FEASIBILITY OF AQUIFER STORAGE RECOVERY FOR THE MUSTANG, OKLAHOMA WELL FIELD

By

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CHAPTER 1

INTRODUCTION

Purpose and Objectives

The purpose of this study is to determine the economic and geochemical feasibility of utilizing aquifer storage recovery (ASR) technology to store water in the Central Oklahoma Aquifer (COA) for use by the City of Mustang. The objectives are twofold:

- Determine whether arsenic concentrations in the COA will be reduced or increased by introducing a new water source via ASR wells.
- Determine whether the costs associated with implementing ASR and the associated benefits would prove more economical than the current means by which Mustang provides water for its residents.

This was accomplished by studying the geology and geochemistry of the COA, and determining the suitability of the aquifer for storage and recovery of a non-native water source, with minimal mixing occurring between the two waters. Water samples from the native ground water and from the proposed non-native source were collected, and the chemistries determined. Computer modeling with WATEQ4F software was utilized to determine whether injecting a foreign water source into the aquifer would cause precipitation of minerals from the surrounding rock and/or mixed waters. Data from previous ASR research and programs were studied in order to identify the costs associated with implementing the technology within the Mustang well field.

Background

The presence of high levels of arsenic in ground water has become almost a worldwide epidemic in the last decade. According to Arthur (2005), ten percent of 30,000 arsenic analyses of ground water exceeded the maximum contaminant level (MCL) established by the U.S. Environmental Protection Agency (EPA) of 10 parts per billion (ppb). Anthropogenic sources of arsenic include insecticides, phosphate fertilizers (phosphate can mobilize arsenic into ground water), and wood preservatives. In nature, arsenic occurs throughout the earth's crust and precipitates into ground water when the minerals surrounding it dissolve (WHO, 2001). It is mostly found as trivalent arsenite (arsenic hydroxide) or pentavalent arsenate (arsenic acid). Arsenic in ground water has received increased attention in recent years because it has been linked to high levels of cancer, skin lesions and other health problems in Bangladesh, China, Argentina and the U.S., among other places (Pearce, 2003). Accordingly, the EPA has mandated that by January, 2006, all public water supplies must meet a new MCL of 10 ppb, lowered from the previous standard of 50 ppb.

Prevention and control of arsenic in drinking water can be complex. Field test kits are not accurate enough to detect concentrations at the low levels that threaten human health. Furthermore, as the targeted concentration of arsenic in a water supply decreases, expenditure and complexity of remediation increase. Technology for removal of arsenic at hand-pumps and other collection points has not been proven, and household removal systems must be adapted to each new setting and tested for sustainability (WHO, 2001).

Aquifer storage recovery (ASR) may be useful in helping to dilute arsenic concentrations in ground water. ASR is the storing of water in a suitable aquifer through a well during times when water is available, and recovery of the water via the same well during times of peak demand or drought (Pyne, 1995). The concept includes pumping the excess water into an aquifer (as underground storage), then reversing the pumps during the dry months to meet demands on water supply. Utilization of ASR to store water of potable quality is routine in many areas of the United States, and is increasing in other countries as well. For example, in 1996 Britain began a study of hydrogeological and regulatory issues pertaining to using ASR technology in Britain (Pyne, 2002). The United States currently has the most operating ASR sites. Australia is second (Dillon, 2004).

Some of the benefits of ASR include:

- Less water evaporates when water is stored underground as compared to a surface reservoir.
- Less impact to the land and environment than surface reservoirs. In fact, the land directly above an ASR project can often continue its prior use.
- The ability to store water during wet periods to use during critical times of drought.
- Water stored underground is less vulnerable to contamination than surface reservoirs.
- Much greater storage capacity than above-ground tanks.
- Eliminates the possibility of structure failure, due to evaporitic sediments such as gypsum (Horvath et al., 1997).

The injected water displaces the ambient ground water and forms a plume. Mixing with the native water occurs at the edges of the plume. The area where mixing occurs is known as the buffer zone. Several test cycles in a new ASR well will help build and define the buffer zone, leading to better recovery of stored water.

Schools of Thought

Arsenic Contamination

The engineering approach to preventing arsenic in drinking water generally involves filtration. Most filtration systems work in one of two ways: either water is passed through a barrier that will not allow the arsenic molecule to pass through, or chemicals are added to water, to which arsenic bonds, and then the water is passed through a barrier that does not allow the arsenic compound to pass through. Reverse osmosis (RO), coagulation filtration (CF), and diatomaceous earth (DE) filtration are three types of filtration that are currently being used or are being considered for use in removal of arsenic from drinking water. According to the EPA Office of Water (1998), CF is an adequate method of treatment for removal of arsenate. Research is currently being conducted on the effectiveness of DE filtration for the removal of arsenic from drinking water. Reverse osmosis systems are available at hardware stores and can be installed under the sink in homes to remove arsenic at the point of use.

The geologic solution to keeping arsenic out of drinking water is to drill in areas where no arsenic is present. For example, geophysical cross-sections can be used to identify the various stratigraphic layers within an aquifer (Figure 1). Once the layers are identified, tests can be performed on waters in each individual layer that can denote which layers contain arsenic-laden waters. The wells can then be modified so that no perforations are made within the arsenic-bearing layers.

A third approach to managing arsenic in drinking water involves utilizing ASR. Recall that effective use of ASR is site-specific. In this instance, ASR becomes a combination of the engineering and geologic approaches, in that water with an arsenic concentration below the acceptable level is stored in the aquifer, displacing the ambient ground water with high arsenic concentrations.

Water Storage

ASR offers several benefits over surface storage. First, storage capacity underground is limited only by the size of the aquifer where the water will be stored. Usually, aquifers

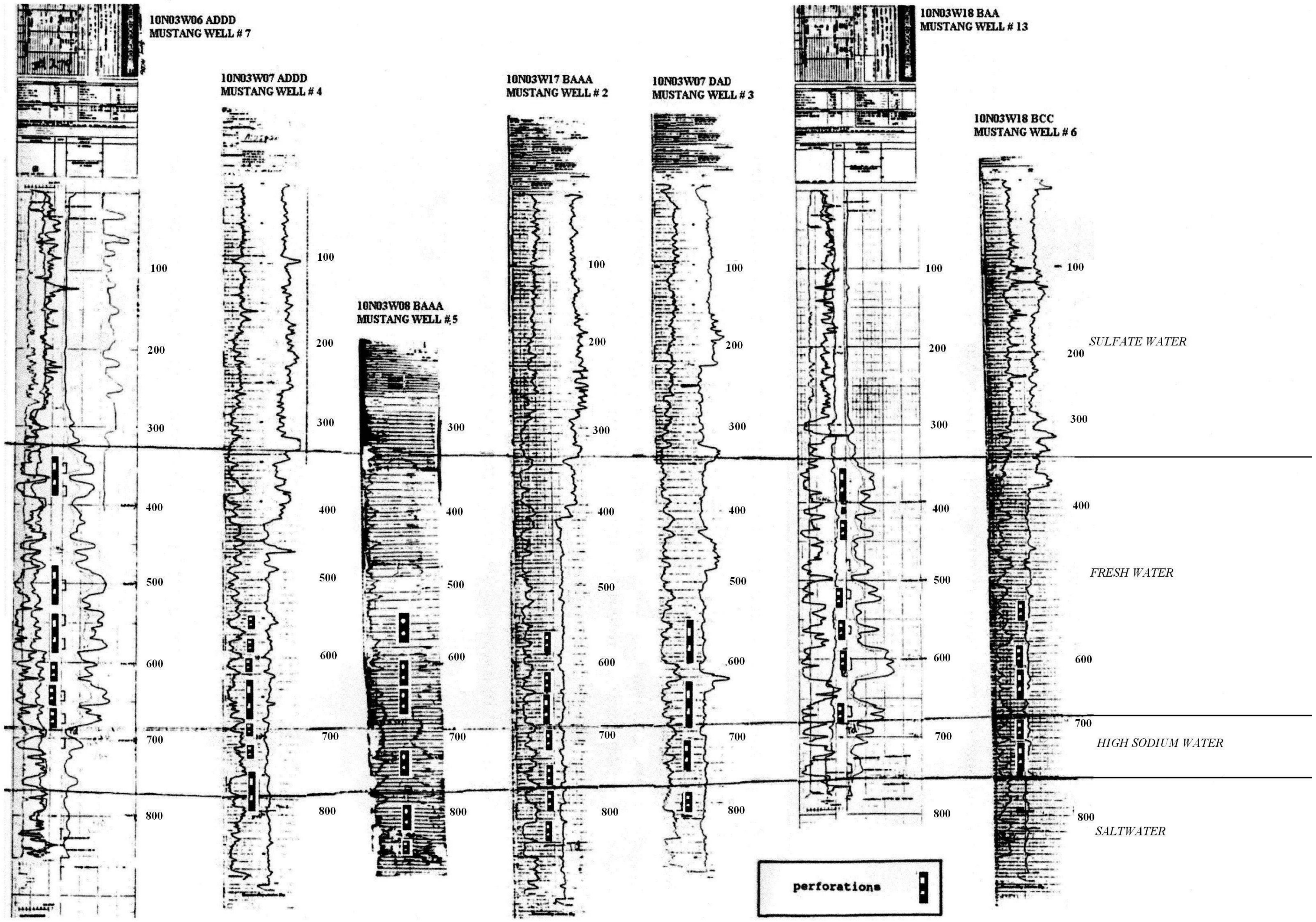
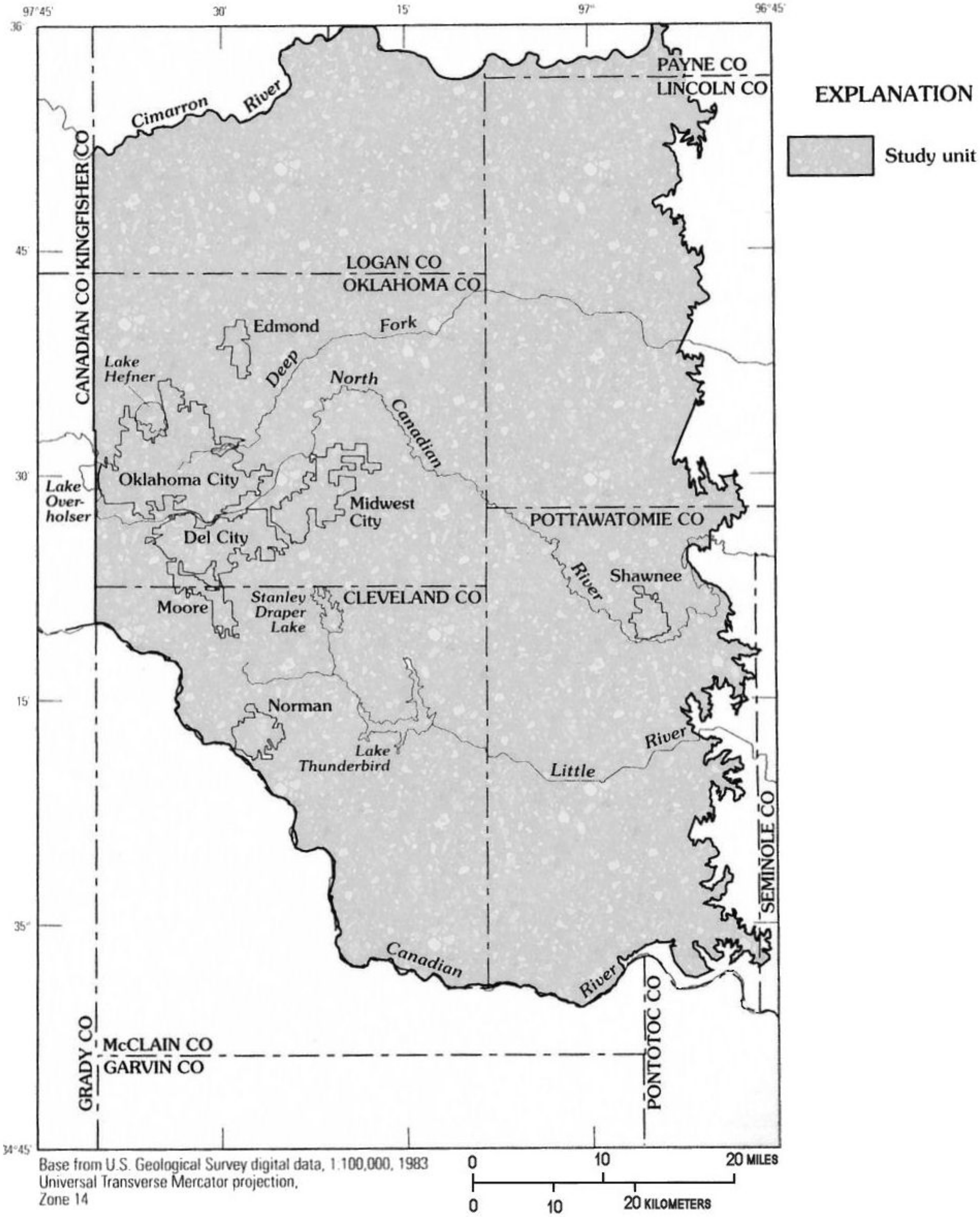


Figure 1. Cross-section of Mustang water wells, showing water chemistries and perforation intervals.



Base from U.S. Geological Survey digital data, 1:100,000, 1983
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Figure 2. Geographic extent of study area. Adapted from Christenson (1998).

are much larger than any surface area. For example, the COA (Figure 2) underlies 3,000 mi^2 beneath all or parts of Cleveland, Lincoln, Logan, Oklahoma, Payne, and Pottawatomie counties (Christenson, 1998). Second, less infrastructure is necessary, which decreases costs. Third, less operation and maintenance are needed since there are fewer infrastructure elements furthering costs.

Implications of the Study

Most of the cities that utilize the COA for drinking water supplies draw water from the western, confined, deeper portion of the aquifer where arsenic concentrations are greatest. According to Schlottmann (2001), at least 37 percent of wells greater than 90 meters (~295 feet) deep will exceed the new standard for arsenic in drinking water.

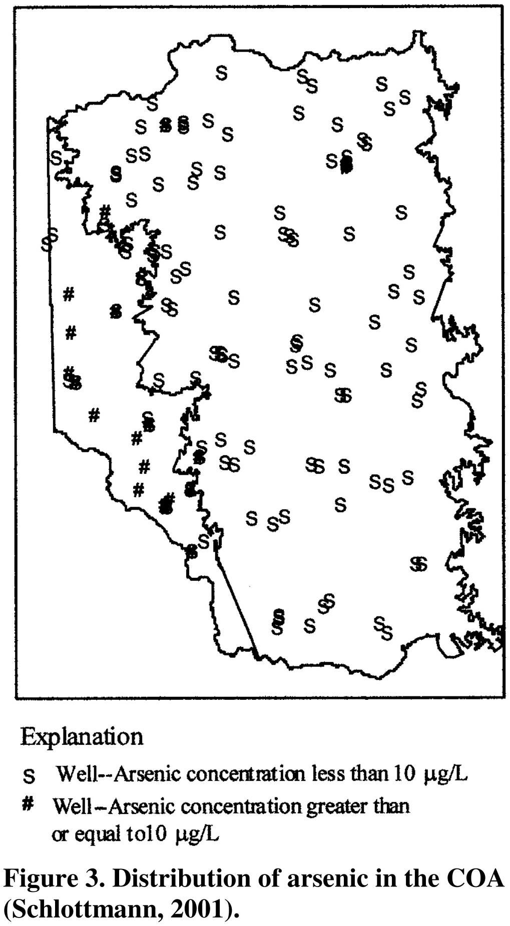

Figure 3. Distribution of arsenic in the COA (Schlottmann, 2001).

By utilizing ASR to store water in the wells where arsenic concentrations are highest, the new water source may displace the native ground water, thereby decreasing the overall arsenic content in the water supply system enough that it will meet the new EPA standard for drinking water. This would prove particularly useful for the city of Mustang in Canadian County, Oklahoma. Mustang is located on the western side of the COA in central Oklahoma, approximately 15 miles southwest of Oklahoma City.

Mustang is currently experiencing high growth rates and correspondingly needs to meet the growing demand for water for its residents. In 2003, Canadian County had the third highest population growth rate of the 77 counties in Oklahoma (5.9%). For comparison, Oklahoma County, which includes the largest city in Oklahoma (Oklahoma City), had a population growth rate of 2.4% the same year. Thirty-five Oklahoma counties experienced a population decrease in 2003 (ePodunk Inc., 2005). Mustang is especially well-suited to achieve the purpose and objectives of this study, as it may lose the use of some of its municipal water wells due to lowering of the MCL of arsenic in drinking water. The city presently has 11 municipal wells which pump at capacity during peak use seasons, but Wells 2 and 6 have been taken off-line due to high levels of arsenic and selenium.

Mustang also purchases water from Oklahoma City to help meet its demand. Mustang could independently meet its drinking water needs during off-peak months, but the current purchase agreement with Oklahoma City stipulates that Mustang must buy a minimum of 250,000 gallons per day (gpd) throughout the year. However, even though the contract stipulates a daily amount, the total is tallied monthly, and must average out to the minimum daily amount (Wilkins, pers. comm., Dec. 8, 2005).

Even if the city does not use the minimum amount, it must still pay for the minimum. Mustang could benefit by using ASR to store the unused portion of the water purchased, so it is not simply wasted.

Moreover, arsenic concentrations in the western portion of the COA do not meet the new lower MCL of 10 ppb. If a solution for the high arsenic levels within the aquifer is not found, Mustang will not be able to utilize at least two of its municipal water wells for drinking water needs.

CHAPTER 2

REVIEW OF LITERATURE

Geology

The Central Oklahoma Aquifer underlies 3,000 mi^2 of central Oklahoma (Christenson, 1992). The major water-yielding geologic formations that make up the Central Oklahoma Aquifer include, from youngest to oldest, the Permian-aged Garber Sandstone, Wellington Formation, Chase Group, Council Grove Group, and Admire Group.

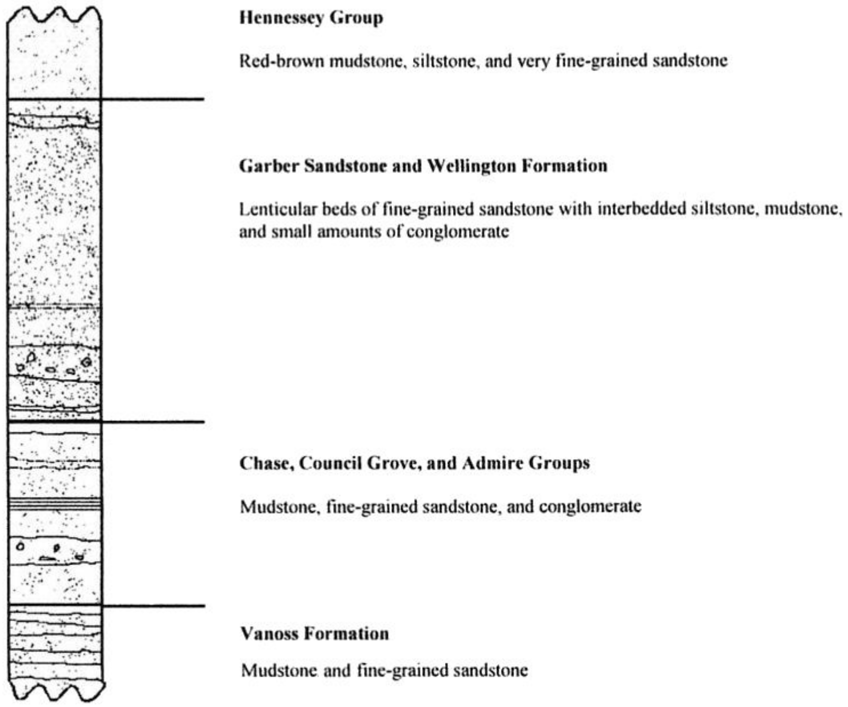

Figure 4. Generalized Stratigraphic column of the COA (adapted from Breit, 1998).

Quaternary terrace and alluvial deposits that occur alongside major streams above the aquifer also contain significant amounts of ground water (Christenson, 1998). These deposits are separated from the western one-third of the COA by the Hennessey Shale, but this formation was eroded away from the eastern two-thirds of the aquifer before the Quaternary deposits occurred.

Christenson and Parkhurst (1987) describe the geology of Quaternary alluvium associated with overlying streams as the youngest geologic deposit of the COA. Clay, silt, sand and gravel make up the deposits, with poorly-sorted quartz sand being the dominant sediment. Brown is the most common shade, but colors range from white to red. While alluvial deposits exist along most of the perennial streams overlying the aquifer, the largest deposits exist along the Canadian and North Canadian rivers, where they can be up to three miles wide. In the thickest parts of the deposits and where gravel beds are present, wells in the alluvium may have yields as high as 700 gallons per minute (gpm).

Terrace deposits formed before the alluvium. These deposits exist above the current floodplain, because the stream valleys have since been deepened by erosion. The breadth of the band of terrace deposits varies from one-half to eight miles, and maximum thickness is about 100 feet. These sediments are channel and floodplain deposits from the Pleistocene Epoch. Like the younger alluvium deposits, the terrace deposits are composed of lenticular beds of clay, silt, sand, and gravel. Well yields in the terrace deposits may be as high as 300 gpm.

The western one-third of the aquifer is confined by the Hennessey Group, but erosion has removed this formation from the eastern two-thirds (Parkhurst, et al., 1995).

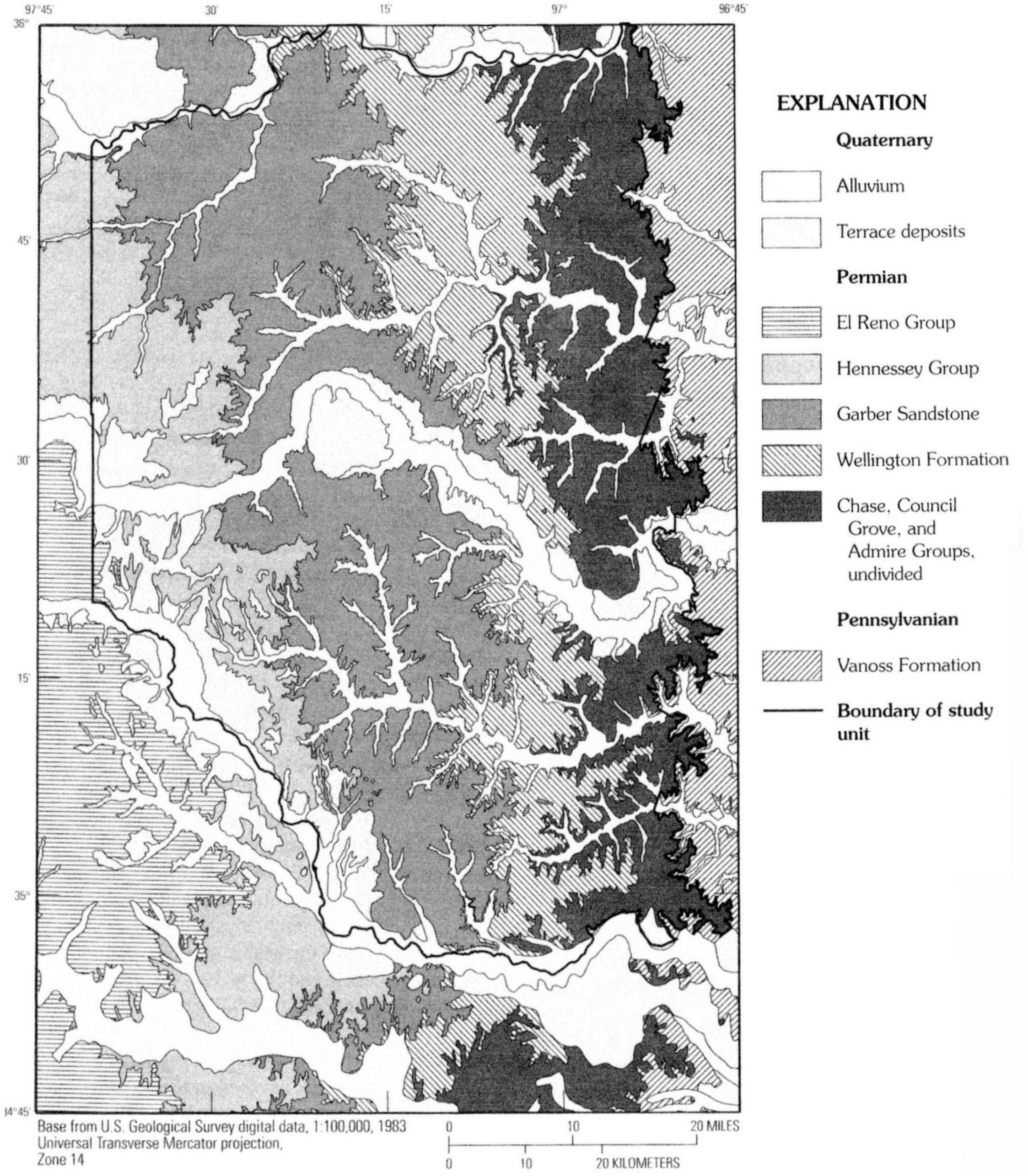

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Figure 5. Geologic map of central Oklahoma with study area defined (Christenson, 1998).

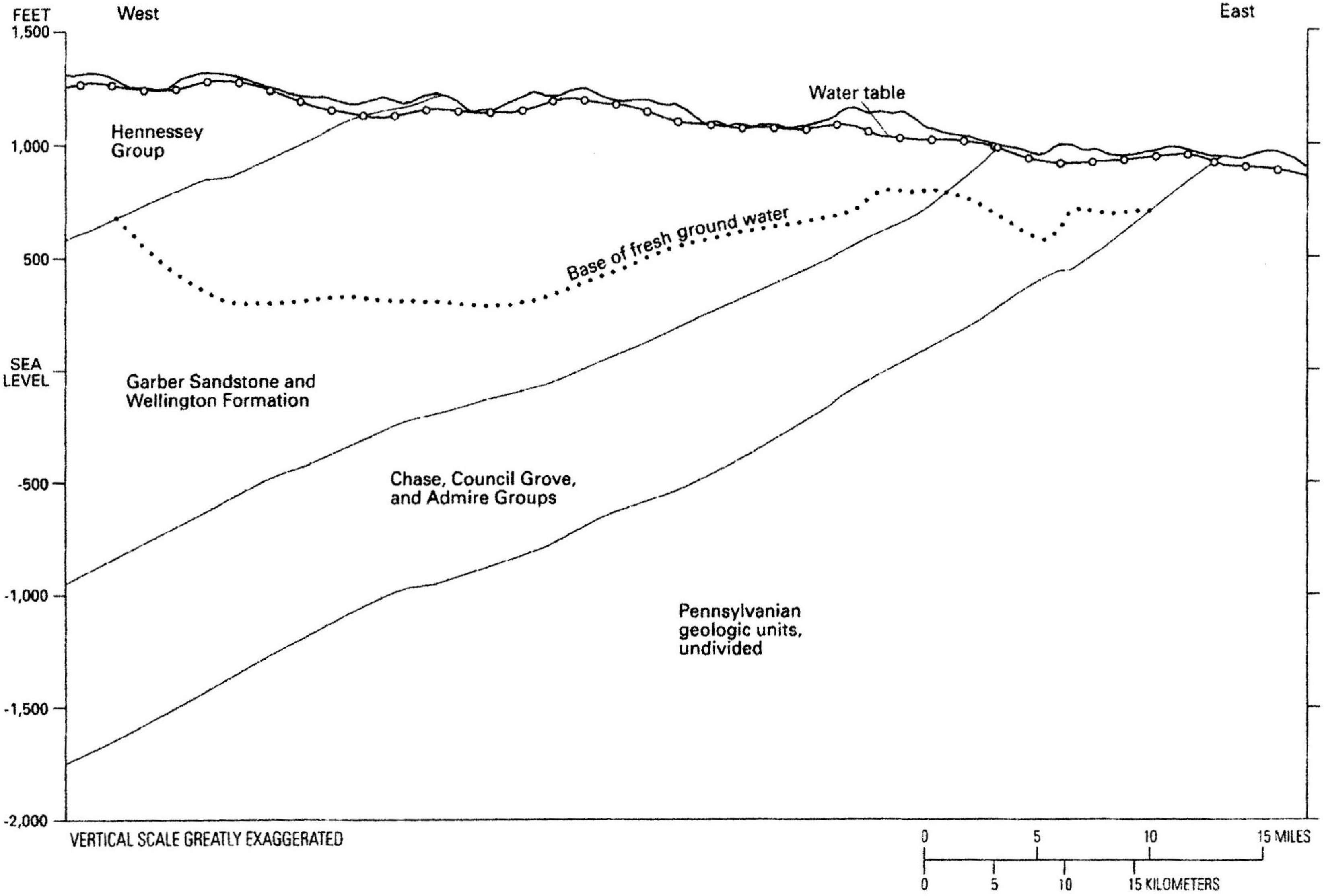


Figure 6. Cross-section through the COA (Christenson, 1998).

The Hennessey Group consists of the Fairmont Shale, Kingman Sandstone, Salt Plains Formation and Bison Formation (Mosier and Bullock, 1988), but is usually undifferentiated in literature. The Hennessey Group is composed of reddish- brown shales and mudstones that are interbedded with thin, very fine-grained sandstone layers (Parkhurst, et al., 1995). The group reaches a maximum thickness of approximately 656 feet (Mosier and Bullock, 1988).

Since the Hennessey Group is mainly composed of siltstone and shale and has little transmissivity, it is not considered as part of the COA. However, a few low-yielding wells have been completed in the Hennessey for domestic and stock uses (Christenson and Parkhurst, 1987).

The Garber Sandstone and Wellington Formation underlie the Hennessey Group in the western one-third of the COA, and extend east at the surface through the center of the aquifer. However, the formations have eroded away in the eastern one-third (Christenson, 1992). Where the complete sequence can be found, the combined thickness of the two geologic formations ranges from 1165 to 1600 feet (Christenson, 1992). The units gently slope westward to the Anadarko Basin at about 50 feet per mile (Figures 6 and 7).

Because the Garber Sandstone and Wellington Formation are lithologically similar, they are often treated as one geohydrologic unit in literature (Breit, 1998; Christenson, 1992; Christenson and Parkhurst, 1987; Gromadzki, 2004; Keester, 2002; Mosier and Bullock, 1988; Parkhurst, et al., 1995; Quint, 1984). Most of the ground water flow occurs within these two formations. These units are composed of siltstone and mudstone that are interbedded with lenticular beds of cross-bedded, fine-grained sandstone. The sand grains within the sequence are predominantly quartz, and the sandstone is brittle. In the central part of the aquifer, approximately 75 percent of the total thickness of the units is sandstone (Christenson and Parkhurst, 1987). However,

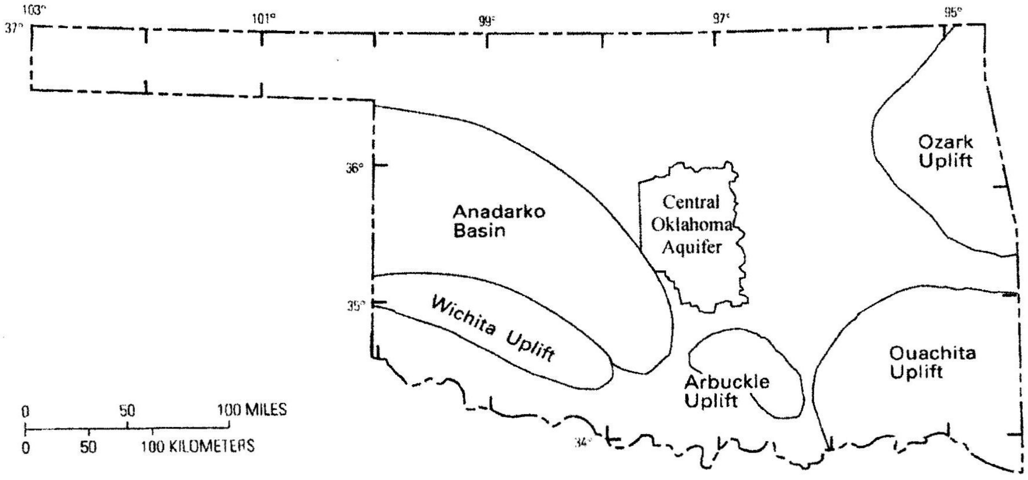


Figure 7. Approximate locations of majors uplifts and basins adjacent to the COA (Breit, 1998).

the percentage of sandstone decreases and the percentage of siltstone and mudstone increases in all directions from the central part of the aquifer (Parkhurst, et al., 1995). The Garber and Wellington formations are believed to have been deposited in a fluvial/deltaic sedimentary environment. Lithology can vary greatly over short expanses (Christenson and Parkhurst, 1987).

The largest ground water yields in the COA come from wells that are completed in both the Garber and Wellington formations. These wells usually yield from 100 to 300 gpm because the sandstone is fine-grained. However, a few of the wells completed in both units will have yields as high as 600 gpm (Christenson and Parkhurst, 1987).

The Chase, Council Grove and Admire Groups are also frequently undifferentiated because of their lithologic similarities (Breit, 1998; Christenson, 1992; Christenson and Parkhurst, 1987; Gromadzki, 2004; Keester, 2002; Mosier and Bullock, 1988; Parkhurst, et al., 1995). These units are composed of shale and thin limestone that are interbedded with beds of cross-bedded, fine-grained sandstone. Where exposed at the surface in the easternmost part of the aquifer, these formations are almost indistinguishable from the Garber and Wellington formations (Christenson and Parkhurst, 1987). The combined thickness of the Chase, Council Grove and Admire Groups varies from 570 to 940 feet, with the median thickness being 745 feet (Breit, 1998). Wells that are completed only in these formations commonly yield 10 to 100 gpm, but some wells yield up to 120 gpm (Christenson, 1992).

The underlying confining layer of the COA is the Pennsylvanian-age Vanoss Formation. This unit is composed mainly of shale interbedded with thin, fine-grained sandstone beds. This formation has very low transmissivity and does not yield significant volumes of water to wells (Christenson and Parkhurst, 1987).

Christenson, et al. (1998) estimated the following median values of aquifer properties: recharge, 1.6 in/yr; porosity, 0.22; storage coefficient, 0.0002; transmissivity, 350 ft^2/day; horizontal hydraulic conductivity of sandstone strata, 4.5 ft/day; and a ratio of horizontal to vertical hydraulic conductivity of 10,000. Christenson, et al. (1992) found the average hydraulic gradient of the aquifer to be .01.

The Central Oklahoma Aquifer is commonly referred to locally as the Garber-Wellington Aquifer, since most of the ground water circulation occurs in the Garber Sandstone and Wellington Formation. However, the alluvium and terrace deposits, Chase, Council Grove, and Admire Groups also contribute to the ground water and flow system that make up the aquifer. Furthermore, a decrease in transmissivity within the Garber Sandstone and Wellington Formation means that parts of these units are not included in the aquifer (Christenson and Parkhurst, 1987). For the purpose of this paper, the aquifer will be referred to as the Central Oklahoma Aquifer.

Geochemistry

In the parts of the aquifer that are less than 100 feet deep, ion concentrations are closely correlated with geologic units. The dominant cations of the Garber Sandstone and Wellington Formation are magnesium and calcium, and the dominant anion is bicarbonate. In the Chase, Council Grove and Admire Groups, as well as in the Hennessey Shale, larger concentrations of sodium, sulfate and chloride can be found. In the deep part of the aquifer (defined as depths greater than 300 feet), calcium magnesium bicarbonate water dominates the unconfined part, while ground water in the western, confined part of the aquifer contains larger sodium concentrations (Christenson and Parkhurst, 1987).

From Figures 8 and 9 (Parkhurst, et al., 1995), some generalized conclusions can be drawn. In the unconfined part of the Garber Sandstone and Wellington Formation and in the alluvium and terrace deposits, calcium, magnesium, and bicarbonate are the dominant ions. In the Hennessey Group, the confined part of the Garber Sandstone and Wellington Formation, and the Chase, Council Grove, and Admire groups, sodium and bicarbonate are the dominant ions. Similar concentrations of bicarbonate are found throughout the aquifer. The largest concentrations of sulfate are found in the Hennessey Group and the southern part of the confined Garber Sandstone and Wellington Formation (Parkhurst, et al., 1995), while the largest concentrations of

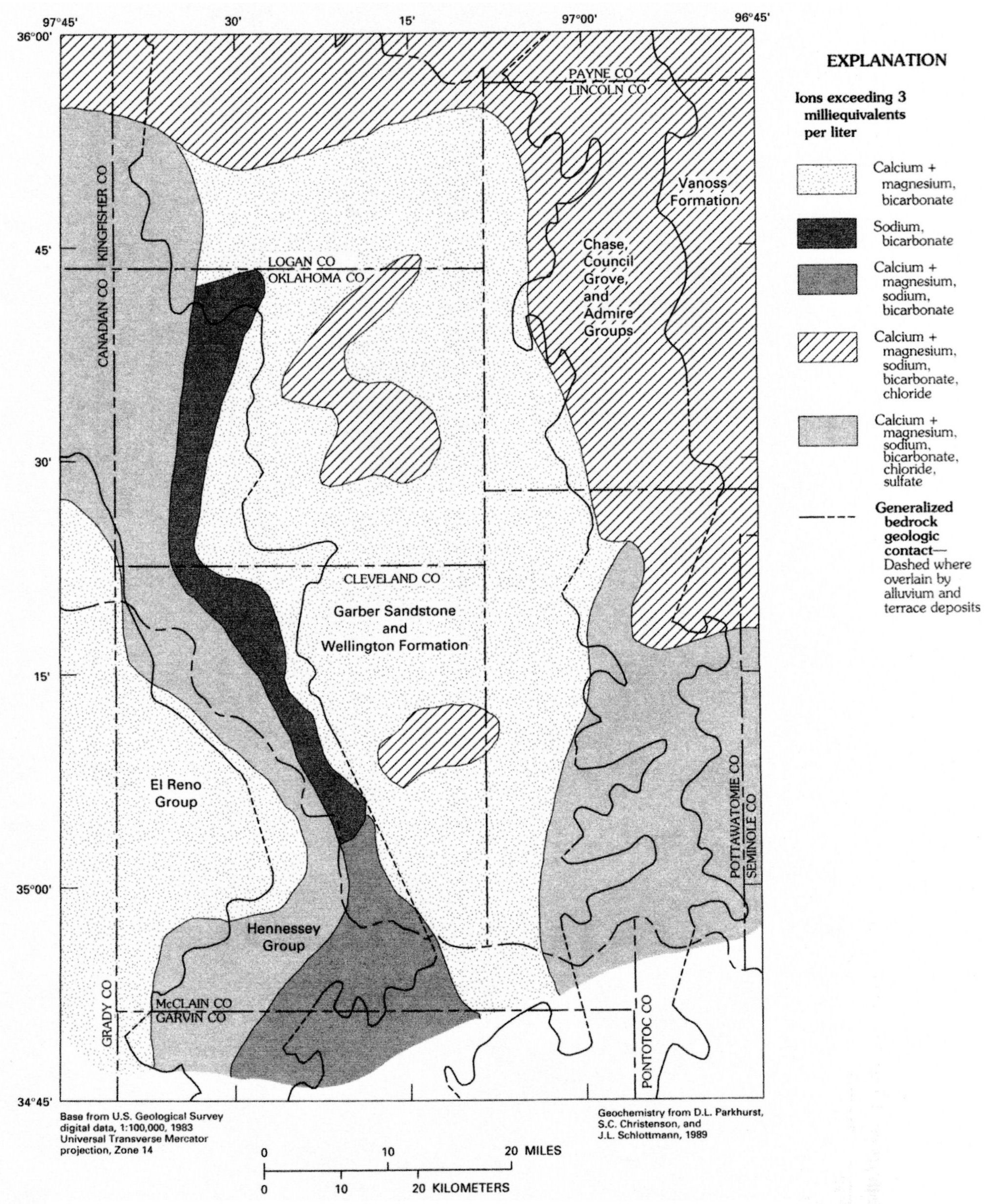


Figure 8. Major element chemistry in the shallow part (<100 ft) of the study area (Parkhurst, et al., 1995).

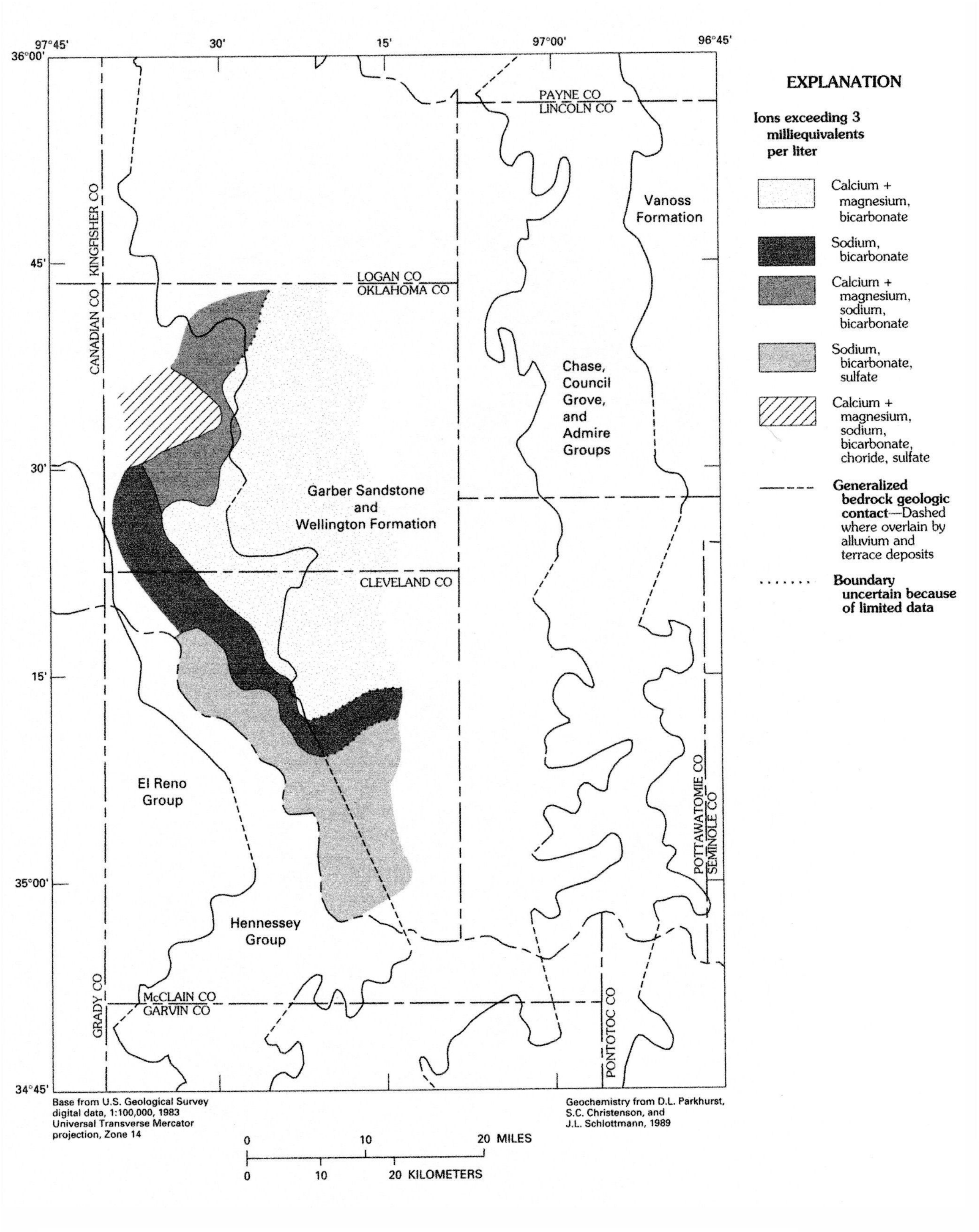


Figure 9. Major element chemistry in the deep part (>300 ft) of the Garber Sandstone and Wellington Formation (Parkhurst, et al., 1995).

chloride tend to be in the deep parts of aquifer and especially in the northwestern part of the deep confined Garber Sandstone and Wellington Formation.

Because brines underlie the entire aquifer, the mixing of fresh water with these sodium chloride brines is a predominant geochemical reaction that affects ground water composition in the COA. Ratios of bromide to chloride within the brines point toward the brines as the source of chloride in the overlying fresh water of the aquifer.

Dissolution of gypsum can account for the large concentrations of sulfate, commonly found in the Hennessey Group. Leakage from the Hennessey Group into the confined part of the Garber Sandstone can account for large concentrations of sulfate within that unit.

Uptake of carbon dioxide is another important geochemical reaction that controls the ground water compositions in the COA. In recently recharged water, partial pressures of carbon dioxide range from .1 to .01 atmospheres, and carbon-13 isotope ratios range from -10 to -20 per mil. These values indicate that the source of carbon dioxide is from the unsaturated zone of the aquifer, and not from the atmosphere. As there is no evidence that indicates carbon dioxide is produced within the saturated zone or that it migrates up from lower depths, it is safe to assume that the unsaturated zone is the only source of carbon dioxide within the aquifer.

Dissolution of dolomite and (to a much lesser extent) calcite within the aquifer is a result of uptake of carbon dioxide by water that leaches through the unsaturated zone to greater depths. As dolomite dissolves in waters rich with carbon dioxide, calcium magnesium bicarbonate water is produced. In shallow parts of the unconfined aquifer, lack of carbonate minerals limits carbonate dissolution and the water becomes undersaturated with dolomite and calcite. The pH in this setting is usually 6.0 to 7.25.

Throughout the rest of the aquifer, water sufficiently saturated with dolomite and calcite signifies dolomite equilibrium. Because the water composition of dolomite equilibrium is similar to calcite equilibrium, the fate of calcite in the aquifer is uncertain. It may dissolve or precipitate, or it may not be present. The pH in water where dolomite equilibrium has occurred is about 7.5.

A cation exchange that occurs on clays that are abundant within the confined part of the aquifer can account for changes in sodium concentrations. In this part of the aquifer as well as in clay-rich parts of the unconfined aquifer, as much as 50 percent of exchangeable cations in the clays is sodium. As sodium is released to the water and calcium and magnesium are taken up by the clays, a small amount of dolomite dissolves to maintain equilibrium, which in turn causes the pH to increase to the range 8.5 to 9.1. However, the bicarbonate concentration increases only slightly (Parkhurst, 1992).

The effect this process has on trace elements within the aquifer is important. As recharge water moves through the aquifer and its chemical composition is altered by the cation exchange on clays, elements such as arsenic disseminated in the rocks are oxidized to more soluble forms. The dissolved-oxygen-rich recharge water, coupled with the high pH of some aquifer waters, encourages oxidation of trace elements and expedites their mobilization in the ground water (Breit, 1992; Mosier and Schlottmann, 1992). Christenson (1998) noted large concentrations of oxygen, nitrate, arsenic (V), chromium (VI), selenium (VI), vanadium, and uranium in both confined and unconfined parts of the aquifer, and referred to them as an indicator of an oxic or post-oxic oxidation-reduction environment. This terminology is borrowed from Berner (1981), who proposed a system of redox environments in sedimentary deposits that can be extrapolated for use with classification of ground water systems as well. The oxidation-reduction environments are categorized based on the absence or presence of specified redox minerals and dissolved redox species. The systems in this classification are oxic, post-oxic, sulfidic and methanic (Parkhurst, et al., 1995). The alluvium and terrace deposits, the Chase, Council Grove and Admire Groups, and the confined and deep, unconfined parts of the Garber Sandstone and Wellington Formation are most commonly post-oxic environments; that is, lacking in any measurable dissolved oxygen. There is almost no instance of sulfidic or methanic environments. Minerals containing elements in reduced oxidation states are limited to diminutive, condensed zones that are less than one centimeter in diameter (Christenson, et al., 1998).

Arsenic in the Central Oklahoma Aquifer

Historic data reviewed by Schlottmann, et al. (1998) revealed that arsenic concentrations greater than the then-current MCL of 50 ppb were common in the deep, confined parts of the Garber Sandstone and Wellington Formation, but were atypical of other parts of the aquifer (Figure 10). The researchers repeated this finding in a 1987-89 study; five of 141 samples collected exceeded the standard, and all five were from the

Table 1. Summary statistics for arsenic, adapted from Schlottmann, et al. (1998).

			Percentiles								
Constituent	**Sample Size**	**Minimum Value**	**5**	**10**	**25**	**50**	**75**	**90**	**95**	**Maximum Value**	**Number That Exceeded Standard**
Arsenic, dissolved (µg/L as As)	141	<1	<1	<1	<1	1	2	19	43	110	5

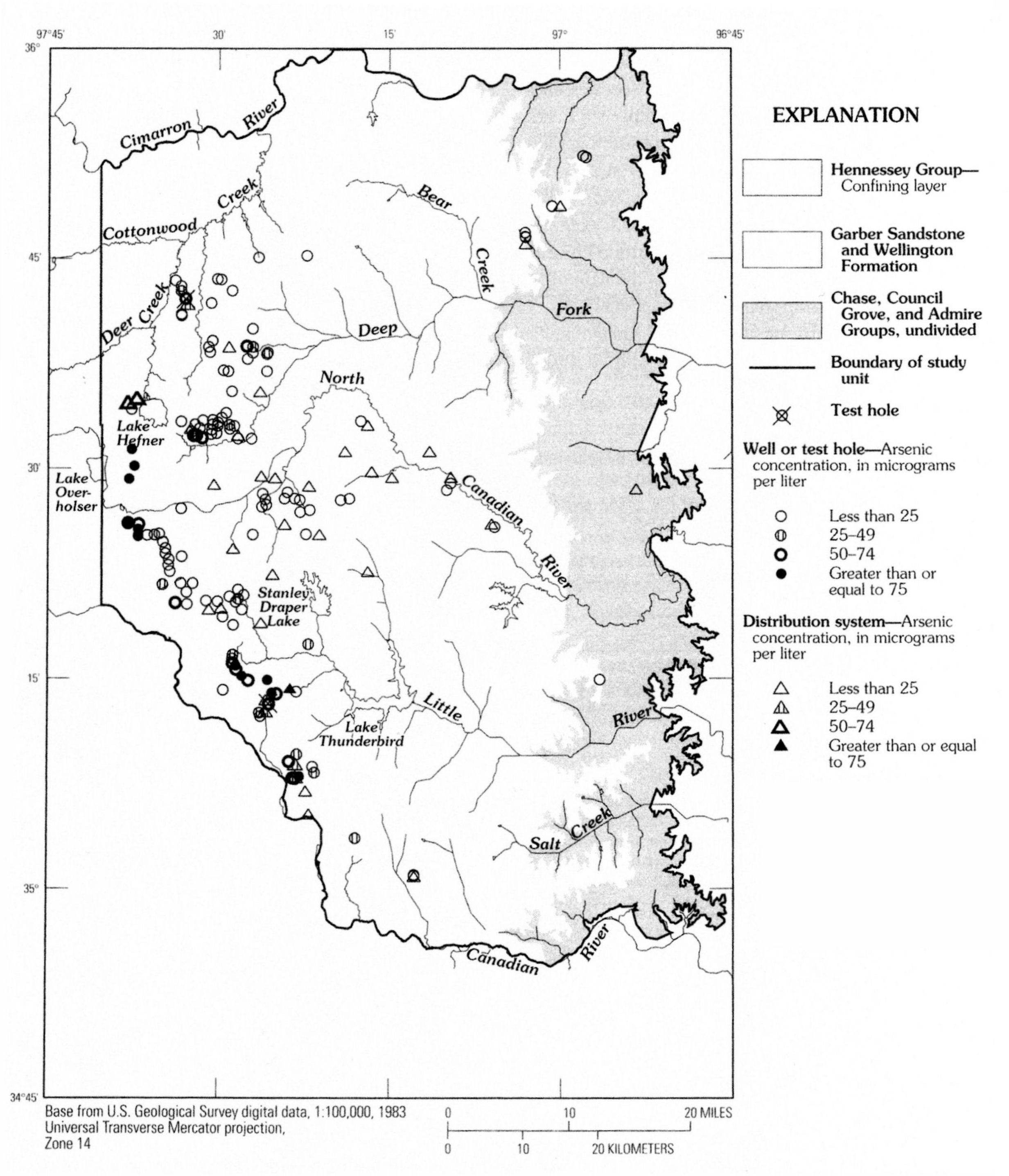


Figure 10. Areal distribution of arsenic concentrations in water from deep (>300 ft) wells, test holes, and distribution systems in the study area. Adapted from Schlottmann, et al. (1998).

deep, confined Garber and Wellington formations (**Error! Reference source not found.**). Similarly, Keester (2002) found that arsenic concentrations increase in the western deep confined part of the aquifer, as well as in Logan County and in the vicinity of the city of Edmond.

Schlottmann (2001) and Breit (1998) found that sandstone with grain coatings of yellow-brown goethite contained the greatest concentrations of arsenic. These layers were most often found in the Garber Sandstone and generally were less than six inches thick (Schlottmann, et al., 1998). Goethite, hematite and dolomite are the major hydrogenous minerals within the aquifer. A notable characteristic of the aquifer is the abundant red coloring of the rocks. This is attributable to grain-coating iron oxides that are typical within the aquifer, signifying the generally oxidized nature of the rocks.

Even though the highest arsenic concentrations are found in sandstones containing goethite grain coatings, the mudstone in the aquifer typically contains higher concentrations of arsenic than the sandstone (Schlottmann, 2001). However, extraction of arsenic from the mudstone is probably insubstantial compared to its extraction from the sandstone. The low permeability and higher concentration of exchangeable cations in the mudstone impact the amount of dissolved arsenic present and affect the water chemistry. The low hydraulic conductivity of mudstones promotes higher residual concentrations of arsenic because less flushing can occur (Schlottmann, et al., 1998).

Even in waters where dissolved oxygen content was too low to be detected, arsenic in its most oxidized state [As(V)] was discovered (Schlottmann, 2001). Thus, it is reasonable to assume that most of the aquifer exists in oxic or post-oxic environments. Moreover, the parts of the aquifer where dissolved oxygen is undetectable are recharge through clay-rich soils, which support development of reducing conditions and may justify the oxygen deficiency (Schlottmann, et al., 1998). In an oxic or post-oxic environment, arsenic exists as As(V), and its mobilization is improved in waters with high pH (Keester, 2002; Schottmann, 2001).

Dissolution of dolomite in the deep or confined parts of the aquifer where carbon dioxide is absent leads to a large increase in pH (8.5-9.1). Data from Schlottmann (2001) point out a strong association involving dissolved arsenic and pH (Figure 11). Twenty-six of 27 samples with arsenic concentrations greater than 10 ppb had a pH of 8.5 or higher. (The 27th sample had a pH of about 7.0, and may be due to water mixing in the borehole).

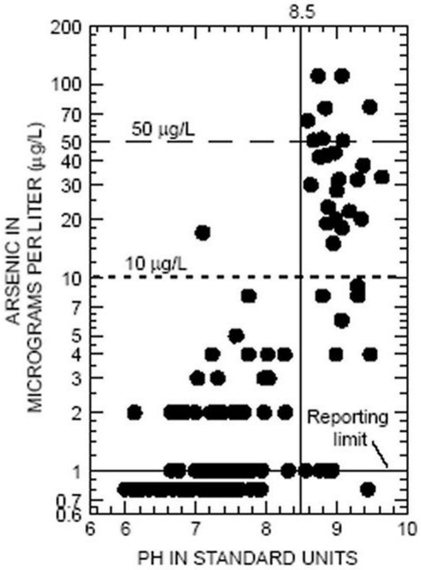


Figure 11. Relation of arsenic to pH.
Adapted from Schlottmann (2001).

In waters with a pH of 7.0 or higher, As(V) exists as the oxyanion arsenate in the monovalent and divalent species $HAsO_4^{2-}$ and $H_2AsO_4^{2-}$ (Mosier, 1998; Schlottmann, 2001). Arsenate sorbs to positively charged iron oxide surfaces, which are abundant in the COA. As pH increases, desorption of arsenate from iron oxide surfaces is augmented, expressive of the positive relationship between arsenic and pH.

Water in the aquifer with a pH of less than 8.5 generally contains low accumulations of arsenic. Concentrations greater than 10 ppb in high-pH waters exist frequently in the confined part and deep, unconfined, clay-rich parts, but are uncommon in the unconfined, sand-rich parts of the aquifer (Keester, 2002; Schlottmann, 2001).

Mosier (1998) performed sequential extractions on samples with high arsenic concentrations. As much as 77 percent of arsenic in the samples dissolved in hydrochloric acid (HCl), but association with iron extracted by HCl in these samples was not strong (r^2=0.2, where r^2=1 is ideal). Thus it is safe to assume that not all iron oxides in the aquifer have equal arsenic concentrations. A significant amount of arsenic that most likely adsorbed on mineral surfaces was extractable using potassium dihydrogen phosphate. Other extractions designed to imitate high pH and oxidizing environments caused a substantial percentage of arsenic to dissolve, suggesting that a considerable amount of dissolved arsenic in the aquifer derives from arsenic adsorbed on mineral surfaces, most likely goethite and hematite. A greater amount of arsenic was extracted using potassium dihydrogen phosphate than sodium bicarbonate (which mimics high pH). This shows that increase in pH and carbonate ligand exchange are not as important as phosphate ligand exchange for release of arsenic from iron oxides.

Table 2. Concentrations of arsenic and major characteristics of water from test holes in the study area. Adapted from Schlottmann, et al. (1998). [Geohydrologic zones: SUGW, shallow unconfined Garber Wellington; SCA, shallow Chase-Admire; DUGW, deep unconfined Garber Wellington; SCGW, shallow confined Garber Wellington; DCGW, deep confined Garber Wellington].

Test Hole	Sampling depth interval (ft)	Arsenic, dissolved (μg/L as As)	pH (std units)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)	Water type	*Geohydrologic zone*
NOTS 1A	166.0-186.0	53	8.8	29	27	Na HCO_3	SUGW
	210.0-248.0	69	8.9	54	39	Na HCO_3	SUGW
NOTS 2	96.4-116.0	20	9.0	13	12	Na HCO_3	SCA
NOTS 3	110.0-129.0	1	7.3	12	25	CaMg HCO_3	SUGW
	110.0-129.0	1	7.3	12	25	CaMg HCO_3	SUGW
	155.4-174.4	23	8.9	13	20	Na HCO_3	SUGW
NOTS 4	87.0-115.0	1	7.7	5.8	4.2	CaMg HCO_3	SUGW
	142.2-170.2	2	7.7	7.2	4.8	CaMg HCO_3	SUGW
	178.0-200.0	1	7.8	5.1	17	CaMg HCO_3	SUGW
	243.5-271.5	1	7.7	9.3	6.9	CaMg HCO_3	SUGW
NOTS 5	48.0-76.0	1	7.5	31	34	Na HCO_3	SCA
	48.0-76.0	1	7.5	31	35	Na HCO_3	SCA
NOTS 6	96.4-116.8	1		9.9	18	CaNaMg HCO_3	SUGW
	121.4-160.5	1		11	18	CaMgNa HCO_3	SUGW
	161.2-200.3	2		12	18	MgCaNa HCO_3	SUGW
	161.2-200.3	2		12	13	MgCaNa HCO_3	SUGW
	203.2-242.3	2		11	11	MgCaNa HCO_3	SUGW
	266.0-286.0	3		11	14	NaCaMg HCO_3	SUGW
	286.0-306.4	1		13	10	Na HCO_3	SUGW
	307.5-346.6	3		11	9.9	Na HCO_3	DUGW
	456.0-494.2	65		110	72	Na HCO_3Cl	DUGW
NOTS 7	229.2-276.2	33	9.6	16	44	Na HCO_3	SCGW
NOTS 7A	316.6-343.6	51	9.1	14	76	Na HCO_3	DCGW
	397.0-418.0	20	9.3	6.8	25	Na HCO_3	DCGW
	460.0-500.0	9	9.3	6.2	17	Na HCO_3	DCGW
	460.0-500.0	8	9.3	8.2	18	Na HCO_3	DCGW

ASR

As previously stated, ASR is a process for storing water in a suitable aquifer through a well during times when water is available, and recovery of the water via the same well during times of peak demand or drought (Pyne, 1995). Figure 12 is a depiction of ASR storage in a confined, brackish aquifer.

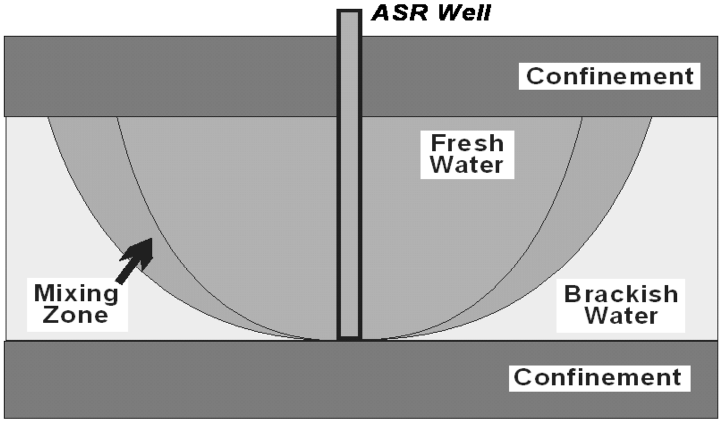


Figure 12. Idealized representation of ASR storage in a confined, brackish aquifer (Missimer, et al., 2004).

The injected water displaces the native water and forms a “bubble” or plume. Mixing with the ambient ground water occurs at the edge of the bubble, creating a buffer zone between the two water sources. The bubble in Figure 12 is idealized for a homogenous and isotropic aquifer with high intergranular porosity. There is some debate about its actual shape. In fact, the shape of the storage bubble is site-specific, owing to the local hydrogeology (Upchurch and Dobecki, 2004). Stratigraphic layers of differing geologies within the same aquifer have different hydraulic characteristics. Some of the factors affecting bubble shape include depositional variations in hydraulic conductivity, dissolution, and fracturing (Missimer et al., 2004). For this reason, Missimer et al. (2004) have proposed that often the “bubble” may take a shape similar to the one in Figure 13.

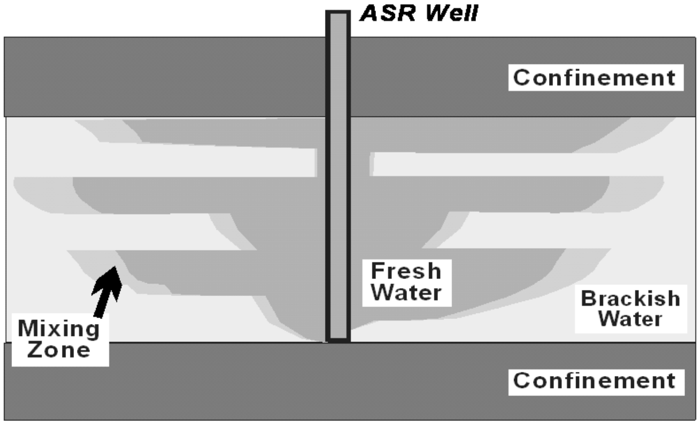


Figure 13. Depiction of the effect of differing geologic layers on the shape of the storage plume (Missimer, et al., 2004).

Vacher et al. (2006) used displacement and dispersion models to predict the shape of an ASR storage plume in a karst limestone aquifer, and identified the shape as a “bottle brush.” The authors also noted that the shape of the plume has no direct bearing on the prediction of recovery efficiency of the injected water; however, the “bottle brush” model accounted for unrecovered tracer chemicals that are not accounted for with the “bubble” model.

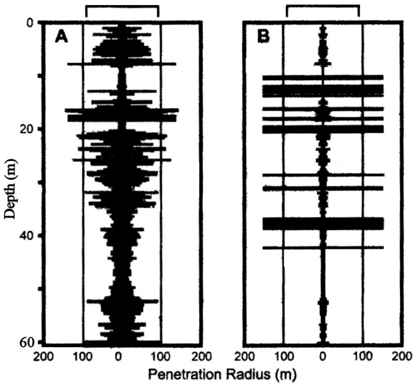


Figure 14. Penetration of injected water into a storage zone with 200 layers using a displacement model. ***A*** **shows matrix permeability alone;** ***B*** **showss matrix plus secondary permeability. The brackets indicate penetration in an equivalent homogeneous bubble (Vacher, et al., 2006).**

Planning Approach

Implementing a site-specific plan for an aquifer storage recovery project increases the chances of success (ASCE, 2001). Dividing the project into phases is the most accepted approach. In this way, fiscal investment and physical effort can be matched to the level of risk. Pyne (1995) states that at least three phases are usually needed:

- Phase 1: Preliminary Feasibility Assessment and Conceptual Design
- Phase 2: Field Investigations and Test Program
- Phase 3: Recharge Facilities Expansion

Funding constraints, especially during field analysis, may necessitate the need for more than three phases. This paper will focus primarily on Phase 1 considerations as defined above.

Economics

ASR is a low-cost alternative to surface reservoirs. Land requirements are minimal; in fact, the land directly above an ASR project can often continue its prior use. Storage capacity is limited only by the size of the aquifer. No structures are needed and hence significantly less maintenance and operation costs are incurred (Bloetscher, et al., 2005; Pyne, 1995).

A preliminary estimate of capital and operating costs for an aquifer storage recovery project should be developed early on. Having a feasible estimate of general costs is necessary for comparison with other water management alternatives (ASCE, 2001). Where external supplies of water are utilized, it may be appropriate to include financing or water payment aspects in the economic analysis. For example, purchasing more water during off-peak times can significantly decrease unit costs. Unit cost reductions have exceeded 50 percent for wholesale purchasers in systems where this method has been evaluated (Pyne, 1995). The economic analysis should also include amortization of capital investment as well as annual operation and maintenance costs.

An ASR project may be economically justifiable without being financially feasible. A financial feasibility assessment should be completed as part of the economic analysis. The purpose is to determine how the ASR project will be financed. For instance, a municipality may sponsor the project through revenue bonds or ad valorem taxes. If bonds are used, the interest rate will affect the financial viability of the project (ASCE, 2001).

ASR is a viable, cost-effective technology. However, feasibility of ASR is site-specific. A test program that incorporates all associated permitting, legal, environmental, economics and water rights issues should be satisfactorily completed as demonstration of ASR feasibility for the site (Pyne, 1995). This typically requires a few months to a year to complete (Rivers, et al., 2003).

Pyne (1995) collected construction and engineering cost data for nine ASR sites in the United States. Some sites retrofitted existing wells for ASR capability, while others developed new wells. Some of the sites provided data on successive phases of ASR expansion, and some sites provided cost information on alternatives to ASR. Three sites provided information on operation and maintenance costs. Individual well yields ranged from 0.5 to 1.5 million gallons per day (mgd). Table 3 provides the data, with all monetary values expressed in 1993 U.S. dollars.

Table 3. Capital and operating costs for nine ASR systems in the U.S. Adapted from Pyne (1995).

Site	**Year**	**Yield (mgd)**	**Cumulative No. of wells**	**Capital Cost**	**$/mgd**	**Operating Cost ($/mgd)**
Peace River, FL	1984	1.5	2	702,000	468,000	
	1988	3.4	6	1,342,000	395,000	
	Est. 1994	3	9	1,300,000	433,000	20,000
	Est. 1997	14	23	8,200,000	586,000	
Cocoa, FL	1987	1.5	1	444,000	296,000	
	1992	6.5	6	1,314,000	202,000	6,000
Marathon, FL	1993	0.5	1	827,000	1,654,000	
	Est. 1995	3	8	3,000,000	1,000,000	40,000
Kerrville, TX	1991	1.8	2	987,000	548,000	
Centennial, CO	1992	0.7	1	410,000	586,000	
Seattle, WA	1993	5.1	3	1,670,000	327,000	
Swimming River, NJ	1993	1.7	1	600,000	353,000	
Callegulas, CA	1991	1	1	459,000	459,000	
	Est. 1994	6.5	6	1,278,000	256,000	
Murray Avenue, NJ	Est. 1994	1.5	1	950,000	633,000	

The following conclusions were drawn by Pyne, based upon analysis of the nine ASR sites:

1. The average cost for an ASR facility is about $400,000/mgd. The first new ASR well generally has higher unit costs associated with it due to the additional equipment required for installation, especially if the well is far from existing pipelines. However, retrofitting of old wells and ASR expansion

projects involving multiple wells generally are associated with lower unit costs.
2. Additional costs are incurred by the first ASR well in order to establish ASR plausibility. Unit costs for subsequent ASR wells are generally lower, because regulatory authorization is more easily obtainable. The difference in unit cost between the first and subsequent wells is usually in the range of $100,000 to $200,000/mgd.
3. ASR is usually less than half the cost of other water supply alternatives, when comparing capital cost per unit of new capacity. Proficient use of pipelines, pumping stations and other major facilities, and the low costs associated with underground storage leads to cost savings that in some cases reach almost 90 percent.
4. Of the sites that provided data, annual operating cost ranges from about $6,000 to $40,000/mgd. This includes operation and maintenance costs as well as nominal costs for power and chemicals needed during recharge and recovery of stored water. The site in Marathon, FL stores treated drinking water in a saltwater aquifer. Accordingly, operation costs are higher, and tend to approach $15,000/mgd of recovery capacity.

It is important to use the same basis when comparing other water management options to ASR. Comparing the cost per unit production is generally appropriate when comparing capital costs, because many ASR wells only recover water during part of the year but still increase system peak capacity. The total annual production from an ASR facility may not be very large if the peak demand period is short. For this reason, it is generally inaccurate to compare capital costs on the basis of dollars per unit volume recovered.

Table 4 gives a comparison of capital costs for comparable levels of service with and without ASR for five water utilities. The savings with ASR was due either to reduction or elimination of a surface reservoir, or to eliminating the need for a pipeline or

Table 4. Capital costs with and without ASR for five utilities (Pyne, 1995).

Location	Expansion Cost ($Million)	
	With ASR	Without ASR
Wyoming, MI	9	31
Peace River, FL	46	108
Manatee County, FL	2	38
Florida Keys, FL	3	38
Kerrville, TX	3	30

treatment plant expansion. The Peace River site shows the least savings through utilization of ASR, but even this site reduced expansion costs by 57 percent. This savings is great enough that even if the ASR facility experiences technical or regulatory challenges, it will still be able to provide gainful service for the owner and consumer. Coupling ASR with more resourceful use of current facilities may enable the provider to defer or even eliminate expansion plans (Pyne, 1995).

Regulatory Issues

State Regulations

Aquifer storage recovery wells are regulated as Class V injection wells by the EPA as part of the Underground Injection Control (UIC) program (EPA, 1999). Oklahoma is a UIC Primacy State for Class V wells, which means that the EPA has delegated primary responsibility for implementing the UIC program to state authorities. No special provisions have been created in the state's Administrative Code (OAC) addressing ASR or artificial ground water recharge. The only criteria specified in the Code pertain to permitting. An applicant for a Class V injection well facility must (EPA, 1999):

- Perform ground water monitoring
- Provide an analysis of injected fluids and a description of the geologic strata through which and into which injection is taking place
- Provide any additional information that the applicant believes is necessary for compliance with the U.S. Code of Federal Regulations (CFR) Title 40, Section 144.12 (252:652-5-3 OAC)

Federal Regulations

A summary of current federal regulatory considerations is presented below.

EPA Surface Water Treatment Rule If a water treatment facility utilizes surface water as its drinking water source, the facility is required to treat the water for viruses and *Giardia lamblia* cysts. This rule results in reduction of organic and solids content in the recharge waters, and supplies a sufficient disinfectant residual. Aboveground storage during chlorination is generally necessary so that the disinfection residual is present when injection occurs (Bloetscher, et al., 2005). The rule became effective in June, 1993 (EPA, 1999).

Increased contact time with the disinfectant residual may be important to adequately treat the water source. Thus, ample water storage space is necessary to provide the required contact time. Utilization of ASR storage instead of storage in a surface reservoir is a more cost-efficient way to provide the necessary time. Data collected at ASR facilities has shown that disinfectant residuals are present in the aquifer for at least one day (Pyne, 1995).

EPA Disinfection Byproduct Rule This rule regulates carcinogenic organic compounds in drinking water more stringently. Concentration of these compounds is dependent on the concentration of organics in the water source, as well as the disinfectant residual and contact time during the treatment process. National Primary Drinking Water Regulations (NPDWRs) were established that set maximum residual disinfectant levels, MCLs, or treatment techniques for the compounds and their byproducts. Monitoring, reporting and public notification requirements were also established by the NPDWRs. The rule went into effect in December, 1998 for public community water systems as well as noncommunity systems that use a chemical disinfectant for either primary or residual treatment (EPA, 1999).

Disinfection with free chlorine is generally associated with high levels of disinfection byproducts (DBPs). Consequently, use of chloramines as a disinfectant is becoming more common. Chloramines ensure adequately low concentrations of DBPs but are a weaker disinfectant than chlorine.

A conflict associated with the Disinfection Byproduct Rule is that by disinfecting a water source enough to meet the standard for fecal coliform, the DBP Rule may be violated. This inhibits the use of waters of reduced quality for injection (Bloetscher, et al., 2005). However, it has been shown that use of ASR for seasonal storage has resulted in significant reduction of DBP concentrations. Further research in this area could point to a resolution of the conflict. Moreover, updating a water treatment facility to include ASR technology could potentially provide an economical means of long-term or seasonal storage while simultaneously ensuring sufficient contact time with a free chlorine residual. At the same time, the requirements of the Disinfection Byproduct Rule are met through the extended treatment that occurs during several weeks of aquifer storage. This idea should be explored further with site-specific evaluations at several representative locations (Pyne, 1995).

EPA Underground Injection Control (UIC) Program Ground water management within the U.S. is a matter governed by individual states. The only federal legislation that addresses the subject is the 1974 Safe Drinking Water Act (SDWA), which provides all citizens with the right to a clean and safe drinking water supply. Part C of the SDWA deals with underground injection control. The UIC program divides injection wells into five categories, with the first four well categories being acutely defined (Table 5).

Table 5. Classes of injection wells as defined by the EPA Underground Injection Control program (CH2MHill, 1997).

UIC Well Classes	
Class I	Inject hazardous and nonhazardous waste beneath the lowermost formation containing, within one-quarter mile, an underground source of drinking water (USDW).
Class II	Used in conjunction with oil and gas production, primarily to inject salt water.
Class III	Used in conjunction with the solution mining of minerals.
Class IV	Inject hazardous or radioactive waste into or above a formation within one-quarter mile of a USDW.
Class V	Includes wells not included in the above four classes.

Any injection well which does not fall into Classes I – IV is placed in Class V, and this includes ASR wells. The numerous injection practices included in the Class V category necessitate stringent regulation, because some of them could potentially be harmful to drinking water supplies. It is unfortunate that ASR technology is subjected to legislation aimed at, for example, septic tanks and poor quality urban runoff (Pyne, 1995).

The purpose of creating the SDWA was to contend with mounting anxiety concerning the susceptibility of drinking water supplies to contamination. The language relating to UIC is found in Part C of the act. It seems clear that its intent is to prohibit contamination of an underground source of drinking water (USDW) with pollutants that would jeopardize the ability of a water treatment plant to readily remove the pollutants before distribution and public consumption:

> Underground injection endangers drinking water sources if such injection may result in the presence in underground water which supplies or can reasonably be expected to supply any public water system of any contaminant, and if the presence of such contaminant may result in such system's not complying with any national primary drinking water regulation or may otherwise adversely affect the health of persons (42 U.S.C. Section 300h(2), et. seq.).

Similarly, the Code of Federal Regulations appears to call for a ban on introduction of a substance into a USDW that still exceeds its MCL after the raw water has been treated and distributed:

> No owner or operator shall construct, operate, maintain, convert, plug, abandon, or conduct any other injection activity in a manner that allows the movement of fluid containing any contaminant into underground sources of drinking water, if the presence of that contaminant may cause a violation of any primary drinking water regulation under 40 CFR Part 142 or may otherwise adversely affect the health of persons. The applicant for a permit shall have the burden of showing that the requirements of this paragraph are met (40 CFR Part 144.12(a)).

Again, the language used gives the impression that the purpose of the legislation is to avoid contaminating an aquifer with pollutants that will force finished water in a public water supply system, not a raw water source, to violate primary standards. Conversely, the EPA interpreted the language to mean that prior to injection, the introduced water must already meet primary drinking water standards. As time goes on, these standards grow more stringent. This interpretation of the rules implies that whenever a proposed recharge source fails to meet drinking water standards, an aquifer exemption would be necessary. An exemption process is available through the UIC program (CH2MHill, 1997). A major exemption (waters with TDS <3,000 ppm) requires approval of the EPA administrator. A minor exemption (waters with TDS

>3,000 ppm) requires the approval of the EPA regional administrator. Through 1995, very few minor exemptions and no major exemptions for Class V wells had been approved. More recent data is not available.

Using ASR to store water of potable quality in fresh or brackish aquifers is a common and acceptable practice in the U.S. (Figure 15). Sixteen states currently operate ASR systems in a method suitable to each state's needs and within UIC guidelines (Pyne, 1995).

Figure 15. Map showing operational ASR sites in the U. S. Current as of March, 2004 (ASR Forum, 2006).

Ownership of the Stored Water The laws of each state determine ground water ownership, but typically if the water user owns the rights to the recharge water prior to aquifer storage, then he has the right to recover the water as well (ASCE, 2001). The California Supreme Court heard a case involving water that had been imported to recharge a groundwater basin. In *Los Angeles v. San Fernando,* the court ruled in favor of the rights of the importer to reclaim the water he injected over the rights of users of native groundwater in the basin. The court held that “the fruits of his expenditures and endeavors” should be credited to the importer (Schneider, 1985).

Even so, in some states where ground water regulations are not specific enough, it is possible for another user to construct a well close enough to the ASR facility to pump out the stored water. The rights owner can protect his resource by locating the ASR site far enough away from property boundaries that the risk of water embezzlement is minimized. Municipal zoning in the vicinity of the facility, establishing a local municipal ordinance, or supplementing state laws to provide for ASR storage may be options for protection as well.

It is important to ensure that once a water user goes through the trouble of diverting, treating and storing surface water underground, he is not limited in the ability to pump the stored water out again at preferred recovery rates because of ground water permitting restrictions. Ground water, surface water, and ASR permitting must be coordinated in such a way that this circumstance is avoided (Pyne, 1995).

Water Level Impacts Long-term recharge circumstances may lead to a significant increase in regional water levels, and significant decline during recovery of the water. Injection into an aquifer that is underutilized could lead to mounding at the surface, resulting in water loss instead of gain. Attempting long-term storage in an aquifer that is consistently overdrafted could result in the injectate being subjected to pumping depressions from other nearby wells (Dickenson, 1997). Both situations must be simulated and calibrated against actual records from observation wells when using computer models for prediction. Otherwise, the calculations of water level impacts may be mistakenly high (Pyne, 1995).

Location for Recovery of Stored Water A benefit of using ASR wells for both injection and recovery of stored water is that this enables the well to be periodically backflushed, which helps maintain its injection capacity. In aquifers where mixing of the native and recharge waters is undesirable, this approach makes it easier to control movement of the storage bubble around the well (Pyne, 1995).

However, sometimes blending of the two water sources is intended in order to create an underground water source of acceptable quality. It is possible to achieve this effect without ASR wells, by designing injection and recovery wells with adequate spacing and capacity between them to allow for the desired blending ratio (Pavelic, et al., 2006; Rinck-Pfeiffer, et al., 2006). There are two problems with this approach. Plugging is a frequent problem with injection wells, and as a result the wells must occasionally be redeveloped. The frequency of redevelopment depends on the frequency of plugging (Pyne, 1995; Segalen, et al., 2006).

The second problem relates to water rights. The ability of a water treatment plant to operate in this fashion may be restricted by laws in some western states where a prior appropriation legal doctrine is adhered to. For example, this type of practice is illegal in Colorado (Pyne, 1995).

Permit Timing Relative to ASR Feasibility Investigations Many different permitting approaches have been used by ASR sites that are now operational. The most economical approach is to construct and test the ASR facilities prior to focusing on permitting issues. Thus, field data can be collected at the ASR facilities under full-scale testing conditions, and subsequent decisions can be made based on actual data for the site rather than on literature values or testing done at other sites (Pyne, 1995).

Technical Issues

Recovery Efficiency

Recovery efficiency is defined as the total volume of water recovered as a percentage of the volume of water recharged, where the recovered water does not exceed pre-established criteria (Pyne, 1995). In the U.S., recorded recovery efficiencies range from 35 to 100 percent. The lower values generally occur in aquifers where transmissivity is high and ambient water has a high saline concentration (Jones, et al., 1999). However, this does not indicate that all saline or brackish aquifers are unfit for ASR storage. Typically after a few cycles where the same volume of water is stored and recovered, brackish water around the well is eliminated and recovery efficiency improves sequentially, often reaching close to 100 percent.

Several factors affect recovery efficiency:

- Bubble movement, as affected by transmissivity of the aquifer, ground water velocity, injection rate, and storage interval
- Density stratification between the ambient and injected waters
- Degree of mixing, and the salinity of the native water
- The dissolution of soluble salts, and other water-rock interactions
- Appropriate design and operation of the borehole or wellfield (Jones, et al., 1999; Merritt, 1985; Petkewich et al., 2004; Reese, 2002)

The definition of recovery efficiency is based on the volume of water stored and recovered. In some cases, recovery efficiency has been evaluated based instead on the amount of a tracer recovered in the recharge water. This approach does not allow for any mixing between the two water sources, and as a result, the measured efficiency will always be lower. It is possible for mixing between the two waters to occur without negating potable use of the recovered water, provided that the degree of mixing does not cause the recovered water to exceed established water quality criteria.

Site-specific hydraulic factors affect the target water quality criteria. Since ASR facilities are generally located near water treatment plants or somewhere along the main water distribution system, blending can occur between the recovered water and the water already in the pipes. As long as this blended water meets the standards for potable water, recovery of stored water can continue. However, once the concentration of the blended water approaches drinking water quality standards, recovery should cease (Pyne, 1995).

The Boynton Beach, FL ASR facility provides an example. Recovery efficiency at this site was reported as 84 percent in a USGS report (Reese, 2002). However, the assumption was made that recovery terminated when the chloride concentration reached 250 mg/l. In reality, recovery at this site generally continues until a chloride concentration of 350 mg/l is reached, because the recovered water is blended with a much larger quantity of fresh water. Pyne (2004) reports a recovery efficiency of 98.6 percent for the same ASR facility.

The initial injection and recovery cycle has several tasks associated with it:

- Verification that wellhead facilities are functioning properly
- Gathering of precursory data concerning aquifer geochemical and biological changes and hydraulic response
- Recovered water quality assessment
- Test program assessment and revisions, if necessary (Pyne, 1995)

The volume of the initial cycle is usually smaller than ensuing cycles.

Water left behind from previous cycles complicates the ability to evaluate recovery efficiency. Thus, the initial storage and recovery cycle is unique in that it provides data that may more accurately reflect the effectiveness of an ASR facility (Jones, et al., 1999; Pyne, 1995). Of even more benefit are graphs detailing the changes in water quality with successive injection and recovery cycles. Mixing and dispersion near the borehole can be determined by examining the shape of the curves. Curves that are flat during the first recovery period signify nominal mixing near the borehole, which in turn suggests that a “buffer zone” will be formed during consecutive cycles leading to higher recovery efficiency (Jones, et al., 1999; Pyne, 1995).

The buffer zone, or zone of dispersion, is usually made of water of marginal quality, because residual water from previous ASR cycles mixes with native water. Additional water from succeeding ASR cycles mixes with this water to increase the volume of the buffer zone, resulting in progressively increasing recovery efficiency for the well (Jones, et al., 1999; Pyne, 1995).

Three to six cycles are usually enough to form an adequate buffer zone and reach the expected recovery efficiency for the site (Pyne, 1995). Merritt (1986) found that recovery efficiency increased by the greatest rate in the first few cycles: 35 percent in the first, 70 percent in the third, and 80 percent in the seventh. However, in more recent years a different approach has been utilized, whereby the buffer zone is created before cycle testing commences. Instead of building the buffer zone through recharge and withdrawal cycles at low flow rates, introducing a supplemental supply of water (for example, having water trucked in) will hasten the formation of the buffer zone leading to higher recovery efficiency over less time (Pyne, 2004). Once this volume is stored in the well, subsequent storage volumes should be fully recoverable so long as the volume recovered varies only slightly from one cycle to the next (Pyne, 2001).

The volume of water required in the buffer zone is site-specific, and is a function of the hydraulic characteristics of the aquifer. Generally it is expressed in terms of days of recovery, ranging from about 50 to 350 (Pyne, 2001).

Aquifers with low permeability, small thickness, and possessing ambient water with low salinity have been shown to yield the highest recovery efficiencies (Kumar and Kimbler, 1970; Merritt, 1985). However, Brown and Silvey (1977) found that in an aquifer that possessed all these characteristics, clay dispersion and swelling still interfered and caused recovery efficiency to decrease with each cycle.

Operational variables also affect recovery efficiency. Storage volume, recharge and recovery rates, and storage time between recharge and recovery can be adjusted for the remainder of the test program according to results from the first cycle. For example, a larger storage volume than initially planned may be necessary to build a more efficient buffer zone (Pyne, 1995). Data collected during the test program can then be used to determine effective ranges for these operational variables with regard to a feasible ASR operation.

A test phase is necessary at any site to verify its maximum recovery efficiency. The buffer zone volume and the number of injection and recovery cycles necessary to achieve maximum efficiency will vary from site to site. There are many factors that can cause less than maximum recovery efficiency to be achieved:

- Density stratification in highly saline aquifers
- Increasing the volume of recharge water in subsequent cycles
- Insufficient number of cycles to develop the buffer zone
- Testing at too small a scale for the storage zone
- High transmissivity values, especially in brackish aquifers
- Large hydraulic gradient (bubble migration)
- Inappropriate ASR well or well field design or operation (Pyne, 1995)

Well Clogging

Clogging, also called plugging, during aquifer recharge can be defined as an increasing resistance to flow, or head buildup near the well. Clogging is the main aspect affecting feasibility of ASR projects (Rinck-Pfeiffer et al, 2000). Clogging generally occurs at the gravel pack, at the borehole wall, or in the formation directly adjoining the borehole wall. Clogging is an unwelcome issue because it changes the hydraulic characteristics of the well and results in a decreasing rate during recharge, and increased drawdown during recovery.

As opposed to injection-only wells, ASR wells can be redeveloped by pumping on a more recurrent basis, since a permanent pump is installed. Given that the ideal approach to redevelopment is periodic pumping, ASR wells are more suited to the task than wells that do not contain a permanent pump.

Several factors affect clogging rates. It is important to understand these factors because the rate of clogging during recharge determines how often redevelopment is necessary, and by understanding, it may be possible to predict redevelopment requirements during the planning stages of an ASR program. Additionally, during the operational stage of the program, this information will be helpful in identifying the source and extent of clogging (Pyne, 1995).

Clogging Processes Five mechanisms are responsible for most clogging issues that occur with recharge wells. These include mechanical clogging due to entrained air and gas binding, physical clogging due to suspended particles, clogging as a result of biological growth, clogging as a result of geochemical reactions, and particle rearrangement (jamming) in the aquifer materials adjacent to the well (Pyne, 1995; Rinck-Pfeiffer et al., 2002; Segalen, et al., 2005).

Air bubbles can be trapped in the well casing or the recharge piping during aquifer recharge. If water with entrained air gets into the well, the air bubbles may be carried into the aquifer formation, where they have a tendency to lodge in pore spaces and cause increased resistance to flow. This can be prevented by proper wellhead operation and design.

A clogging process associated with air entrainment results when dissolved gases are released within the aquifer after injection, causing gas binding. Gas binding occurs when the pump casing becomes so filled with gases or vapor that the impeller cannot contact enough water to operate properly. The impeller spins in the gas bubble, but is unable to force water through the pump. This can lead to cooling problems for the pump's packing and bearings. Gas binding leads to reduced permeability. A decrease in pressure may lead to dissolution of gases in the recharge water, but pressure tends to increase in ASR wells as water is pumped into the aquifer (Pyne, 1995).

Physical clogging occurs when suspended solids from the recharge water clog the pores of the gravel pack, well screens, or aquifer formation. Resistance to flow increases as the particles condense around the recharge well (EPA, 1999).

Practically all recharge water used in ASR wells contains suspended solids, partly due to the fact that data on suspended solid content of a water source are not readily available. Thus, it makes sense to determine the solids content of prospective recharge waters before injection (Pyne, 1995). One source (Okubo and Matsumoto, 1983) recommends that suspended solids content should be less than 2 mg/l to maintain a high infiltration rate.

Backflushing, or pumping the ASR well to waste, may dispose of clogged particles. Backflushing is a site-specific process, since suspended solids content is different with each scenario (EPA, 1999). By calculating the occurrence and representative concentration of solids in the recharge water, an effective duration can be determined (Pyne, 1995).

Bacterial growth is the second largest clogging problem in injection wells. Recharge water that has not been sterilized will invariably contain microorganisms. In a high-nutrient setting, the microorganisms will multiply and cause well clogging problems (Rinck-Pfeiffer et al., 2000). Maintaining a chlorine residual in the recharge water may be a solution. However, bacterial growth can form in as little as two days, so it is wise to maintain a trickle flow of chlorinated water in the well between recharge and recovery sessions (Pyne, 1995).

Geochemical reactions between native ground water and recharge water can lead to clogging problems caused by clay particle dispersion and precipitates (Pitt and Magenheimer, 1997). These reactions may negatively affect permeability of the aquifer or recovered water quality. Precipitation of calcite and of iron and manganese hydroxides and the dispersion of clay colloids are among the more common undesirable chemical reactions (Pyne, 1995).

Using a corrosion inhibitor to acidize the well will lower pH and dissolve calcite precipitation. Adding chemical stabilizers to the recharge water will reduce swelling of clay particles, and treating the water to remove sodium will minimize hydration of clay particles as well (EPA, 1999).

Aquifer jamming may result from particle displacement during successive recharge and recovery cycles. This rearranging and resettling of aquifer materials near the well could decrease available pore space and consequently decrease aquifer permeability for as much as several feet from the borehole. Permeability reduction is insignificant, however, and will only nominally affect recharge (Pyne, 1995). This issue is only experienced in loosely consolidated aquifers or where the gravel pack around a well is made of uniform pieces. By making certain that the gravel pack and the screen closely resemble the aquifer materials and maintaining low recovery velocities, aquifer jamming can generally be avoided (EPA, 1999).

Measuring Clogging in ASR Wells Water level data collected from an ASR well during recharge can be compared to similar sites in order to evaluate plugging susceptibility. The data should be modified to reflect regional ground water level changes and barometric variations. Pyne (1995) identifies three methods to evaluate clogging, based on the adjusted data: specific time of injection, water level difference, and observed versus theoretical water level rise.

In the specific time of injection method, water level rise in the ASR well is monitored during a recharge event where the rate of recharge is held constant. If the rise in water level is simply a result of well losses, then it should be possible to repeat the recharge event and achieve the same water level rise. Conversely, any variation in water level rise can be an indication of clogging.

Water level rise is measured in the ASR well and one or more observation wells when utilizing the difference in water level rise method. As with the specific time of injection method, the recharge rate is held constant. It is also imperative that the ASR well and observation well(s) be screened in the same interval. Once relatively steady state flow has been reached in the aquifer, the theory is that the difference in water levels in the ASR and observation wells will remain constant. Clogging is indicated by a change in water level difference between the wells.

The theoretical water level response of an aquifer is projected by using estimates of transmissivity, storativity, and other aquifer parameters, and assuming a homogenous, isotropic aquifer of infinite size. The difference between this calculated water level and the actual observed water level in an ASR well during constant-rate recharge is assumed to be a result of clogging.

Redevelopment

Backflushing, or reversing the flow of the well, is the preferred redevelopment technique. Depending on the site, the appropriate backflushing duration could be anywhere from 10 minutes to two hours (EPA, 1999). Similarly, the frequency with which redevelopment takes place is also site-specific. Table 6 gives some examples of operating ASR sites and their respective redevelopment frequencies.

Redevelopment pumping is typically to waste or to a treatment facility. An advantage of pumping to waste is that pumping can occur at a high rate, which helps to remove solids from the well. However, some states have stringent regulations which mandate that backflushed water must be contained and treated.

Table 6. Backflushing frequencies at ten ASR facilities (Pyne, 1995).

Site	Backflushing Frequency	Lithology
Wildwood, NJ	Daily	Clayey sand
Gordons Corner, NJ	Daily	Clayey sand
Peace River, FL	Seasonal	Limestone
Cocoa, FL	Seasonal	Limestone
Port Malabar, FL	Monthly	Limestone
Las Vegas, NV	Seasonal	Alluvium
Chesapeake, VA	Bimonthly	Sand
Seattle, WA	Weekly	Glacial drift
Callegulas, CA	Monthly (approx.)	Sand
Highlands Ranch, CO	Monthly	Sandstone

ASR wells will typically need full redevelopment every five years or so. This includes pulling, cleaning, acidizing, disinfecting, and resetting the pump. Sites in consolidated aquifers may not have to be redeveloped as often (Pyne, 1995). Polyphosphates diminish the stability of retained particles in physical clogging. Chemical oxidants can be used to reduce bioclogging and decrease bacterial growth. Removing mineral encrustations with acid will reduce chemical clogging (Segalen, et al., 2005).

Wellhead Filtration

A preventive technique concerning clogging is to keep solids out of the well in the first place. At a minimum, this includes pumping the recharge piping to waste before commencing recharge. Several ASR facilities have incorporated wellhead filtration into their operating practices, utilizing filters specific to the clogging problem encountered. A facility in New Jersey added a piece of 60-inch pipe at the wellhead, with the aim of reducing recharge velocity and causing any solids to settle out.

Wellhead filtration technology is widely used, and as a result is widely available. The size of the particles intended for removal generally dictates the cost of the system. If the cost of incorporating wellhead filtration into a facility seems prohibitive at first, it may be wise to provide space in the wellhead design to integrate wellhead filtration in the future, if necessary (Pyne, 1995).

Flow Control

Sometimes water mounding occurs during recharge when water cascading into the sealed well causes a vacuum to develop. Clogging issues combined with water mounding can cause the water level to rise above the ground surface. Increasing recharge pressure to compensate for head loss may solve this problem. However, once the maximum pressure of the source supply is reached, redevelopment of the well is necessary to restore well capacity. To avoid this scenario, flow control during recharge is usually integrated.

The increase in the amount of water injected and recovered from an ASR well means that the fluctuation in static water level is greater than with a standard production well. Consequently, it is more difficult to determine the size and power of pump needed to consistently maintain the necessary pumping rate.

Flow control is often essential for ASR facilities, because of the greater fluctuation in water levels and pressures. High flow rates at the wellhead caused by low pressure can cause operational malfunctions in the distribution system during recharge or in the drainage system during backflushing. By installing a pressure control valve on the recovery piping, it is possible to ensure that the pump is constantly functioning at an acceptable flow rate (Pyne, 1995).

An example of a flow control valve applicable to ASR wells is the V-SMART Valve. This valve includes two concentric cylinders or tubular members. One contains flow control ports, and the other is connected to and selectively moved by the hydraulic actuator section, thereby setting the flow through the ports by varying their size (VoV Enterprises, 2002).

A second example is the Baski Inflex Flow Control Valve. This fluid-actuated valve “permits pumping water to the surface or regulating the flow of water from the surface into the well, while using the same column pipe and maintaining a column of water in it at all times” (Baski, 2004). The small diameter of this valve makes it especially preferential for deep, small-diameter wells. Recharge can occur down the pump column without having to add injection tubes inside the casing to control flow rates and cascading. A Baski Flow Control Valve was incorporated in an ASR well in Mannheim, as part of a design which effectively eliminated water cascading and air entrainment (Segalen, et al., 2005).

Flow meters, sampling taps and pressure gauges must operate under positive pressures in order to be accurate and functional. If pressures at the wellhead are negative, ample valving must be utilized to establish positive pressures upstream of the wellhead (Pyne, 1995).

Disinfection Byproduct Reduction

Disinfection byproducts are formed when natural organic matter reacts with bromine and chlorine (Mirecki, 2004). More specifically, natural organic matter and bromide react with free chlorine residuals in treated water to form haloacetic acids (HAAs) and trihalomethanes (THMs) (McQuarrie and Carlson, 2003). The EPA has regulated concentrations of THMs and HAAs in drinking water because they are carcinogenic.

At many different locations, ASR has been shown to result in a reduction in DBPs (Dillon, 2004; Mirecki, 2004; Mirecki et al., 1998; Pyne, 1995; Pyne, 2003; Thomas et al., 2000). HAAs attenuate rapidly. Thomas et al. (2000) found that HAA concentrations were undetectable after less than one month of storage. Dillon (2004) found that HAAs attenuated first, followed by brominated THMs and then chloroform. Aerobic microbial reactions that occur in the storage zone are responsible for the rapid attenuation (Pyne, 2003; Thomas et al., 2000).

Total THM concentrations in an aquifer are a function of several factors: residual halogen gases in the recharge water; the redox environment of the aquifer; and the mixing and dilution effects in the buffer zone that surrounds the ASR well (Mirecki, 2004; Pyne, 2003). Pyne (2003) has found that anaerobic microbial reactions generally commence within a few days after recharge, and the subsequent biodegradation is a principal mechanism of declining THM concentrations in ASR storage. After the chlorine in the recharge water dissipates underground, reducing conditions are reestablished in the aquifer. These reactions lead to degradation of THMs in the recharge water. Thomas, et al. (2000) found dissimilar results. The authors drew several conclusions. First, total THM decline was attributed primarily to dilution of recharge water by native ground water or residual recharge water from previous ASR cycles. In particular, chloroform declinations were attributed solely to dilution, and brominated THMs were found to decline due to dilution and other processes, one of which may be biotransformation.

Simulation Modeling

Modeling in association with an ASR scheme is most cost-effective once site-specific data has been collected from a pilot ASR well and associated monitor wells. Data from the first ASR well at the site are needed to calibrate the model in order to obtain reliable results. Several facets of an ASR system can benefit from modeling.

ASR Water Supply System Model CH2M HILL developed a model that depicts operation of an ASR facility that utilizes a river as a supply source. The model simulates the following parameters:

- River flow and quality (defined by TDS)
- Regulatory and alternate diversion schedules
- Raw water treatment, definable by system demand or recharge capacity
- Storage of treated water in ASR wells, including simulated mixing as defined by relationships established during initial testing
- No-flow conditions from the river source

The model was developed with the Peace River, FL water supply facility in mind, and was successful in demonstrating how incorporating ASR into a complex water system would result in substantial cost savings while helping to meet water use demands (Pyne, 1995).

ASR Wellfield Operations Model The most commonly used model for ASR wellfield operations is MODFLOW. MODFLOW is a three-dimensional, finite-difference model, which means it uses a finite difference equation to simulate water level response to recharge and recovery. Different conditions can be input via a series of subroutines. The program is easily adaptable to specific applications. It is capable of simulating steady- and unsteady-state flow of a system, in which aquifers may be confined, unconfined, or both (Bloetscher et al., 2005; USGS, 1997). MODFLOW has been utilized at an ASR facility in Kerrville, TX, to evaluate its use in maintaining a sufficient water supply during a simulated recurrence of the worst drought in the history of the area. It has also been used at the Peace River, FL, system to approximate the effects of municipal well drawdown on nearby residential wells caused by seasonal recharge and recovery operations (Pyne, 1995).

Solute Transport Models These models are useful for interpreting movement of water underground. But often, they must rely on assumptions about aquifer dispersion qualities, as these data are not usually known. As a result, the outcomes derived may not be specifically accurate depictions of a system's response to ASR operations. The general outcome, however, may prove useful.

The three-dimensional model HST3D approximates heat and solute transport in saturated ground water flow systems (Bloetscher et al., 2005). This model was used in conjunction with ASR technology in Marathon, FL, in order to determine if a thin, confined, unconsolidated, saltwater aquifer could be used to store an emergency supply of drinking water. Construction and design of the test program was guided by the model. It was proven that potable water could be stored for at least 60 days within the aquifer (Pyne, 1995).

CFEST is another transport model that can be used to show velocity and direction of movement of an ASR freshwater bubble in an aquifer. Additionally, the model can estimate the concentration of total dissolved solids near the well during ASR cycles. This model could be a useful tool for predicting recovery efficiency and water quality (Pyne, 1995).

Geochemical Models Hounslow (1995) created a water quality program called WATEVAL that evaluates data based on several parameters:

- Reliability
- Aquifer mineralogy
- Determination of chemical trends based on generated Piper, Stiff, and sodium adsorption ratio diagrams
- Comparison of two analyses
- Estimation of aquifer redox conditions

The program will make simple calculations, such as calculating bicarbonate concentrations from alkalinity, or converting carbonate to bicarbonate (Hounslow, 1995).

Another program distributed by the USGS is WATEQ4F. This water equilibrium model calculates the distribution of major ions in a given water analysis using temperature, pH, and redox potential measurements. The mineral saturation of the water is then calculated (Hounslow, 1995).

WATEVAL and WATEQ4F are useful in determining how the chemistries of a water source used for recharge and the native ground water will interact during ASR operations.

CHAPTER 3

SUGGESTED USE OF ASR TECHNOLOGY FOR MUSTANG

Mustang purchases water from Oklahoma City to help meet its demand. Even though Mustang could independently meet its drinking water needs during off-peak months, the purchase agreement with Oklahoma City stipulates that Mustang must buy a minimum amount of water monthly throughout the year.

Even if the city does not use the minimum amount, it must still pay for the minimum. Mustang could benefit by using ASR to store the unused portion of the water purchased, so it is not simply wasted.

As will be discussed in **Chapter 4** of this volume, the activity coefficients of both the ground water and the surface water supplied to Mustang by Oklahoma City are low. This indicates that introducing the new water source into the aquifer will not result in precipitation of minerals from the surrounding rock. In fact, introducing a new water source into the aquifer may help dilute unacceptable levels of arsenic and selenium that occur naturally in the ground water.

Mustang Water Usage

Before an efficient plan for implementing ASR can be established, it is important to understand the supply and demand scenario for Mustang. Monthly water consumption data for 2003-2005 were provided by Severn Trent Environmental Services (STES, unpub. data, 2006), a contract operator that manages the Mustang water works. The data are shown in Tables 7, 8 and 9 for easy comparison.

Table 7. 2003 monthly water consumption (STES, unpub. data, 2006).

	WELLS	OKC	TOTAL
Jan '03	31	5.4	36.4
Feb '03	27.6	4.9	32.5
Mar '03	31.7	5.5	37.2
Apr '03	34.3	6.1	40.4
May '03	39.3	6.3	45.6
Jun '03	37.7	5.9	43.6
Jul '03	50.2	22.5	72.7
Aug '03	49.8	14.2	64
Sep '03	34.2	6.1	40.3
Oct '03	33.4	7	40.4
Nov '03	31.4	5.5	36.9
Dec '03	30.5	5.1	35.6
Total	**431.1**	**94.5**	**525.6**
Average	**35.925**	**7.875**	**43.8**
Minimum	**27.6**	**4.9**	**32.5**
Maximum	**50.2**	**22.5**	**72.7**

Table 8. 2004 monthly water consumption (STES, unpub. data, 2006).

	WELLS	OKC	TOTAL
Jan '04	39.9	5.8	45.7
Feb '04	37.2	6.9	44.1
Mar '04	29.7	6	35.7
Apr '04	31	7	38
May '04	49.3	7.8	57.1
Jun '04	47.7	4.9	52.6
Jul '04	42.8	11.4	54.2
Aug '04	34.5	9	43.5
Sep '04	40.9	8.1	49
Oct '04	30.5	7	37.5
Nov '04	24.7	7.8	32.5
Dec '04	26.8	9.8	36.6
Total	**435**	**91.5**	**526.5**
Average	**36.25**	**7.625**	**43.875**
Minimum	**24.7**	**4.9**	**32.5**
Maximum	**49.3**	**11.4**	**57.1**

Table 9. 2005 monthly water consumption (STES, unpub. data, 2006).

	WELLS	OKC	TOTAL
Jan '05	27.4	9	36.4
Feb '05	27.4	6.6	34
Mar '05	28.5	7.9	36.4
Apr '05	38	7	45
May '05	42.7	7.9	50.6
Jun '05	41.5	10.4	51.9
Jul '05	55.4	8.6	64
Aug '05	52.4	5	57.4
Sep '05	42.6	8.2	50.8
Oct '05	38.2	6.7	44.9
Nov '05	33.9	8.5	42.4
Dec '05	31.7	7.8	39.5
Total	**459.7**	**93.6**	**553.3**
Average	**38.30833**	**7.8**	**46.10833**
Minimum	**27.4**	**5**	**34**
Maximum	**55.4**	**10.4**	**64**

Demand is greatest each year from May to September. The highest usage for the 3-year period occurred in July and August 2003, when the western two-thirds of Oklahoma were experiencing moderate drought (OWRB, 2003).

Ground water and total water usage closely correlate. However, purchased water does not parallel the other two. Eleven times in the 36-month period shown in the data, ground water and total water usage simultaneously increase or decrease, while purchased water does the opposite. The amount of water purchased should correlate with the amount of ground water that is used, because it should not be necessary to purchase greater amounts of water if ground water usage is not maximized. This reinforces the concept that water purchases are driven by the necessity of meeting the terms of the contract just as much as by high water demand during peak months.

However, according to the data, Mustang does not always utilize the minimum amount of water purchased from Oklahoma City. In fact, in 20 of the 36 months represented, less than the minimum amount of water is used. Since Mustang has to pay for the minimum amount regardless of whether they use it, this represents a loss in assets.

The city of Mustang owns eleven fully operational ground water wells (Table 10). Due to high levels of both arsenic and selenium, Wells 2 and 6 have been taken off line (Wilkins, pers. comm., Oct. 30, 2005). These two wells represent almost 20 percent of the system's average daily flow. Converting Well 2 into an ASR well will allow it to continue contributing to the system, while not introducing arsenic or selenium. Unused purchased water can be stored in the aquifer via Well 2 and recovered at a later time when it is needed. If ASR of Well 2 is successful, retrofitting Well 6 for ASR purposes should also be considered.

Table 10. The City of Mustang has 11 municipal water wells. Wells 2 and 6 have been taken off-line due to high arsenic and selenium concentrations (STES, unpub. data, 2006).

Well No.	Status	As (ppb)	Se (ppb)	Avg. Flow (gpm)	Avg. Flow (mgd)	% of Avg. Flow	Comments
1	Operational	4.0	10.0	120.0	0.17280	6.9	On-line
2	Operational	91.0	370.0	175.0	0.23040	10.1	Operational: not on-line
3	Operational	0.0	16.0	142.0	0.20448	8.2	On-line
4	Operational	11.0	14.0	192.0	0.27648	11.1	On-line
5	Operational	32.0	22.0	149.0	0.21456	8.6	On-line
6	Operational	57.0	9.6	171.0	0.24624	9.9	Operational: not on-line
7	Operational	0.0	0.0	141.0	0.20304	8.1	On-line
8	Operational	0.0	0.0	183.0	0.17280	10.6	On-line
11	Operational	0.0	0.0	148.0	0.21312	8.5	On-line
12	Operational	36.0	42.0	180.0	0.25920	10.4	On-line
13	Operational	6.7	0.0	130.0	0.18720	8	On-line
	MINIMUM	**0.00**	**0.00**				
	MAXIMUM	**91.00**	**370.00**				
	AVERAGE	**21.61**	**43.96**				

Implementing ASR

The smallest monthly purchase of water from Oklahoma City during the three-year period was 4.9 million gallons. Because an average month has 30 days, and the minimum daily purchase as stipulated by the contract is 250,000 gallons, then the average minimum monthly purchase is 7.5 million gallons. Thus, during times of lowest demand, it is necessary to be able to recharge 2.6 million gallons per month. Recovery will occur during the peak months of May through September, which means recharge is possible from October through April. Hence, the target storage volume is 18.2 million gallons (2.6 million gallons times 7 months), and the average daily recharge rate is 86,667 gallons, or 60.2 gpm.

The previous paragraph describes a "worst-case scenario," assuming that during every month of recharge it will be necessary to store 2.6 million gallons. The average monthly water purchase from October through April is 6.8 million gallons. Using the same calculations, the target storage volume becomes 4.9 million gallons over seven months, or 23,334 gpd and 16.2 gpm.

Cone of Recharge

An important concern during recharge is that mounding of the recharge water may cause the water level to rise above land surface. When a well is pumping, a cone of depression forms around the well as the water table is lowered in the immediate vicinity.

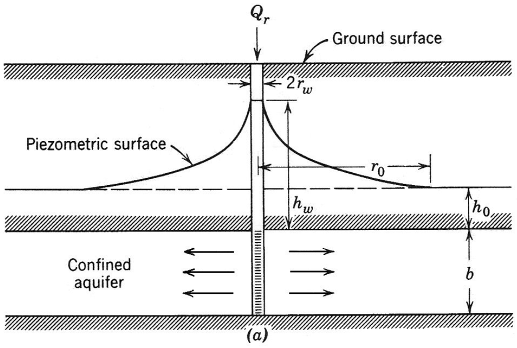


Figure 16. Injected water forms a cone of recharge as it penetrates the aquifer (Todd, 1980).

During recharge of an ASR well, the opposite occurs and a cone of recharge forms as water penetrates the aquifer (Figure 16). In situations such as this one where only one recharge well is present, the cone of recharge mirrors the cone of depression. A drawdown test was conducted on Well 2 (Table 11). Static water level was determined to be 242.55 feet and drawdown was determined to be 115.5 feet. The top of the cone of recharge is the reverse of the drawdown. Thus, by subtracting drawdown from static water level, the top of the cone of recharge is determined to be 127.05 feet below land surface. It does not appear that recharge will lead to oversaturation of the ground media.

Table 11. Results from a drawdown test conducted on Well 2 (STES, unpub. data, 2006).

Date	Tested Static PSI	Tested Running PSI	Calculated Static Water (ft)	Calculated Running Water (ft)	Drawdown	kPa	
						Static	Running
3/16/2006	105	55	242.55	127.05	115.5	379.2	723.9

Bubble Movement

As previously mentioned in **Chapter 2**, the injected water displaces the native water and forms a “bubble” of recharge water. Mixing with the ambient ground water occurs at the edge of the bubble, creating a buffer zone between the two water sources. Movement of this bubble within the aquifer is of concern in any ASR operation. It is important to consider the hydraulic characteristics of the aquifer before implementing ASR. The hydraulic gradient of the aquifer and aquifer transmissivity are key to estimating bubble movement within the aquifer. If the hydraulic gradient is too steep and transmissivity too high, migration of the bubble away from the recharge well will reduce recovery efficiency.

A hydraulic gradient of zero is ideal for minimization of bubble movement within the aquifer. For the COA, a median value of .01 has been established (Christenson et al., 1992). Similarly, a low median transmissivity value of 350 ft^2/day (Christenson et al,. 1998) is encouraging for ASR implementation. However, these values are representative of the entire COA. Values pertaining to the local area should be obtained as a part of further consideration of ASR for the Mustang well field.

CHAPTER 4

GEOCHEMISTRY

Problem Statement

An important question that must be asked is whether the introduced water will be chemically compatible with the native water. When water that is purchased from a surface reservoir in Oklahoma City is pumped into the COA and the two waters combine, it is possible that a chemical reaction may occur which could cause minerals to precipitate.

Materials and Methods

Many analyses of water samples from the COA and from the surface water reservoirs pertinent to this research have been published; however, none of the analyses reviewed provided all the information necessary for this study. Therefore, on October 31, 2005, six new samples were obtained and submitted for analysis. The analyses for these samples are included in **Appendix A.**

Three samples of ground water from the COA were obtained from the Rockwell Booster Station for the Mustang well field. Three samples of the surface water provided to Mustang by Oklahoma City were collected from a fire hydrant at the corner of County Line Road and SW 84th Street, just outside the Mustang city limits. Lastly, two samples were obtained by mixing equal parts of one ground water sample and one surface water sample. These samples were mixed using two 500-ml graduated cylinders in a laboratory setting. One sample each of ground water, surface water and mixed water were submitted to the Soil, Water and Forage Analytical Laboratory at Oklahoma State University. The analyses performed included major ions, boron, sulfur, bicarbonate, pH, electrical conductivity, and alkalinity. Values were also derived using standard calculations for potassium and sodium adsorption ratios, total soluble salts and hardness. Samples were collected and submitted in 50-ml bottles provided by the Oklahoma County Extension Office. Electrical conductivity and pH were determined using their respective meters. Chloride was analyzed with a flow injection analyzer using mercuric thiocyanate. Nitrate was analyzed with a flow injection analyzer using cadmium reduction. Alkalinity was analyzed using a titration meter. Carbonates and bicarbonates were analyzed using the same titration method as used for alkalinity. Sodium, magnesium, calcium, potassium, sulfur and boron were analyzed using an inductively coupled argon plasma torch (ICP). All of the analyses were performed using methods published in **Standard Methods for Examination of Water and Wastewater, 19th ed., 1995**.

One sample each of ground water, surface water and mixed water were submitted to Accurate Environmental Labs, the only laboratory in Oklahoma that is certified to analyze drinking water for trace metals. The samples were analyzed only for arsenic. Samples were collected and submitted in 100-ml bottles provided by Accurate Labs. A liquid-soluble, 1000 ppm arsenic oxide compound that is 4% nitric acid was used as the standard. The samples were analyzed on a mass-selective, inductively coupled argon plasma torch (ICP-MS), following EPA Method 200.8, Standards for Determination of Trace Elements in Water and Wastes.

Once the lab results were obtained, the data were input in WATEQ4F (Ball and Nordstrom, 2001), a software program provided by USGS that computes major and trace element speciation and mineral saturation for natural waters. The data compiled by WATEQ4F is included in **Appendix B**.

Results and Interpretation

Data were compiled by WATEQ4F from analyses of samples of ground water, surface water, and an equally mixed sample of the two. In each case, the minerals were speciated and the activity coefficient for each species was derived. The activity coefficient is a fractional number which, when multiplied by the molar concentration of a substance in solution, yields the chemical activity (Hounslow, 1995). This number gives an idea of how much interaction exists between molecules at higher concentration. The lower the activity coefficient, the less concentration is available to react with other ions.

In the cases of the three samples analyzed, the mineral species in each sample showed low activity coefficients. The activity coefficients for the mineral species of the surface water sample were only slightly higher than those of the ground water sample, but not sufficiently higher to cause concern about reactions during mixing. Because both water sources are very dilute, precipitation reactions are not expected. This is important because precipitation of some minerals such as calcite or iron can cause clogging in the well screens. Since the waters are dilute, mixing of waters in the borehole does not have to be regulated to avoid well clogging.

The sample of ground water analyzed for arsenic showed a concentration of 20 ppb. The sample of mixed water showed a concentration of 11 ppb. This is consistent with an equal mixture of the two waters. Thus, so long as the concentration of arsenic in the ground water does not exceed 20 ppb, then an equal mixture within the borehole will result in water of acceptable quality for potable use. However, arsenic concentrations as high as 71 ppb (Association of Central Oklahoma Governments, unpub. data, 2005) have been recorded in Mustang Well 6. Therefore, some control over the mixing of waters in the borehole or at the treatment plant will have to be exerted to ensure that drinking water quality standards are maintained before distribution.

CHAPTER 5

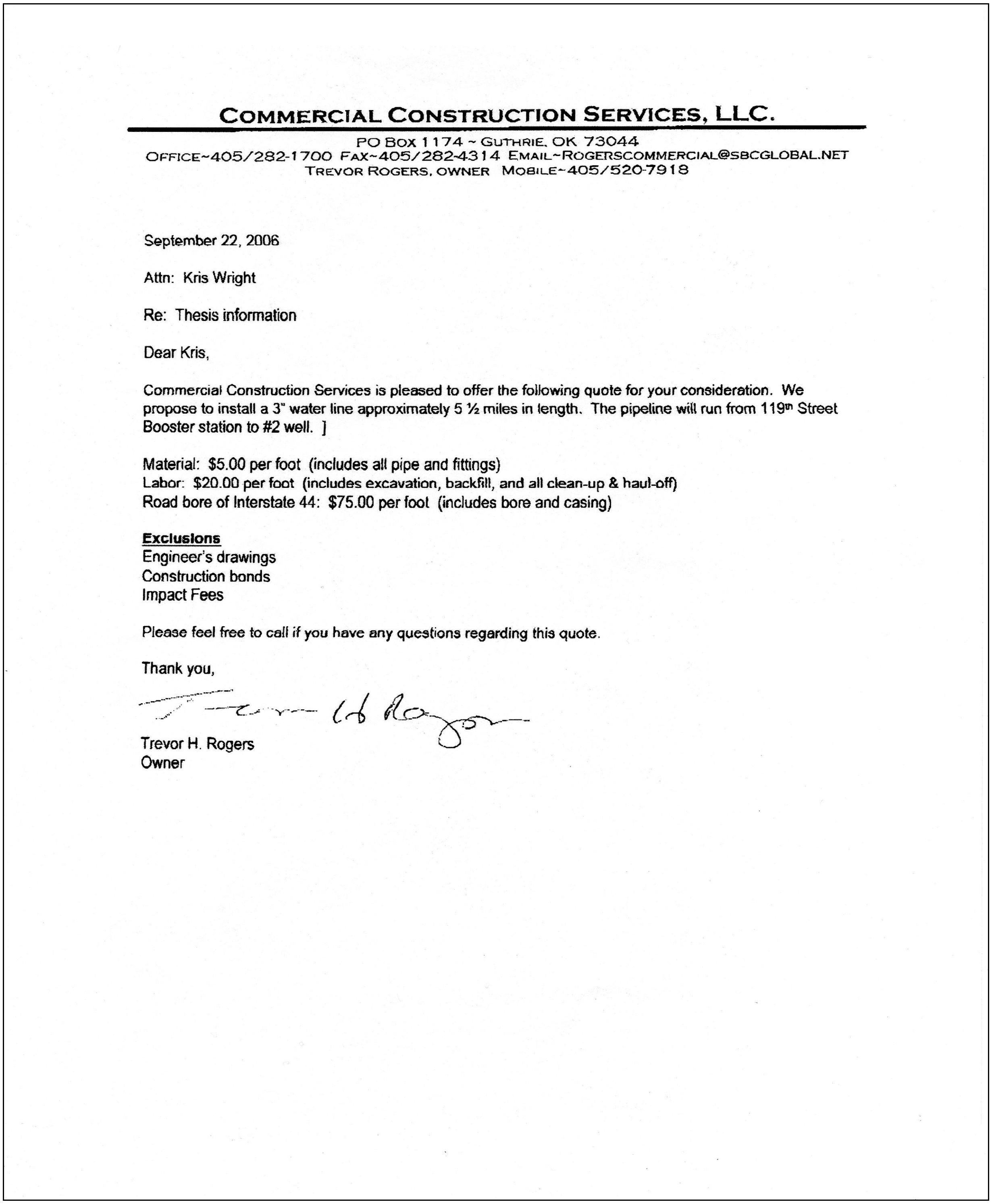
ECONOMICS

Capital Investment

The additional equipment needed to alter Well 2 for ASR operation is really quite minimal. The injectate will be introduced by gravity, so no additional pumping equipment is needed. A dedicated injection pipeline must be run from the Rockwell Booster Station to the well. The distance is approximately 5.5 miles, and the pipe can be laid along the same line as the existing extraction pipeline, thereby negating the need for obtaining additional right-of-way permissions. Riser pipes which allow air to escape should be placed in any high spots along the pipeline, and a gate or ball shut-off valve should be installed at either end of the line as well. A sanitary well cap should be placed over the well at the wellhead.

Capital labor costs associated with this ASR project include digging the trench and laying the pipe, attaching the new system at the booster station and at the wellhead, and preoperational testing. The most expensive and most time-consuming of these costs is the preoperational testing.

Figure 17 shows a bid summarizing the costs associated with installing the pipeline, including parts and labor. No creeks or other water bodies intersect the right of way; however, Interstate 44 lies directly in the path. A typical interstate highway lane is



COMMERCIAL CONSTRUCTION SERVICES, LLC.
PO BOX 1174 ~ GUTHRIE, OK 73044
OFFICE~405/282-1700 FAX~405/282-4314 EMAIL~ROGERSCOMMERCIAL@SBCGLOBAL.NET
TREVOR ROGERS, OWNER MOBILE~405/520-7918

September 22, 2006

Attn: Kris Wright

Re: Thesis information

Dear Kris,

Commercial Construction Services is pleased to offer the following quote for your consideration. We propose to install a 3" water line approximately 5 ½ miles in length. The pipeline will run from 119th Street Booster station to #2 well.]

Material: $5.00 per foot (includes all pipe and fittings)
Labor: $20.00 per foot (includes excavation, backfill, and all clean-up & haul-off)
Road bore of Interstate 44: $75.00 per foot (includes bore and casing)

Exclusions
Engineer's drawings
Construction bonds
Impact Fees

Please feel free to call if you have any questions regarding this quote.

Thank you,

Trevor H. Rogers
Owner

Figure 17. Quote from Commercial Construction Services regarding installation of a pipeline to inject water into Well 2 for storage.

12 feet wide, and the shoulder is 10 feet wide. At the point of intersection, I-44 consists of four lanes (two going either direction) with a median in the center. The interstate width in each direction, then, is 44 feet (24 feet for two traffic lanes and 10 feet for a shoulder on either side of the traffic lanes). Thus, the pipeline must pass under 88 feet of interstate.

Since there are 5,280 feet in a mile and the pipeline is 5 ½ miles long, a total of 26,928 feet of pipe must be laid, including the footage that underpasses the interstate. Using the price estimate from the bid in Figure 17 of $25/foot (parts and labor), the projected cost of laying the pipeline can be calculated as follows:

88 feet x $75.00 for interstate bore = $6600

26,928 feet – 88 feet of interstate = 26,840 feet

26,840 feet x $25.00 per foot parts and labor = $671,000

2, 3" PVC ball check valves = $670 (RSMeans, 2006)

10" Sanitary well cap = $153.75 (Boshart, 2006)

The total estimated cost of installation, then, is approximately $678,424 (as of December, 2006).

Funding

The City of Mustang often utilizes revenue bonds when borrowing for municipal projects (Cockrell, pers. comm., Mar. 9, 2007). A revenue bond is a bond that is repaid by the revenue generated from the project it funds. In this case, the money that would be saved by utilizing all of the water purchased from Oklahoma City could be construed as revenue. Revenue bonds typically have an interest rate between 3.75 and five percent. The longer the repayment term, the higher the interest rate. Assuming the worst, a bond for $678,424 at five percent for a term of 30 years would require a monthly payment of $3677.70.

In **Chapter 3**, it was determined that between 700,000 and 2.6 million gallons of water were purchased each month simply to satisfy the terms of the contract. The cost of the water is $1.65 per 1,000 gallons (Wilkins, pers. comm., Dec. 8, 2005). Hence, the monthly revenue generated by utilizing ASR to store this water ranges from $1155 to $4290. However, recharge only takes place for seven months. For the loan described above to be economical, Mustang must store about 3.8 million gallons per month for the seven months of recharge. Even if the loan could be obtained at 3.75 percent, the monthly payment of $3170.93 would necessitate storing about 3.3 million gallons for the seven months of recharge. It does not appear that a revenue bond would be economically sound in this situation.

A second option is a general obligation bond. General obligation bonds are issued with the belief that a municipality will be able to repay its debt obligation through, for instance, taxation. No assets are used as collateral. Mustang typically obtains general obligation bonds at an interest rate between 4.5 and 5.75 percent, with higher interest rates corresponding to longer repayment schedules. A repayment period of 20 years would most likely be financed at 5.75 percent (Cockrell, pers. comm., Mar. 19, 2007). Assuming this scenario, the monthly payment would be $4829.45. The payments can be offset by the revenue generated through ASR storage, with the difference being financed through taxation.

Permitting

Well Permits

As discussed in **Chapter 2**, Oklahoma is a UIC Primacy State. The state has incorporated by reference into the Oklahoma Administrative Code those parts of 40 CFR Parts 144 and 146 that apply to the UIC program (252-652-1-3 OAC). Thus, aquifer recharge and ASR wells in the state are authorized by rule in accordance with the existing federal requirements. When a well is authorized by rule, then no permit is required.

Subpart 144.84 describes exceptions to the process whereby a permit is required, none of which apply to a well retrofitted for ASR:

- failing to comply with the prohibition of fluid movement standard in 144.12(a)
- operating a Class V large-capacity cesspool or a Class V motor vehicle waste disposal well in a ground water protection area or sensitive ground water area
- as specifically required by the UIC Program Director
- failing to submit inventory information to the UIC Program Director
- failing to comply in a timely manner with a request received from the UIC Program Director in a non-primacy state for additional information under 144.83(b)

The only other federal requirement is to provide "inventory information" to the UIC Program Director. Part 144.83 says to contact the UIC Director to inquire about what needs to be turned in and when, while Part 144.26 requires the following information be submitted:

- Facility name and location
- Name and address of legal contact
- Ownership of facility
- Nature and type of injection wells
- Operating status of injection wells

The Oklahoma Administrative Code requires permitting for some UIC wells but not all. Part 252:652-1-6(c)(1)(B)(iv) describes one type of Class V well that requires a permit and fee as "injection wells used in experimental technologies." If, upon notification of the existence of the ASR well, the UIC Program Director applied this description to the well, then a permit fee of $600 would be required.

The Code says additionally in 252:652-5-3 that “the applicant shall perform ground water monitoring, provide an analysis of injected fluids and a description of the geologic strata through and into which injection is taking place, and provide any additional information which the applicant determines is necessary to comply with 40 CFR 144.12.”

Water Permits

The Oklahoma Water Resources Board (OWRB) governs the permitting and usage of both surface waters and ground water in the state. The water that Mustang purchases from Oklahoma City has already been permitted for use by Oklahoma City, so no further permitting is necessary. Furthermore, Mustang already has a permit to withdraw a specified amount of water annually from the COA. So long as the total amount of water withdrawn from the ASR well does not exceed the amount injected plus the amount permitted for withdrawal from the aquifer, then no further permitting is required (Phyllis Robertson, pers. comm., Oct. 12, 2006).

Preoperational Testing

As the term implies, preoperational testing includes gathering water quality and baseline hydraulic data as well as ASR cycle testing. Additionally, some facility operators may desire to run a modeling program during this part of the testing phase. Costs associated with preoperational testing are site-specific and are difficult to estimate without initiating a full pilot project design report. Such a report is outside the scope of this project. However, some factors to consider when creating such a report are mentioned here with regard to this scenario.

Modeling

The variables affecting ASR system performance are numerous. Utilizing a ground water modeling program to simulate the ASR system may prove to be a valuable tool. Occasionally, sufficient information can be found in previously published literature to supply the required data for useful modeling. However, prior experiences at ASR facilities have shown that the best time to incorporate a ground water model generally is after data has been collected from a trial test of the ASR well (Pyne, 1995). Attempting to run a model prior to data collection may actually cause more confusion, as not enough information is available to calibrate the model. Once site-specific data have been collected, however, simulation of the system using a numerical model can be used to evaluate parameters such as water mounding and also to identify potential problems or uncertainties.

Baseline Testing

Collecting data prior to commencing ASR cycle testing will provide an initial data point for each hydraulic characteristic. Future results during and after ASR cycle testing can then be compared to the initial results to determine ongoing success or failure of the project. A step drawdown test to determine well efficiency followed by a pumping test lasting one day or longer to determine hydraulic characteristics of the aquifer near the ASR well are the typical tests associated with baseline data collection. When performing the pumping test, Pyne (1995) advises that all monitoring wells should be included in order to better estimate storativity and transmissivity. Median values for aquifer properties were given in **Chapter 2**; however, these values represent a median for the entire COA, where localized data should be collected prior to performing ASR cycle testing.

Monitoring

Monitoring serves several purposes: evaluating system performance, evaluating geochemical reactions, and demonstrating regulatory compliance are three examples.

Recharge Even though the recharge water in this scenario already meets drinking water standards, a water quality assessment should be performed so that the parameters are available for comparison with the recovered water. Additionally, the recharge rate, volume of water recharged, and wellhead pressure should be monitored. The potential for well plugging can be estimated by comparing the recharge rate with the wellhead pressure.

Storage The chemical composition of the recharge water may be affected by storage time. Mixing, chemical and biological reactions could occur. Of particular interest to this facility will be the effect of storage time on arsenic mobilization within the well.

Recovery During preoperational cycle testing, water will be recovered to waste. The current well system already has in place a valve that can discharge ground water to waste by way of a storm drain located just outside the pump house. The quality of water collected during recovery should be compared to recharge water quality. Data should also be collected to evaluate the resulting arsenic concentrations in the recovered water.

As previously discussed in **Chapter 2**, recovery efficiency is directly related to the size of the buffer zone surrounding the injected water. Several cycles of injection and extraction are needed in order to build up the buffer zone and accurately determine the recovery efficiency. The recovery phase of each cycle can be operated until a predetermined water quality criterion is met. The criterion can be adjusted in each cycle to aid in the creation of a buffer zone between the native water and the recharge water. An increasing percentage of the recharge water should be recoverable with successive cycles.

Data Collection Collection of data during monitoring is necessary to evaluate the operational efficiency of the system. Data that need to be collected include:

- Recharge and recovery flow rates and volumes
- Volume of water stored and duration of storage
- Water quality of the injected and recovered water
- Pressures during recharge and recovery at the ASR and monitor wells (Bloetscher, et al., 2005).

Cycle Testing

It is a good idea to perform a short recharge and subsequent recovery on the initial cycle. This allows for quick confirmation of ASR performance, and provides an opportunity to evaluate any plugging or geochemical reactions. Rigorous data collection should be performed during recharge.

During the recovery phase of the first cycle, the goal should be to recover water back to native water quality. Recovering 150 to 200 percent of the recharge water typically accomplishes this goal (Pyne, 1995). However, collecting and testing water samples on a predetermined schedule throughout the recovery phase is a more accurate way to establish when native water quality has been reached.

Subsequent cycles should be used to monitor recovery efficiency, water quality, and other parameters. A cycle testing plan for this scenario is given in **Chapter 7.**

Ongoing Investment

Labor

STES utilizes a supervisory control and data acquisition (SCADA) system, which allows the well functions to be controlled from a computer in the main office. Maintenance and tests can be performed simultaneously with general well maintenance. Thus, additional ongoing labor costs to maintain the operation are nominal.

Energy

It is necessary to identify the values of certain variables in order to estimate energy costs.

Water horsepower refers to the power required to move water at a desired flow rate and head:

$$\text{WHP} = \frac{HQ}{3960}$$

Where:

H = total head (ft);

Q = flow rate (gpm); and

3960 is a conversion factor derived by dividing 33,000 ft-lb/min (1 horsepower) by 8.34 lb/gal (weight of 1 gallon of water).

Data collected by Severn Trent Environmental Services (2006), shown in **Chapter 3** (Table 11), were used to calculate a total head of 347.05 feet for Well 2.

In **Chapter 3**, the range for the target storage volume was determined to be between 4.9 and 18.2 million gallons. Since the goal is to recover all of the stored water, the target storage volume now becomes the target recovery volume. Recovery will occur during the peak months of May through September. Assuming an average of 150 days of recovery at 24 hours per day, the target recovery rate becomes 22.69 to 84.26 gpm. Utilizing these values and the formula above, the range for water horsepower is 1.99 to 7.38.

Brake horsepower is the power provided to the pump shaft, and consumed by a pump in order to move water at a desired flow rate and head. The ratio of water horsepower to brake horsepower is the pump's efficiency. Typically, pump efficiencies range from 50 to 85 percent (Spellman, 2003).

$$\text{BHP} = \frac{\text{WHP}}{\text{Pump \% Efficiency}}$$

The pump in Well 2 is a Peerless, 75-horsepower submersible turbine pump, with a pump efficiency rating of 62 percent. Thus, the brake horsepower becomes 3.21 at 22.69 gpm, and 11.91 at 84.26 gpm.

Motor horsepower refers to the amount of horsepower that must be produced by the motor in order to generate the needed water and brake horsepower.

$$\text{MHP} = \frac{\text{BHP}}{\text{Motor \% efficiency}}$$

Motor efficiency is always less than 100 percent, but typically ranges between 95 and 98 percent. Using a conservative motor efficiency value of 95 percent, the motor horsepower is 3.38 at 22.69 gpm, and 12.54 at 84.26 gpm.

In order to determine how much energy is consumed during operation, motor horsepower must be converted to kilowatts (one horsepower is equal to .746 kilowatt).

Multiplying this number by the operating time of the well yields kilowatt-hours (kwh). Assuming that the well will operate non-stop during recovery, operating time becomes 720 hours per month. Thus, using the same recovery rates as in previous calculations, the range of kilowatt-hours used per month becomes 1813.37 to 6374.02.

Finally, the cost per kilowatt-hour for municipal water pumping during peak months is 6.07 cents (OG&E, 2006). Accordingly, the monthly cost of electricity for recovering 4.9 million gallons would be $110.07, while recovering 18.2 million gallons would cost $408.75 per month. Table 12 compiles the values for the variables discussed.

Table 12. Values for WHP, BHP, and MHP over the target recovery volume range of 4.9 to 18.2 MG.

	Recovery Rate = 22.69 gpm **Target Recovery Volume = 4.9 MG** **Pump Efficiency = 62%** **Motor Efficiency = 95%**	**Recovery Rate = 84.26 gpm** **Target Recovery Volume = 18.2 MG** **Pump Efficiency = 62%** **Motor Efficiency = 95%**
Water Horsepower (WHP)	1.99	7.38
Brake Horsepower (BHP)	3.21	11.91
Motor Horsepower (MHP)	3.38	112.54
Kilowatt-hours/month	1813.37	6374.02
Cost/month	$110.07	$408.75

Pump Cost

The cost of the Peerless pump currently installed in Well 2 is $10,000, and the life expectancy of the pump is 15 years. Assuming the pump was purchased with a loan at five percent interest for 15 years, the annual cost associated with the pump is $963.42, or about $80.29 per month.

Total Monthly Cost

As shown in Table 13, the total monthly cost to implement an ASR scheme is estimated at $5,318.49. This estimate includes the highest expected monthly energy costs of $408.75. However, the revenue generated through ASR storage will compensate for almost half of the associated monthly costs. As previously discussed in this chapter, storing 2.6 million gallons of water is equal to about $4,290. The revenue generated from seven months of storage at this rate, spread over a full year, is equivalent to about $2,502.50 per month. The total monthly cost, then, to implement the project is about $2,815.99.

Table 13. Estimated monthly costs and revenue generated.

Component	**Cost**
Pump	$80.29
Electricity	$408.75
G.O. Bond	$4,829.45
Total	**$5,318.49**
Revenue Generated	-$2,502.50
Total Monthly Cost	**$2,815.99**

Cost Comparison

Table 3 in **Chapter 2** depicts the costs associated with nine different ASR projects. Because Mustang already has a well in place that simply needs to be retrofitted as an ASR well, associated costs will tend toward the lower end of the spectrum.

To date, no ASR facilities have been erected in Oklahoma with which to compare this project. However, from 1992 to 1997 a ground water recharge demonstration project was conducted in the Blaine Aquifer in the southwestern part of the state. Five gravity-flow artificial recharge wells were constructed and utilized to introduce surface water into the aquifer, which is used mainly for irrigation purposes. The total budget for the project was $2.14 million. The Blaine Aquifer recharge project is comparable to the ASR project proposed in this paper because both scenarios employ gravity-flow wells, and because pretreatment of the injected water is not necessary in either case. The fact that pretreatment of the injected water is not required adds greatly to the cost effectiveness of both projects.

The annual cost of each recharge well in the Blaine Aquifer project was $2,899, including construction, operation and maintenance. The study also found the cost of recharge to be $0.13 per 1,000 gallons, while the value of water pumped from the aquifer was $0.53 per 1,000 gallons, yielding an approximate four to one benefit-to-cost ratio (Osborn, et al., 1997).

CHAPTER 6

SUMMARY AND CONCLUSIONS

As more people become aware that surface water and ground water are closely related and should be considered as one hydrologic system, studies are increasing concerning their conjunctive use and management. A fairly new technique is that of aquifer storage recovery (ASR). Aquifer storage recovery is the storage of water in a well during times when water is available, and recovery of the water from the same well during times when it is needed. The concept includes diverting the excess water to an aquifer (as underground storage), then reversing the pumps during the dry months to meet demands on water supply.

Arsenic has been linked with severe health defects, including cancer, skin lesions, and heart and lung problems. In January, 2006, the USEPA decreased MCL for arsenic in drinking water from 50 ppb to 10 ppb. As a result, many previous sources of drinking water are no longer usable without additional treatment. The western portion of the Central Oklahoma Aquifer in central Oklahoma is an example. Mustang, a small city that relies on the COA as a major source of drinking water, would benefit from utilizing ASR in conjunction with a municipal water well (Well 2) that is currently unusable due to high arsenic concentrations in water extracted from the well.

Storing water of acceptable quality in the aquifer through Well 2 and withdrawing it again during times of high demand is beneficial in two ways. First, Well 2 will be able to contribute to the municipal water system again. Mustang has eleven municipal water wells that serve a population of about 15,000. Wells 2 and 6 are currently off-line due to high concentrations of both selenium and arsenic. During peak use periods, it is optimal to have all eleven wells online, not only to provide water but also to contribute pressure to the system. ASR should be tested first on Well 2, and if the results are favorable, ASR retrofitting of Well 6 should be considered.

Second, during the colder months when water usage is not as high, Mustang must still purchase water from Oklahoma City to meet the terms of the contract despite not needing any additional water. By storing the purchased water in the aquifer through Well 2, Mustang will be able to extract the water again during the summer when demand is high. This saves Mustang from essentially having to waste the water. Furthermore, at times during the summer when water demand is at its highest, Mustang occasionally must purchase more water than the contract stipulates, at stiff penalties. Thus, the saved water proves beneficial again in that it may be useful in avoiding additional water costs during peak demand times.

A geochemical study was performed to determine if precipitation reactions that would lead to clogging of the well screens could be expected when the injectate was introduced into the aquifer. The study, discussed in **Chapter 4,** showed that both water sources are dilute and have low activity coefficients. As a result, precipitation reactions are not expected and the project appears to be geochemically feasible.

Some concern exists that high levels of arsenic within the aquifer might lead to unacceptable arsenic levels in the recovered water. However, this can be controlled by establishing a buffer zone of sufficient size between the native and injected waters, and recovering water only until the MCL of 10 ppb is reached. Additionally, water recovered from the ASR well will be mixed with ground water from the other municipal wells prior to public distribution. Because high levels of arsenic are only associated with two of the eleven wells in the well field (including Well 2), this blending may also be utilized as a dilution tactic.

Preoperational testing comprises the most expensive and time-consuming of the costs. Components include gathering baseline hydraulic data and water quality data, performing ASR cycle tests, and possibly utilizing modeling software. Costs associated with preoperational testing are site-specific and are difficult to estimate without initiating a full pilot project design report. Such a report is outside the scope of this paper.

Capital investment is estimated at about $680,000. Mustang typically utilizes either municipal bonds or general obligation bonds to fund such projects. In **Chapter 3,** it was determined that the maximum monthly target storage volume is 2.6 million gallons. In **Chapter 5,** it was determined that for a municipal bond to be cost-effective, at least 3.3 million gallons would need to be stored during each month of recharge. Thus, it appears that the economically feasible funding choice is a general obligation bond. A monthly payment of about $4,830 at 5.75 percent would repay the bond in 20 years. Associated electrical costs of, at most, $410 per month brings monthly charges to about $5,240. However, the city will generate "revenue" by utilizing all of the water purchased from Oklahoma City each month, which will lessen the impact of associated costs.

Maintenance and tests can be performed simultaneously with general well maintenance. Thus, additional ongoing labor costs to maintain the operation are nominal.

It appears that ASR is a feasible technology for Mustang. Low overhead costs, energy costs and ongoing labor costs are partially offset by the revenue generated through more effective use of water supplies. Costs associated with preoperational testing must still be estimated. However, once the preoperational and construction costs are paid, continued use of the technology will enable Mustang to operate its water supply facilities at a greater profit than previously realized.

CHAPTER 7

FUTURE DIRECTIONS

As shown in this report, implementation of ASR technology should prove beneficial for Mustang. However, it is prudent to test the operation prior to full-scale realization. The US Army Corps of Engineers (2004) developed a list of objectives for five planned ASR facilities in Florida. Table 14 was created by altering those objectives to fit this scenario.

Table 14. Objectives of the recommended cycle testing plan. Adapted from USACE (2004).

CYCLE TESTING OBJECTIVES	
Purpose/Objective	**Cycle Testing Implications**
Begin preliminary ASR operation	Perform a short initial cycle to test ASR performance and to rule out any plugging or geochemical problems. Extensive hydraulic and water quality data collected during this cycle.
Evaluate water quality changes during the initial cycle	Recover water back to native water quality (or as close as possible); typically 150-200% recovery
Determine if recovery efficiency increases with successive identical cycles, and conduct baseline geochemical testing.	Provide a longer recharge period to increase stored water volumes and increase recovery efficiency. Maintain the same recharge volume and storage period for three cycles. This should be conducted at the start of cycle testing to minimize antecedent changes to subsurface water quality from previous cycles.
Build up the Target Storage Volume (TSV) to increase recovery efficiency	Increase recharge volume over subsequent cycles (three or more) to build up the buffer zone and increase water quality. Recover water to a target criterion for arsenic.
Evaluate pressure buildup at/around the ASR well.	Include a longer recharge period on at least one cycle to estimate "steady-state" pressures.
Evaluate geochemical changes as the injected water front moves through the aquifer from and to the ASR well	Recharge for a long enough period to observe stored water at all/most monitor wells.
Estimate the characteristics of the stored water volume (shape, thickness, expansion rate, etc.)	Recharge for long enough for the stored water to arrive at the monitor wells.
Tracer test--tracer placed in the ASR well	Provide adequate recharge time to allow a tracer placed in the ASR well to be detected in the designated monitor wells.
Evaluate the effect of decreased recovery rates on recovery efficiency	Vary (decrease) the recovery rate in successive cycles.
Evaluate cycle testing routines and requirements	Evaluate the O&M requirements and the implications for continued operation.

The purpose of varying the recharge, storage and recovery times is to evaluate the effect that each scenario has on system performance. For instance, varying the duration of storage allows observation of the effect of storage time on recovery efficiency and water quality. Likewise, altering the length of time spent on recovery allows for evaluating how the change in recovery rates affects recovery efficiency.

Mustang is a growing community located in one of the fastest growing counties in Oklahoma. As the city grows, demand for water resources grows with it. It may be in Mustang's future to retrofit more than one well for ASR purposes.

In the not too distant future, another option that might become available to Mustang is that of stormwater ASR. The ability to utilize the aquifer, not only as a storage reservoir but also as a natural treatment process, could ultimately eliminate the need to purchase water from Oklahoma City to meet peak demands.

Currently in the U.S., ASR is accepted as a means of storing water already of potable quality in a drinking water aquifer. However, Australia and Europe are successfully using ASR with waters of non-potable quality as well (Dillon et al., 2003). For example, treatment of stormwater for irrigation and other non-potable uses is common in Australia. Twelve sites are operational in Adelaide that use wetlands to treat stormwater before introducing the water into an ASR scheme (Rinck-Pfeiffer, 2006). A total of 22 ASR facilities in the Adelaide region inject about 528 million gallons of rural and urban stormwater runoff annually, with another five facilities currently in the planning stages (DWLBC, 2006). An ASR facility in Bolivar, Australia, uses tertiary treated municipal sewage effluent as injectate for storage, treatment and reuse as unrestricted irrigation water (Dillon et al., 2006). In Belgium, ASR is being used as a natural treatment process with wastewater effluent as part of a sustainable groundwater management plan (Macdonald, 2005). According to Dillon (1999), highly treated sewage effluent is commonly used in the United States as well. For example, the city of Tampa Bay utilizes an ASR scheme to store treated wastewater for irrigation use in golf courses, parks and gardens (ASR Forum, 2006).

The use of stormwater or wastewater through ASR processes to reuse as potable water is not yet accepted. However, a study has been started that focuses on creating drinking water from stormwater in Salisbury, South Australia (Rinck-Pfeiffer, 2006). If the process proves to be effective, the United States could benefit by considering similar application of the technology in this country.

Locally, nitrates in ground water are of concern. Thirty-two public water supply facilities in Oklahoma, that serve about 34,100 residents and 4500 wholesale businesses, have had at least one violation for nitrate levels in their drinking water supplies since January 2005 (Shawn Brandt, pers. comm., Dec. 10, 2005). Introduction of a new water source into the aquifer via ASR wells could be used to help dilute the concentration of nitrates in the ground water and bring it to an acceptable level for potable water use.

The EPA’s Underground Injection Control (UIC) program divides injection wells into five categories, with the first four well categories being acutely defined. ASR wells are not covered by the first four categories, and consequently are lumped together in Class V with septic tanks and injection wells used for poor quality urban runoff. The numerous injection practices included in the Class V category necessitate stringent regulation, because some of them could be harmful to drinking water supplies.

It is unfortunate that ASR technology is subjected to these same rules. It seems clear that the intent of the language in the 1974 Safe Drinking Water Act (SDWA) that relates to UIC is to prohibit contamination of an underground source of drinking water (USDW) with pollutants that would jeopardize the ability of a water treatment plant to remove the pollutants before distribution and public consumption. However, the EPA interpreted the language to mean that prior to injection, the introduced water must already meet primary drinking water standards. As time goes on, these standards grow more stringent. This interpretation of the rules implies that whenever a proposed recharge source fails to meet drinking water standards, an aquifer exemption would be necessary.

As previously mentioned in this chapter, ASR facilities in Australia and Europe have demonstrated that ASR of non-potable water is possible without compromising the aquifer. ASR in the U.S. would benefit from the creation of sample legal and regulatory processes for states to follow. This framework would provide guidance when confronted with situations where the quality of the recharge water does not already meet drinking water standards prior to injection, but would still be appropriate in light of the original intent of the SDWA. Moreover, a model framework may encourage the application of ASR in areas where it otherwise might not have been considered, leading to extensive implementation of ASR and the consequent reaping of associated benefits. Guidance of this sort would assist the EPA as well, by making state-level ASR programs easier to evaluate without compromising on other well types covered in Class V of the UIC program.

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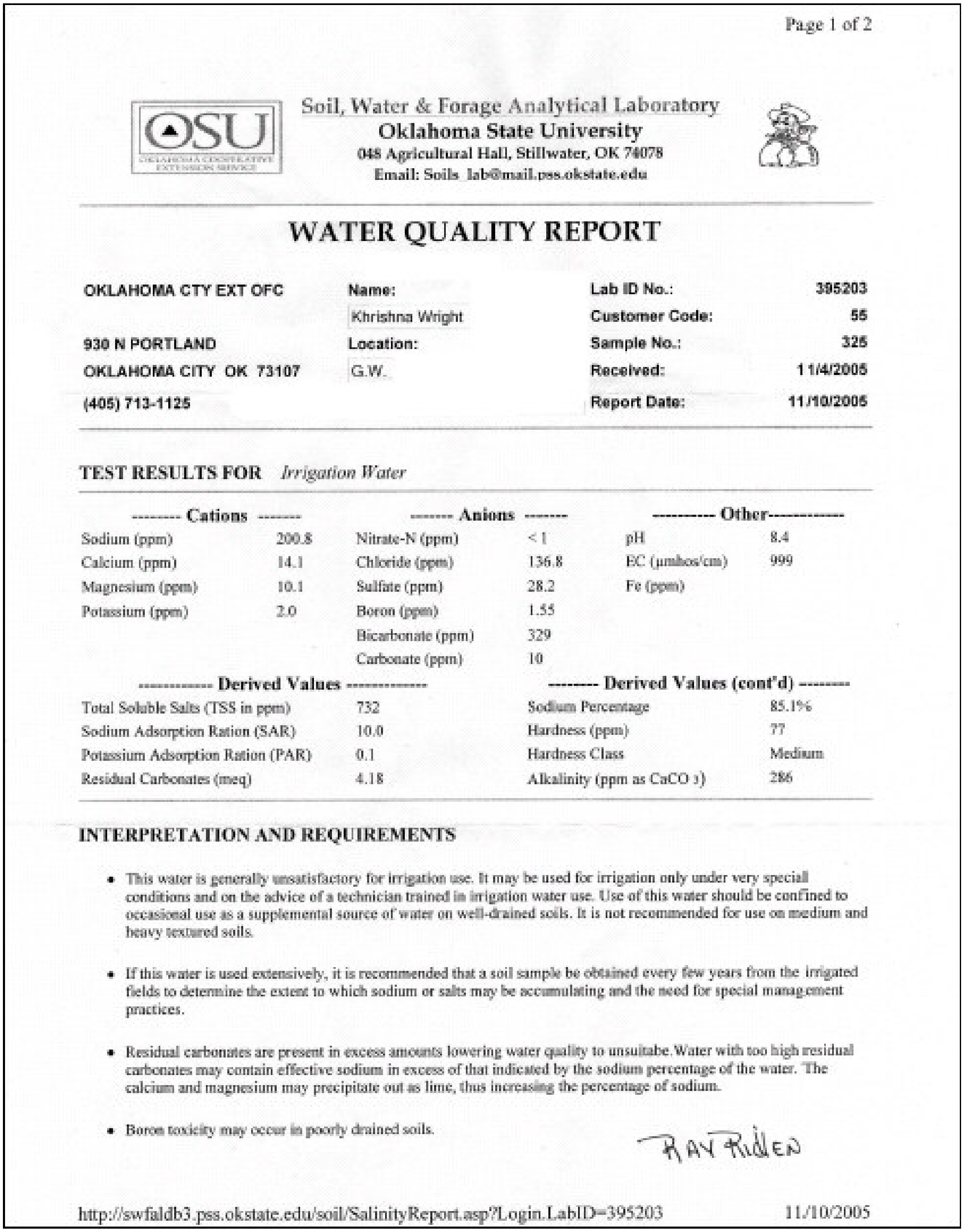
APPENDICES

APPENDIX A: WATER SAMPLE ANALYSES



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Soil, Water & Forage Analytical Laboratory
Oklahoma State University
048 Agricultural Hall, Stillwater, OK 74078
Email: Soils lab@mail.pss.okstate.edu

WATER QUALITY REPORT

OKLAHOMA CTY EXT OFC	**Name:**	**Lab ID No.:**	**395203**
	Khrishna Wright	**Customer Code:**	**55**
930 N PORTLAND	**Location:**	**Sample No.:**	**325**
OKLAHOMA CITY OK 73107	G.W.	**Received:**	**11/4/2005**
(405) 713-1125		**Report Date:**	**11/10/2005**

TEST RESULTS FOR *Irrigation Water*

-------- Cations -------		------- Anions -------		---------- Other------------	
Sodium (ppm)	200.8	Nitrate-N (ppm)	< 1	pH	8.4
Calcium (ppm)	14.1	Chloride (ppm)	136.8	EC (µmhos/cm)	999
Magnesium (ppm)	10.1	Sulfate (ppm)	28.2	Fe (ppm)	
Potassium (ppm)	2.0	Boron (ppm)	1.55		
		Bicarbonate (ppm)	329		
		Carbonate (ppm)	10		

------------ Derived Values -------------		-------- Derived Values (cont'd) --------	
Total Soluble Salts (TSS in ppm)	732	Sodium Percentage	85.1%
Sodium Adsorption Ration (SAR)	10.0	Hardness (ppm)	77
Potassium Adsorption Ration (PAR)	0.1	Hardness Class	Medium
Residual Carbonates (meq)	4.18	Alkalinity (ppm as $CaCO_3$)	286

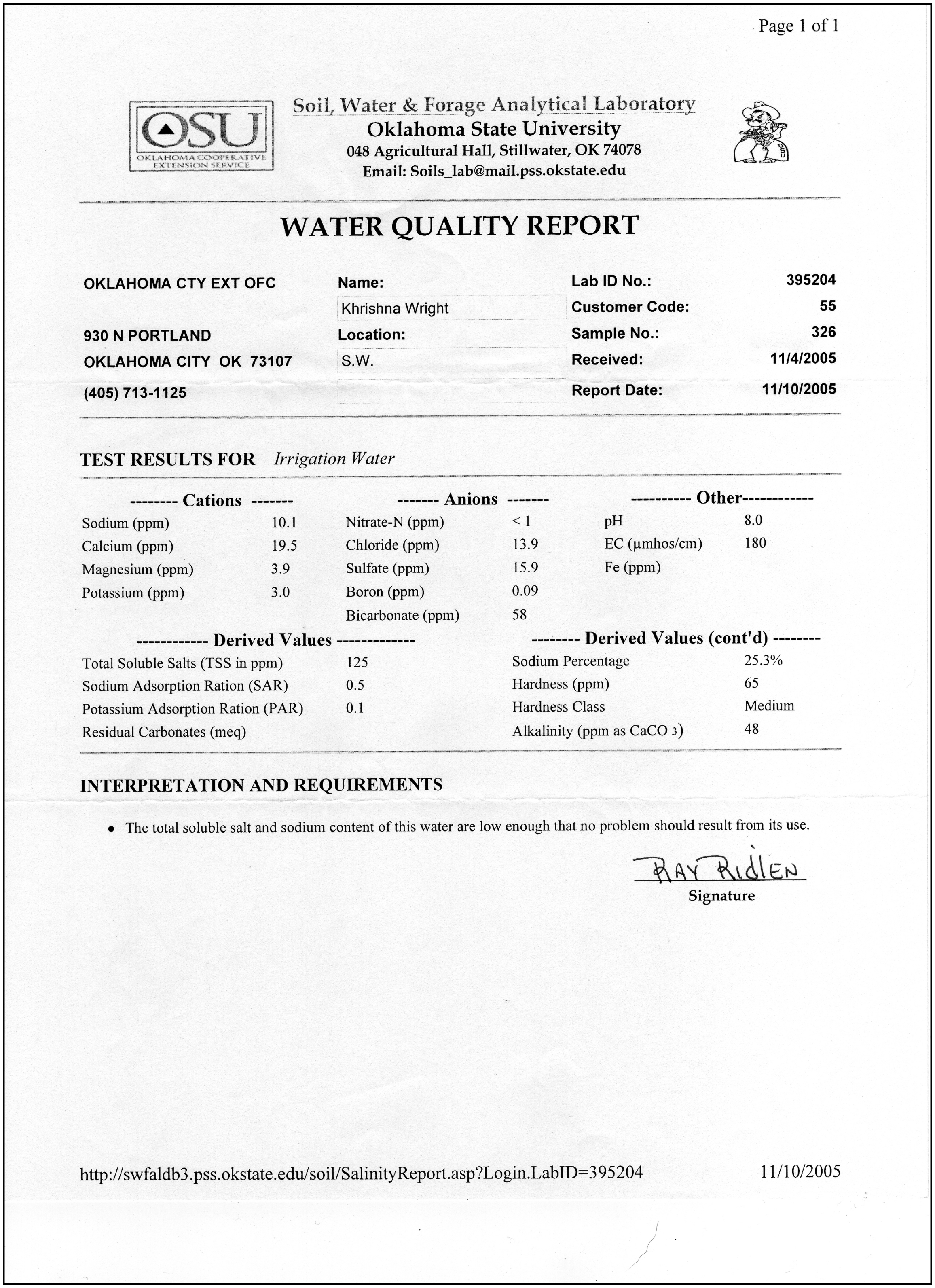
INTERPRETATION AND REQUIREMENTS

- This water is generally unsatisfactory for irrigation use. It may be used for irrigation only under very special conditions and on the advice of a technician trained in irrigation water use. Use of this water should be confined to occasional use as a supplemental source of water on well-drained soils. It is not recommended for use on medium and heavy textured soils.
- If this water is used extensively, it is recommended that a soil sample be obtained every few years from the irrigated fields to determine the extent to which sodium or salts may be accumulating and the need for special management practices.
- Residual carbonates are present in excess amounts lowering water quality to unsuitabe.Water with too high residual carbonates may contain effective sodium in excess of that indicated by the sodium percentage of the water. The calcium and magnesium may precipitate out as lime, thus increasing the percentage of sodium.
- Boron toxicity may occur in poorly drained soils.

RAY RIDLEN

http://swfaldb3.pss.okstate.edu/soil/SalinityReport.asp?Login.LabID=395203 11/10/2005

Water quality analysis of ground water sample.



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Soil, Water & Forage Analytical Laboratory
Oklahoma State University
048 Agricultural Hall, Stillwater, OK 74078
Email: Soils_lab@mail.pss.okstate.edu

OSU
OKLAHOMA COOPERATIVE EXTENSION SERVICE

WATER QUALITY REPORT

OKLAHOMA CTY EXT OFC	**Name:**	**Lab ID No.:**	**395204**
	Khrishna Wright	**Customer Code:**	**55**
930 N PORTLAND	**Location:**	**Sample No.:**	**326**
OKLAHOMA CITY OK 73107	S.W.	**Received:**	**11/4/2005**
(405) 713-1125		**Report Date:**	**11/10/2005**

TEST RESULTS FOR *Irrigation Water*

-------- Cations -------		------- Anions -------		---------- Other------------	
Sodium (ppm)	10.1	Nitrate-N (ppm)	< 1	pH	8.0
Calcium (ppm)	19.5	Chloride (ppm)	13.9	EC (μmhos/cm)	180
Magnesium (ppm)	3.9	Sulfate (ppm)	15.9	Fe (ppm)	
Potassium (ppm)	3.0	Boron (ppm)	0.09		
		Bicarbonate (ppm)	58		

------------ Derived Values -------------		-------- Derived Values (cont'd) --------	
Total Soluble Salts (TSS in ppm)	125	Sodium Percentage	25.3%
Sodium Adsorption Ration (SAR)	0.5	Hardness (ppm)	65
Potassium Adsorption Ration (PAR)	0.1	Hardness Class	Medium
Residual Carbonates (meq)		Alkalinity (ppm as $CaCO_3$)	48

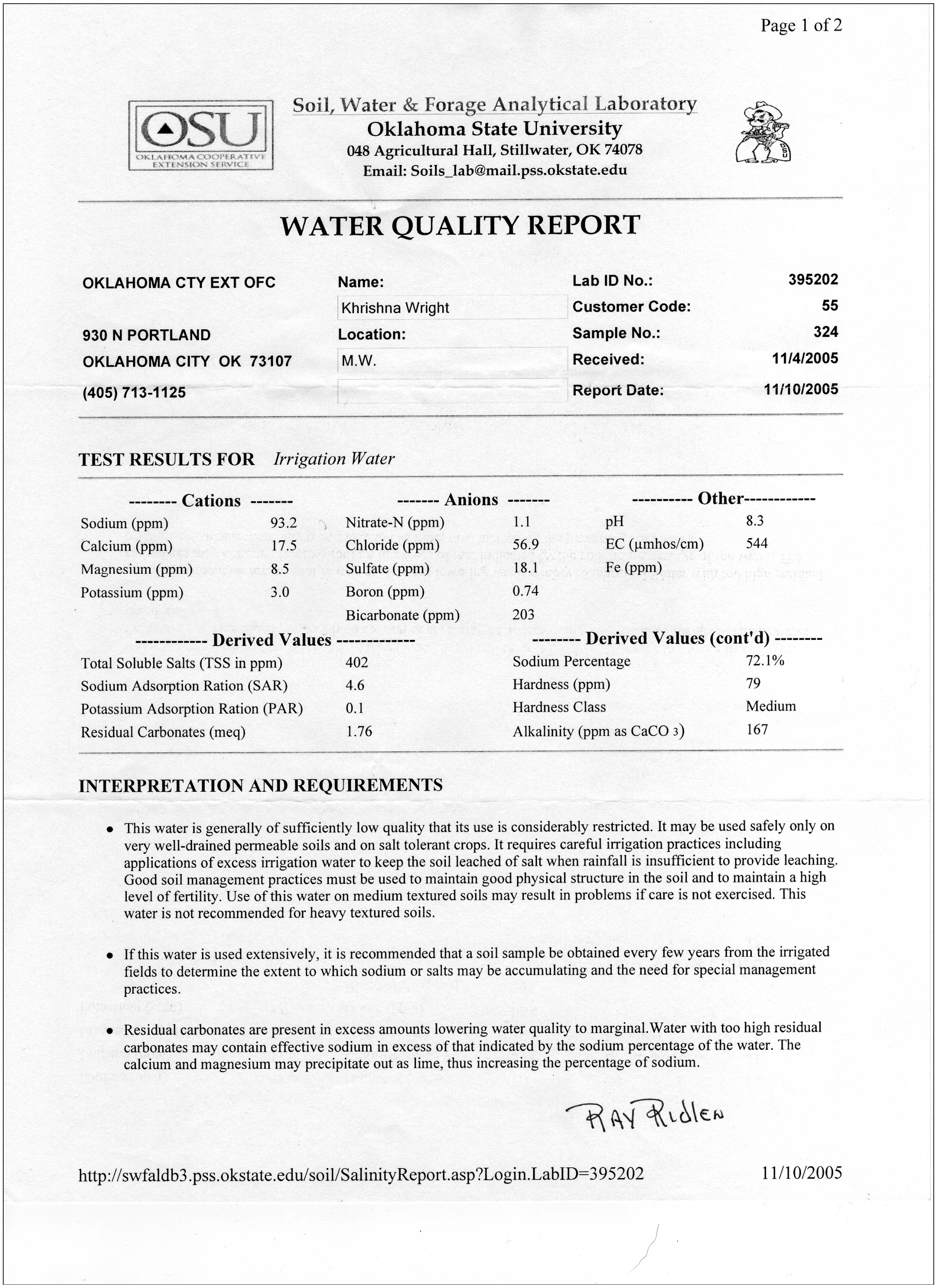
INTERPRETATION AND REQUIREMENTS

- The total soluble salt and sodium content of this water are low enough that no problem should result from its use.

RAY RIDLEN
Signature

http://swfaldb3.pss.okstate.edu/soil/SalinityReport.asp?Login.LabID=395204 11/10/2005

Water quality analysis of surface water sample.



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OSU
OKLAHOMA COOPERATIVE EXTENSION SERVICE

Soil, Water & Forage Analytical Laboratory
Oklahoma State University
048 Agricultural Hall, Stillwater, OK 74078
Email: Soils_lab@mail.pss.okstate.edu

WATER QUALITY REPORT

OKLAHOMA CTY EXT OFC	**Name:**	**Lab ID No.:**	**395202**
	Khrishna Wright	**Customer Code:**	**55**
930 N PORTLAND	**Location:**	**Sample No.:**	**324**
OKLAHOMA CITY OK 73107	M.W.	**Received:**	**11/4/2005**
(405) 713-1125		**Report Date:**	**11/10/2005**

TEST RESULTS FOR *Irrigation Water*

-------- Cations -------		------- Anions -------		---------- Other------------	
Sodium (ppm)	93.2	Nitrate-N (ppm)	1.1	pH	8.3
Calcium (ppm)	17.5	Chloride (ppm)	56.9	EC (µmhos/cm)	544
Magnesium (ppm)	8.5	Sulfate (ppm)	18.1	Fe (ppm)	
Potassium (ppm)	3.0	Boron (ppm)	0.74		
		Bicarbonate (ppm)	203		

------------ Derived Values -------------		-------- Derived Values (cont'd) --------	
Total Soluble Salts (TSS in ppm)	402	Sodium Percentage	72.1%
Sodium Adsorption Ration (SAR)	4.6	Hardness (ppm)	79
Potassium Adsorption Ration (PAR)	0.1	Hardness Class	Medium
Residual Carbonates (meq)	1.76	Alkalinity (ppm as $CaCO_3$)	167

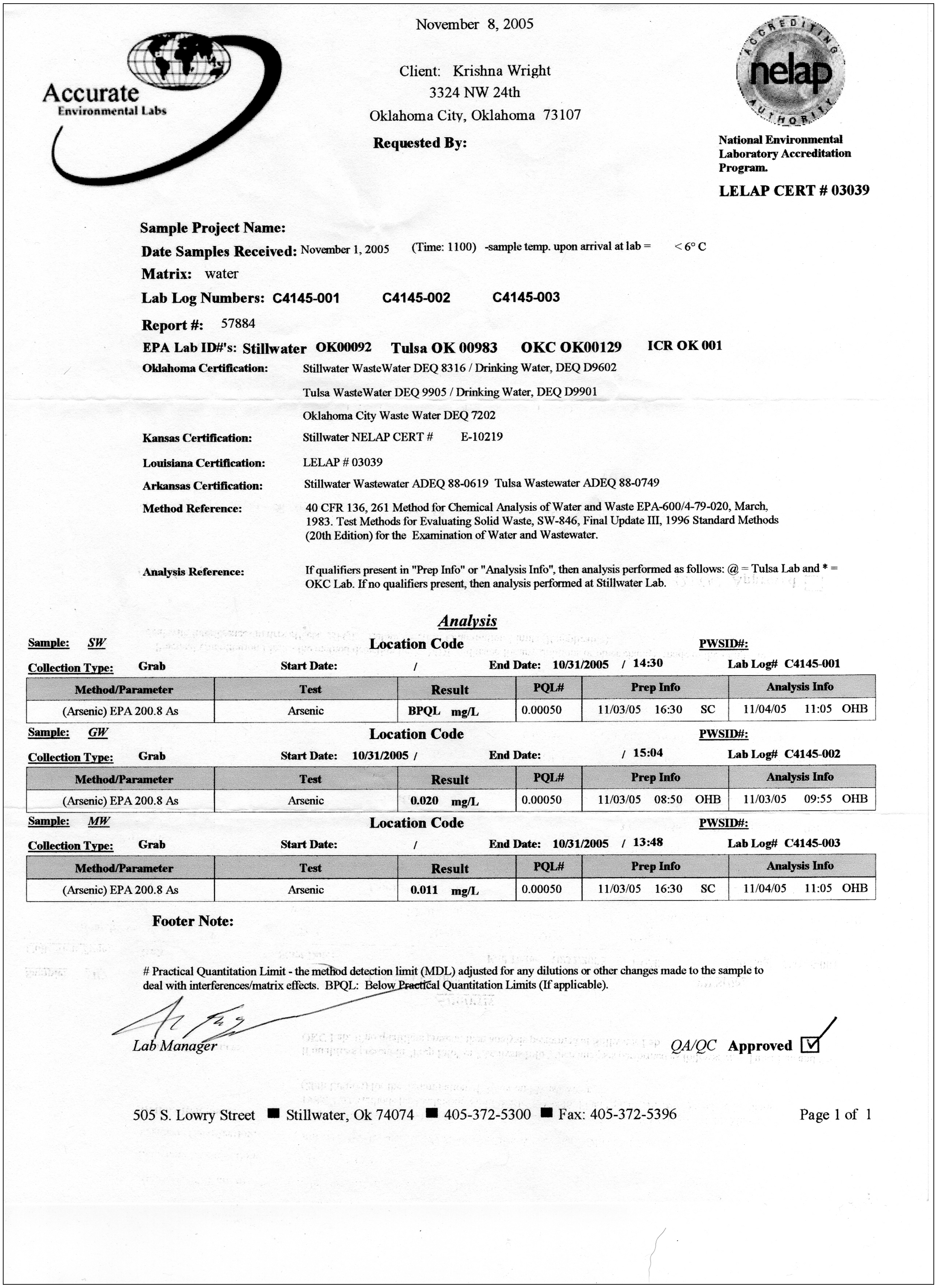
INTERPRETATION AND REQUIREMENTS

- This water is generally of sufficiently low quality that its use is considerably restricted. It may be used safely only on very well-drained permeable soils and on salt tolerant crops. It requires careful irrigation practices including applications of excess irrigation water to keep the soil leached of salt when rainfall is insufficient to provide leaching. Good soil management practices must be used to maintain good physical structure in the soil and to maintain a high level of fertility. Use of this water on medium textured soils may result in problems if care is not exercised. This water is not recommended for heavy textured soils.
- If this water is used extensively, it is recommended that a soil sample be obtained every few years from the irrigated fields to determine the extent to which sodium or salts may be accumulating and the need for special management practices.
- Residual carbonates are present in excess amounts lowering water quality to marginal.Water with too high residual carbonates may contain effective sodium in excess of that indicated by the sodium percentage of the water. The calcium and magnesium may precipitate out as lime, thus increasing the percentage of sodium.

RAY Ridlen

http://swfaldb3.pss.okstate.edu/soil/SalinityReport.asp?Login.LabID=395202 11/10/2005

Water quality analysis of mixed water sample.



Accurate
Environmental Labs

November 8, 2005

Client: Krishna Wright
3324 NW 24th
Oklahoma City, Oklahoma 73107

Requested By:

National Environmental Laboratory Accreditation Program.

LELAP CERT # 03039

Sample Project Name:
Date Samples Received: November 1, 2005 (Time: 1100) -sample temp. upon arrival at lab = < 6° C
Matrix: water
Lab Log Numbers: **C4145-001** **C4145-002** **C4145-003**
Report #: 57884
EPA Lab ID#'s: Stillwater OK00092 Tulsa OK 00983 OKC OK00129 ICR OK 001

Oklahoma Certification:	Stillwater WasteWater DEQ 8316 / Drinking Water, DEQ D9602 Tulsa WasteWater DEQ 9905 / Drinking Water, DEQ D9901 Oklahoma City Waste Water DEQ 7202
Kansas Certification:	Stillwater NELAP CERT # E-10219
Louisiana Certification:	LELAP # 03039
Arkansas Certification:	Stillwater Wastewater ADEQ 88-0619 Tulsa Wastewater ADEQ 88-0749
Method Reference:	40 CFR 136, 261 Method for Chemical Analysis of Water and Waste EPA-600/4-79-020, March, 1983. Test Methods for Evaluating Solid Waste, SW-846, Final Update III, 1996 Standard Methods (20th Edition) for the Examination of Water and Wastewater.
Analysis Reference:	If qualifiers present in "Prep Info" or "Analysis Info", then analysis performed as follows: @ = Tulsa Lab and * = OKC Lab. If no qualifiers present, then analysis performed at Stillwater Lab.

Analysis

Sample: *SW* **Location Code** **PWSID#:**
Collection Type: **Grab** **Start Date:** / **End Date: 10/31/2005 / 14:30** **Lab Log# C4145-001**

Method/Parameter	Test	Result	PQL#	Prep Info	Analysis Info
(Arsenic) EPA 200.8 As	Arsenic	**BPQL mg/L**	0.00050	11/03/05 16:30 SC	11/04/05 11:05 OHB

Sample: *GW* **Location Code** **PWSID#:**
Collection Type: **Grab** **Start Date: 10/31/2005 /** **End Date:** **/ 15:04** **Lab Log# C4145-002**

Method/Parameter	Test	Result	PQL#	Prep Info	Analysis Info
(Arsenic) EPA 200.8 As	Arsenic	**0.020 mg/L**	0.00050	11/03/05 08:50 OHB	11/03/05 09:55 OHB

Sample: *MW* **Location Code** **PWSID#:**
Collection Type: **Grab** **Start Date:** / **End Date: 10/31/2005 / 13:48** **Lab Log# C4145-003**

Method/Parameter	Test	Result	PQL#	Prep Info	Analysis Info
(Arsenic) EPA 200.8 As	Arsenic	**0.011 mg/L**	0.00050	11/03/05 16:30 SC	11/04/05 11:05 OHB

Footer Note:

Practical Quantitation Limit - the method detection limit (MDL) adjusted for any dilutions or other changes made to the sample to deal with interferences/matrix effects. BPQL: Below Practical Quantitation Limits (If applicable).

Lab Manager *QA/QC* **Approved** ☑

505 S. Lowry Street ■ Stillwater, Ok 74074 ■ 405-372-5300 ■ Fax: 405-372-5396 Page 1 of 1

Arsenic analyses of all three samples.

APPENDIX B: DATA COMPILED WITH WATEQ4F SOFTWARE

Appendix B. Data compiled with WATEQ4F, including mineral speciation, molality and activity coefficients.

GROUNDWATER SAMPLE

Effective T	pH	TDS ppm	Ionic Str	pO2 Atm	pCO2 Atm	pCH4 Atm	CO2 Tot	Uncom CO2 ppm	Uncom CO2	Ncrb Alk	aH2O
25	8.4	732.6	0.01113	0.00E+00	1.28E-03	0.00E+00	0.00562	5.57E-03	2.45E+02	2.28E-05	0.9997

SURFACE WATER SAMPLE

Effective T	pH	TDS ppm	Ionic Str	pO2 Atm	pCO2 Atm	pCH4 Atm	CO2 Tot	Uncom CO2 ppm	Uncom CO2	Ncrb Alk	aH2O
25	8	124.4	0.00249	0.00E+00	5.77E-04	0.00E+00	0.00096	9.37E-04	4.12E+01	1.54E-06	1

MIXED WATER SAMPLE

Effective T	pH	TDS ppm	Ionic Str	pO2 Atm	pCO2 Atm	pCH4 Atm	CO2 Tot	Uncom CO2 ppm	Uncom CO2	Ncrb Alk	aH2O
25	8.3	402.1	0.00637	0.00E+00	9.64E-04	0.00E+00	0.00329	3.25E-03	1.43E+02	9.80E-06	0.9998

GROUNDWATER SAMPLE

I	Species		Anal ppm	Calc ppm	Anal Molal	Calc Molal	Activity	Act Coeff	-Log Act
0	Ca	2	14.1	12.449	3.52E-04	3.11E-04	2.05E-04	0.6587	3.689
28	CaOH	1		0.000823		1.44E-08	1.30E-08	0.8976	7.888
31	CaSO4 aq	0		1.004		7.38E-06	7.40E-06	1.0026	5.131
81	CaHSO4	1		0		1.88E-13	1.69E-13	0.8976	12.773
29	CaHCO3	1		1.429		1.42E-05	1.27E-05	0.8976	4.896
30	CaCO3 aq	0		1.96		1.96E-05	1.97E-05	1.0026	4.707
1	Mg	2	10.1	9.188	4.16E-04	3.78E-04	2.51E-04	0.6633	3.601
18	MgOH	1		0.004654		1.13E-07	1.01E-07	0.8976	6.995
22	MgSO4 aq	0		0.949		7.89E-06	7.91E-06	1.0026	5.102
21	MgHCO3	1		1.347		1.58E-05	1.42E-05	0.8976	4.848
20	MgCO3 aq	0		1.153		1.37E-05	1.37E-05	1.0026	4.863
2	Na	1	200.8	199.916	8.74E-03	8.70E-03	7.82E-03	0.8988	2.107
43	NaSO4	-1		0.921		7.75E-06	6.95E-06	0.8976	5.158
42	NaHCO3aq	0		1.791		2.13E-05	2.14E-05	1.0026	4.67
41	NaCO3	-1		0.767		9.25E-06	8.31E-06	0.8976	5.081
3	K	1	2	1.997	5.12E-05	5.11E-05	4.58E-05	0.8959	4.339
45	KSO4	-1		0.008589		6.36E-08	5.71E-08	0.8976	7.243
63	H	1		0.000004		4.38E-09	3.98E-09	0.91	8.4
26	OH	-1		0.048		2.81E-06	2.52E-06	0.8976	5.599
17	CO3	-2	10	5.212	1.67E-04	8.69E-05	5.73E-05	0.6591	4.242
6	HCO3	-1	329	329.031	5.40E-03	5.40E-03	4.86E-03	0.901	2.313
85	H2CO3 aq	0		2.69		4.34E-05	4.35E-05	1.0027	4.361
5	SO4	-2	28.2	25.984	2.94E-04	2.71E-04	1.77E-04	0.6552	3.751
62	HSO4	-1		0.000007		7.64E-11	6.85E-11	0.8976	10.164
4	Cl	-1	136.8	136.799	3.86E-03	3.86E-03	3.46E-03	0.8959	2.461
86	B tot	0	1.55		1.44E-04				
35	H3BO3 aq	0		7.631		1.24E-04	1.24E-04	1.0026	3.907
36	H2BO3	-1		1.213		2.00E-05	1.79E-05	0.8976	4.747
249	As total	0	0.02		2.67E-07				

GROUNDWATER SAMPLE

	Phase	Log AP/KT	Sigma(A)	Sigma(T)	Log AP/MinKT	Log AP/MaxKT	Log AP	Log KT	Log MinKT	Log MaxKT
17	Anhydrite	-2.803					-7.44	-4.637		
21	Aragonite	0.405		0.02			-7.931	-8.336		
150	Artinite	-4.42					5.18	9.6		
19	Brucite	-3.595					-14.799	-11.204		
12	Calcite	0.549		0.02	0.629		-7.931	-8.48	-8.56	
11	Dolomite	1.227					-15.773	-17		
340	Epsomite	-5.213					-7.353	-2.14		
18	Gypsum	-2.84					-7.44	-4.6		
64	Halite	-6.15					-4.568	1.582		
117	Huntite	-1.49					-31.458	-29.968		
38	Hydrmagnesite	-9.407					-46.169	-36.762		
10	Magnesite	0.186			0.436	-0.064	-7.843	-8.029	-8.279	-7.779
66	Mirabilite	-6.852					-7.966	-1.114		
58	Nahcolite	-3.872					-4.42	-0.548		
60	Natron	-7.146					-8.457	-1.311		
149	Nesquehonite	-2.222			-2.71	-3.297	-7.843	-5.621	-5.133	-4.546
65	Thenardite	-7.786					-7.965	-0.179		
61	Thermonatr	-8.58					-8.455	0.125		
59	Trona	-12.081					-12.876	-0.795		

DOX =	0	**DOC =**	0	**INPUT TDS =**	0
Anal Cond =	999	**Calc Cond =**	1012		
Anal EPMCAT =	10.3275	**Anal EPMAN =**	10.1809	**% difference in input cation/anion balance =**	1.4292
Calc EPMCAT =	10.1616	**Calc EPMAN =**	10.013	**% difference in calc cation/anion balance =**	1.4731
Total Ionic Strength (T.I.S.) from input data =	0.01148				
Effective Ionic Strength (E.I.S.) from speciation =	0.01113				

GROUNDWATER SAMPLE

TEMP	25
PH	8.4
EHM	9.9
DOC	0
DOX	0
CORALK	0
FLG	MG/L
DENS	1
PRNT	0
PUNCH	1
EHOPT	0
EMPOX	0
ITDS	0
COND	999
SIGMDO	0
SIGMEH	0
SIGMPH	0

		Input
Species	**Index No**	**Conc.**
Ca	0	14.1
Mg	1	10.1
Na	2	200.8
K	3	2
Cl	4	136.8
SO4	5	28.2
HCO3	6	329
Fe total	16	0
H2S aq	13	0
CO3	17	10
SiO2 total	34	0
NH4	38	0
B total	86	1.55
PO4	44	0
Al	50	0
F	61	0
NO3	84	0
As total	249	0.02

Mole ratios from analytical molality - Log activity ratios			
Cl/Ca	1.10E+01	Log Ca/H2	13.1112
Cl/Mg	9.29E+00	Log Mg/H2	13.1994
Cl/Na	4.42E-01	Log Na/H1	6.2933
Cl/K	7.54E+01	Log K/H1	4.0609
Cl/Al	0.00E+00	Log Al/H3	0
Cl/Fe	0.00E+00	Log Fe/H2	0
Cl/SO4	1.31E+01	Log Ca/Mg	-0.0882
CL/HCO3	6.74E-01	LOG Na/K	2.2324
Ca/Mg	8.47E-01	Log Ca/K2	4.9895
Na/K	1.71E+02	Log Diss Fe/H2	16.8

SURFACE WATER SAMPLE

I	Species	Valence	Anal ppm	Calc ppm	Anal Molal	Calc Molal	Activity	Act Coeff	-Log Act
0	Ca	2	19.5	18.834	4.87E-04	4.70E-04	3.79E-04	0.8063	3.421
28	CaOH	1		0.000575		1.01E-08	9.54E-09	0.9467	8.02
31	CaSO4 aq	0		1.294		9.50E-06	9.51E-06	1.0006	5.022
81	CaHSO4	1		0		5.75E-13	5.45E-13	0.9467	12.264
29	CaHCO3	1		0.453		4.48E-06	4.25E-06	0.9467	5.372
30	CaCO3 aq	0		0.262		2.61E-06	2.62E-06	1.0006	5.583
1	Mg	2	3.9	3.787	1.60E-04	1.56E-04	1.26E-04	0.8078	3.9
18	MgOH	1		0.000882		2.14E-08	2.02E-08	0.9467	7.694
22	MgSO4 aq	0		0.332		2.76E-06	2.76E-06	1.0006	5.56
21	MgHCO3	1		0.116		1.36E-06	1.29E-06	0.9467	5.891
20	MgCO3 aq	0		0.042		4.95E-07	4.95E-07	1.0006	6.306
2	Na	1	10.1	10.088	4.39E-04	4.39E-04	4.16E-04	0.947	3.381
43	NaSO4	-1		0.032		2.71E-07	2.57E-07	0.9467	6.591
42	NaHCO3aq	0		0.017		2.05E-07	2.05E-07	1.0006	6.688
41	NaCO3	-1		0.002782		3.35E-08	3.17E-08	0.9467	7.499
3	K	1	3	2.997	7.67E-05	7.67E-05	7.26E-05	0.9463	4.139
45	KSO4	-1		0.008966		6.63E-08	6.28E-08	0.9467	7.202
63	H	1		0.000011		1.05E-08	1.00E-08	0.9503	8
26	OH	-1		0.018		1.06E-06	1.00E-06	0.9467	5.999
17	CO3	-2		0.306		5.11E-06	4.12E-06	0.8066	5.385
6	HCO3	-1	58	56.531	9.51E-04	9.27E-04	8.78E-04	0.9477	3.056
85	H2CO3 aq	0		1.224		1.97E-05	1.97E-05	1.0006	4.705
5	SO4	-2	15.9	14.69	1.66E-04	1.53E-04	1.23E-04	0.8054	3.909
62	HSO4	-1		0.000012		1.26E-10	1.20E-10	0.9467	9.922
4	Cl	-1	13.9	13.9	3.92E-04	3.92E-04	3.71E-04	0.9463	3.431
86	B tot	0	0.09		8.33E-06				
35	H3BO3 aq	0		0.485		7.85E-06	7.85E-06	1.0006	5.105
36	H2BO3	-1		0.029		4.78E-07	4.52E-07	0.9467	6.344
1									

SURFACE WATER SAMPLE

	Phase	Log AP/KT	Sigma(A)	Sigma(T)	Log AP/MinKT	Log AP/MaxKT	Log AP	Log KT	Log MinKT	Log MaxKT
17	Anhydrite	-2.694					-7.331	-4.637		
21	Aragonite	-0.471		0.02			-8.807	-8.336		
150	Artinite	-5.828					3.772	9.6		
19	Brucite	-4.694					-15.898	-11.204		
12	Calcite	-0.327		0.02	-0.247		-8.807	-8.48	-8.56	
11	Dolomite	-1.092					-18.092	-17		
340	Epsomite	-5.67					-7.81	-2.14		
18	Gypsum	-2.731					-7.331	-4.6		
64	Halite	-8.394					-6.812	1.582		
117	Huntite	-6.695					-36.663	-29.968		
38	Hydrmagnesite	-16.277					-53.039	-36.762		
10	Magnesite	-1.256			-1.006	-1.506	-9.285	-8.029	-8.279	-7.779
66	Mirabilite	-9.558					-10.672	-1.114		
58	Nahcolite	-5.89					-6.438	-0.548		
60	Natron	-10.837					-12.148	-1.311		
149	Nesquehonite	-3.664			-4.152	-4.739	-9.285	-5.621	-5.133	-4.546
65	Thenardite	-10.493					-10.672	-0.179		
61	Thermonatr	-12.273					-12.148	0.125		
59	Trona	-17.791					-18.586	-0.795		

DOX =	0	**DOC =**	0	**INPUT TDS =**	0
Anal Cond =	180	**Calc Cond =**	188.6		
Anal EPMCAT =	1.8102	**Anal EPMAN =**	1.6749	**% difference in input cation/anion balance =**	7.7643
Calc EPMCAT =	1.773	**Calc EPMAN =**	1.6367	**% difference in calc cation/anion balance =**	7.9917
Total Ionic Strength (T.I.S.) from input data =	0.00255				
Effective Ionic Strength (E.I.S.) from speciation =	0.00249				

SURFACE WATER SAMPLE

TEMP	25
PH	8
EHM	9.9
DOC	0
DOX	0
CORALK	0
FLG	MG/L
DENS	1
PRNT	0
PUNCH	1
EHOPT	0
EMPOX	0
ITDS	0
COND	180
SIGMDO	0
SIGMEH	0
SIGMPH	0

		Input
Species	**Index No**	**Conc.**
Ca	0	19.5
Mg	1	3.9
Na	2	10.1
K	3	3
Cl	4	13.9
SO4	5	15.9
HCO3	6	58
Fe total	16	0
H2S aq	13	0
CO3	17	0
SiO2 total	34	0
NH4	38	0
B total	86	0.09
PO4	44	0
Al	50	0
F	61	0
NO3	84	0

Mole ratios from analytical molality - Log activity ratios			
Cl/Ca	8.06E-01	Log Ca/H2	12.5786
Cl/Mg	2.44E+00	Log Mg/H2	12.0999
Cl/Na	8.92E-01	Log Na/H1	4.6187
Cl/K	5.11E+00	Log K/H1	3.8606
Cl/Al	0.00E+00	Log Al/H3	0
Cl/Fe	0.00E+00	Log Fe/H2	0
Cl/SO4	2.37E+00	Log Ca/Mg	0.4787
CL/HCO3	4.12E-01	LOG Na/K	0.7581
Ca/Mg	3.03E+00	Log Ca/K2	4.8573
Na/K	5.73E+00	Log Diss Fe/H2	16

MIXED WATER SAMPLE

I	Species		Anal ppm	Calc ppm	Anal Molal	Calc Molal	Activity	Act Coeff	-Log Act
0	Ca	2	17.5	16.196	4.37E-04	4.04E-04	2.91E-04	0.72	3.536
28	CaOH	1		0.000908		1.59E-08	1.46E-08	0.9191	7.835
31	CaSO4 aq	0		1.002		7.37E-06	7.38E-06	1.0015	5.132
81	CaHSO4	1		0		2.30E-13	2.12E-13	0.9191	12.674
29	CaHCO3	1		1.193		1.18E-05	1.09E-05	0.9191	4.964
30	CaCO3 aq	0		1.333		1.33E-05	1.33E-05	1.0015	4.875
1	Mg	2	8.5	8.005	3.50E-04	3.29E-04	2.38E-04	0.7231	3.623
18	MgOH	1		0.00343		8.30E-08	7.63E-08	0.9191	7.117
22	MgSO4 aq	0		0.633		5.26E-06	5.27E-06	1.0015	5.278
21	MgHCO3	1		0.751		8.81E-06	8.10E-06	0.9191	5.092
20	MgCO3 aq	0		0.523		6.21E-06	6.22E-06	1.0015	5.206
2	Na	1	93.2	92.954	4.06E-03	4.05E-03	3.72E-03	0.9198	2.429
43	NaSO4	-1		0.3		2.52E-06	2.32E-06	0.9191	5.635
42	NaHCO3aq	0		0.513		6.11E-06	6.12E-06	1.0015	5.214
41	NaCO3	-1		0.17		2.05E-06	1.89E-06	0.9191	5.724
3	K	1	3	2.997	7.68E-05	7.67E-05	7.04E-05	0.9181	4.152
45	KSO4	-1		0.009048		6.70E-08	6.16E-08	0.9191	7.211
63	H	1		0.000005		5.41E-09	5.01E-09	0.9271	8.3
26	OH	-1		0.037		2.18E-06	2.00E-06	0.9191	5.699
17	CO3	-2		2.278		3.80E-05	2.74E-05	0.7205	4.563
6	HCO3	-1	203	193.507	3.33E-03	3.17E-03	2.92E-03	0.9213	2.534
85	H2CO3 aq	0		2.039		3.29E-05	3.29E-05	1.0016	4.482
5	SO4	-2	18.1	16.639	1.89E-04	1.73E-04	1.24E-04	0.7179	3.905
62	HSO4	-1		0.000006		6.58E-11	6.05E-11	0.9191	10.218
4	Cl	-1	56.9	56.9	1.61E-03	1.61E-03	1.47E-03	0.9181	2.831
86	B tot	0	0.74		6.85E-05				
35	H3BO3 aq	0		3.761		6.09E-05	6.09E-05	1.0015	4.215
36	H2BO3	-1		0.463		7.62E-06	7.01E-06	0.9191	5.155
202	NO2	-1	1.1	1.1	2.39E-05	2.39E-05	2.20E-05	0.9191	4.658
249	As total	0	0.011		1.47E-07				
1									

MIXED WATER SAMPLE

	Phase	Log AP/KT	Sigma(A)	Sigma(T)	Log AP/MinKT	Log AP/MaxKT	Log AP	Log KT	Log MinKT	Log	MaxKT
17	Anhydrite	-2.804					-7.441	-4.637			
21	Aragonite	0.237		0.02			-8.099	-8.336			
150	Artinite	-4.635					4.965	9.6			
19	Brucite	-3.817					-15.021	-11.204			
12	Calcite	0.381		0.02	0.461		-8.099	-8.48	-8.56		
11	Dolomite	0.715					-16.285	-17			
340	Epsomite	-5.389					-7.529	-2.14			
18	Gypsum	-2.841					-7.441	-4.6			
64	Halite	-6.843					-5.261	1.582			
117	Huntite	-2.689					-32.657	-29.968			
38	Hydrmagnesite	-11.003					-47.765	-36.762			
10	Magnesite	-0.157			0.093	-0.407	-8.186	-8.029	-8.279	-7	0.779
66	Mirabilite	-7.651					-8.765	-1.114			
58	Nahcolite	-4.416					-4.964	-0.548			
60	Natron	-8.111					-9.422	-1.311			
149	Nesquehonite	-2.565			-3.053	-3.64	-8.186	-5.621	-5.133	-4	0.546
65	Thenardite	-8.585					-8.764	-0.179			
61	Thermonatr	-9.547					-9.422	0.125			
59	Trona	-13.59					-14.385	-0.795			

DOX =	0	**DOC =**	0	**INPUT TDS =**	0
Anal Cond =	544	**Calc Cond =**	553.7		
Anal EPMCAT =	5.7055	**Anal EPMAN =**	5.3368	**% difference in input cation/anion balance =**	6.6783
Calc EPMCAT =	5.6096	**Calc EPMAN =**	5.2391	**% difference in calc cation/anion balance =**	6.8306
Total Ionic Strength (T.I.S.) from input data =	0.0065				
Effective Ionic Strength (E.I.S.) from speciation =	0.00637				

MIXED WATER SAMPLE

TEMP	25
PH	8.3
EHM	9.9
DOC	0
DOX	0
CORALK	0
FLG	MG/L
DENS	1
PRNT	0
PUNCH	1
EHOPT	0
EMPOX	0
ITDS	0
COND	544
SIGMDO	0
SIGMEH	0
SIGMPH	0

		Input
Species	**Index No**	**Conc**
Ca	0	17.5
Mg	1	8.5
Na	2	93.2
K	3	3
Cl	4	56.9
SO4	5	18.1
HCO3	6	203
Fe total	16	0
H2S aq	13	0
CO3	17	0
SiO2 total	34	0
NH4	38	0
B total	86	0.74
PO4	44	0
Al	50	0
F	61	0
NO3	84	0
NO2	202	1.1
As total	249	0.011

Mole ratios from analytical molality - Log activity ratios			
Cl/Ca	3.68E+00	Log Ca/H2	13.064
Cl/Mg	4.59E+00	Log Mg/H2	12.9769
Cl/Na	3.96E-01	Log Na/H1	5.8706
Cl/K	2.09E+01	Log K/H1	4.1476
Cl/Al	0.00E+00	Log Al/H3	0
Cl/Fe	0.00E+00	Log Fe/H2	0
Cl/SO4	8.52E+00	Log Ca/Mg	0.0871
CL/HCO3	4.82E-01	LOG Na/K	1.723
Ca/Mg	1.25E+00	Log Ca/K2	4.7688
Na/K	5.28E+01	Log Diss Fe/H2	16.6

VITA

Khrishna Erika Wright

Candidate for the Degree of

Master of Science

Thesis: FEASIBILITY OF AQUIFER STORAGE RECOVERY FOR THE MUSTANG, OKLAHOMA WELL FIELD

Major Field: Environmental Science

Biographical:

Education: Graduated from Keystone Heights High School, Keystone Heights, FL, in June 1989; received Associate of Arts degree from St. Johns River Community College, Palatka, Florida in December 1992; received Bachelor of Science degree in Recreation, Parks and Tourism from the University of Florida, Gainesville, Florida in December 1999. Completed the requirements for the Master of Science degree with a major in Environmental Science in May, 2007.

Experience: Employed by Oklahoma State University, Water Quality Extension Office as a graduate research assistant from January 2003 to September 2005; employed by the Association of Central Oklahoma Governments as a hydrogeologist intern from April 2004 to September 2005; employed by Greystone Environmental Services as an intern from May to November 2005; employed by the Oklahoma Corporation Commission as an Oil and Gas Specialist from January 2006 to present.

Professional Memberships: Oklahoma Clean Lakes and Watersheds Association, National Ground Water Association.

Name: Khrishna Wright Date of Degree: May, 2007

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: FEASIBILITY OF AQUIFER STORAGE RECOVERY FOR THE MUSTANG, OKLAHOMA WELL FIELD

Pages in Study: 118 Candidate for the Degree of Master of Science

Major Field: Environmental Science

Scope and Method of Study: The purpose of this study was to determine the economic and geochemical feasibility of utilizing aquifer storage recovery (ASR) technology to store water in the Central Oklahoma Aquifer for use by the City of Mustang. The objectives were twofold:

- Determine whether arsenic concentrations in the COA will be reduced or increased by introducing a new water source via ASR wells.
- Determine whether the costs associated with implementing ASR would prove economically feasible for Mustang.

Findings and Conclusions: The chemistries of the native ground water and the proposed injectate were analyzed, and both were found to have low activity coefficients, signifying that precipitation of arsenic (or other minerals such as calcite) is not expected. Low overhead costs and ongoing operation and maintenance costs are partially offset by more efficient use of water resources. Aquifer storage recovery is geochemically and economically feasible for Mustang.

Advisor's Approval: Dr. Michael D. Smolen