Status of Aquifer Storage and Recovery in the United States – 2013

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Author's contributions

FB developed the survey and conducted the survey. CH reviewed the survey, reviewed the data and worked on the statistical analysis. JD and SR developed the statistical analysis.

ABSTRACT

Aquifer storage and recovery (ASR) is a tool employed for the management of water supplies for both potable and non-potable water systems. There are over 200 sites that have looked into this concept in the US and at least one in Canada. However there is no "how to" guide for ASR well programs and to date there has been no comprehensive survey of the commonalities of ASR systems. Likewise little effort has been placed on the status of the ASR systems or why.

Alma: A major goal of the study was to determine where ASR sites were, how long they had been there, the operational parameters and the construction details. A series of graphics represent these issues. Aside from developing summary statistics, a goal of the project was to identify any explanatory variables that contribute to the success of ASR systems in the United States.

Results: This paper summarizes a survey of available data from the 204 known Aquifer Storage and Recovery (ASR) sites in the United States. Data on well sites was culled from emails, permit records, engineering reports and phone conversations. Of interest is that 35% of the 204 sites are currently active and another 20% are currently inactive, with the rest in the planning or test stage. The latter are projects that are in the early stages of investigation and in some cases no well has actually been drilled. The vast majority of sites injected treated surface waters, although raw water ASR wells exist and reclaimed water AR well use is expanding. The most common formations used for ASR storage are alluvial sand and gravel formations and limestone, although most systems in the northwest inject into basalt. Most of these aquifers are confined, except in California glacial deposits. Steel is the most common casing material but the use of PVC and fiberglass has increased recently. The wells vary from a few hundred to over 2000 feet deep.

Key Words: Aquifer Storage and Recovery

1. INTRODUCTION

Aquifer storage and recovery (ASR) is tool employed by water utilities to better manage water supplies for both potable and non-potable water systems where the geology permits it and where there is a need such as significant variation in season demands, drought risk or differences in demand and supply cycles (Bloetscher et al. 2005; Pyne, 1995, 2005; Missimer and Maliva, 2010). The concept of ASR have been employed to use an underground formation to store water that is not needed at present in the ground for later retrieval (Bloetscher et al. 2005; Muniz et al. 2003). Because the water is underground, is will not evaporate or run off the land surface. Large reservoirs do not need to be constructed if the water will remain in the formation adjacent to the injection horizon and water quality can be maintained.

The concept of ASR allows excess groundwater, reclaimed water, storm water and surface runoff to be captured, treated, injected, and stored. During high demand periods, the well can be pumped thereby supplementing water supplies. ASR sites include one or more wells that inject and withdraw water, and may be located at treatment plants or in the distribution system (Pyne, 1995, 2005).

Operations of ASR wells are therefore intermittent which makes them different from most water supply wells that operate consistently. Water treatment plants can be operated more consistently if ASR is viable because some or all of the unused water treatment plant capacity can be used for treatment of water to be injected for storage. The technology allows treatment plants to be sized for average daily demands as opposed to seasonal high demands and thereby saves capital infrastructure costs (Bloetscher et al. 2005).

1.1 Prior Work

There have been no prior attempts to survey and report all ASR sites in the US. However, several authors have surveyed a number of sites (Bloetscher et al. 2002, 2005; Pyne, 1995, 2005; AWWA, 2002; Missimer and Maliva, 2010; Muniz et al. 2003). In all of these studies, is was found that ASR was used to meet several objectives, the most common of which include maximization of storage (including seasonal, long-term, and drought or emergency water supplies); physical management of the aquifer; water quality management; management of water distribution systems; and ecological benefits (Bloetscher et al. 2002, 2005; Pyne, 1995, 2005; Missimer and Maliva, 2010; Muniz et al. 2003).

In all prior data gathering, most ASR systems generally drew their water supply solely from surface water bodies, with lesser contributions from groundwater, a combination of groundwater and surface water, or treated effluent (AWWA, 2002; Bloetscher et al. 2002; Muniz et al. 2003). Injected water was generally potable water, treated to drinking water standards (AWWA, 2002; Bloetscher, et al, 2002; Muniz, et al, 2003). Most of the responding systems injected potable water without additional pre-injection treatment, and discharged the withdrawn water into the distribution system without additional post-recovery treatment beyond disinfection (AWWA, 2002; Bloetscher et al. 2002; Muniz et al. 2003). The storage zones used for the ASR systems were typically sandstone, limestone or alluvial formations, and tended to vary according to the area of the country (AWWA, 2002; Bloetscher et al. 2002; Muniz et al. 2003). The depths of the storage zones varied significantly, indicating that the geology drives the location of storage zones for ASR systems (AWWA, 2002; Bloetscher et al. 2002; Muniz, et al, 2003).

In a 2002 survey, of the 43 survey respondents who answered the question “Would your utility make the investment in ASR again if you were starting over?” only one respondent answered “no,” because of geologic constraints at that site (AWWA, 2002). ASR is therefore popular among the prior respondents who had operating systems. Some systems reported problems with clogging, lower-than-expected yields, and geological or geochemical concerns with their systems (Bloetscher et al. 2002, 2005; Pyne, 1995, 2005, 2007; Missimer and Maliva, 2010; Muniz et al. 2003; Pyne et al, 1995; Reese, 2010; Thomas et al. 2000; USGS, 2002).

Challenges to ASR systems included permitting issues, geochemical problems, geological constraints, clogging, disinfection byproducts and water rights issues (e.g. who owns the injected water - Bloetscher, et al, 2002, 2005; Pyne, 1995, 2005, 2007; Missimer and Maliva, 2010; Muniz, et al, 2003; Pyne et al, 1995; Reese, 2010; Thomas et al. 2000; USGS, 2002). Siting and public relations were also commonly reported issues (AWWA, 2002; Bloetscher, et al, 2002; Muniz, et al, 2003).

ASR systems generally withdraw the stored water from the same well as used for injection (Bloetscher et al. 2002, 2005; Pyne, 1995, 2005, 2007; Missimer and Maliva, 2010; Muniz et al. 2003; Pyne et al. 1995;

Reese, 2010; Thomas et al. 2000). For the purposes of this paper, ASR is assumed to exist where the same well is used for injection of water for storage and for later recovery. This definition differentiates ASR from other water management practices such as "artificial aquifer creation" or "artificial recharge," which involve the introduction of large quantities of water into an aquifer zone for retrieval down-gradient, and from "aquifer reclamation" where large quantities of higher quality water are injected into an aquifer that has been impacted by salinity (AWWA, 2014; Bloetscher, et al. 2005). Such examples are practiced more frequently and in some cases with less specific intent that ASR is.

1.2 Regulations

ASR regulations result from the Underground Injection Control (UIC) Program, promulgated in 1981 pursuant to the Safe Drinking Water Act (SDWA) (40 CFR 144, 146 and 148). Two purposes of the UIC rules are to protect the quality of potential underground sources of drinking water (USDW) and to prevent degradation of the quality of other aquifers adjacent to the injection zone, both vertically and horizontally, that may be used for other purposes (Bloetscher et al. 2005). This purpose is achieved through rules that govern the construction and operation of injection wells in such a way that the injected fluid does not migrate into the USDW and thereby contaminate drinking water sources. The USDW is defined as an aquifer containing groundwater with total dissolved solids (TDS) less than 10,000 mg/L (USEPA, 2012; Tieman, 2010).

The cornerstone of the UIC regulations is on well construction, maintenance, and operation. US EPA has established 6 classes of injection wells. On the basis of a classification scheme developed by USEPA, all ASR wells are Class V n wells that inject water that is not oil and gas related, non-hazardous, and non-radioactive. Examples of Class V wells include (from 40 CFR 146):

- Air conditioning return flow wells used to return to the supply aquifer the water used for heating or cooling in a heat pump;
- Cooling water return flow wells used to inject water previously used for cooling
- Drainage wells used to drain surface fluids, primarily storm runoff, into a subsurface formation
- Recharge wells used to replenish the water in an aquifer
- Salt water intrusion barrier wells used to inject water into a fresh water aquifer and create a subsurface density buffer zone to prevent the intrusion of salt water into the fresh water
- Sand backfill and other backfill wells used to inject a mixture of water and sand, mill tailings or other solids into mined-out portions of subsurface mines, whether the injectate contains radioactive waste or not
- Subsidence control wells (not used for the purpose of oil or natural gas production) used to inject fluids into a non-oil or gas producing zone to reduce or eliminate subsidence associated with the overdraft of groundwater
- Injection wells associated with the recovery of geothermal energy for heating, aquaculture and production of electric power
- Wells used for solution mining of conventional mines such as stope leaching

Under the rules were established under the authority of Safe Drinking Water Act approved in in 1974 and amended in 1986 and 1996, states can apply to take on oversight and enforcement the underground injection control (UIC) program by adopting regulations at least as stringent as federal rules, have primacy under Section 1413. UIC primacy can be obtained by states under Section 1422 (all classes, with the exception of Florida where EPA runs the Class II program) and Section 1425 (Class II for oil and gas related activities). Forty states have delegation or partial delegation. The current UIC rules vary in complexity from extensive rules in states like

Florida, regional regulation in California, to minimal rules in states lacking extensive experience. All programs require the federal UIC rules as a minimum with state adjustments for local concerns but are otherwise not remarkable (for more information the reader is referred to www.h2o-pe.com). Ten states rely solely on UE EPA to administer the programs.

1.3 Aims of the Study

There were three goals of this project. The first was to try to identify all sites that had pursued an ASR project, even if the project was later abandoned. No comprehensive database had previously been created to the authors' knowledge. The second goal was to develop some summary statistics on the status and trends with ASR systems. The final goal of the project was to identify any explanatory variables that contribute to the success of ASR systems in the United States.

2 METHODOLOGY

2.1 Data Collection

There are two parts to the study: data collection and data analysis. The more challenging data collection exercise was to obtain data from each of the ASR systems, some of which have been inactive for over 20 years. Unlike previous efforts, every utility that was identified as having evaluated, tested or constructed an ASR well or system, whether they proceeded or not to full operating permits, and whether they were currently active or not, were investigated. Many systems had data available in the literature which was used herein. These data are collected on the internet at www.h2o-pe.com. Where data was missing from the literature, utilities, engineers, regulatory agencies and others were contacted by phone or email. Nine months of data collection, literature reviews, online searches, phone calls, emails, file searches and permit collection yielded data on operations of the ASR systems, associated stratigraphy, various ASR challenges, and many miscellaneous data in generating the most complete dataset to date.

The variables used for analysis were selected based on availability and the authors' prior experience in dealing with ASR programs with the intention to account for operational issues, construction approaches, and local differences. These variables were extracted from the compiled dataset. It should be noted that because of the start dates for exploration (back over 40 years), changes in technology for drilling and analyzing subsurface conditions, 27 different jurisdictional requirements and advancements in the literature, there were many inconsistencies in the data and parameters that were not collected in the early years. For example, the hydraulic conductivity of the formation and TDS of receiving water was often absent, especially older data.

The data on the number of storage and recovery cycles varies because many ASR systems have only been in service for a limited time period. Other data was not available – data on the engineers, drillers, and in some states, exact location. In some cases, different sources had different opinions about the ASR well status, which required some analysis and decision-making on the part of the authors. Efforts were made to collect as much data as possible from all 204 sites and to report it as accurately as possible with respect to well construction, water supply and use, well operations and injection formation data. Outside reviewers were asked to comment of the data and changes were made based on their knowledge and suggestions. Because the status of ASR wells changes with time, the dataset is a representation of the ASR inventory as of July 1, 2013 (realizing some of the data was collected in mid-2012).

Among the data that was queried were data about the well sites and status including: state; date the program was initiated or first well drilled; stage of development/status, categorized as study, testing, operational or abandoned; number of wells drilled: the number of individual ASR wells onsite to accommodate the designed injection capacity; and number of abandoned wells, the number of individual ASR wells onsite no longer in service. Data on the operations that was queried included: source of water, categorized as ground, surface, reclaimed or industrial water; use of recovered water, categorized by irrigation, potable water supplies, raw water supplies, and surface water augmentation; number of storage cycles (estimated), which may be indicative of age of the system; injection rate per well as a measure of injection capacity (converted to millions of gallons per day (MGD)); withdrawal rate per well as a measure of withdrawal capacity (converted to MGD); peak flow as a measure of total available capacity on the site (converted to MGD); and total water stored is a measure of total net stored water as estimated by regulators or the utilities (converted to millions of gallons). Data on the wells themselves was more difficult to obtain completely, but included: depth of well casing below the surface which is a measure of depth in feet of the most interior and deepest well casing that is installed at the final construction stage; depth of well borehole which is a measure of depth in feet of the deepest point of the well; casing diameter which is a measure of diameter in inches of the most interior and deepest well casing that is installed at the final construction stage; whether tubing and packer wells were used; and casing material - which is the final casing categorized as steel, PVC, fiberglass or stainless steel. It should be noted that many steel wells use stainless steel screens. These wells were classified as steel regardless of the screen. Finally data was gathered on the injection horizon including the injection zone formation, categorized into formation type such as limestone, sand, sandstone, basalt, and alluvial formation as the likely options; injection zone transmissivity as the measure the ability of water to maneuver through a porous media. It is the rate of flow per unit time per unit cross-sectional area (converted to gallons per day/ft); the total dissolved solids (TDS) of formation to separate fresh aquifers from brackish formations because fresh water is less dense than brackish water so injection into brackish aquifer may encourage the water to migrate vertically out of the storage zone, a problem with several Florida Class I wells (Bloetscher, et al, 2005); the type of confinement (formation type) categorized into formation type such as clay, dolomite, silt, shale, sandstone, basalt, or no confinement and the ;number of monitoring wells. Finally if there were operational issues, these were noted. It should be noted that not all data were available for all wells, especially in the cases of the aquifer parameters of the older wells (such as TDS and hydraulic conductivity).

2.2 Methods of Data Analysis

To better understand the differences of ASR systems among the regions, the collected data was managed, summarized, and analyzed using Microsoft EXCEL®. Additional analyses were conducted using SPSS®. There are a total of 204 ASR sites in the United States, which can be classified as operational, not in operation, or tests and study sites, meaning the site is in the investigative stage and no decision on operations can yet be made. Eliminating these sites, of the total 130 remaining sites, approximately 58% are considered operational.

The data collected from each ASR site were used to compile a dataset that includes 24 predictor variables: 15 continuous and 9 categorical variables. Analysis were performed as described in Bloetscher et al (2014). Chi-square tests were used to determine if there is a statistically significant relationship between two categorical variables. Logistic regression is a probabilistic statistical technique that uses a logistic function to predict the outcome of a dichotomous variable based on one or more predictor variables. This was employed to analyze the critical query - the commonalities of operational ASR wells. Variables shown to be measuring similar phenomena through correlation analysis, such as well depth and casing depth, were not used together in the tested models.

3. FINDINGS

There are 204 sites in the US that are in some stage of feasibility study, operation or are not in service. There are a total of 204 ASR sites in the United States, which can be classified as operational, not in operation, or tests and study sites, meaning the site is in the investigative stage and no decision on operations can yet be made. Eliminating these sites, of the total 130 remaining sites, approximately 58% are considered operational.

The state with the most number of ASR sites is Florida (54 sites), followed by California, New Jersey, Arizona and Oregon (see Figure 1 - from Bloetscher, et al 2014). Most of Oregon systems appear to be new ventures. Figure 1 shows the number of sites in each state. Figure 2 shows the growth of ASR programs since the 1960s. There was a marked rise in the 1990s and early 2000s, but the new sites appear to have declined since 2005.

3.1 Physical Information on Sites

Nationally, the majority of ASR systems are for potable water supply purposes (either potable recovery or raw water supplies for treatment plants - see Figure 3a). The source waters are a mix of surface, potable, and reclaimed waters (see Figure 3b). When analyzed on a state-by-state basis, it was determined that Florida and South Carolina have primarily focused on storing treated potable drinking water for later retrieval during peak demand seasons, California projects have mostly been on the diversion of surface water flows for potable water supply storage that can be recovered in the summer. Florida and Arizona both have reclaimed water programs within their ASR programs that recover water for irrigation purposes.

With respect to the specifics of the ASR wells, Figure 4 shows that the typical casing material was steel, and the diameters were typically 12 or 16 inches, although there were a variety of other options (e.g., 6, 12, 24 and 30 inches were the most common other options – see Figure 4b). Many ASR wells were screened (or cut casings in California); the notable exception was that most of the Florida wells were open hole completion. The depths of the casings and the wells ranged from 90 to over 3,000 feet deep (see Figure 5a). Typical well depths were over 1,000 ft (Figure 5b). The injection zone was usually limited to less than 150 feet thick (Figure5c). TDS in the injection zones were almost commonly under 500 mg/L which minimized the potential vertical migration of the injected water due to density differential of the injected and native waters, an issue associated with some of the south Florida wells (see Figure 5d). The most common injection zone formation lithology were limestone and alluvial formations (see Figure 6a). Although data was lacking for many ASR wells, the confining unit information indicated clay, dolomite, and shale (Figure 6b). Confinement is critical to the success of an ASR project because it is crucial to prevent fluid migration of the water upward into overlying USDWs. While limited, data on the transmissivity of the injection zone in gallons per day per square foot (gpd/sf) indicated most were under 100,000 gpd/sf, which comports with findings from modeling simulations in the Netherlands (Bloetscher et al 2005). Several wells ranged upwards of 600,000 gpd/sf.

3.2 Operational Parameters of ASR Systems

Injection and withdrawal rates are shown in Figure 7a. Withdrawal rates and also typically about 1 MGD (see Figure 7b). Note that very few wells had high injection or recovery rates. The ratio between injection and withdrawal is essentially unity, meaning the same volume going in and also removed (see Figure 7c). Given some sites have multiple ASR wells, the capacity of ASR recovery systems by site typically increases incrementally by 1 MGD increments (see Figure 7d).

Successful ASR system are likely to have more water stored and better injection and recovery rates. The number of cycles is an indication of how many times injection and recovery have occurred. More successful programs, and those that have been in existence for longer periods, are likely to have more cycles.

Figure 8 shows the number of cycles for the 204 wells. A quick review of the data revealed that operational systems tend to have greater than 10 cycles of injection and recovery, which means that they have been in service longer and/or the ongoing test programs have been successful and lead to ongoing operations. The total water stored at ASR sites was approximately 0.5 billion gallons if operational, although several were much higher – largest 80 billion (see Figure 9). Active sites generally had significant storage.

3.3 Statistical Analysis

Table 1 summarizes the descriptive measures for the continuous varaiables. Chi-square analysis results indicate that there are statistically significant associations ($p<0.05$) between operational well status and the following categorical variables: region, operational issues, the number of storage cycles, casing material, and injection formation. For region, the chi-square and logistic regression analyses suggested that the noncoastal states (Arizona, Nevada, Texas and the like), California, the Mid-Atlantic (North and South Carolina), and Pacific Northwest states have higher likelihood of having operational systems, while Mid-West and Southeast coastal states have lower than the predicted number of operational systems (Bloetscher et al 2014). Operational systems tended to have a greater number of storage and recovery cycles, steel casings and formations of alluvial, basalt, sand, and sand clay mixtures.

The results of the logistic regression suggested that the likelihood of operational status was greater in California, Pacific Northwest and noncoastal states areas ($P<0.05$), just as it was for the Chi-squared test. On the other hand, operational status was less likely for ASR sites with deeper wells, clogging problems, and water quality/arsenic issues. These sites tended to have restriction on recovered water. No definition of acceptable recovery was noted but eh range was from under 10 to 100% during a typical cycle. It was suggested that the acceptable range might be 40-70 percent depending on costs, and water supply restrictions.

Chi-square tests and logistic regression analysis results indicate that there are no statistical differences between ASR systems being operational and the following categorical variables: water source, water use, and confinement unit formation code. The logistic regression added withdrawal capacity, in/out water volume ratio, and casing diameter to these factors. Ultimately it appears that operation status is dependent on local geology and operational parameters near the mean (see Table 1).

4. CONCLUSIONS AND RECOMMENDATIONS

ASR sites have been active in the United States for over 40 years, with over 200 sites in 27 states that have either used or investigated the use of ASR. The principal objective of these ASR projects is to provide both long- and short-term storage of water in aquifers and recover the stored water for use when conditions at the water systems require additional water. ASR allows communities to retain water that would otherwise be discharging into rivers, surface waters, reservoirs, oceans or other sources. Most sites had one well, injected into limestone, basalt or alluvial formations, and was confined from the surface. Operationally, the ASR systems had similar injection and withdrawals rates, and the long-term successful systems stored in excess of 500 million gallons.

While there is some variety in the locations and purposes of ASR facilities around the nation, there are a few factors that would affect the feasibility of ASR development: the region, a greater number of successful storage cycles, casings that are steel and injection formation.

Ultimately the project indicated a lot of data was available, but much was missing. Data on drilling operations, water quality in the injection zone, transmissivity of the injection zone and confining unit would have been useful, but was missing in many of the older wells. The lack of a centralized system for permitting makes data gathering difficult in California. Data on 40 year old wells was difficult to come by, and the lack of institutional knowledge after 20 years was a barrier in several jurisdictions, especially if the project never moved past the test stage.

There were 75 systems in operation (see Figure 10). Some were very successful. Many systems were investigating the program. About 20% had encountered issues with clogging, metals leaching, or recovery that had caused the utility to discontinue efforts, suspend them or in several cases abandon the effort, indicating that ASR success is not guaranteed. It takes planning and forethought, but ASR remains a tool that is viable in some communities that face water supply challenges.

COMPETING INTERESTS

The Authors declare no competing interests. No grants or industry monies were used to develop this study.

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Table 1 Descriptive Statistics

	Number of ASR wells in the project	Storage Cycles	injection Cap (MGD)	Withdr Capacity (MGD	Ratio in/out	Peak Flow on Site (MGD)
Min	0	0	0	0	0	0
Max	87	74	15	15	2.5	714
Avg	3.6	5.0	1.4	2.0	0.8	8.8
Std Dev	7.9	10.5	1.9	2.3	0.3	55.9

	Depth of Casing	Depth of well	Injection Horizon	Casing Diam. (in)	Transm gpd/sf	TDS
Min	9	33		5.5	0.65	50
Max	2185	3832	3832	40	300000	37000
Avg	622	815	236	15	35206	2151
Std Dev	443	568	381	6	60654	4823

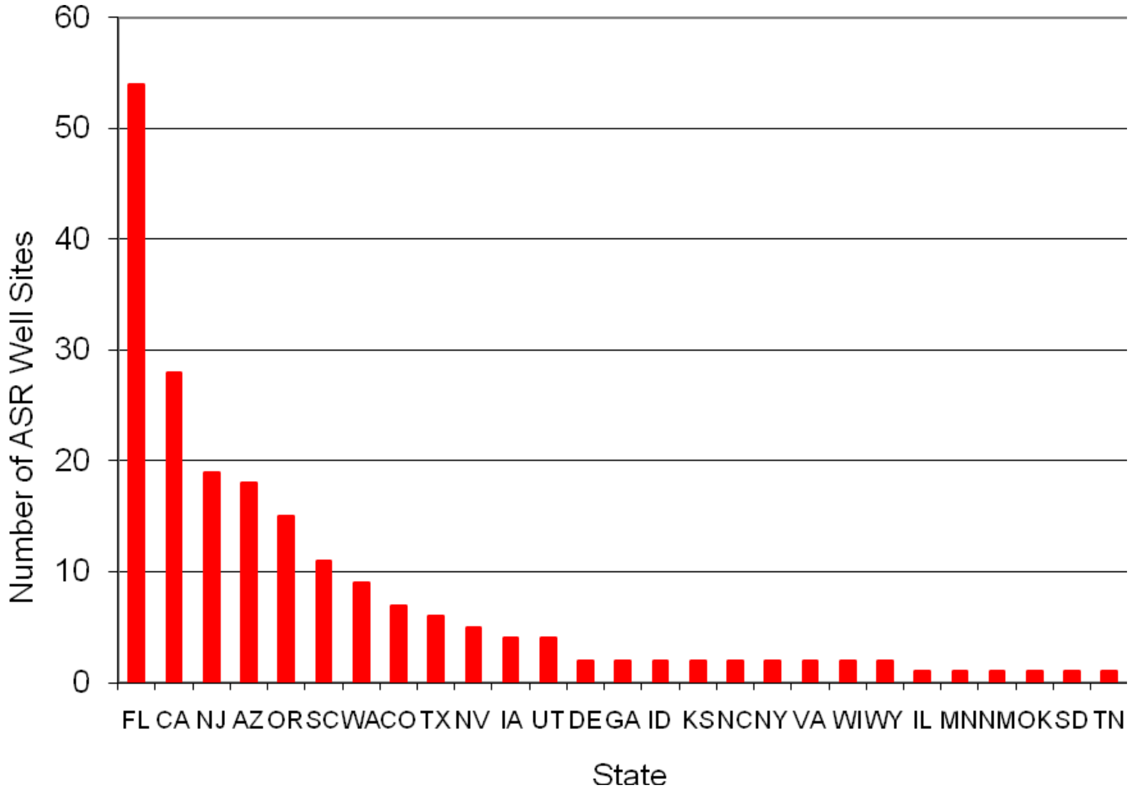


Figure 1 ASR projects by State

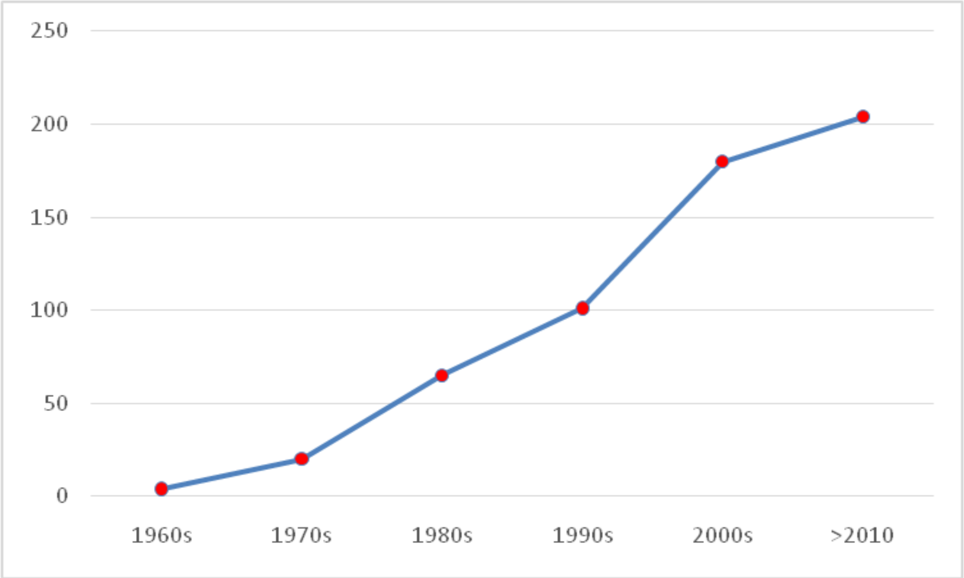
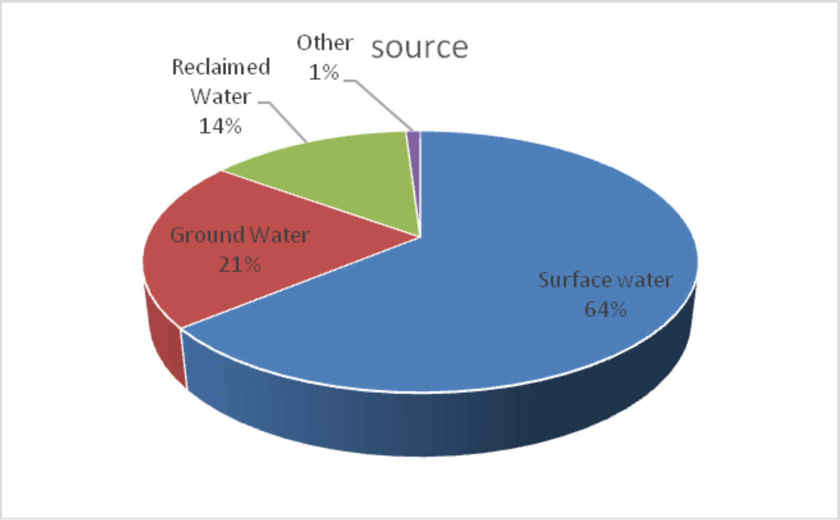
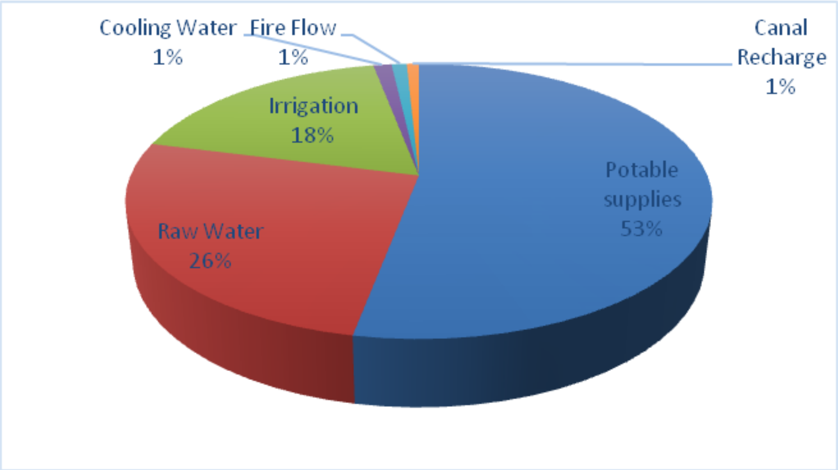


Figure 2 Growth of ASR wells since 1960



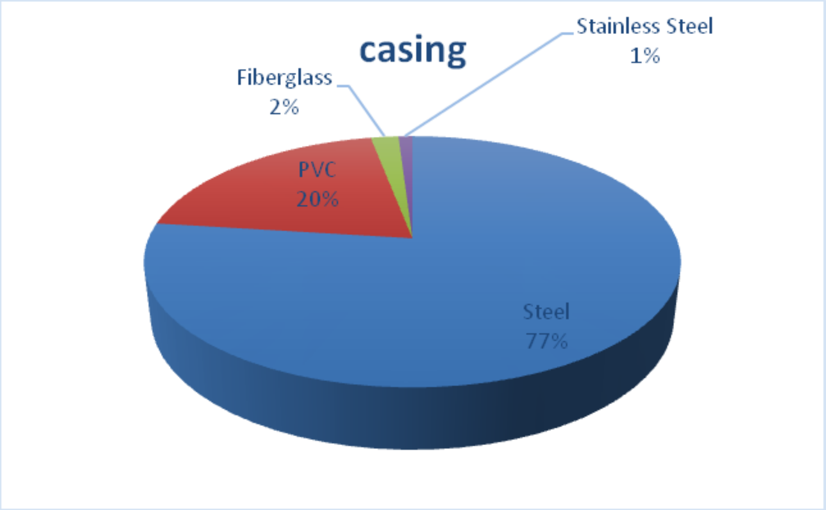
a



b

Figure 3 Source of Water Used in ASR wells b) Use of Water Stored in ASR wells

a)



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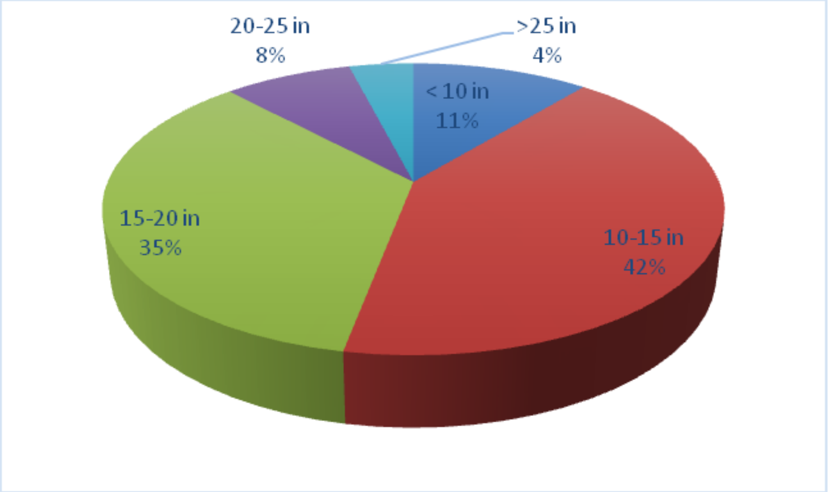
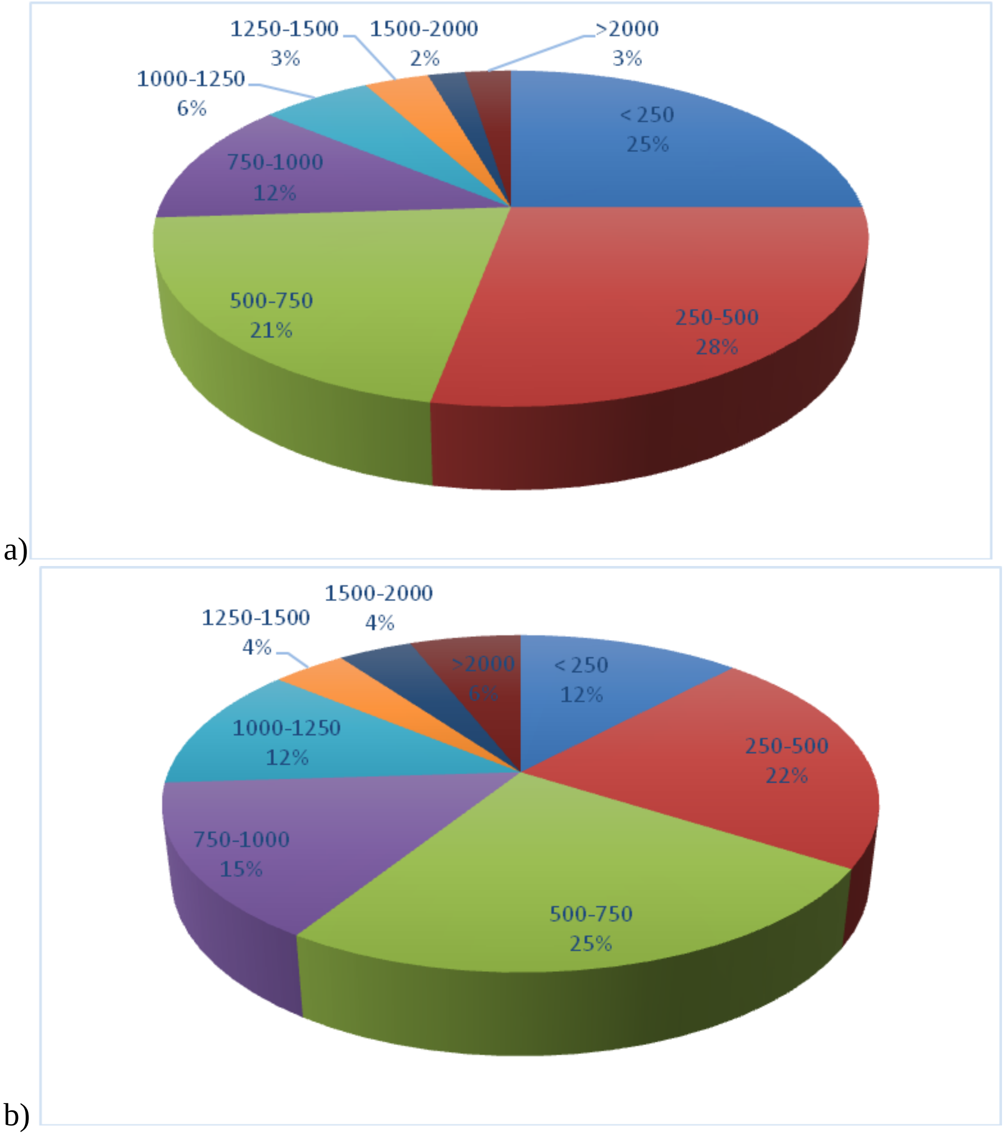
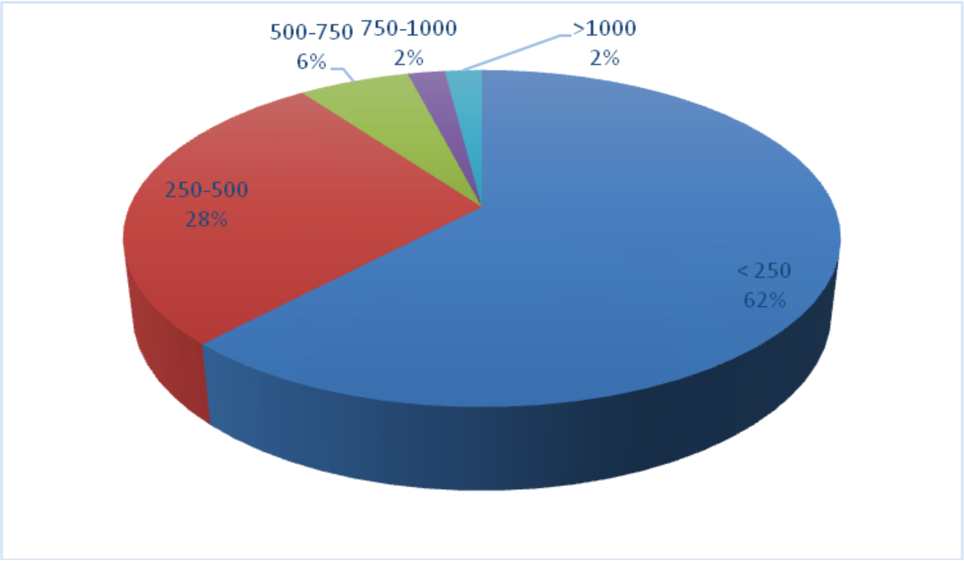
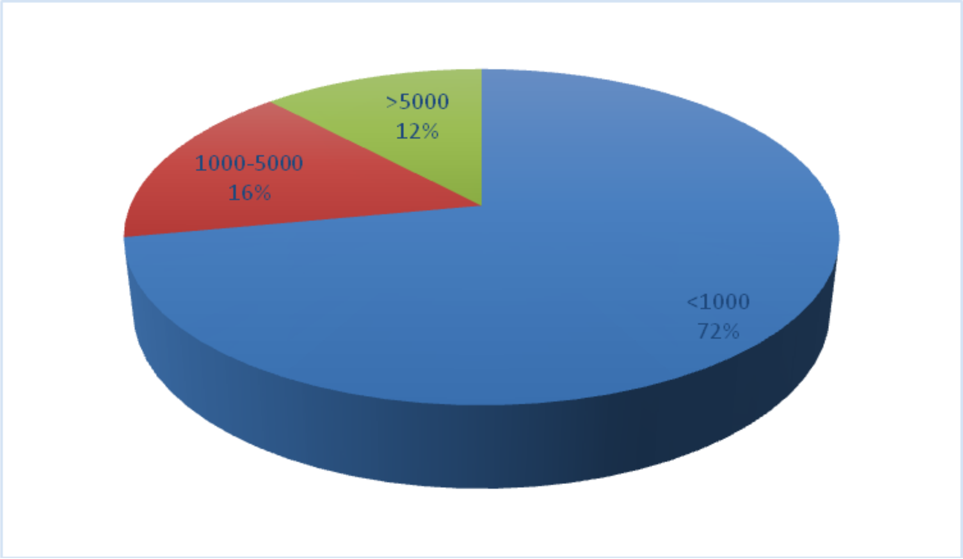


Figure 4 a) Type of Casing b Casing diameter



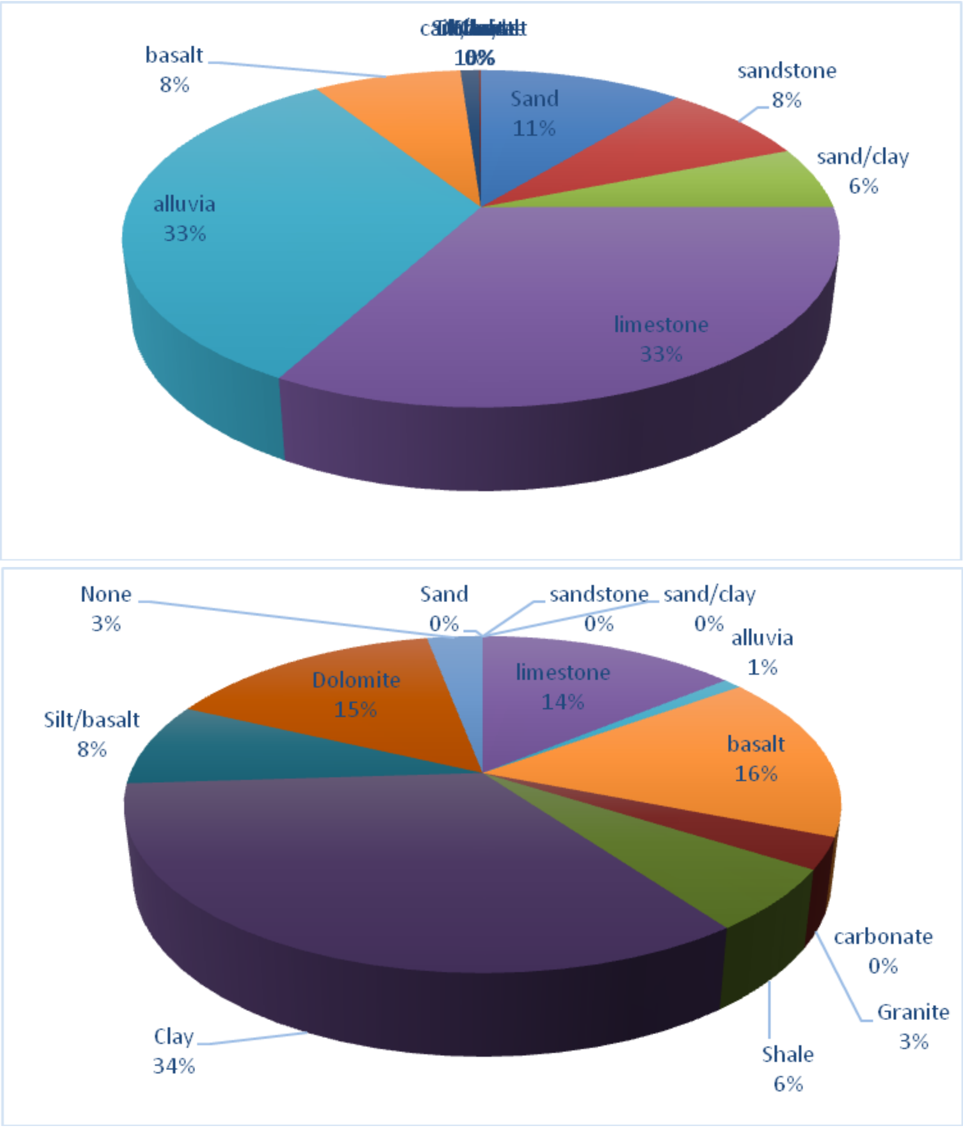

500-750
6%
750-1000
2%
>1000
2%
250-500
28%
< 250
62%

c)


>5000
12%
1000-5000
16%
<1000
72%

d)

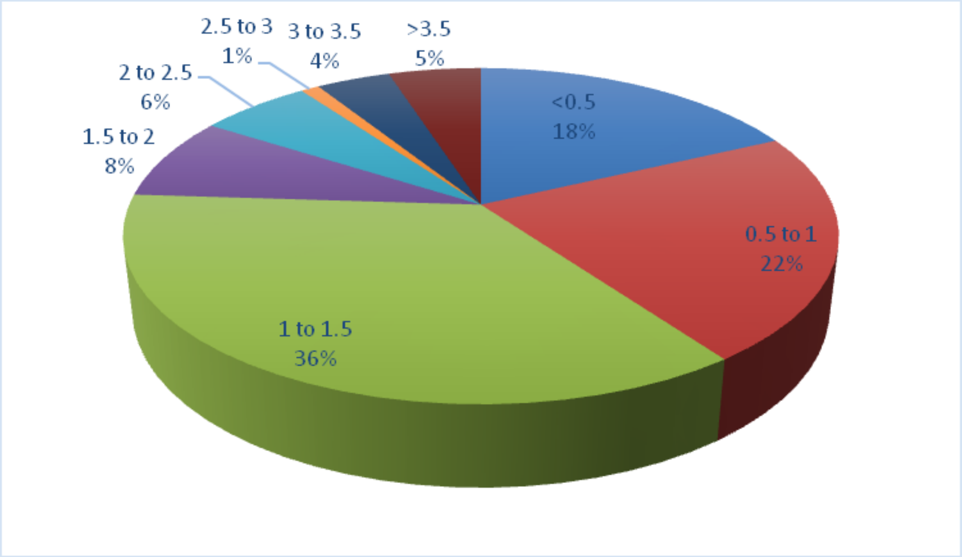
Figure 5a) depth of Casing (ft) b) depth of Well (ft) c) thickness of Injection horizon (ft) d) TDS of Formation



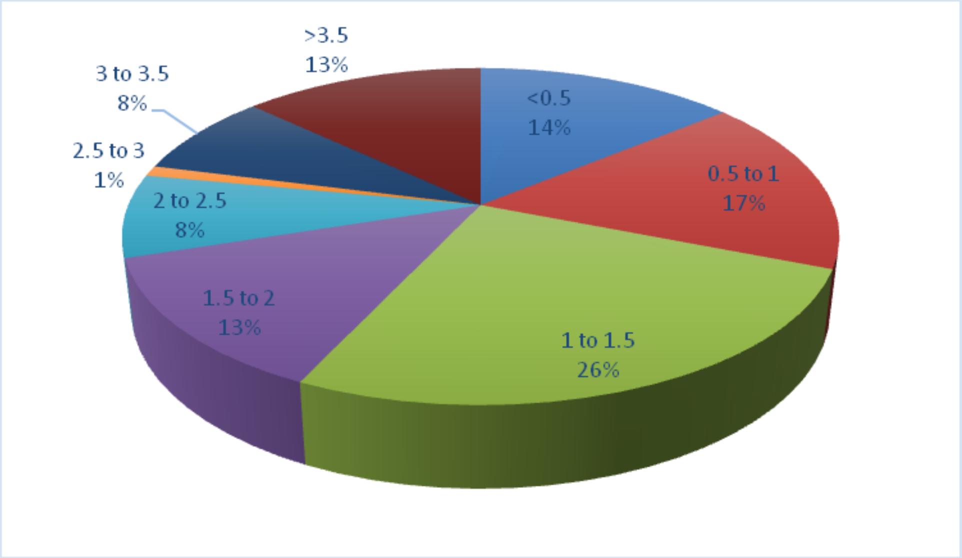
a)

b)

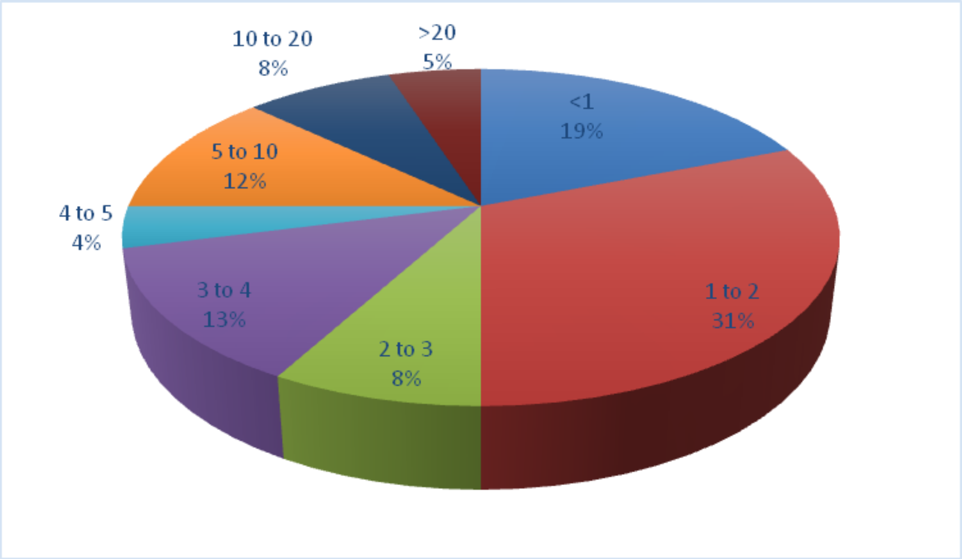
Figure 6 a) Injection Horizon Formation b) Overlying confining unit



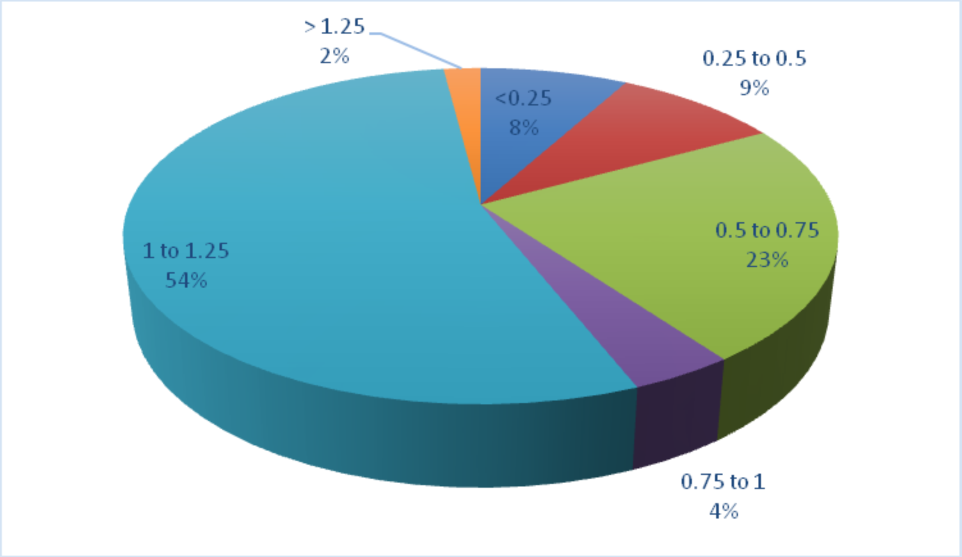
a)



b)


10 to 20
8%
>20
5%
<1
19%
5 to 10
12%
4 to 5
4%
1 to 2
31%
3 to 4
13%
2 to 3
8%

c)


> 1.25
2%
0.25 to 0.5
9%
<0.25
8%
0.5 to 0.75
23%
1 to 1.25
54%
0.75 to 1
4%

d)

Figure 7 a) Injection Rate (MGD) b) withdrawal Rate (MGD) c) Total Flow on Site (MGD) d) Ratio Injection to Withdrawal

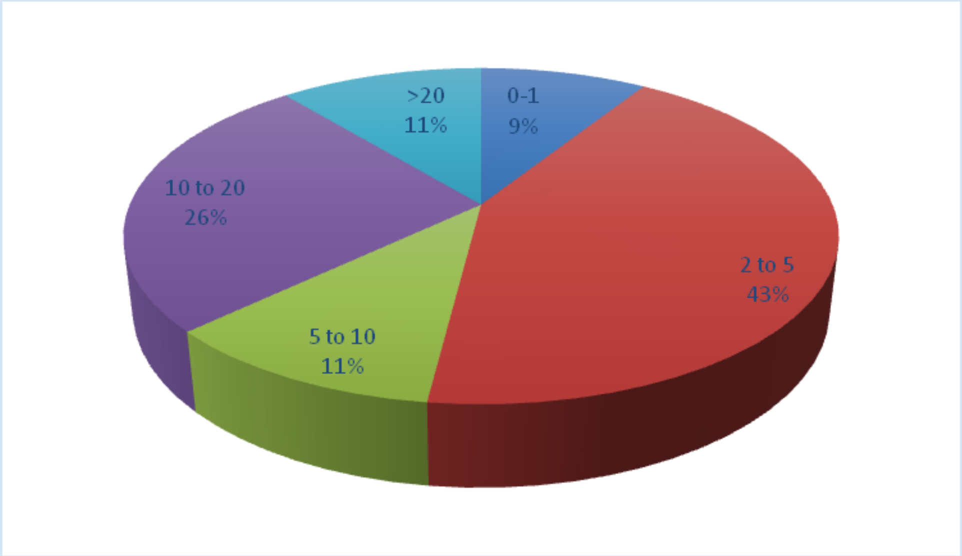


Figure 8 Total Injection/Withdrawal Cycles

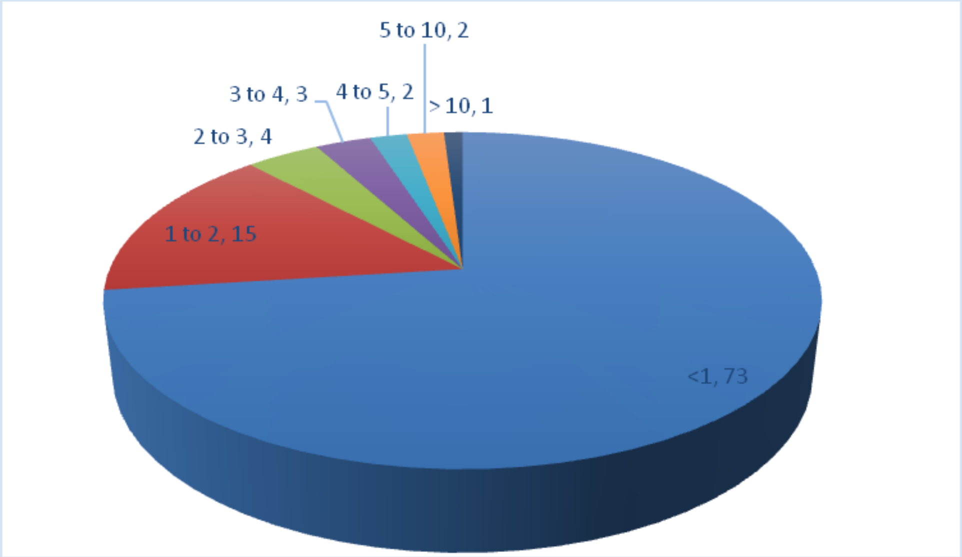


Figure 9 Total Water Stored (BG)

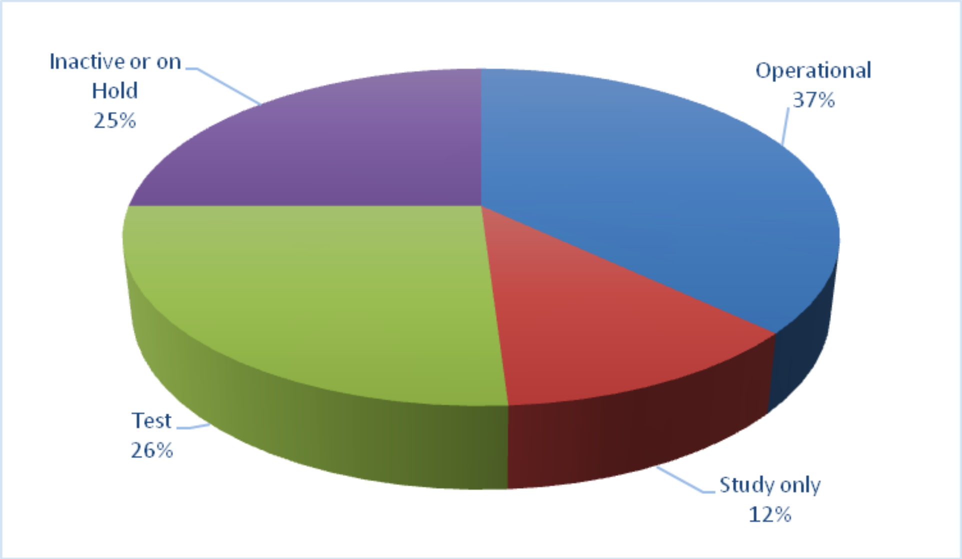


Figure 10 Status of ASR Projects