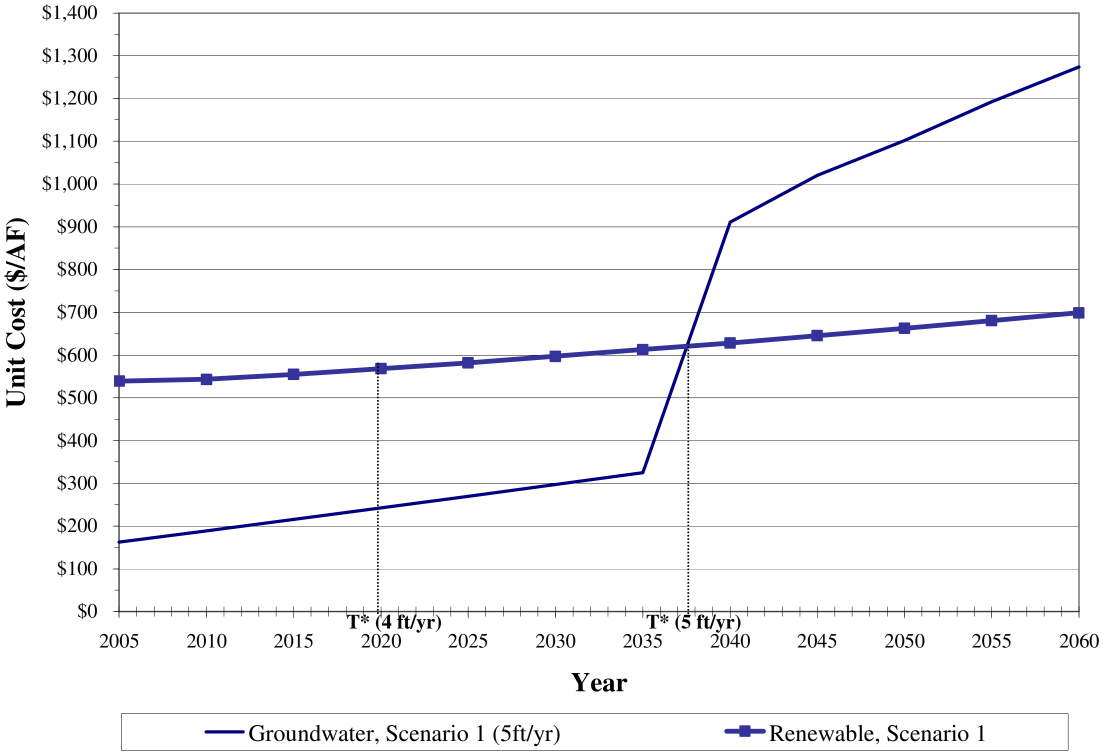
APPENDIX C-16: *Alternative Situation: Community Water Becomes Designated Water Provider and is Forced to Pay CAGRD for Replenishment Upon Violation of ADWR's Water Level Decline Standard (Scenario 2 assumptions)*



APPENDIX C-17: *Alternative Situation: Community Water Becomes Designated Water Provider and is Forced to Pay CAGRD for Replenishment Upon Violation of ADWR's Water Level Decline Standard (Scenario 3 assumptions)*



APPENDIX C-18: *Community Water Company Case Study, Scenario 1 Switch Point Compared to Switch Point Under Hypothetical Situation in which ADWR's Water Level Decline Standard is 5 ft/yr*



APPENDIX D:
List of Interviewees

SOURCES OF QUALITATIVE DATA		
Developers	***Water Providers***	***Present and Former Government Officials***
Peter Culp, *Attorney, Squires, Sanders & Dempsey*	Dennis Rule; *Manager, Tucson Water*	Tom Buschatzke; *Water Advisor, City of Phoenix*
Karl Polen; *VP, The Pivotal Group*	Brad Hill, *Director, Peoria Water Utility*	Jim Holway; *Professor, Arizona State University*
Jerry Ellsworth; *Water Manager, SunCor Development Company*	Brad DeSpain; *Manager, Marana Water*	Cliff Neal; *Manager, CAGRD*
Rich Williamson; *Water Manager, Diamond Ventures*	Mike Block; *Hydrologist, Metro Water*	Chris Avery; *Attorney, City of Tucson*
Sheryl Sweeney; *Attorney, Ryley Carlock and Applewhite*	Philip Saletta; *Manager, Oro Valley Water Utility*	Grady Gammage, Jr.; *Professor, Arizona State University*
	Mark Seamans; *Manager, Rancho Sahuarita Water Company*	Sharon Megdal; *Director, Water Resources Research Center, University of Arizona*
	Steve Olson, *Director, AMWUA*	Randy Edmond; *Director, Pinal AMA*