LESSONS LEARNED FROM A REVIEW OF 50 ASR PROJECTS FROM THE UNITED STATES, ENGLAND, AUSTRALIA, INDIA, AND AFRICA

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The formulation of an improved planning methodology for ASR projects should be based upon results and experience at existing operating projects. In an effort to provide a sound underpinning of an improved ASR planning framework, a review of 50 ASR projects from around the world was undertaken in order to provide fundamental data and lessons learned. First, existing published data was collected and collated. Published ASR data ranged from a brief project summary to extensive reports. Some published data were available for a total of 30 sites. In addition to the published data, numerous ASR owners and developers from around the world were requested to provide key ASR operating data. A total 20 ASR project sites were contacted and agreed to send data. Some of the ASR projects were constructed for testing purposes only, while others were planned to supply irrigation or municipal water supply. The setting, background, and operational histories of twenty (20) non-brackish water ASR projects were reviewed along with thirty (30) brackish water ASR projects. After the compilation and review of the data was completed, the various sites were compared and contrasted to reveal key similarities and differences. Common lessons learned derived from the site operating data provided sound support for a new planning decision framework currently under development.

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Lessons Learned from a Review of 50 ASR Projects from the United States, England, Australia, India, and Africa

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Abstract: The University of Florida has conducted a significant research program over the last four years investigating various aspects of Aquifer, Storage and Recovery (ASR). One pillar of this research effort was the compilation of ASR field data from around the world. Data and supporting information was compiled for over 50 ASR sites located in the United States, England, Australia, India, and Africa. This field data review was completed with two main objectives. First, the ASR operating data was reviewed to evaluate operational similarities and differences. Second, the ASR field data was reviewed to identify fatal flaws that could be avoided at future ASR projects or lessons learned that could aid existing and future ASR projects. Summary tables were prepared comparing basic site information, such as geologic environment or aquifer transmissivity, and site operational characteristics, such as recharge water quality and geochemical issues. Data from 50 of the ASR sites are reviewed in this article. The data revealed that a majority of the sites have been successful in meeting their project goals and objectives; however, a few of the sites have had considerable problems that have limited their overall feasibility.

Introduction

Modern artificial recharge (AR) is the process of augmenting natural recharge of groundwater aquifers. According to the National Research Council (NRC), AR is:

> *a process by which excess surface water is directed into the ground – either by spreading on the surface, by using recharge wells, or by altering natural conditions to increase infiltration – to replenish an aquifer. (NRC, 1994, p. 1)*

AR provides a means to store water underground in times of water surplus to meet demand in times of shortage. Water recovered from AR projects can be utilized for a variety of potable and non-potable uses. AR can also be used to control seawater intrusion in coastal aquifers, control land subsidence caused by declining ground water levels, maintain base flow in some streams, and raise water levels to reduce the cost of groundwater pumping (NRC, 1994).

Recharge can be introduced through various surface infiltration methods or through wells. Recharge can be introduced into the saturated or unsaturated portions of an aquifer. Both unconfined and confined aquifers have been used for AR (ASCE, 2001). Surface spreading methods are mainly amenable in unconfined aquifers (Asano, 1985), while wells are utilized to recharge confined aquifers (NRC, 1994).

Aquifer Storage and Recovery (ASR) is a simple concept in which water is stored in subsurface permeable aquifers when water is plentiful and extracted during times of peak demand. According to the British Geological Survey (Jones et al. 1999, p. 3), ASR is a sub-set of AR and is defined as:

> *storage of treated, potable water in the aquifer local to the borehole(s) that is (are) used for both injection and abstraction. A high percentage of the water injected is abstracted at a later date and the scheme may utilize an aquifer containing poor quality or brackish water, although this does not exclude the use of aquifers containing potable water. ASR schemes enable maximum use to be made of existing licensed resources.*

ASR projects are utilized in three broad areas to augment water supplies. The largest and most common use of ASR projects is in support of potable water supply projects. The second most common use of ASR projects is in support of agriculture in the form of irrigation water supply. The newest alternative use for ASR is in support of environmental water supply to support in-stream uses, as is the case with the Everglades Restoration (USACE and SFWMD, 1999). Each of these categories presents great opportunities to exploit ASR technology, however, each option is subject to many constraints. The primary constraints can be grouped into four general categories including:

- Regulatory
- Recharge and recovered water quality
- Water availability and demand
- Availability of a suitable storage aquifer

ASR project planning consists of multiple parts and iterations. Many planning factors need to be evaluated to determine the ultimate feasibility of a prospective project. As ASR projects are located throughout the world in diverse environments, no two projects are alike. However, many sites share common issues, constraints or problems. A majority of these can be determined through judicious review of the relevant ASR literature including operating site data. Based upon a thorough review of the available literature by the author, no comprehensive ASR site comparison has been completed anywhere in the world. Several investigators (Pyne, 1998; Dillon and Pavelic, 1996) have compiled information for a limited number of sites to analyze specific ASR issues but no comprehensive evaluation has been completed. Comparisons among brackish water ASR sites are even less available in the literature. A comprehensive comparison of site data would provide an impetus for the further development of the ASR technology.

Means and Methods

If ASR technology is to continue advancing, new projects should be based upon successful results and “lessons learned” at existing operating projects along with a reliance on “best practices”. With that theme in mind, the authors undertook a large data collection effort for this research report. First, existing published data were collected and collated. Published ASR data ranged from a brief project summary to extensive reports. Some published data were available for a total of thirty (30) sites. In addition to the published data, the author contacted numerous ASR owners and developers across the USA, Australia and England to request key ASR operating data. A total of twenty (20) ASR project sites were contacted and agreed to send data. The data sent by the ASR proponents varied in importance and scale as well as format (e.g., hard copies vs. electronic data deliverables). A net sum of fifty (50) sites is discussed herein and located on Figure 1. A few of these sites have only been operated in recharge mode but could recover water also at some point in the future.

The available data were organized into several categories. First, basic site background information was gleaned from the datasets. Relevant basic site data consists of the site location, geologic environment, and ambient groundwater quality (brackish water vs. freshwater). For approximately one third to one half of the ASR project sites, operational data included influent level of total suspended solids (TSS), degree of well clogging observed, extent of disinfection by-products recorded at the site, extent of geochemical issues, and total cost per cubic meter to develop the water supply. The various data collected from each of the 50 sites was then compared and contrasted. Lastly, key findings regarding the 50 sites were developed with an emphasis towards improving operation at future projects such as the Everglades ASR program (USACE and SFWMD, 1999). For this research effort, brackish water ASR sites have been segregated from non-brackish water sites since each is significantly different.

The non-brackish water ASR sites reviewed for this report include sites across the United States, England, and Namibia, Africa. They represent diverse geologic environments as well as different operating types. Twenty (20) sites were reviewed for this effort. Available data ranged from extensive reporting for Oak Creek and Green Bay, Wisconsin to short summaries available for the Huron, South Dakota site. Electronic data were provided for a number of sites also. This data facilitated development of unit water costs as well as lessons learned and best practices. Thirty (30) brackish water ASR sites were reviewed for this report. Of the 30 sites surveyed, 21 of them are located in the State of Florida within the United States.

Results and Discussion

The 20 non-brackish sites and 30 brackish sites chosen for discussion in this article represent a multitude of different geologic environments as well as a wide variety of locations in the United States, England and Australia. Some of the ASR projects were constructed for testing purposes only (Bureau of Reclamation, 1996; Bureau of Reclamation, 1997; Merritt, 1997; Miller, 2001), while others were planned to supply irrigation or municipal water supply in order to meet peak demands or for emergency purposes (Meyer, 1989; Castro, 1995; CH2M Hill, 1999; CH2M Hill, 2001; CH2M Hill, 2002; Portland Water Works, 2001; Sibenaler et al., 2002; Reese, 2002; Calleguas, 2004; Groundwater Solutions, 2004; Mirecki, 2004). Tables 1 to 3 summarize key data from the non-brackish ASR projects evaluated. Note that the Huron and Washoe County sites are capable of recovering recharged water but have never done so.

The surveyed ASR projects are located in five countries and fourteen states within the USA. The geology varies across the sites and includes both bedrock (35 sites) as well as unconsolidated sediments (15 sites). Of the bedrock sites, the predominant rock type is sedimentary (32 of 35 sites) with two located in fractured igneous rock (basalt) type and one located in a fractured metamorphic rock (quartzite) type. Twenty eight (28) of the 35 sedimentary rock sites are composed of carbonate sequences including limestone, dolomite, sandy limestone or chalk, while the remaining four sedimentary rock sites are composed of predominately sandstone. For the case of the fifteen (15) sites situated in unconsolidated geologic environments, sands and gravels dominated the composition of

Table 1 – ASR Non-brackish Water Site Data for sites 1 to 7

	Highline - Seattle	**Columbia South Shore – Portland**	**Beaverton – Oregon**	**Salem – Oregon**	**SE Salt Lake City - Utah**	**Huron – South Dakota**	**Washoe County - Nevada**
Site Geology	**Sand and Gravel**	**Sand and Gravel**	**Basalt**	**Basalt**	**Sand and Gravel**	**Glacial Sand**	**Glacial Sand**
T (m^2/day)	**277**	**251**	**1,242**	**2,973**	**460 ****	**372**	**NA**
TSS of influent (mg/l)	**1.0 to 4..0**	**1.0 to 1.67**	**1.0 to 10**	**0.30 to 1.0**	**<1.0**	**NR**	**NR**
Well Clogging Issues ?	**Yes – due to algae in recharge water**	**Yes – Major problems being investigated**	**No – Use regular redevelopment program**	**No – Use regular redevelopment program**	**Yes – Minor due to algae in recharge water**	**NA**	**Yes – Minor**
Geochem or recovered water quality Issues ?	**None to Minor - Radon issues in recovered water**	**None**	**None**	**Minor – DBP problems and natural radon**	**None**	**Minor – Atrazine in source water**	**None**
Primary Purpose	**Meet seasonal demands**	**Meet seasonal demands**	**Meet seasonal demands**	**Emergency water supply**	**Meet seasonal demands**	**Restore aquifer water levels**	**Meet seasonal demands**
Cost per cubic meter	**$ 2.04**	**$ 1.10**	**$ 4.77**	**NR**	**$ 0.34**	**$ 1.89**	**$ 5.68**

Notes: LS is “Limestone”; SS is “Sandstone”; NA is “not available”; TSS is “total suspended solids”; NR is “not reported”; ** denotes unconfined aquifer; ** denotes unconfined aquifer

the sediments. The aquifer transmissivities for the 50 ASR sites ranged from 15 m^2/day to 19,500 m^2/day with a majority having values less than 2,000. The geometric mean transmissivity for the 20 non-brackish sites is approximately 466 m^2/day. The geometric mean transmissivity for the 30 brackish sites is approximately 715 m^2/day. A majority of the sites studied had confined aquifer storage zones. Forty-five (45) of the ASR sites stored excess potable water treated at a municipal water treatment plant, while the others utilized tertiary wastewater or excess storm water as the source water. Twenty-eight (28) of the sites reported minor to moderate problems with well clogging due to physical clogging, particle rearrangement, air entrainment, or biological growth. One site, Columbia South Shore in Portland, Oregon, reported major losses of well capacity (Moncaster, 2004).

Multiple sites have experienced some form of water quality challenge. At least five of the sites surveyed reported major problems with heavy metals in the recovered water due to in-situ geochemical reactions between the aquifer matrix and the source water. Gauss et al. (2002) discusses one of these sites in England where fluoride in the recovered water rendered the project infeasible. Mirecki (2004) discusses several southwest Florida sites where arsenic in the recovered water is the primary concern. The ASR site in Green Bay, Wisconsin was abandoned entirely for similar reasons due to arsenic, manganese, nickel, and cobalt in the recovered water. Three of the sites reviewed experienced in-situ formation of various disinfection by-products included trihalomethanes and haloacetic acids. Two of the sites, Las Vegas, Nevada and Lancaster, California, have been studied in detail (Katzer and Brothers, 1989 and Baqai, 2002). Several other sites including Tampa Rome Avenue reported minor upconing of

Table 2 – ASR Non-brackish Water Site Data for sites 8 to 14

	Calleguas - California	**Las Vegas - Nevada**	**Antelope Valley - California**	**Highlands Ranch - Denver**	**Denver Basin Demo – South Denver**	**Alamogordo – New Mexico**	**Greenbay - Wisconsin**
Site Geology	**Sand**	**Sand and Gravel**	**Sand and Gravel**	**SS**	**SS**	**Sand and Gravel**	**SS & LS**
T (m^2/day)	**929**	**2,349 ***	**232 ***	**93**	**79**	**232**	**102**
TSS of influent (mg/l)	**1.0 to 3.0**	**<1.0**	**1.0 to 1.67**	**1.0 to 2.0**	**<1.0**	**<1.0**	**<1.0**
Well Clogging Issues ?	**Yes – due to TSS and air entrainment**	**Yes – due to air entrainment**	**Yes – Minor due to TSS and biological growth**	**Yes – Moderate due to TSS and low T of aquifer and possibly air entrainment**	**No – Use regular redevelopment program**	**None**	**Yes – Minor due to TSS**
Geochem or recovered water quality Issues ?	**Minor – low concen. of mangan. & iron in recovered water**	**Major – In-situ formation of DBPs**	**Major – In-situ formation of DBPs**	**None**	**Minor – Highly oxygenated water led to biological growth in wells**	**Minor – Iron precipitation**	**Major – arsenic, mangan. & cobalt in recovered water**
Primary Purpose	**Emergency water supply**	**Meet peak and seasonal demands**	**Meet seasonal demands**	**Meet seasonal demands**	**Meet seasonal demands**	**Meet seasonal demands**	**Meet peak demands**
Cost per	**2.46**	**$ 2.84**	**NR**	**NR**	**$ 9.27**	**$ 0.38**	**NR**

cubic meter							

Notes: LS is "Limestone"; SS is "Sandstone"; NA is "not available"; TSS is "total suspended solids"; NR is "not reported"; * denotes semi-confined aquifer; ** denotes unconfined aquifer

highly brackish water. ASR project sites in Oregon and Washington also reported minor issues with naturally occurring radon in the recovered water. Aeration of the water easily eliminated the problem in one case.

All of the sites underwent some form of pilot testing during an early stage of the project in order to develop site-specific information on the hydrogeology and water quality. Ultimately, the cost of a cubic meter of recovered water is a function of the source water quality, ambient groundwater quality, geochemical reactions, and the water treatment required to meet regulatory standards. Costs were previously calculated by others or estimated by the author for nineteen (19) sites. The costs ranged from $0.34 to $9.27 per cubic meter water recovered. The geometric mean unit cost for the non-brackish sites was $1.54 while it was $3.56 for the brackish water sites, although this only represented costs for five (5) sites as compared to fourteen (14) non-brackish projects.

Table 3 – ASR Non-brackish Water Site Data for sites 15 to 20

	Oak Creek - Wisconsin	**Hilton Head Island – South Carolina**	**Myrtle Beach – South Carolina**	**Wildwood**	**Lychett Minster - England**	**Windhoek – Namibia Africa**
Site Geology	**SS**	**LS**	**Sand**	**Sand**	**Chalk**	**Fractured Quartzite**
T (m^2/day)	**305**	**3,530**	**149**	**1,078**	**200**	**1,951**
TSS of influent (mg/l)	**<1.0**	**1.0 to 2.0**	**1.0 to 1.50**	**<1.0**	**<1.0**	**NR**
Well Clogging Issues ?	**Yes – due to TSS**	**Yes – due to TSS and hydraulic effects**	**Yes – Minor due to TSS and biological growth**	**Yes – Minor due to TSS**	**None**	**None**
Geochem or recovered water quality Issues ?	**Minor – low concen. of mangan. & iron in recovered water**	**None**	**Minor – low concen. of mangan. & iron in recovered water**	**Minor – formation of iron hydroxide precipitate**	**Major – fluoride in recovered water**	**None**
Primary Purpose	**Meet peak and seasonal demands**	**Meet peak and seasonal demands**	**Meet seasonal demands**	**Meet seasonal demands**	**Meet seasonal demands**	**Meet seasonal demands**
Cost per	**$ 0.42**	**NR**	**$ 1.82**	**$ 0.38**	**NR**	**NR**

cubic meter						

Notes: LS is "Limestone"; SS is "Sandstone"; NA is "not available"; TSS is "total suspended solids"; NR is "not reported"; * denotes semi-confined aquifer; ** denotes unconfined aquifer

Conclusions and Lessons Learned

Several key issues and lessons learned can be drawn from the review of 50 ASR projects. First, well clogging is still a problem at many ASR projects worldwide, although experience using ASR has reduced the overall severity of the problem. Well clogging issues have been managed successfully through the use of a regular back flushing program. Frequency is dependent upon the aquifer material with sand aquifers requiring daily to weekly cycles while karstic limestone aquifers may only require monthly back flushing episodes. Specific capacity or injectivity can be monitored over time to evaluate declines due to well clogging. Once the specific capacity has diminished a set percentage, back flushing activities can be started. One specific cause of well plugging is the entrainment of air. This can happen due to cascading water in cases of deep static water tables or excess oxygen can be released due to changes in pressure or temperature. In either case, removing the air from the aquifer storage zone can be difficult and time consuming. Entrainment of air via cascading water can be controlled with a downhole control valve.

The second major problem observed at ASR projects is various water quality issues. Geochemical reactions between highly oxygenated source water and aquifer matrix materials can be quite problematic. In some cases, arsenic, iron, manganese or other metals can be released from intrinsic minerals such as pyrite. The use of ozone as a disinfectant can greatly exacerbate this problem since ozonation adds additional oxygen to the source water. Other geochemical issues can be helped using pH control of the source water. Certain metals may only be mobile within limited pH ranges.

The third major lesson learned at ASR sites is that well hydraulics are very important when evaluating multi-well clusters. Well interference effects can be modeled using accepted analytical techniques or numerical models. Nearby well users also should be considered. These users can pull recharged water away from ASR wells reducing the overall recovery efficiency of the system. Also, nearby users can be impacted by ASR systems if proper precautions are not followed. Large ASR drawdowns can result in larger energy costs for nearby users or possibly can result in pumps hanging "high and dry" in the user's well casing.

The last lesson learned is that ASR well designers should not skimp on monitoring equipment for a system. Extra water level tubes in an ASR well are useful to periodically check automated equipment such as pressure transducers. Sampling ports along recharge or discharge lines can allow real-time monitoring of specific conductivity or turbidity.

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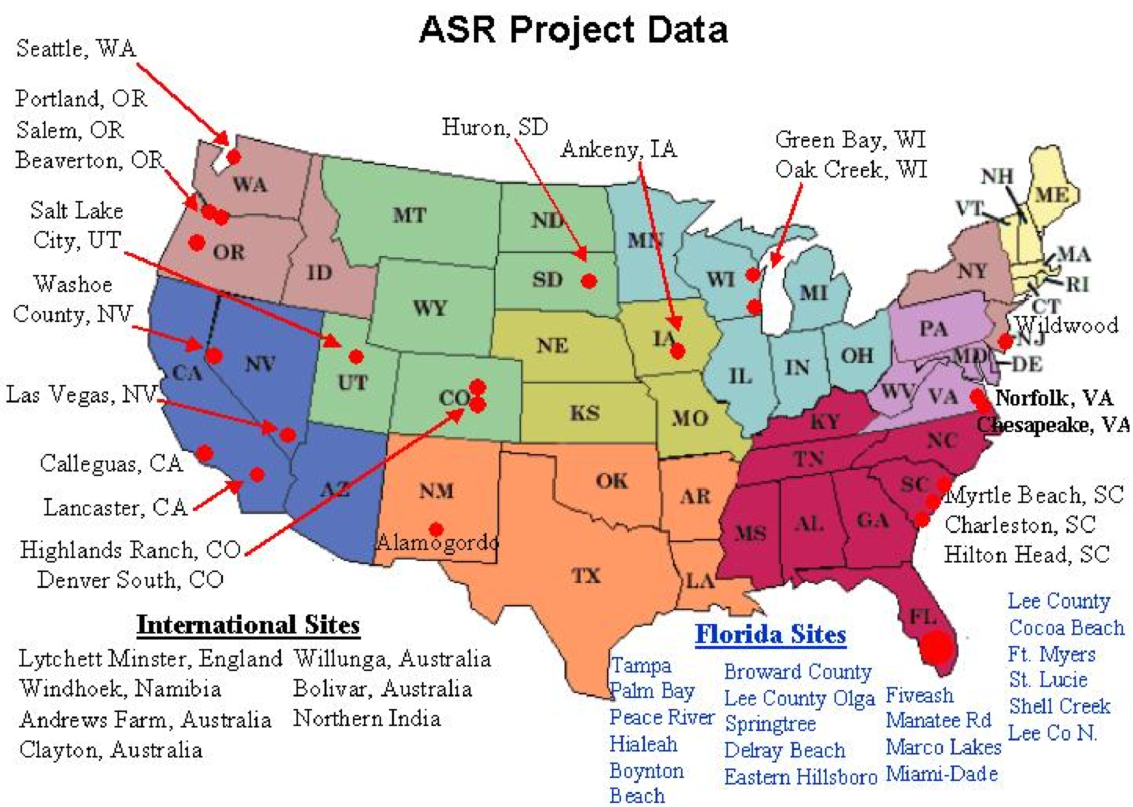

Figure 1. Location of ASR projects summarized for the research effort.

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