TECHNICAL PAPER

WATER RESOURCES AUGMENTATION FOR THREE METROPOLITAN AREAS IN THE ARID WESTERN UNITED STATES

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Introduction

Urban areas in the arid western United States are facing the need to supply rapidly growing populations using finite water resources. State water agencies and cities are considering many options to meet these expanding water demands. Historically, large dams and massive diversions of water were the preferred option to bring water to agriculture and urban areas. The pressures of increasing population and people wanting to live in different areas are creating conditions where less expensive, less environmentally damaging, and less controversial solutions or options must be developed (Western Resource Advocates 2007).

Three options for meeting expanding demand that are discussed in the literature are water conservation, transfers from agriculture, and reuse. Cities that are located in exceptionally dry regions are confronted with some of the most acute problems of water shortage and need to consider all the options. Three of these cities are Phoenix, Arizona, Las Vegas, Nevada, and Salt Lake City, Utah and their metropolitan areas. This technical paper will describe the effort to develop new water resources to meet the present and future demands of these water-strapped cities. Potential water resources and obstacles related to obtaining and using these resources will be discussed.

Augmented Water for Central Arizona

Central Arizona contains some of the fastest growing urban areas in the United States and the semi-arid environment creates conditions of limited water availability throughout the region. The city of Phoenix and its surrounding suburbs lie in a geographic zone called the Phoenix Active Management Area (AMA). Cities in the AMA have enacted extensive water management practices to avoid a major crisis of water shortage with continued growth. They must be able to obtain and manage more extensive water supplies to sustain the population growth today and into the future. A map of the location of the Phoenix AMA is shown in Figure 1 on the following page. Figure 2 on the next page is an enlarged picture of the AMA showing Phoenix and surrounding cities.

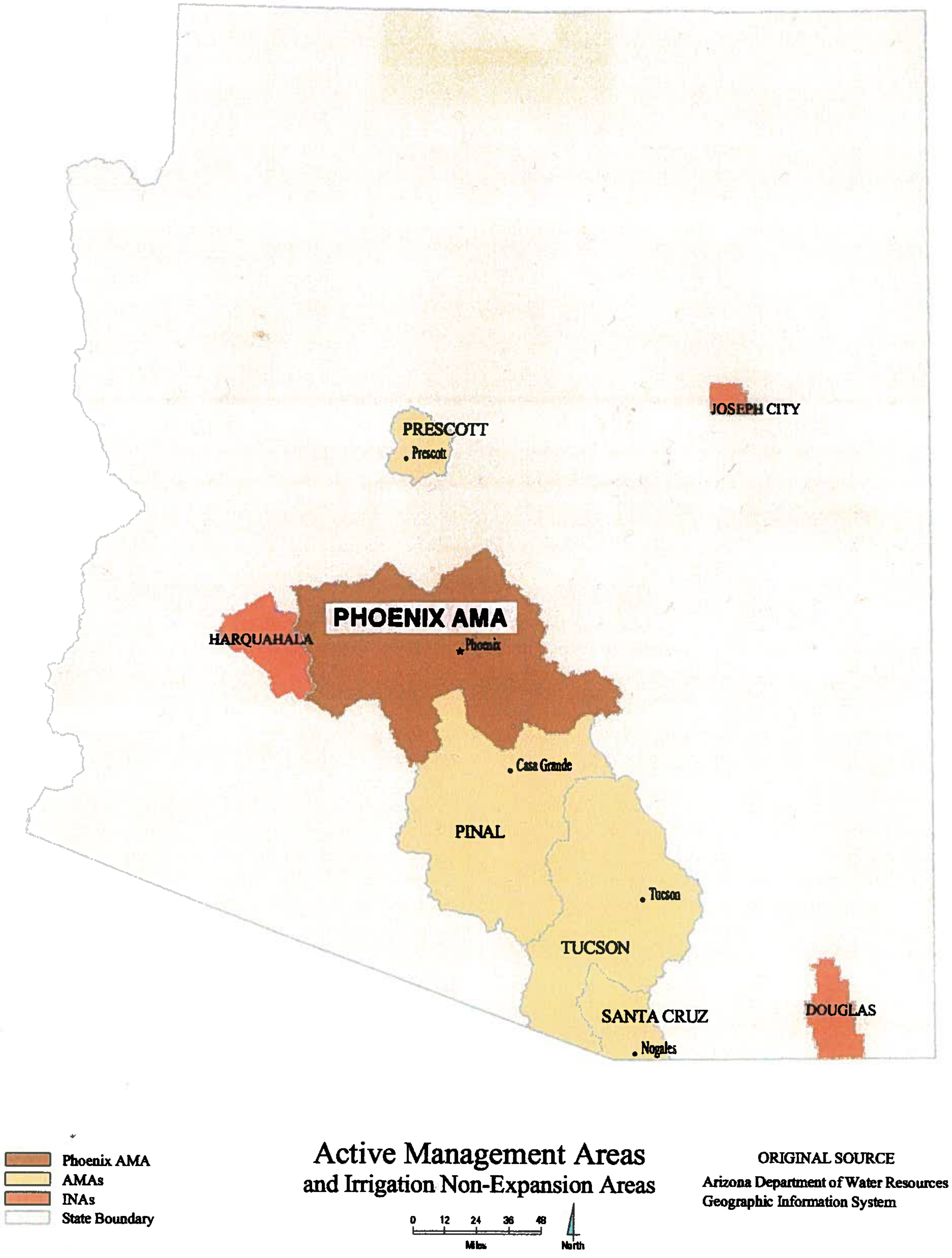

Figure 1: Phoenix Active Management Area (Shown as brown colored area)

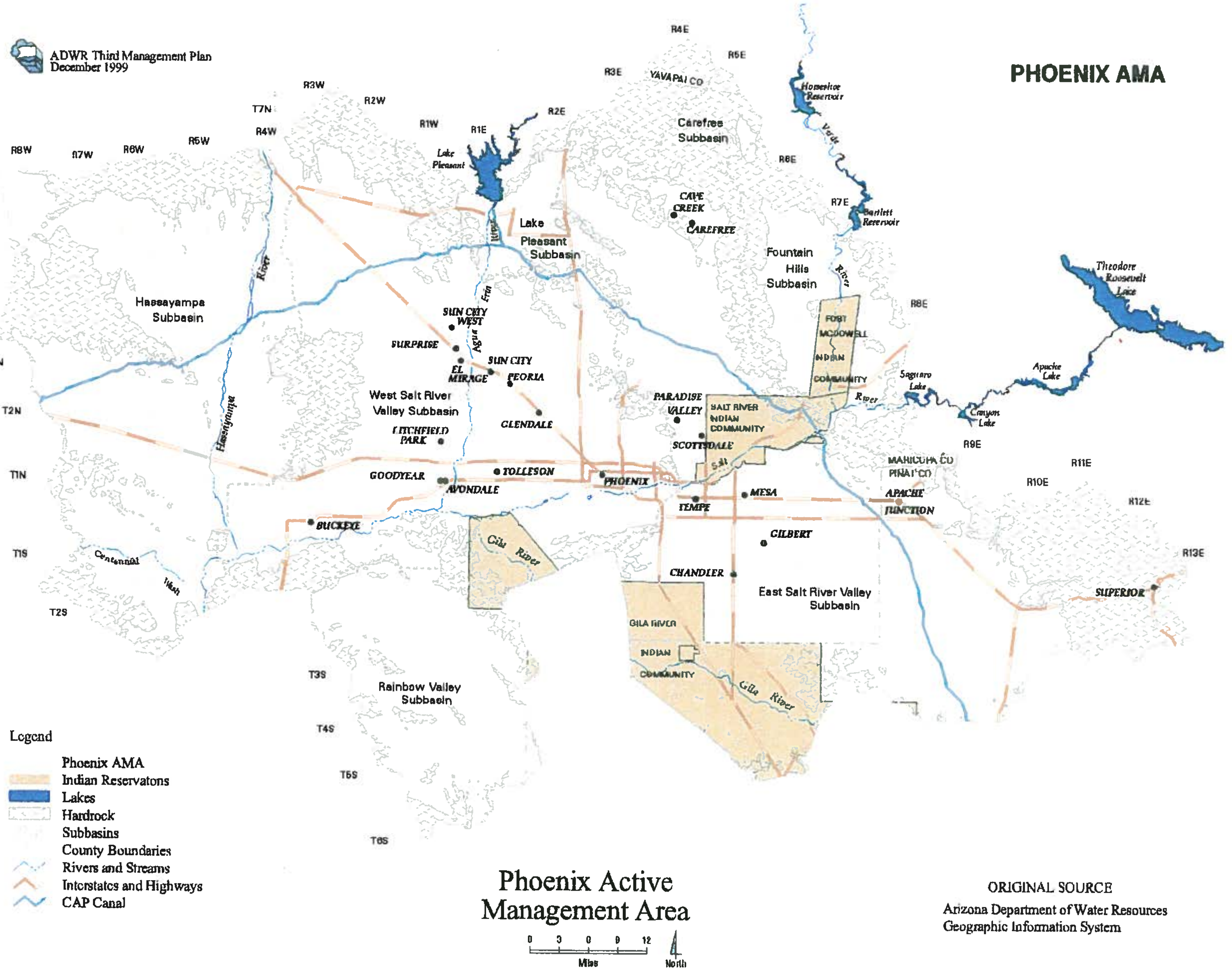

Figure 2: Phoenix Active Management Area showing Phoenix and other cities in the metro area

The city of Phoenix sits in a groundwater basin called the Salt River Basin. This basin forms a relatively wet region of the state due to the fact that four rivers and three confluences of the rivers flow through it. In prehistoric times, Hohokam Indians farmed large portions of the Salt River Valley due to its extensive water resources in the form of rivers and underlying alluvial aquifers. With the westward expansion in the 1800's many settlers realized the potential to farm the valley and set up permanent settlement. Although farming was the initial reason for the valley's settlement, cities and towns began to appear as more people moved to the region. The city of Phoenix was thus established and has continued to grow very rapidly, especially since the 1950s. Although the water resources in the valley are considered extensive by Arizona standards, Phoenix is situated in a semi-arid environment that receives less than 8 inches of rain per year on average. With a rapidly increasing population, the water resources are barely sufficient to meet the needs of the growing Phoenix area (Arizona Department of Water Resources, 1999).

Current Water Resources of the Salt River Basin

Today, the Salt River Basin contains three main sources of water. These sources supplied a Phoenix AMA demand of 2,520,436 acre-feet in 2005, and are projected to supply 2,758,730 by 2015. The first source and one of the most closely managed is groundwater. Groundwater that existed in the basin before significant development was thousands of years old, the accumulation of precipitation and seepage from the four rivers that flow into the basin. The Salt River Basin is underlain by seven closely managed groundwater sub-basins. The perimeters of these basins define the borders of the Phoenix AMA. The basins contain a huge quantity of water which has not been accurately quantified. Although water is present, most of the groundwater is too deep to be pumped economically. The aquifers are very heterogeneous; they include an upper alluvial geological unit, a middle fine grained unit, and a lower conglomerate unit. Most of the water that is extracted comes from the middle fine grained unit. The amount of groundwater in the basin has decreased rapidly since the 1950s due to the huge population growth in Phoenix.

The second water source for the Phoenix area is the surface water that is conveyed to the basin in the Salt River, the Gila River, and three of the Salt River's tributaries, the

Hassayampa River, the Agua Fria River, and the Verde River. Several large dams have been built on these rivers creating large reservoirs for flow control and regulation for the Salt River Basin. The largest of these dams is the Roosevelt Dam on the Salt River. It is about 50 miles east of Phoenix and contains the Roosevelt Reservoir, which has a typical capacity of 1.5 million acre-feet. The system of dams, reservoirs and rivers, and the agricultural lands in the valley served by these water resources, are called the Salt River Project. The Salt River Project has a total storage capacity of almost 3.6 million acre-feet. In 2005, the Phoenix AMA diverted 978,187 acre-feet of Salt River Project water for municipal, industrial, agricultural, and riparian (wetland) use. By 2015, the amount diverted is projected to be 1,070,160 acre-feet. Today much of the Phoenix area is located in the old irrigation district of the Salt River Project and many municipalities in the Phoenix metropolitan area own rights to Salt River Project water (Salt River Project, 2007).

The third primary water resource for the Phoenix metropolitan area and the surrounding agricultural lands is Colorado River water delivered via the Hayden-Rhodes aqueduct which is a component of the Central Arizona Project (CAP). The aqueduct was designed to deliver 1.5 million acre-feet of a total Arizona allotment of 2.8 million acre-feet per year of Colorado River water to central Arizona—the locale of the Phoenix and Tucson metropolitan areas. Today this aqueduct delivers water to irrigation, municipal, and industrial demands in the Phoenix area. The Phoenix AMA diverted 213,824 acre-feet of CAP water in 2005, and is projected to divert 489,513 acre-feet by 2015. A surplus of Colorado River water is often delivered via the aqueduct, because the rights to all of the water delivered via the canal have not been adjudicated. This "excess CAP" water is currently used primarily by the Central Arizona Water Conservation Board (CAWCB) and the Central Arizona Groundwater Replenishment District (CAGRD) which is responsible for water recharge in the Salt River Valley. As the Phoenix area grows, however, the excess water delivered via the CAP canal will be acquired by municipal and industrial entities in the urban area. This will remove the CAWCB board's only current surplus water source and therefore the organization will have to acquire additional water supply. The following outlines Central Arizona's issues that lead to the need to increase water supplies for the city of Phoenix (CAGRD, 2004).

Central Arizona's Water Supply Issues

With several decades of increasing growth in Central Arizona, especially in the Phoenix and Tucson metropolitan areas, the Salt River Project water was not nearly sufficient to meet the demands in the Salt River Valley. Overuse of groundwater in the valley spurred the construction of the Central Arizona Project and the Hayden-Rhodes aqueduct. While much of the development had been made possible by the continued use of groundwater, the levels dropped dramatically in the past fifty years, leading to legislation by the Arizona state government to protect the diminishing groundwater resource for the Salt River Valley.

The 1980 *Groundwater Management Act* created a system of rules for Central Arizona that today more effectively regulate the use of groundwater. The act created water resources "active management areas" (AMA) in regions of the state where groundwater was the most threatened. Three initial AMAs were created. They include the Phoenix AMA, the Tucson AMA, and the Pinal AMA. The Phoenix AMA's purpose is more effective management of the diminishing groundwater resource for the metropolitan area. This AMA is 5600 square miles in size and contains the entire Phoenix metropolitan area. It is underlain by seven groundwater sub-basins (CAGRD, 2004).

The act also created the Arizona Department of Water Resources (ADWR) which is charged with implementation of the Groundwater Management Code defined by the *Groundwater Management Act*. The ADWR began to supervise the operations of the existing CAWCB. The CAWCB was held responsible by the ADWR for mitigating groundwater losses. In 1993, a new branch of the CAWCB was created and charged with the duty of replenishing groundwater mined in the Phoenix AMA. The new branch was named the Central Arizona Groundwater Replenishment District (CAGRD). The CAGRD must use renewable water resources, such as Colorado River Water from the CAP system, to replenish mined groundwater in the Phoenix AMA. The CAGRD replenishes the groundwater by means of two direct recharge facilities. Water is diverted from the CAP canal to spreading basins so that water may seep into the ground. Portions of cities that are served by private water companies or new subdivisions are legally required to prove a reliable water supply before new building may occur. In order for the

CAGRD to replenish water for a particular water user, the water user must be a dues-paying member (CAGRD, 2004).

Since not all of the water coming through the Hayden Rhodes Aqueduct from the Colorado River is adjudicated, the CAGRD has used the excess water to replenish groundwater used by entities in the Phoenix AMA. This excess supply could diminish to zero within 10 to 20 years due to Indian water rights claims and the continued growth of the municipal and industrial sector in the Phoenix AMA. For this reason the CAGRD must find new water resources. The overall goal of the Groundwater Management Code as it applies to the Phoenix AMA is the achievement of "safe yield" for the AMA. "Safe yield" means that entities in the AMA may not withdraw more groundwater than is replenished, either by the CAGRD, other entities such as the Salt River Project recharge effort, or natural recharge. According to the code, safe yield must be achieved by the year 2025. The following sections detail what water resources will be obtained by the CAGRD and how municipalities will play a role in helping CAGRD as the organization attempts to achieve safe yield for the Phoenix AMA (CAGCD, 2004).

Water resources for Phoenix from Eastern Valleys and Irrigation Districts

Cities within the Phoenix AMA are trying to acquire additional water resources to supplement their current supply situation. The city of Scottsdale, a portion of the metropolitan area to the east of the Phoenix downtown, has acquired 1,215 acres of land in the Harquahala Valley, which is an alluvial valley to the west of Phoenix consisting of 18,000 acres of irrigated land. Scottsdale bought this land with the intention of retiring agriculture on the new holdings and using the groundwater once applied to crops to supplement the city's water supply. The water is intended specifically for irrigation of at least two new golf courses. Scottsdale obtained land and the associated groundwater right in this valley because of the valley's proximity to the Central Arizona Project Canal. The canal passes about 8.8 miles to the north of the land. The city will withdraw the groundwater and convey it via pipeline to the CAP canal. The water then travels in the canal eastward to the Phoenix and Tucson AMAs. Upon arriving in the AMAs the water may be withdrawn via Scottsdale's canal turnout structure and transferred to its water supply system. This water could also be legally transferred to the CAGRD so that the

CAGRD may replenish groundwater in the Phoenix AMA. A legal arrangement will have to be made to transport non-Colorado River water in the CAP canal, since the CAP is a federal project intended to transport Arizona's Colorado River entitlement only (M. Brown, personal communication, February 15, 2007).

Assuming the Harquahala Valley land is cultivated year round, the 1,215 acres would produce 6,150 acre-feet of groundwater per year. Scottsdale is entitled to only 3,645 acre-feet of water because this is the amount purchased in 2002 from the Vidler Water Company to accompany the land holding. To obtain the water, Scottsdale will have to develop a new well field in this area; however, thanks to the presence of excess CAP water coming to the Phoenix AMA, this water source will not be needed for at least another decade. (M. Brown, personal conversation, February 15, 2007)

The proposed well field in the Harquahala Valley may be similar to well fields that already exist. For example, the existing well field located in the Avra Valley that serves the city of Tucson is one that could serve as a model. The adoption of the features of the Avra Valley well field could proceed as follows:

1. The Avra Valley field includes 22 wells, some dug for the purpose of potable use and some earlier wells dug originally for irrigation. The irrigation wells (now converted to potable use) often do not perforate as deeply as the potable use wells which perforate the entire water-bearing geologic layer. The 22 wells each have a pipeline leading into a larger mainline that carries water to Tucson.

   The wells in the Avra Valley often have a capacity of around 1000 gallons per minute. The hypothetical well field in the Harquahala Valley could only sustain 3 or 4 wells that pump at this rate, assuming that the wells pump constantly. This estimate is based on the current rate of irrigation water application per acre in the Harquahala Valley. To increase reliability, it will be assumed that a greater number of wells pumping at a lower flow rate will be used in the Harquahala Valley. If the land is divided into 16 equal plots of about 76 acres each, one well pumping groundwater at a rate of around 250 gallons per minute could be drilled in the center of each 76-acre plot and be used to withdraw ground water from the well's respective portion of the land. The pumps would have to pump water as high as 650 feet, the current maximum depth of the water table in the Harquahala Valley.

2. Buried pipelines could lead out from each of the sixteen wells toward a main line running down the center of the Harquahala valley land holding. In the Avra Valley, pipelines that lead from individual wells to a larger main line are usually 12-inch concrete asbestos pipe. The flow in these pipes is always turbulent with the large flow rates coming from the well pumps in the Avra Valley. Assuming a Reynold's Number that is in the turbulent range and close to the Reynold's Number for pipelines from individual wells in the Avra Valley, a pipe diameter of 8 inches could be assumed for pipes leading from individual wells in the Harquahala valley. These 8-inch lateral pipelines will no doubt include an isolation valve per pipeline near the point at which each joins the main line. Isolation valves might also be located along the mainline's length so that sections of the well field system could be shut down for servicing or emergency. The interior surfaces of all the pipes are not perfectly smooth. Small ridges are found on the surfaces of the pipe materials. The vertical height of these ridges is called the "pipe roughness height". The roughness in the interior of the pipes increases pipe friction or resistance to the flow of water. A pipe roughness height of 0.006 inches for concrete-asbestos pipe causes additional loss of energy in the flowing water due to pipe friction.

   The mainline down the center of the well field will become progressively larger in diameter with the direction of the flow. As the pipe diameter of the mainline increases, concrete pipe will have to be used in place of concrete-asbestos pipe because concrete-asbestos pipe is not available in the required larger diameters of more than 12 inches. The water flowing through the main line would be flowing turbulent, in about the same range of Reynold's Number calculated for the Avra Valley case. At the outlet of the pipe network, the mainline would increase to a diameter of 16 inches then remain at this diameter for the 8.8 mile length leading to the CAP canal. This pipe will be made of concrete with a roughness of 0.0006.

3. The outlet of the network in the well field will no doubt be the location of a pump station that would impart enough energy to the water to allow it to flow the 8.8 miles to the CAP canal. The pump station would have to pump water to an elevation of 1397 feet, the elevation of the CAP canal at the point where the pipeline will discharge water to the canal. This elevation is 285 feet higher than the well field.

   A booster pump station along the way to the canal might be needed—providing a pipe network essentially the same as in the Avra Valley well field.

4. The ground water wells in the Harquahala valley would also be similar to the wells in the existing Avra Valley in that the perforated sections of the well borings would penetrate the entire geologic layer that yields the majority of the extractable water from the ground. In the Avra Valley, newer potable wells penetrate an upper layer of alluvial sediment that bears the majority of the ground water. This layer, composed of silt and gravel, is between 100 and 1000 feet deep. The potable production wells in the Avra Valley fully penetrate the upper layer so the maximum amount of water may be extracted. The perforated portion of the borings extends from below the water table to the bottom of the upper layer thus allowing the well to continue producing its full yield even if the water table declines during a period of drought (Tucson Public Works, E-mail communication, March 9, 2007).

In the Harquahala Valley, the depth to which water may feasibly be withdrawn is about 1200 feet below the ground surface. Because of historic pumping of groundwater in the Harquahala Valley, water levels have declined to anywhere between 200 feet to 654 feet below the land surface. Any well dug on the Scottsdale land in the Harquahala Valley would probably have a perforated section that begins below the water table (which could be as deep as 654 feet, to about the maximum depth feasible for wells in the valley, 1,200 feet). A well with this sort of perforated section would not be immediately affected by a water table decline and could continue to produce a maximum flow rate despite drought in the region, thus again imitating the Tucson's Avra Valley (Tucson Public Works, E-mail communication, March 9, 2007).

The water provided by the Harquahala Valley is projected to supplement the Scottsdale water supply by 2.5 percent. The following bar graph shows the relation of supply to demand for the years 2017 and 2020 as well as 2024 when the city's water supply infrastructure reaches its maximum size and extent. This condition is known as "build out."

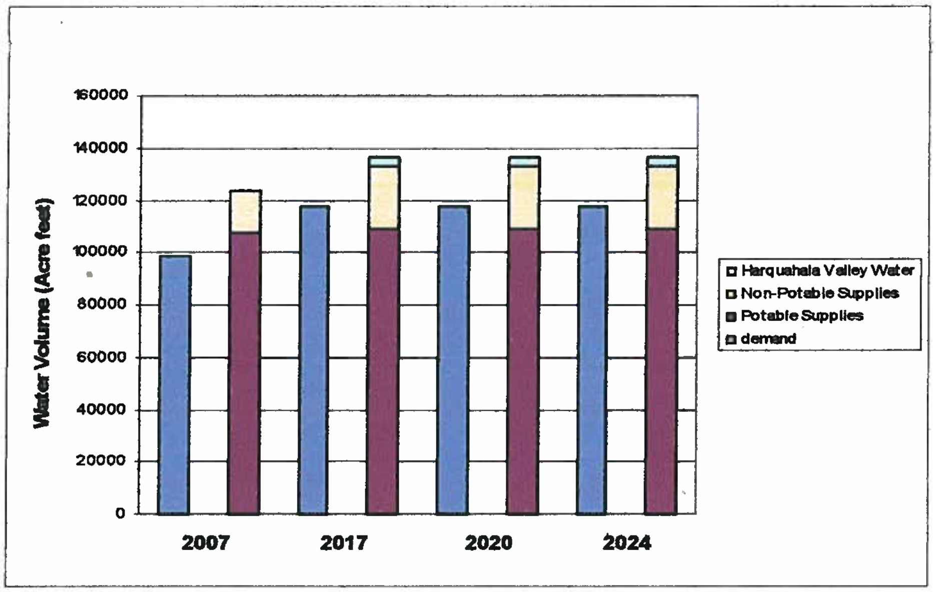

Figure 3. Scottsdale water demand and supply for build-out years (M. Brown personal conversation, March, 2007)

The City of Phoenix has also bought farmland whose groundwater will be extracted and transported to the Phoenix AMA in the CAP canal. Today this land in the McMullen Valley is still being farmed. As Colorado River water flowing in the CAP canal is allocated in the future, the excess (unallocated) water will be awarded to other entities and will disappear. To mitigate the situation, McMullen Valley water will be pumped from the McMullen Valley and conveyed via a 34 mile-long pipeline to the CAP canal. Phoenix owns legal entitlement to this water and may use it for any purpose needed upon arrival in the Phoenix AMA. The groundwater resource available from the

McMullen Valley land holding is very large. It is estimated to produce 38,000 acre-feet per year for 150 years (Checchio, 1988).

The purchase and removal of water resources from rural areas by large municipalities destroys agriculture and harms rural counties and the small communities in these counties (McEntire, 1989). Rural counties suffer from a loss of tax revenue because land owned by large municipalities is not taxable. Therefore, small communities in these counties have fewer resources to fund basic services such as public schools. The retirement of agriculture due to water transfers also means fewer local workers who would spend money in the area which harms all of the small businesses that cater to the farming community (Checchio, 1988). "Water transfers create disaster areas for economic development in rural communities" (McEntire, 1989). Many rural communities in Arizona that are affected by water transfers would like municipalities to pay "in lieu tax" payments to the county. However, such action would require an amendment to the Arizona State Constitution. Rural communities also would like a higher tax rate when the land is owned by the municipalities. A 1987 bill does allow lands owned by municipalities to be included in the rural counties' "net assessed valuation". Thus allowing state taxes to be distributed more equitably and benefit rural counties and communities (Checchio 1988).

In addition to the purchase and retirement of agricultural land and water rights, Phoenix will also initiate the lease of water. Phoenix is projected to begin the lease of 15,000 acre-feet per year of Colorado River water from the Gila River Indian Community (GIRC) in late 2007. The GRIC is on an Indian reservation several miles south of the Phoenix metropolitan area. Entities like the GRIC are entitled to huge quantities of high-priority water rights by the *Winters Doctrine* of 1908. The *Winters Doctrine* states that when an Indian reservation is created, a quantity of water "sufficient to effectuate the purposes of the reservation" will be reserved. With rapid growth in central Arizona, municipalities have pressured the state to settle the details of Indian water rights claims so that supplies of water could be identified. The Gila River Indian Water Rights settlement of 2004 was a direct result of a determined state effort in this regard. The settlement awards 653,500 acre-feet of water per year to the GRIC. Much of this water will be allocated for agricultural irrigation as the GRIC wishes to return to a more "agrarian" society. This allocation does not affect flows in the Colorado River which supplies some of this water. CAP water already allocated to cities in the Phoenix area was reassigned to the GRIC in payment of a federal debt. (J. Thestan, personal communication, July, 2006). With ownership of these rights established, municipalities can approach communities like GRIC for leasing agreements. Phoenix will withdraw its lease of 15,000 acre-feet from the CAP canal for a period of 100 years under the planned leasing agreement (Colby, 2004).

Water Resources to Phoenix Made Available Through Reuse

Municipalities in the Phoenix AMA have also employed and continue to improve on water reuse. Water reuse is the treatment of municipal and industrial wastewater to a very high quality. This water may then be used for a city's purposes, with the exception of water for household or human consumption. New subdivisions are served by waste water treatment plants that may treat water to a high enough quality for use in irrigation of city parks, golf courses, or restoration of water ways. If enough effluent is produced, large scale reuse may occur in the form of irrigation water for agricultural areas and cooling water for industrial or even nuclear power plants.

As a city's population increases, water resources made available from the treatment of waste water also increase, making reuse a very significant water resource augmentation method. The city of Phoenix's two largest waste water treatment plants treat waste water in order to serve the resource needs of several major water users in the area. The 91st Avenue Waste Water Treatment Plant provides effluent that is used to irrigate crops in the Buckeye Irrigation District east of the city. The effluent water treated at the plant is discharged into the dry Salt River Channel and travels through the channel to the Buckeye Irrigation District. This river channel is dry in the Phoenix AMA because of the Granite Reef Diversion Dam upstream of the 91st Avenue plant diverts water to a network of canals for the Salt River Project. The 91st Avenue plant also provides cooling water via pipeline for the Telaverde Nuclear Power Plant—the largest nuclear plant in the United States. The 91st Avenue plant treats an average of 145,000,000 gallons of waste water per day. A volume of 35,000,000 to 75,000,000 gallons of treated effluent goes to the Telaverde Nuclear Plant, the rest of the effluent goes to the Buckeye Irrigation District (B. Waterman, personal communication, March, 2007).

Another waste water treatment plant serving Phoenix is the 23rd Avenue Waste Water Treatment Plant. It is significantly smaller than the 91st Avenue plant, but still provides large amounts of treated effluent for reuse. The 23rd Avenue plant produces from 48,000,000 to 50,000,000 gallons of treated effluent per day for irrigation in the Roosevelt Irrigation District to the west of the city. (B. Waterman, personal communication, March, 2007).

These plants yield effluent that meets strict quality and health standards imposed by federal and Arizona laws which are intended to prevent disease as the effluent is placed back in the environment outside of the closed system of the sewage lines. The 91st Avenue plant's treatment processes illustrate a common method of producing high quality effluent. Waste water arriving at the plant travels through the sequence of treatment processes illustrated in Figure 4 to yield effluent clean enough for reuse in the outdoors.

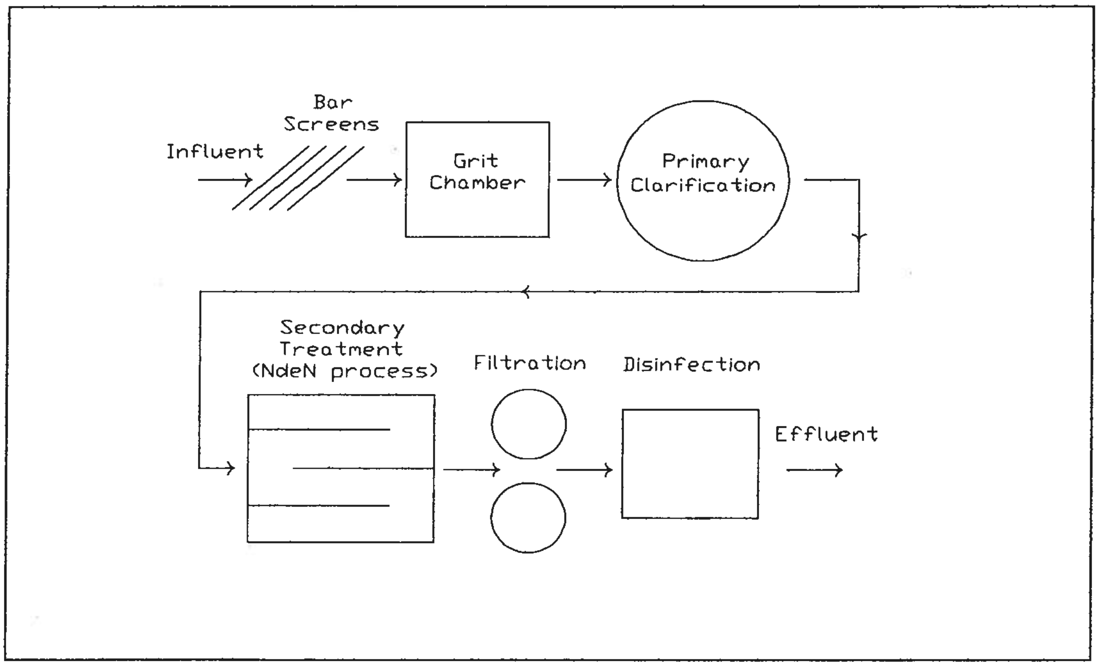

Figure 4. 91st Avenue Treatment Plant process

(B. Waterman, personal communication, March 2007)

As the diagram in Figure 4 shows, waste water and other solid matter in the waste stream pass through bar screens. Bar screens are simply large gates perpendicular to the flow of the waste water that prevent the entry of trash or large debris into the plant. The next stage consists of grit chambers that prevent the entrance of sand, gravel, cinders, and other non-organic material into the downstream treatment processes. If not removed, grit can interfere with the mechanical workings and biological processes in the plant and can fill downstream pipelines. The waste flow then enters a primary clarifier which allows the settling of solid organic waste present in sewage, thus separating waste water from solid waste and allowing the two to be treated in separate processes. For the purposes of this paper, only the treatment of the waste water will be detailed (Tchobanoglous & Schroeder, 1985).

From the primary clarifier, waste water travels to secondary treatment where a wide variety of biological treatment processes may be used to remove chemical compounds containing nitrogen and phosphorous. Several types of bacteria consume compounds containing nitrogen and phosphorous in waste water and use the nitrogen and phosphorous to survive and to increase their population. The multiplication and sustainment of the bacterial population in the secondary process is accomplished through the biochemical process of nitrification-denitrification (Jeyanayagam, 2005).

In the nitrification process a particular type of bacteria oxidizes ammonium (NH4+) using oxygen dissolved in the waste stream. The result of this reaction is the compound nitrite (NO_2^-). Nitrite is then further oxidized by different bacteria yielding the compound nitrate (NO_3^-). The bacteria *nitrosomonas* begins the process by oxidizing ammonium (NH_4^+) and creating nitrite (NO_2^-). The process proceeds by the following chemical reaction:

$$2NH_4^+ + 3O_2 \xrightarrow{(nitrosomonas)} 2NO_2^- + 2H_2O + 4H^+ + \text{New bacterial cells}$$

The bacteria *nitrobacter* then further oxidizes the newly created nitrite (NO_2^-) to yield nitrate (NO_3^-).

$$2NO_2^- + O_2 \xrightarrow{(nitrobacter)} 2NO_3^- + \text{New bacterial cells}$$

Both of these reactions require initiation with ammonium (NH_4^+) and oxygen, which are dissolved into the waste stream by aeration. The result of the two-step reaction given above is nitrate (NO_3^-) and an increased number of new cells or bacteria (Jeyanayagam, 2005).

After ammonium is oxidized to nitrate, the waste stream flows to the de-nitrification step. In de-nitrification, bacteria classified as "heterotrophic" use the newly created nitrate along with available organic matter to yield nitrogen gas. The organic matter comes from the waste in the stream. Some of the nitrogen gas dissolves in the waste stream and some volatizes into the atmosphere. The de-nitrification process proceeds by the following reaction, where "RBOM" stands for "rapidly biodegradable organic matter."

$$NO_3^- + \text{RBOM} \xrightarrow{\textit{(heterotrophs)}} N_2\,\text{(gas)} + CO_2 + H_2O + OH^- + \text{New bacterial cells}$$

This process must proceed without the presence of oxygen in the stream so the bacteria will consume the nitrate in the stream instead of consuming oxygen. A lack of dissolved oxygen implies an "anoxic" condition in the waste stream (Jeyanayagam, 2005).

At the 91st Avenue plant, the nitrification-denitrification process is carried out in a bio-reactor. The bio-reactor is a basin divided into four equally-long portions that allow the waste stream to flow through in a back and forth motion as illustrated in Figure 5.

Each alternating direction of flow is called a "pass" through the basin. Portions of the passes may be aerated while other portions have no oxygen dissolved (B. Waterman, personal communication, March, 2007). The waste stream is split before it enters the reactor because there are two different zones in the passes where the constituents of the entering waste stream are utilized. As the waste stream enters the bio-reactor, anoxic conditions are created that allow the de-nitrification reaction to proceed first. The incoming waste stream is very rich in rapidly biodegradable organic matter (RBOM);

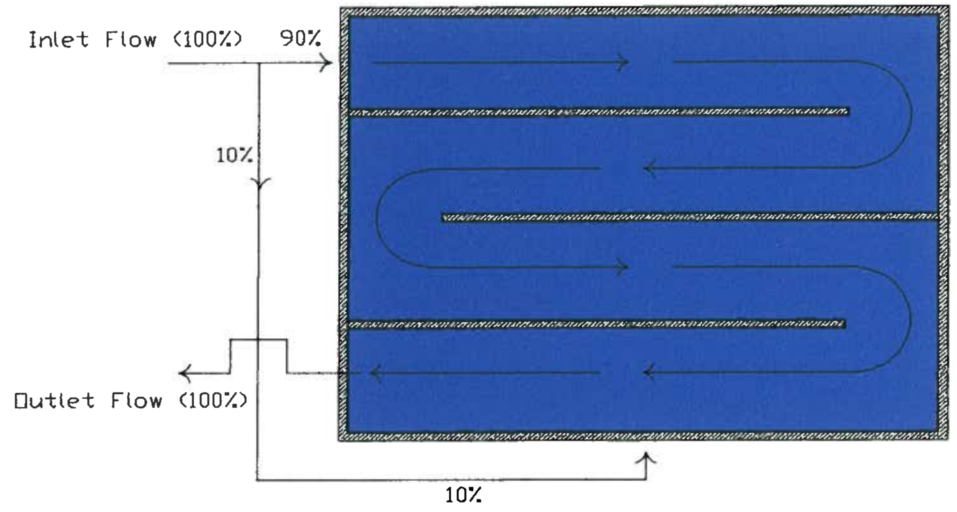

Figure 5. Schematic sketch of Phoenix 91st Ave. Plant Bio-Reactor
(B. Waterman, personal communication, March, 2007)

therefore, one of the reactants for de-nitrification is already present. The second reactant, nitrate, is supplied by a recycle system described below and illustrated in Figure 6 (Jeyanayagam, 2005).

After the initial de-nitrification reaction is allowed to occur in the first and part of the second passes, oxygen is bubbled into the waste stream. Now the two nitrification reactions can begin. *Nitrosomonas* and *nitrobacter* create nitrate from the ammonium (NH_4^+) in the waste stream through part of the second pass, all of the third, and part of the fourth passes. Near the middle of the fourth pass, a large portion of the waste stream is diverted via a pipeline back to the bio-reactor entrance. This diversion is called the Internal Mixed Liquor Recycle (IMLR). The de-nitrification reaction occurring in the first and second passes is thus supplied with the nitrate it needs to proceed (Jeyanayagam, 2005).

A small portion of the entering untreated waste stream is diverted directly to the fourth pass where oxygen bubblers are turned off and existing nitrate and RBOM allow an additional de-nitrification reaction to occur in the final stage of the bioreactor. As the stream exits the bioreactor at the end of the fourth pass, much of the nitrogen present in the raw feed has been removed (B. Waterman, personal communication, March, 2007).

Phosphorous compounds are also removed in a process called Enhanced Biological Phosphorous Removal (EBPR). The bacteria *acinetobacter* uses the anoxic and oxic stages in the bio-reactor to accumulate phosphorous in its cells. This process results in phosphorous removal from the waste stream (Jeyanayagam, 2005).

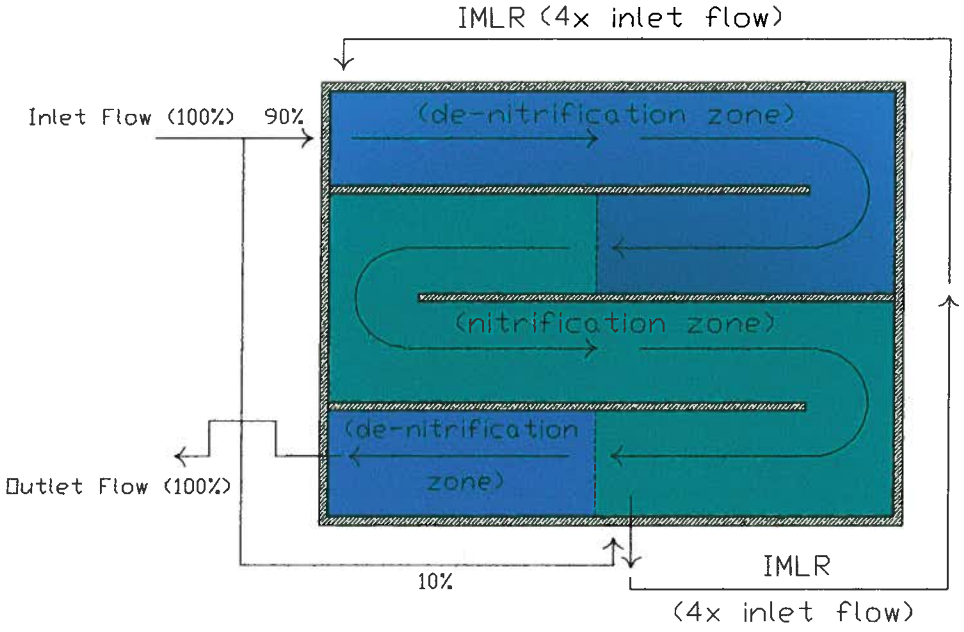

Figure 6. Bio-reactor for secondary treatment
(B. Waterman, personal communication, March, 2007)

The entire nitrification de-nitrification process used at the 91st Avenue plant is the Barnard Process for secondary treatment (Barnard, 1975). It proceeds in the three stages described above—anoxic de-nitrification, oxic nitrification, and fourth pass anoxic de-nitrification. The final result is an effluent with 6 to 8 milligrams per liter of total nitrogen (TKN), and a similar low value for total phosphorous (B. Waterman, personal communication, March, 2007). This level of total nitrogen puts the concentration in a range that is acceptable for reuse as potable water. The United States Environmental Protection Agency (U.S.E.P.A) requires maximum concentrations of 10 milligrams per liter (mg/L) of nitrate and 1 mg/L of nitrite for drinking water. The maximum concentration for ammonia is considered to be around 1.5 mg/L, when odor becomes an issue. Nitrogen and phosphorous in effluent is considered to be beneficial for irrigation because the application of waters with these constituents reduces the need for fertilizer.

After leaving the bio-reactor, the waste stream goes to a filtration system to remove any remaining nitrogen in particulate form. The final step is disinfection, in which chlorine gas is bubbled through the stream to remove any residual bacteria or pathogens. Finally, sodium bisulfate is dissolved in the stream to allow the precipitation of sodium chloride. The result is an effluent similar to natural waters, disinfected and suitable for irrigation purposes in an urban environment (Jeyanayagam, 2005).

In the future, the 91st Avenue plant will have some of its effluent diverted to the Agua Fria Linear Recharge Project (AFLRP) where the water will be allowed to seep into the groundwater basin. The AFLRP will enable the city of Phoenix and other cities that use the 91st Avenue plant to earn groundwater storage credits by recharging effluent. A pipeline will run from the plant to the dry Agua Fria River Channel to the north of the plant so that the water may be recharged in the dry channel. The city of Phoenix will be able to earn about 55,000 to 60,000 acre-feet of groundwater storage credits a year when the Phoenix water system reaches its maximum size, in about 2055.

Recharge to the aquifer is considered beneficial to the effluent's water quality. "Soil aquifer" filtration and treatment may remove some residual contaminants in the effluent water (Eden and Megdal, 2006). Salinity is not controlled in the wastewater treatment process and may eventually have a negative affect on aquifer water quality, as effluent often has a concentration of salts that is 1.5 times higher than many original fresh water sources. Recharging effluent to the aquifer before it is reused for potable purposes helps to diminish public opposition to direct waste water reuse for potable supply. This does not eliminate public objections, however. Public opposition halted a recent recharge and reuse plan in Los Angeles, California because a journalist described the project as "toilet to tap" (Chapman, 2005).

The combination of water from the McMullen Valley, leased water from the Gila River Indian Community, and recharge credits earned with effluent recharge from the 91st Avenue and 23rd Avenue plants, will significantly augment the water resources for

Phoenix as it grows. These resources will enable Phoenix to meet and surpass its future water demands as shown in Figure 7 (ADWR Third Management Plan, 1999).

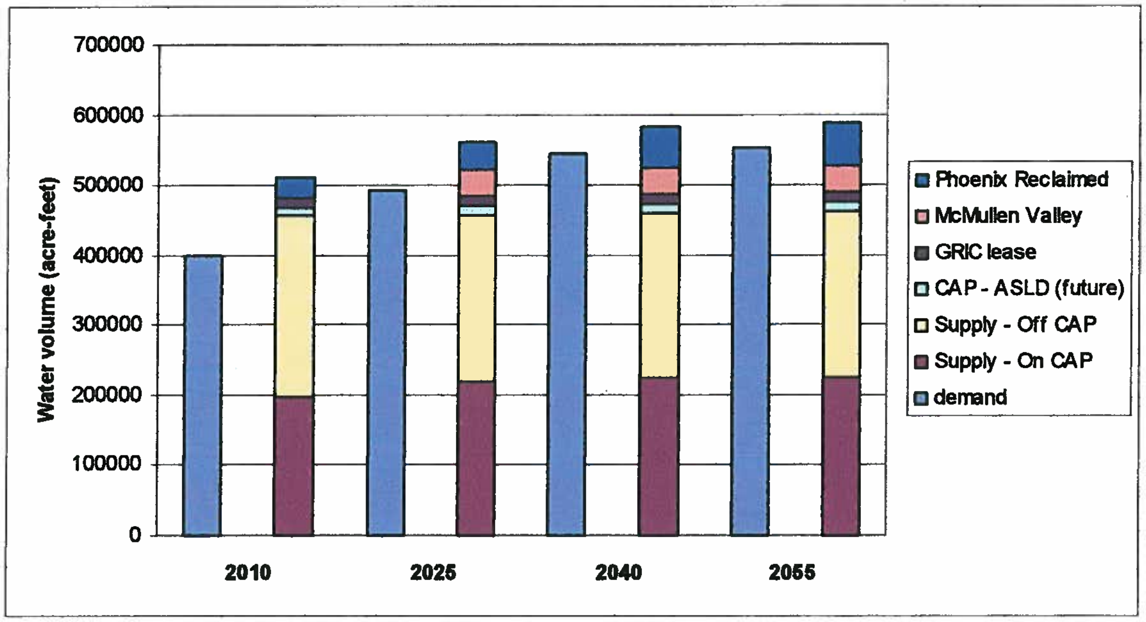

Figure 7. City of Phoenix water supply and demand for the future (ADWR, Third Management Plan, 1999)

Another example of the reuse of effluent is the South Waste Water Treatment Plant in the city of Surprise, Arizona, a suburb of Phoenix. The South Waste Water Treatment Plant (WWTP) will serve as a model for other city waste water plants due to its effective use of effluent for the city's needs. The plant supplies treated effluent via pipeline to several public facilities requiring irrigation, as well as several agricultural fields (Figure 8). The pipeline, which has an initial diameter of 30 inches, is able to carry 5,650 gallons per minute. After approximately three-fourths of a mile, the pipeline's diameter drops to 24 inches. Within another half mile, two laterals (branches), each 12 inches in diameter, take water from the mainline to irrigated fields lying to the west and to the east. The main line runs another half mile where another 12 inch lateral carries water to the west to irrigate another field. At this point the diameter of the main line drops to 16 inches.

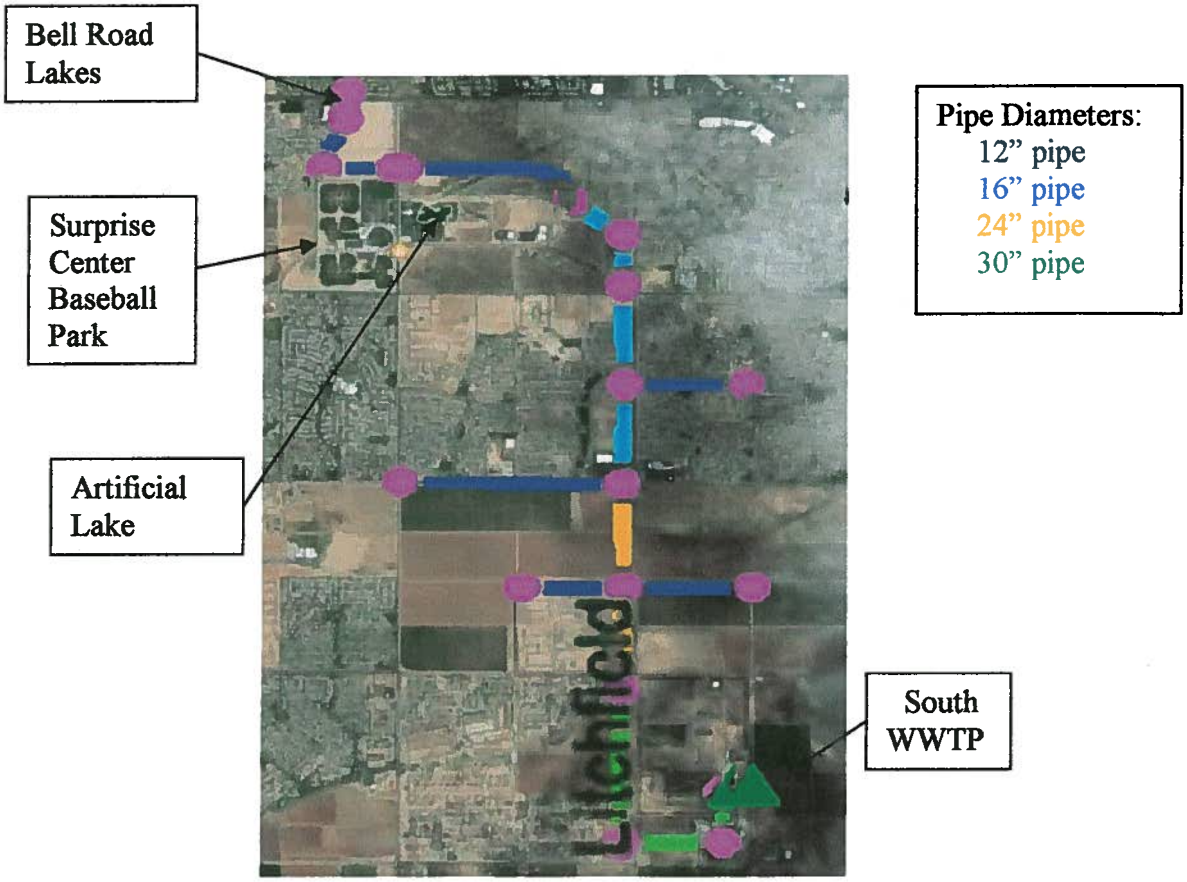

Figure 8. Arial photograph of Surprise reclaimed water system and pipeline (Google Earth, 2007 and City of Surprise Water Resources Master Plan, 2004)

A half mile later another lateral line carries water to a subdivision for irrigation of small parks. Traveling 0.63 miles further north, the pipeline bends to the northwest and the diameter drops to 12 inches. About 1 mile later it reaches the Surprise Center baseball park where reclaimed water from the plant is used to irrigate 13 regulation baseball fields. Just east of the Surprise Center is an artificial lake with a sand beach used for recreation. Water for this lake is also provided by the pipeline. Finally approximately a half mile further on, reclaimed water from the pipeline supplies water to create the Bell Road Lakes. This lake area is a city park for the city of Surprise, and includes a large grassed area and several artificial lakes complete with water features (S. Pezzelle, personal conversation, March, 2007).

Summary

In the United States primary responsibility for water resources management rests with the individual states, therefore, local planning and responsibility over water supplies is crucial. In the first half of the 20th century the federal government took the lead in water management by initiating large water development projects in the western United States by building huge dams that the Department of Interior still manages. However, the states and local governments that make use of the water are the primary managers through laws, contracts, and regulations. State agencies also set rules for drilling wells and pumping water from underground. Municipalities ensure that the water they deliver meets health and quality specifications.

Water resources engineers working in the metropolitan areas of Phoenix, Arizona, Las Vegas, Nevada, and Salt Lake City, Utah are continuing to develop projects that will provide more water to these areas through conservation and more efficient pipeline systems, agricultural transfers, and reuse. One of the major issues to be resolved is the needs and wants of rural versus urban areas. Rural has water, urban wants it, and the money and influence are largely on the side of the cities (Roessler, 2006). In the West, the adage that "water flows uphill to money," appears to be confirmed by the vigorous expansion of cities (Fort, 2006). The life of rural America in the West depends on the decisions about how water is shared and how to strike the right balance.

Phoenix, Las Vegas, and Salt Lake City are all transferring water from farming and irrigation to municipal use. In the case of Phoenix, a finite water supply from the Colorado River, the Salt River Project, and underlying groundwater is being supplemented with a few in-state groundwater development projects. Much of the water is saved, banked, and traded in an effort to distribute the finite resource among an expanding population. The level of complexity of the water management system both in terms of legality and facilities requires a sophisticated and varied approach. In addition, Phoenix must negotiate with Indian communities who have claims to water resources.

The Southern Nevada Water Authority pipeline system that would take underground water from the Great Basin aquifer system and pump it to Las Vegas is an expensive project to build and maintain and some questions remain about the availability of the water the SNWA needs to make the project feasible. The pipeline extends 285 miles and environmentalists are concerned that the Snake and Spring valleys will achieve the same fate of rural areas in California after the Owens River Aqueduct project. The Owens Lake which used to be one of the largest natural lakes in California and the surrounding Owens Valley are now sources of dust pollution and the city of Los Angeles is being required to spend nearly $500 million to bring the area into compliance with the air quality regulations under the Clean Air Act (Roessler, 2006).

In general, the removal of large quantities of groundwater harms streams and surface water in arid areas. The zone of vegetation near a stream known as the riparian zone may disappear as streams lose more of their water to a drier earth. Eventually, species of fish, birds and other inhabitants of these oases disappear. Desert environments are fragile and drying up of streams, ponds, and wetland can have very profound effects.

Because water in the Great Basin is shared across state boundaries—Nevada, Utah, California, Oregon, Wyoming and Idaho—and different states have different laws and plans for water, decisions about water are difficult and divisive. Hydrologists attempt to get an idea of what will happen when water is removed from an aquifer, but often disagree about what the models predict (Roessler, 2006). In the case of Salt Lake City, transfers of water from agriculture are the largest source for increasing urban demand. Water quality in Salt Lake City is a primary factor that limits development, the need to treat water for salinity and organic material makes providing water a very expensive prospect for an expanding population.

Climate research data reveal that in the southwestern United States temperatures are expected to increase. While predictions vary as to whether the climate will be wetter or drier, variability in precipitation is expected that may result in higher frequencies of drought and intense storms. Glacier and snowpack levels are also expected to decrease. The water level in the Colorado River water has been decreasing substantially for the past 10 years. In opposition to this data, the assumption behind the rapid growth in western cities is that water supplies are more than sufficient to provide for urban uses and that piped water, desalinization, and recycling will provide water into the future (Fort, 2006).

As the western climate changes and the population grows, officials are searching for water to fill current and future needs. Competing water users are battling each other and some states are waging legal fights. Seven states that draw water from the Colorado

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