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Lessons Learned from Aquifer Storage and Recovery (ASR) Systems in the United States

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Abstract

This paper is the result of a survey and analyses of available data from 204 Aquifer Storage and Recovery (ASR) sites in the United States. This ASR site survey included all active and inactive sites and collected both operational and construction details. The inactive sites are of particular interest here because these are the projects from which valuable lessons can often be learned. The intent of this paper is to examine the reasons for those projects that are terminated. Statistical analyses indicated that there were factors associated with terminated ASR projects: general geographic location (e.g., region), operational issue, storage cycle, casing material, and injection formation. The injection formation involves local geology and aquifer characteristics (*i.e.*, whether the aquifer is leaky and/or unconfined, and if water can be displaced to surface water bodies or adjacent aquifers). Operational problems associated with inactive projects include well clogging, metals mobilization, a low percentage of recovery for injected water, and disinfection byproducts in the recovered water.

Keywords

Aquifer Storage and Recovery, Inactive, Clogging, Recovery

1. Introduction

In some areas of the world, treated or treatable water is being injected and stored beneath the earth's surface in aquifers (*i.e.*, aquifer storage programs) to preserve current water resources for future uses, plan for future droughts, retain instead of releasing surplus water during times of plenty, recharge wellfields and/or store water

for use at a later point in time to sustain development [1]. As a result, most aquifer storage programs are found in arid areas (with consistent water deficits) or coastal areas (subjected to salt water intrusion) or areas with pronounced seasonal wet and dry periods (mismatched demands and supplies). The beneficial use of water that is not needed at the present is the main driver for the various aquifer storage programs. To date, all aquifer storage strategies are proven, comparatively cost-effective programs that are capable of successfully managing existing water resources to increase reliability for long-term water supply. But that does not mean all such programs are or will be successful to the client.

For the purpose of this discussion, *AWWA Manual M*21 on *Groundwater* [1] divides aquifer storage programs into four categories: Artificial Aquifer Creation, Aquifer Recharge, Aquifer Reclamation, and Aquifer Storage and Recovery (ASR). All of these approaches are used by the water supply industry to insure that reliable water resources are available for agricultural, environmental and urban uses. The focus of this paper is on ASR projects which are different from the other aquifer storage strategies because the associated injection and recovery wells are generally the same wells.

ASR has been a viable approach in the management of both potable and non-potable water supplies. In general, ASR technology can be used to increase the efficiency of water system operations because during the wet, low-demand portion of the year, some or all of the unused water treatment plant capacity can be used to treat water and store it in an aquifer for later retrieval and usage. Common applications are the injection of potable or raw water into an aquifer, with the intention to provide future withdrawal for augmentation of water supplies at a later time. The storage period can be over multiple months to allow the stored water to meet the next high demand season or an emergency (e.g., a severe drought or an extreme flood) or during an interruption of water withdrawal (e.g., due to equipment breakdown or water right dispute). **Figure 1** shows the concept behind ASR graphically [2].

A benefit of ASR technology in areas with significant fluctuations in raw water supplies and/or demands during the year is that it may allow the water utility to size its treatment plants for average conditions rather than seasonal high demands; thereby saving capital infrastructure costs. Once treated, potable water is often stored and recovered to deal with unmet demands. The use of potable water in ASR projects often allow the water utility to withdraw the injected water, disinfect it, and pump it directly to the distribution system without much further treatment, although this objective may not be met for various reasons. Other sources may require treatment after recovery like untreated raw water surface and ground sources, stormwater runoff and reclaimed water (Englewood, FL, Las Vegas Valley and several Arizona wells do this among others). All have been captured, injected, stored, and recovered.

In the United States, ASR wells are covered under U.S. Environmental Protection Agency (EPA)'s Underground Injection Control (UIC) program that was promulgated under the Safe Drinking Water Act (SDWA) Sections 1421 through 1426. U.S. EPA's authority to govern underground injection programs is codified at 40 Code of Federal Regulation (CFR) 144 through 148. The purpose of the rules is to protect underground sources of drinking water (USDWs[1]). The UIC program requirements were developed to ensure that emplacement of fluids via injection wells did not endanger current and future USDWs. Much of the UIC regulations were aimed at regulating disposal of waste fluids via underground injection, and focused on the injection of hazardous wastes (Bloetscher, *et al*., 2002). As a part of delegation of federal programs to the states, 40 states and territories, along with 2 tribes, now administer all or a portion of the UIC programs in their jurisdiction [1]. Under the auspices of protecting public health, the regulatory agencies have the authority to require, accept, and reject permits for underground injection wells on the basis of their successes or failures to protect USDWs.

Based on a survey conducted in 2013, there are 204 ASR sites in the United States [3]. Data were collected for each site via the survey and subsequent follow-up phones and email communication. As a part of this survey, the status of the various ASR systems was obtained and reviewed. Valuable information can be drawn from the data and analyses regarding lessons learned on the various ASR projects. **Figure 2** shows the status of the ASR wells by site. Approximately 37% of the ASR sites are considered to be operational, while 24% are under various stages of testing. In addition, feasibility studies were conducted at 12% of the surveyed sites but these projects were not pursued further (as of the date of the survey); while 26% of the sites were associated with the cessation of ASR activities (see **Figure 2**). It is these inactive projects that are the focus of this paper and their

[1]An USDW as defined at 40 CFR 144.3 is an aquifer or its portion: 1) a) which supplies any public water system; *or* b) which contains a sufficient quantity of ground water to supply a public water system; *and* i) currently supplies drinking water for human consumption; *or* ii) contains fewer than 10,000 mg/l total dissolved solids; *and* 2) which is not an exempted aquifer.
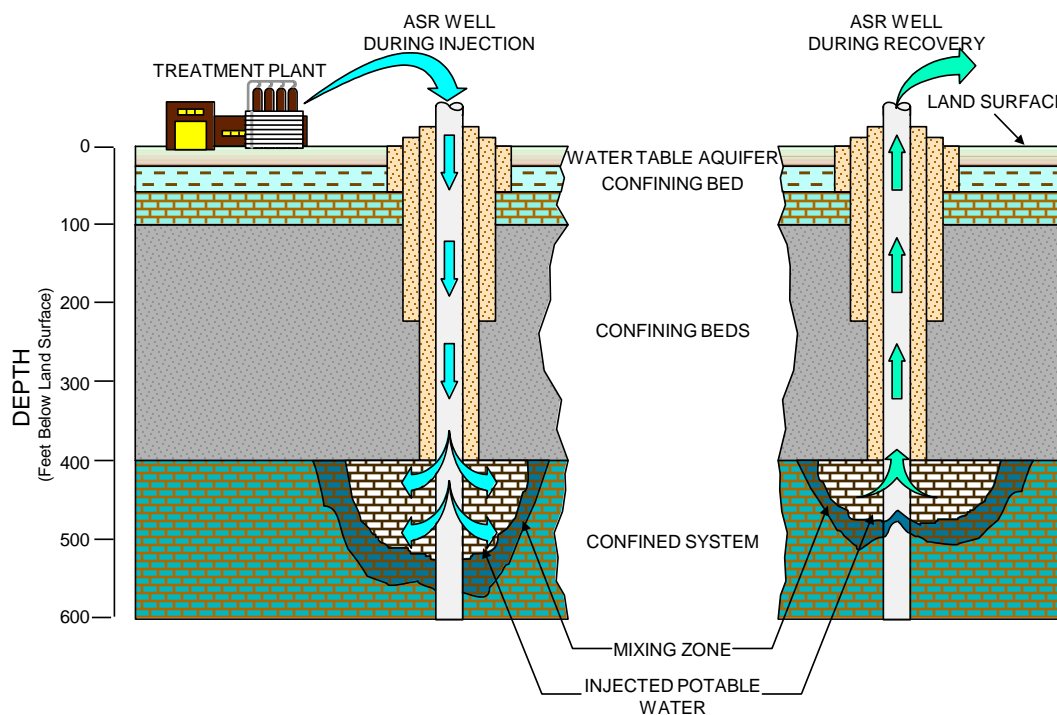
Figure 1. Aquifer storage and recovery concept.
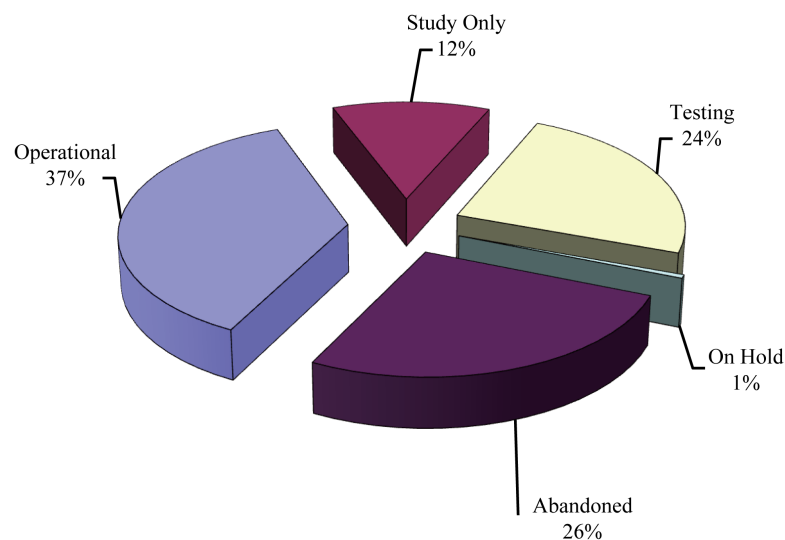
Figure 2. Status of ASR project sites.

failures would help provide insight into the challenges associated with the ASR technology. For instance, inactive and discontinued project sites comprise 26% of the 204 sites, and a total of 220 wells (see **Table 1**), indicating that ASR projects are not always successful. While a lot can be learned from successful projects, reviewing the failed systems provides insights into some of the criteria and process associated with the development of ASR programs.

2. Methodology

The project comprised two phases, data collection and data analysis. Data were collected in two steps. States and U.S. EPA were contacted by phone or email to track down the regulations that govern ASR programs from state

Table 1. Summary of inactive ASR programs.

State	Project/Location	Number of Wells in the Project	Number of Abandoned Wells in the Project	Source Water	Reason For Abandon
AZ	Chandler Intel	4	3	River Water	Clogging
AZ	Gilbert	2	1	Reclaimed RO	Clogging
AZ	North Scottsdale	3	2	Raw Surface	Clogging
AZ	Peoria-Stone Street	1	1	Raw Surface	Clogging
AZ	Phoenix 1-Salt River Project	8	8	Raw Surface	Clogging
AZ	Phoenix 2-Tormanto	2	2	Raw Surface	Clogging
AZ	Phoenix 3-Cave Creek	2	2	Recalimed	Clogging
CA	Antelope Valley Los Angeles PWD	2	2	Ground	
CA	Boron CSD well 15 58 & gephardt water fr AV ab project no water provided-shortage retro fit 1967 well	1	1	Surface	No Water
CA	Camarillo	2	2	Surface	Recovery
CA	East Bay MUD	1	1	Surface	
CA	Eastern Municipal Water District, Perris (follic)	1	1	Surface	Mn, Thm
CA	Fresno	1	1	Surface	Unknown
CA	Oxnard, City of	5	5	Surface	Clogging
CA	PALo Alto	1	1	Surface	Unknown
CA	Pasadena, City of (thm)	3	3	Surface	Thm
CA	Pleasanton, Zone 7 Livermore	4	4	Surface	
CA	Santa Clara County Water District, San Jose	1	1	Surface	
CA	Sonoma County Water Agency-Santa Rosa ASR 1 aband to std wll	1	1	Surface	Conv To Well
CA	Sweetwater/National City	2	2	Surface	Clogging
CA	Tracy, City of	2	1	Surface	Clogging
CA	Valley Water Company Foothills	2	2	Surface	Clogging
CA	Valley Water District Monk Hill	4		Surface	
CA	Victorville (Victor Valley Water District)	4	4	Surface	
CO	Castle Pines North (Worley) AR4	2	2	Surface	Recovery
CO	Colorado Springs Utilitie Park Forest/Donata	2	2	Surface	Recovery
CO	East Cherry Creek Valley Water District and Sanitation/Willows Water District acq 2001	4	4	Surface	Recovery
CO	Parker Water and Sanitation District	1	1	Surface	Recovery
FL	Bonita Springs San Carlos	1	1	Drinking Water	Arsenic
FL	Bradenton-Reservoir As	1	1	Surface	Arsenic

Continued

FL	Broward County	1	1	Raw GW	Recovery
FL	CERP Hillsboro Basin	1	1	Surface	Arsenic
FL	CERP Lake Okeechobee	1	1	Surface Water	Arsenic
FL	CERP St Lucie	1	1	Raw GW	Arsenic
FL	CERP Taylor Creek SFWMD (Cl 61k)	1	1	Surface	Arsenic
FL	Collier County North	1	1	Reclaimed	Arsenic
FL	Collier County, Manatee Rd	1	1	Drinking Water	Permit Expired
FL	Deerfield Beach, City of	1	1	Ground	Recovery
FL	Delray Beach	1	1	PWS GW	Recovery
FL	Englewood	1	1	Reclaimed	Arsenic
FL	Fort Lauderdale Fiveash	1	1	Raw GW	Recovery
FL	Ft. Myers Winkler	1	1	Drinking Water	Clogging
FL	Hialeah	1	1	Raw GW	Unknown
FL	Lee County, Corkscrew	6	6	Drinking Water	Recovery
FL	Lee County, North Reservoir	1	1	Surface	Clogging
FL	Lee County, Olga WTP (as)	1	1	Ground	Arsenic
FL	Manatee Southwest	1	1	Reclaimed	Unknown
FL	Marathon	1	1	Drinking Water	Recovery
FL	Miami Beach	1	1	Drinking Water	Recovery
FL	Miami-Dade Water & Sewer Dept. NW	3	3	Raw GW	Recovery
FL	North Port s	1	1	Reclaimed	Unknown
FL	NW Hillsborough (WQ deter)	1	1	Reclaimed	WQ Deterioration
FL	PBC 3	1	1	Raw GW	Recovery
FL	PBC System 9 Hillsboro	1	1	Surface	Recovery
FL	Punta Gorda-hell Creek	4	4	Drinking Water	Arsenic
FL	SFWMD Jupiter	1	1	Raw GW	Recovery
FL	St. Lucie Co SFWMD	1	1	Surface	Unknown
FL	St. Petersburg, City of	2	2	Reclaimed	Unknown
FL	Sunrise Springtree	1	1	Drinking Water	Recovery
FL	West Palm Beach	1	1	Surface	Recovery
GA	Dalton (carpet industry-small test wells only-no formation)	5	5	Raw GW	Recovery
ID	Boise, United Water	5	1		Clogging
NJ	Monroe Township Municipal Util Auth	2	2	Ground	Unknown
NM	Alamogordo	1	1	Ground	
NV	N Las Vegas	10	6	Varies, Icn Reuse	Clogging
NV	Washoe County (Truckee) gravity flow	4	2	Surface	Clogging

Continued

NY	Bay Park (clog)	1	1	Pws	Clogging
NY	East Meado Reclaimed Water (Clog)	5	5	Reclaimed	Clogging
OR	Clackamas River Water (radon)	1	1	Surface	Radon
OR	Pendleton, City of	2	2	Surface Via RBF	Clogging
OR	Portland Water Bureau (Shore)	7	2	Surface	
OR	Tigard, City of	2	1	Surface	
OR	Tualatin, City of	1	1	Pws	
SC	Mt Pleasant Waterworks & Sewer Commission	3	1	Surface Water	Unknown
SC	Myrtle Beach	1	1	Surface Water	WQ Deterioration
SD	Huron (used prod wells)	6	6	Surface Water	
TN	Memphis Light Gas and Water	1	1	Ground	
TX	Laredo	4	4	Surface	Recovery
UT	Cachw/Leamington Town Culinary Water Well	1	1	Ground	Clogging
UT	Jordan Valley Water District (retro wells, clogging)	18	18	Surface	Clogging
UT	Salt Lake City/High Plains? Clog	40	40	Surface	Clogging
VA	Norfolk	1	1	Surface	Test Only
WA	Lakehaven/Tacoma	2	2	Surface	Unknown
WA	Sammamish Water	3	3	Surface	Unknown
WA	Seattle Public Utilities Highline radon	3	3	Surface	Radon
WA	Walla Walla	2	2	Surface	Unknown
WA	Yakima	1	1	Pws	THM
WI	Green Bay Utlility	1	1	Surface	Metals Mobilization
WI	Oak Creek	2	2	Surface	Metals Mobilization
	TOTAL	246	220		

regulatory agencies and to determine whether the state had such programs in place or not. Note that there is a lack of ASR specific regulations at the federal level because the states are only required to submit inventory information on Class V wells and ensure non-endangerment of USDWs. While prior inventories were prepared by regulatory agencies and consultants, none were complete, comprehensive, and inclusive of all inactive projects. The regulatory investigations undertaken for this paper yielded a comprehensive list of ASR sites in the U.S., which was a critical component of the project. For the ASR projects included in the survey, variables of interest were used to account for operations, physical construction, and localized differences. These variables were extracted from the data sets. During the data extraction process, a number of wells were found to be older and/or not in service. In addition, data for some ASR sites were lost or missing. A confounding problem is that some states (e.g., California) have no centralized data sources, so there is a lack of consistency in the parameters collected.

The dataset collected for this project is the latest and most comprehensive representation of the ASR site inventory as of July 1, 2013. Data collected included:
- State (where the ASR site is located);
- 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;
- Number of abandoned wells, the number of individual ASR wells onsite no longer in service;
- Source of water, categorized as ground, surface, reclaimed of 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 is 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);
- Total water stored (converted to millions of gallons);
- Depth of well casing below the surface: 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 below the surface: A measure of depth in feet of the deepest point of the well;
- Casing material which is the final casing categorized as steel, PVC, fiberglass or stainless steel, separating stainless steel screens form stainless steel casings;
- 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;
- Injection zone formation category, categorized into formation type such as limestone, sand, sandstone, basalt, and alluvial formation;
- Injection zone transmissivity or hydraulic conductivity (converted to transmissivity); as the measure the ability of water to maneuver through a porous media (the rate of flow per unit time per unit cross-sectional area, which is converted to gallons per day/ft);
- Total dissolved solids (TDS) of the water in the injection formation fluid;
- Type of confinement (formation type) categorized into formation type such as clay, dolomite, silt, shale, sandstone, basalt, or no confinement;
- Number of monitoring wells if known; and
- Operational issues reported. This is the area that provides much information on the inactive wells.

It should be noted that not all of the data listed above were available for all wells in the survey, especially the aquifer parameters associated with the older wells (e.g., TDS and hydraulic conductivity).

Methods of Data Analysis

This study examines a set of 24 ASR data elements, including 15 continuous and 9 categorical variables. Continuous variables are estimated start date, number of active wells, number of abandoned wells, injection capacity, withdrawal capacity, in/out ratio, peak flow on site, amount of water stored, depth of well, depth of casing, injection horizon, diameter of casing, transmissivity, total dissolved solids (TDS), and number of monitoring wells. Descriptive statistics for the 15 continuous variables are summarized in **Table 2(a)**. Categorical variables are geographic region, issues arisen for an ASR program, water source, water use, number of storage cycles (there were grouped because of the range of numbers), casing material, tubing and packer (T&P) code, injection formation code and confinement unit formation code. Descriptive statistics for the 9 categorical variables are summarized in **Table 2(b)**. Geographic regions are summarized in **Table 3**. **Table 4** shows the summary of logistic regression statistics predicting ASR success in the United States by region. Statistically significant coefficients are highlighted in bold and include issues or the lack thereof predominate by region with clogging, metals migration and recovery as the major issues (95% confidence).

A Chi-square test was performed to determine if there is a statistically difference between program status (*i.e.*, active versus inactive) and each of the categorical variables (**Table 5**). A Chi-square test is a statistical test to determine if there is a statistically relationship between two categorical variables. When the association between two categorical variables is statistically significant, a contingency table of the residual values would reveal if these values make sense based on a priori knowledge of the two phenomena being compared (**Table 5**). Residual values are calculated by subtracting the observed value (O_{ij}) by the expected value (E_{ij}) in each cell of a

Table 2. (a) Descriptive statistics of continuous variables related to the ASR sites in the United States; (b) Descriptive statistics of categorical variables per ASR program status in the United States.

(a)

	Observation	Missing	Minimum	Maximum	Average	Standard Deviation
Estimated Start Date	204	0	1963	2014	1999	10
Active	75	0	1968	2010	1996	8
Inactive	55	0	1963	2007	1995	10
Test/Study	74	0	1970	2014	2004	9
Number of Active Wells	201	3	0	87	4	8
Active	75	0	0	87	6	11
Inactive	54	1	0	40	3	5
Test/Study	72	2	0	15	2	2
Number of Inactive Wells	201	3	0	40	1	3
Active	75	0	0	18	1	2
Inactive	54	1	0	40	3	5
Test/Study	72	2	0	5	0	1
Number of Monitoring Wells	203	1	0	10	1	1
Active	74	1	0	6	1	1
Inactive	55	0	0	10	1	2
Test/Study	74	0	0	7	0	1
Injection Capacity	178	26	0	15	1.4	1.9
Active	73	2	0.1	10	1.3	1.6
Inactive	49	6	0	9	1.4	1.7
Test/Study	56	18	0	15	1.5	2.4
Withdrawal Capacity	180	24	0	15	1.9	2.2
Active	74	1	0.1	10	1.9	1.9
Inactive	52	3	0	9	1.9	2
Test/Study	54	20	0	15	2.1	2.7
In/Out Ratio	174	30	0.02	5.25	0.9	0.5
Active	73	2	0.06	5.25	0.9	0.7
Inactive	48	7	0.19	1.02	0.8	0.3
Test/Study	53	21	0.02	2.5	0.8	0.4
Peak Flow on Site (MGD)	175	29	0	40	3.9	5.3
Active	73	2	0.1	23	4.7	4.9
Inactive	49	9	0	23.7	3.3	4
Test/Study	53	21	0	40	3.6	6.7

Continued

Amount of Water Stored (MG)	162	42	0	78,400	1282.1	6262.5
Active	69	6	0.2	78,400	2166.5	9462
Inactive	46	9	0	3800	654	1039.3
Test/Study	47	27	0	8400	598.4	1347.5
Depth of Well (ft)	181	23	33	3882	801.3	560.5
Active	73	2	75	2523	789.7	489.7
Inactive	52	3	33	1770	728.3	456.1
Test/Study	56	18	50	3882	884.2	713.6
Depth of Casing (ft)	178	26	9	3832	594.6	489.4
Active	50	5	39	2185	550.5	424.8
Inactive	52	3	10	1457	561.4	371.9
Test/Study	56	18	9	3832	680.5	636.4
Injection Horizon	159	45	7.5	1501	225.6	234.3
Active	65	10	7.5	1000	231	214.8
Inactive	46	9	12	1186	200.2	228
Test/Study	48	26	21	1501	242.7	266.3
Diameter of Casing (ft)	136	68	6	40	14.9	5.3
Active	56	19	6	26	14.5	4.2
Inactive	43	12	6	40	15.6	6.9
Test/Study	37	37	6	24	14.7	4.7
Transmissivity (gpd/sf)	127	77	0.1	620,136	75534.6	137647.4
Active	30	45	1	620,136	79157.60	154511.30
Inactive	21	34	1.2	264,000	56732.30	90237.60
Test/Study	26	48	0.1	600,000	86540.8	151498.6
Total Dissolved Solids (TDS) (ppm)	66	138	50	6000	1563.50	1732.50
Active	23	52	150	5500	1117.10	1569.50
Inactive	28	27	140	6000	1896.40	1783.40
Test/Study	15	59	50	6000	1631	1837.50

(b)

	Observations	Missing	Basin Range	California	Mid-Atlantic	Mid-West	Pacific NW	SE Coast
Region	204	0	44	28	23	8	29	72
Active	75	0	23	14	12	3	7	16
Inactive	55	0	12	3	3	3	5	29
Test/Study	74	0	9	11	8	2	17	27
% Success of Non-Testing/Study Sites			66%	82%	80%	50%	58%	36%

	Observations	Missing	None	Clogging	Expired Permit	PWS Conversion	Recovery	Tested then Abandoned	Water Quality/ Arsenic
Issues with ASR	190	14	111	29	1	1	20	6	22
Active	72	3	56	13	1	0	0	0	2
Inactive	48	7	3	12	0	0	17	3	13
Test/Study	70	4	52	4	0	1	3	3	7
% Success of Non-Testing/Study Sites			95%	52%	100%	N/A	0%	0%	13%

	Observations	Missing	Groundwater	Industrial	Reclaimed	Surface Runoff
Water Source	204	0	41	1	28	134
Active	75	0	13	1	9	52
Inactive	55	0	17	0	7	31
Test/Study	74	0	11	0	12	51
% Success of Non-Testing/Study Sites			43%	100%	56%	63%

	Observations	Missing	Cooling	Fire	Irrigation	PWS	Raw	RSW
Water Use	203	0	5	2	28	108	52	8
Active	75	0	3	1	9	45	14	3
Inactive	55	0	0	0	5	28	18	4
Test/Study	73	0	2	1	14	35	20	1
% Success of Non-Testing/Study Sites			100%	100%	64%	62%	44%	43%

	Observations	Missing	0 - 1	2 - 5	6 - 10	11 - 20	>20
Number of Storage Cycles	204	0	38	73	28	46	19
Active	75	0	2	14	11	32	16
Inactive	55	0	8	31	10	4	2
Test/Study	74	0	28	28	7	10	1
% Success of Non-Testing/Study Sites			20%	31%	52%	89%	89%

	Observations	Missing	PVC	Fiber Glass	Stainless Steel	Steel
Casing Material	157	47	18	3	14	122
Active	67	8	5	0	7	55
Inactive	45	10	7	2	1	35
Test/Study	45	29	6	1	6	32
% Success of Non-Testing/Study Sites			42%	0%	88%	61%

	Observations	Missing	None	T&P
T&P Code	185	19	180	5
Active	74	1	73	1
Inactive	53	2	50	3
Test/Study	58	16	57	1
% Success of Non-Testing/Study Sites			59%	25%

	Observations	Missing	Alluvial	Basalt	Carbonite	Granite	Limestone	Sand	Sand/Clay Mixture	Sandstone
Injection Formation Code	185	19	61	14	2	1	62	16	12	17
Active	70	5	31	4	1	0	13	9	6	6
Inactive	51	4	12	1	1	0	26	4	1	6
Test/Study	64	10	18	9	0	1	23	3	5	5
% Success of Non-Testing/Study Sites			72%	80%	50%	N/A	33%	69%	86%	50%

	Observations	Missing	None	Alluvial	Basalt/Clay Mixture	Bedrock	Clay	Dolomite	Limestone	Silt	Shale/Sedimentary
Confinement Unit Formation Code	90	114	3	2	14	3	30	13	13	7	5
Active	32	43	1	1	3	2	12	5	3	3	2
Inactive	28	27	1	0	2	0	11	3	6	3	2
Test/Study	30	44	1	1	9	1	7	5	4	1	1
% Success of Non-Testing/Study Sites			50%	100%	60%	100%	52%	63%	33%	50%	50%

Table 3. Description of region categories for the ASR sites (developed by Bloetscher).

	Basin Range	California	Mid-Atlantic	Mid-West	Pacific NW	SE Coast
	Arizona	California	Delaware	Illinois	Idaho	Florida
	Colorado		New Jersey	Iowa	Oregon	North Carolina
	Kansas		New York	Minnesota	South Dakota	South Carolina
States	New Mexico			Wisconsin	Washington	Tennessee
	Nevada					Virginia
	Texas					
	Utah					

Table 4. Summary of logistic regression statistics predicting ASR success in the United States. Statistically significant coefficients are highlighted in yellow bold (95% confidence). Coefficients that were not included in this analysis are denoted by the "-" sign.

Missing values omitted for…	All	Issues	Withdrawal capacity	In/out ratio	Well depth	Injection horizon	Casing material	Casing diameter	Injection formation	Transmissivity	Confinement
Model Statistics											
Observations	204	120	126	121	125	111	112	99	121	51	60
Classification accuracy (null model) (%)	57.7	59.5	58.3	59.8	57.9	58.0	59.3	56.0	57.4	57.7	52.5
Classification accuracy (with variables) (%)	67.7	90.1	69.3	69.7	68.3	71.4	69.0	69.0	72.1	61.5	77.0
Improvement of classification accuracy (%)	10	30.6	11	9.9	10.4	13.4	9.7	13.0	14.7	3.8	24.5
P-value of Hosmer and Lemeshow test [39]	0.267	0.837	0.329	0.220	0.528	0.506	0.308	0.218	0.238	0.421	0.475
Cox & Snell Pseudo R^2 [40]	0.142	0.583	0.170	0.178	0.161	0.173	0.197	0.115	0.211	0.039	0.432
Nagelkerke Pseudo R^2 [41]	0.192	0.788	0.229	0.241	0.216	0.233	0.266	0.155	0.284	0.053	0.576
Regression Coefficients (Log-Odds)											
Constant	21.021	−1.868	−0.162	−0.184	−0.752	−0.883	−19.841	−0.152	−0.890	−0.215	−21.203
Region-Southeast Coast	−0.389	1.573	−0.414	−0.460	0.140	0.550	0.195	0.369	−0.103	0.983	−2.569
Region-California	1.571	**5.559**	**2.645**	2.569	2.342	**2.720**	2.056	1.889	0.831	1.029	36.197
Region-Pacific Northwest	0.182	**3.737**	0.320	0.088	0.802	1.300	0.537	0.530	−22.309	0.390	29.670
Region-Basin Range	0.713	**3.277**	0.634	0.757	1.003	2.066	1.031	1.050	−0.030	1.124	−0.413
Region-Mid-Atlantic	1.588	1.710	1.567	1.459	1.897	2.534	2.239	2.157	0.462	0.590	18.767
Issue-Clogging	-	**−4.490**	-	-	-	-	-	-	-	-	-
Issue-Tested then abandoned	-	−26.549	-	-	-	-	-	-	-	-	-
Issue-Recovery problems	-	−25.282	-	-	-	-	-	-	-	-	-
Issue-Water quality or arsenic problems	-	**−5.616**	-	-	-	-	-	-	-	-	-
Issue-Expired permit	-	18.236	-	-	-	-	-	-	-	-	-
Water source-groundwater	−21.476	3.263	−0.289	−0.469	−0.411	−0.997	−20.048	−0.503	0.244	−0.270	5.097
Water source-reclaimed water	−21.102	3.871	0.133	−0.349	0.077	−0.776	−19.139	−0.038	0.394	−0.833	4.658
Water source-surface runoff	−21.021	2.774	0.191	−0.039	−0.032	−0.379	−19.477	0.011	0.645	−0.253	6.235
Withdrawal capacity (MGD)	-	-	0.001	−0.004	-	-	-	-	-	-	-
In/out ratio	-	-	-	−0.432	-	-	-	-	-	-	-
Well depth (ft)	-	-	-	-	0.001	0.001	0.000	-	-	-	-
Injection horizon (ft)	-	-	-	-	-	−0.001	-	-	-	-	**−0.003**
Casing material-steel	-	-	-	-	-	-	38.840	-	-	-	-
Casing material-PVC	-	-	-	-	-	-	38.116	-	-	-	-
Casing material-stainless steel	-	-	-	-	-	-	39.562	-	-	-	-
Casing diameter (ft)	-	-	-	-	-	-	-	−0.028	-	-	-
Injection formation-sandstone	-	-	-	-	-	-	-	-	0.203	-	-
Injection formation-sand	-	-	-	-	-	-	-	-	1.097	-	-
Injection formation-limestone	-	-	-	-	-	-	-	-	−0.144	-	-
Injection formation-alluvial	-	-	-	-	-	-	-	-	1.352	-	-

Continued

Injection formation-basalt	-	-	-	-	-	-	-	-	24.090	-	-
Injection formation-sand/clay mixture	-	-	-	-	-	-	-	-	1.702	-	-
Transmissivity (gpd/sf)	-	-	-	-	-	-	-	-	-	−0.215	-
Confinement-silt	-	-	-	-	-	-	-	-	-	-	16.474
Confinement-shale/sedimentary mixture	-	-	-	-	-	-	-	-	-	-	17.410
Confinement-clay	-	-	-	-	-	-	-	-	-	-	20.179
Confinement-limestone	-	-	-	-	-	-	-	-	-	-	19.141
Confinement-bedrock	-	-	-	-	-	-	-	-	-	-	38.478
Confinement-dolomite	-	-	-	-	-	-	-	-	-	-	21.010
Confinement-basalt/clay	-	-	-	-	-	-	-	-	-	-	−12.637
Confinement-alluvial	-	-	-	-	-	-	-	-	-	-	4.298

Table 5. Contingency tables of residual values (observed-expected) and Chi-Square test results comparing ASR success and each categorical variable of ASR sites. Statistically significant Chi-Square statistics are highlighted in yellow (95% confidence).

		State of the ASR site																								Total
		AZ	CA	CO	DE	FL	IA	ID	IL	KS	MN	NC	NJ	NM	NV	NY	OR	SC	SD	TN	TX	UT	VA	WA	WI	
ASR success	Active	1.8	4.2	−1.5	0.4	−11.2	0.8	0.8	−0.6	0.4	0.4	0.4	4.1	−0.6	1.7	−1.2	0.1	1.5	−0.6	−0.6	0.7	0.3	−0.2	−0.3	−1.2	0
	Inactive	−1.8	−4.2	1.5	−0.4	11.2	−0.8	−0.8	0.6	−0.4	−0.4	−0.4	−4.1	0.6	−1.7	1.2	−0.1	−1.5	0.6	0.6	−0.7	−0.3	0.2	0.3	1.2	0
	Total	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

$\chi_c^2 = 48.905$.

		Region of ASR site						Total
		Basin Range	California	Mid-Atlantic	Mid-West	Pacific NW	SE Coast	
ASR success	Active	2.8	4.2	3.3	−0.5	0.1	−10.0	0
	Inactive	−2.8	−4.2	−3.3	0.5	−0.1	10.0	0
	Total	0	0	0	0	0	0	0

$\chi_c^2 = 17.399$.

		Issues with ASR site						Total
		None	Clogging	Expired Permit	Recovery	Tested then abandoned	Water quality/ arsenic	
ASR success	Active	20.6	−2	0.4	−10.2	−1.8	−7	0
	Inactive	−20.6	2	−0.4	10.2	1.8	7	0
	Total	0	0	0	0	0	0	0

$\chi_c^2 = 74.913$.

		Water Source				Total
		Groundwater	Industrial	Reclaimed	Surface Runoff	
ASR success	Active	−4.3	0.4	−0.2	4.1	0
	Inactive	4.3	−0.4	0.2	−4.1	0
	Total	0	0	0	0	0

$\chi_c^2 = 4.117$.

ASR success		Water Use						Total
		Cooling	Fire	Irrigation	PWS	Raw	RSW	
	Active	1.3	0.4	0.9	2.9	−4.5	−1.0	0
	Inactive	−1.3	−0.4	−0.9	−2.9	4.5	1.0	0
	Total	0	0	0	0	0	0	0

$\chi_c^2 = 6.829.$

ASR success		Number of Storage Cycles					Total
		0 - 1	2 - 5	6 - 10	11 - 20	>20	
	Active	−3.8	−12.0	−1.1	11.2	5.6	0
	Inactive	3.8	12.0	1.1	−11.2	−5.6	0
	Total	0	0	0	0	0	0

$\chi_c^2 = 40.621.$

ASR success		Casing Material				Total
		PVC	Fiber Glass	Stainless Steel	Steel	
	Active	−2.2	−1.2	2.2	1.2	0
	Inactive	2.2	1.2	−2.2	−1.2	0
	Total	0	0	0	0	0

$\chi_c^2 = 7.236.$

ASR success		T&P Code		Total
		None	T&P	
	Active	1.3	−1.3	0
	Inactive	−1.3	1.3	0
	Total	0	0	0

$\chi_c^2 = 1.880.$

ASR success		Injection Formation Code							Total
		Alluvial	Basalt	Carbonite	Limestone	Sand	Sand/Clay Mixture	Sandstone	
	Active	6	1	0	−10	1	2	−1	0
	Inactive	−6	−1	0	10	−1	−2	1	0
	Total	0	0	0	0	0	0	0	0

$\chi_c^2 = 17.470.$

ASR success		Confinement Unit Formation Code									Total
		None	Alluvial	Basalt/Clay Mixture	Bedrock	Clay	Dolomite	Limestone	Silt	Shale/Sedimentary	
	Active	−0.1	0.5	0.3	0.9	−0.3	0.7	−1.8	−0.2	−0.1	0
	Inactive	0.1	−0.5	−0.3	−0.9	0.3	−0.7	1.8	0.2	0.1	0
	Total	0	0	0	0	0	0	0	0	0	0

$\chi_c^2 = 4.497.$

contingency table between the two categorical variables of interest, where the expected values are defined as:

$$E_{ij} = \frac{(R_i)(C_i)}{n}$$

(1)

where R_i is the row total corresponding to row i, C_i is the column total corresponding to column i and n is the total number of observations. The association between two categorical variables can be assessed using the Chi-Square statistic $\left(\chi_c^2\right)$, which can be defined as:

$$\chi_c^2 = \sum_i^r \sum_j^c \frac{\left(O_{ij} - E_{ij}\right)^2}{E_{ij}}$$

(2)

In addition to Chi-Square tests, logistic regression was performed to identify explanatory variables of ASR success in the United States. 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. A logistic function $F(t)$ can be defined as:

$$F(t) = \frac{e^t}{e^t + 1} = \frac{1}{1 + e^{-t}}$$

(3)

where t is a linear function of at least one or more explanatory variables. Equation (1) can also be rewritten as:

$$F(x) = \frac{1}{1 + e^{-\beta_0 + \beta_1 x_1 + \cdots}}$$

(4)

where β_0 is the intercept from the linear regression equation and β_1 is a regression coefficient for one of the explanatory variables. Equation (2) can be interpreted as the probability of $F(x)$ equaling a value of 1 (rather than 0). One can also define the inverse of the logistic function, $G(x)$, which is also called the logit, log-odds or natural logarithm of the odds function:

$$G(x) = \ln \frac{F(x)}{1 - F(x)} = \beta_0 + \beta_1 x_1 + \cdots$$

(5)

The β coefficients in logistic regression are estimated using a maximum likelihood estimator.

We used success (1) or failure (0) of ASR sites in the United States, as the dichotomous dependent variable. A number of different logistic regression models were tested by varying the sets of continuous (**Table 2(a)**) and categorical (**Table 2(b)**) explanatory variables; the model sets were driven by the exploratory questions and missing data. Variables shown to be measuring similar phenomena (*i.e.*, based on physical characteristics and correlation analysis) such as well depth and casing depth, were not used together in the tested models to avoid multi-co-linearity and other artifacts. Seven continuous explanatory variables were used in the logistic regression analyses: estimated start date, withdrawal capacity, in/out water volume ratio, depth of well, injection horizon, casing diameter and transmissivity. Six categorical variables were transformed into dummy variables and then used as explanatory variables in the logistic regression analyses: region, issues with ASR program, water source, casing material, injection formation code and confinement unit formation code.

3. Results and Discussion

The state with the largest numbers of ASR programs are Florida (54), followed by California, New Jersey, Arizona and Oregon (see **Figure 3**). However, the presence of ASR sites is not necessarily indicative for success of ASR projects. For example, in Florida, over half the sites are no longer active or have wells that are no longer used (see **Figure 4**). Other states that have large numbers of inactive sites are California and Arizona. With the elimination of inactive and test sites, there are only 22 active ASR sites (as compared to the total of 54 ASR sites) in Florida. **Figure 5** shows the number of sites in the test phase by state. It should be noted that most of the inactive ASR sites have only one well, although a few outliers with many wells skews the average number of wells per site in **Table 1**. There also appears to be a slowing of ASR development after a marked rise in the 1990s and early 2000s (see **Figure 6** [3]).
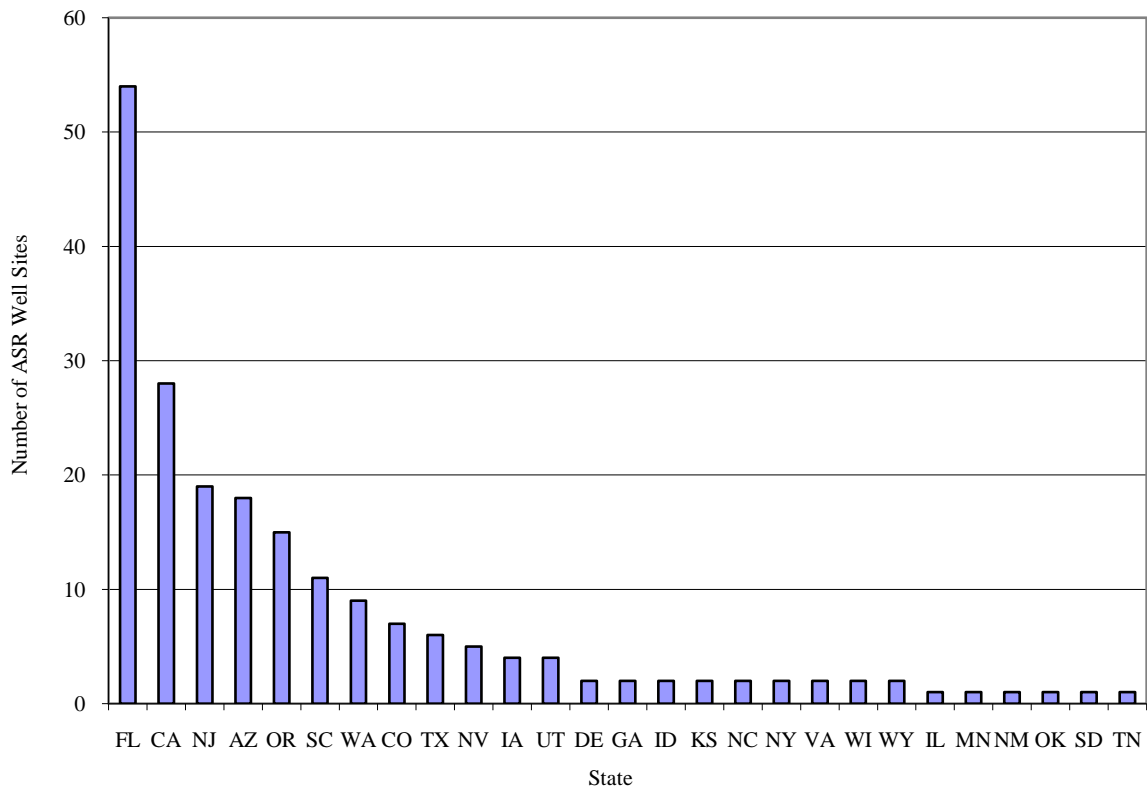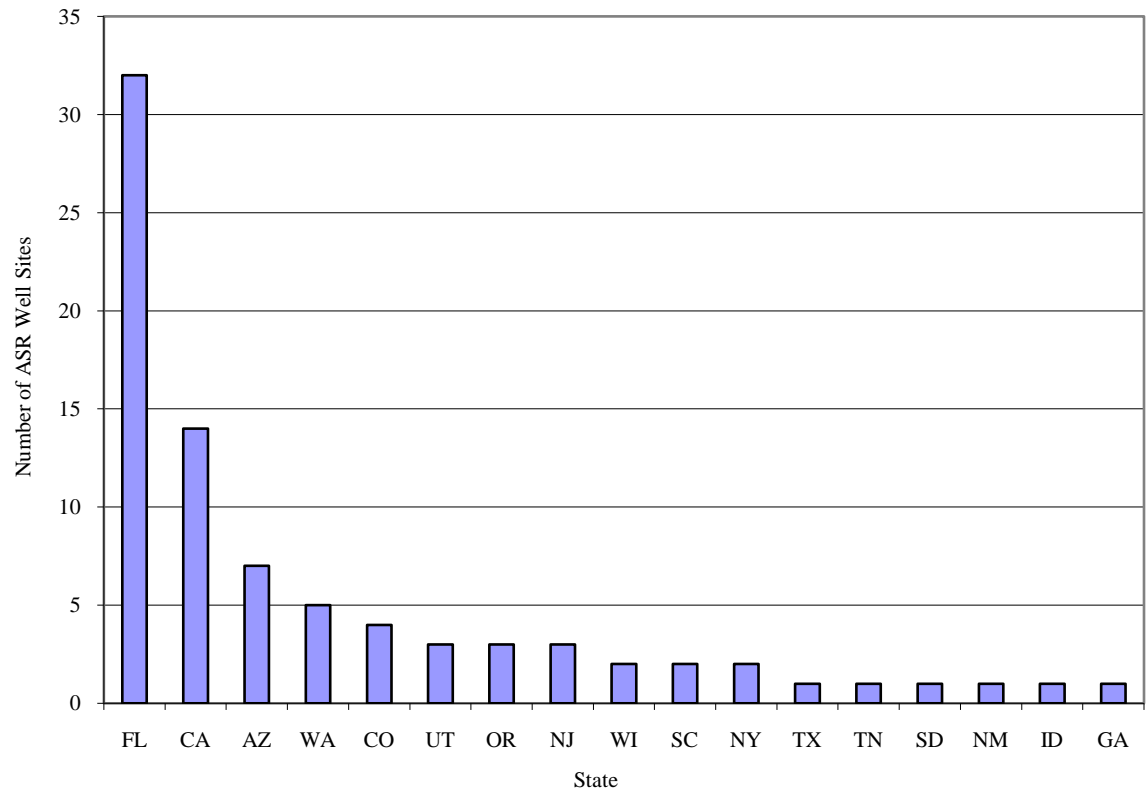
Figure 3. Number of ASR wells by state.

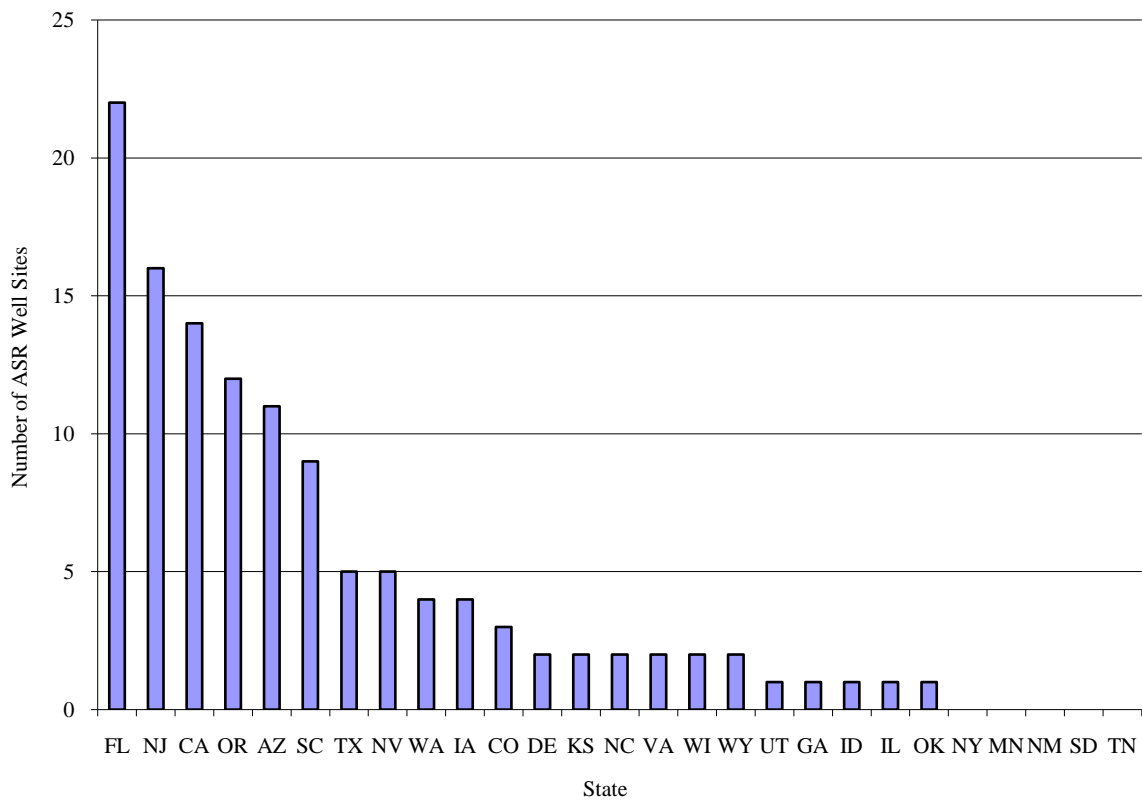**Figure 4.** Systems not in operation by states.

Figure 5. Net systems in operation, investigation or test phase by state.
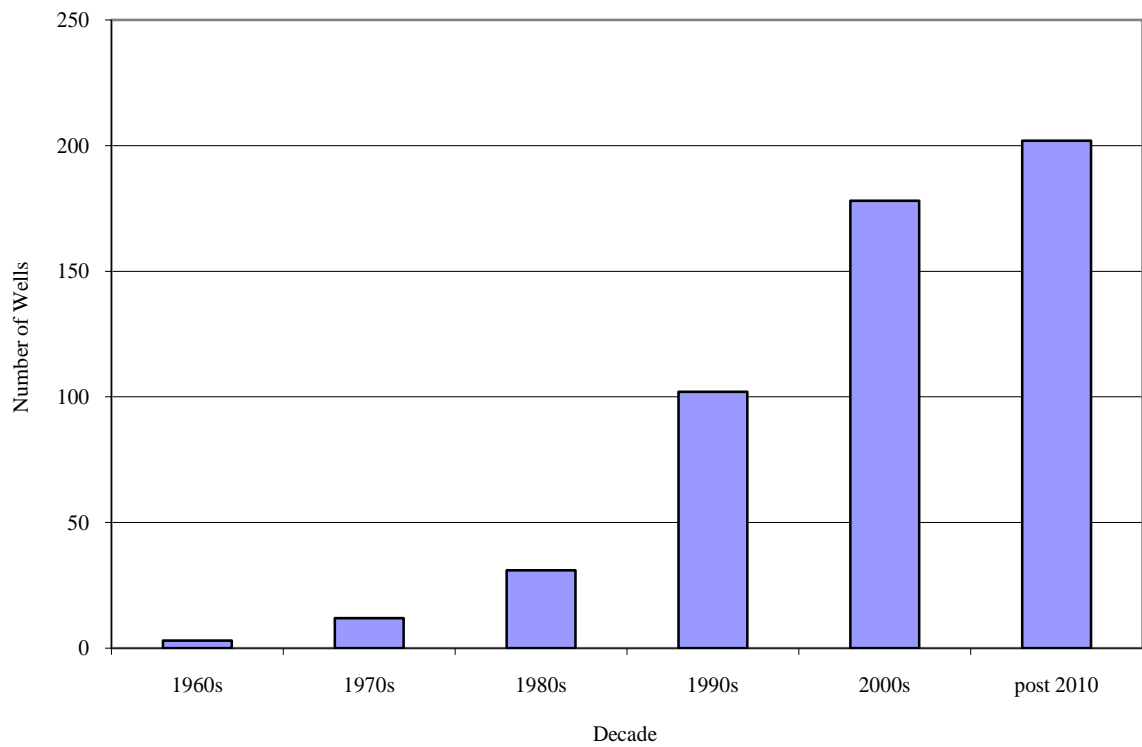

Figure 6. Growth of ASR investigations by decade.

With 95% confidence, chi-square tests results indicate that there are no statistical differences between ASR program status (active & inactive) and the following categorical variables: water source, water use, casing material, T&P code and confinement unit formation code. With 95% confidence, regression findings suggest that success rate is higher for ASR sites located in California, the Pacific Northwest, and Rocky Mountain/Plains.

Chi-square tests results indicate that there are statistically differences between ASR program status (active and inactive) and the following categorical variables: state, region, operational issues, storage cycles and injection formation code. Success rate is lower for ASR sites with deeper wells, clogging problems and water quality/ arsenic issues; clogging and water quality are operational issues. Based on these observations, the authors re-examined the data in order to discern the causes of operational issues with ASR systems, focusing primarily on the inactive wells, and those that have indicated issues with operations.

Table 6 outlines the information related to wells that are inactive. Table 7 outlines issues that have been raised with respect to active wells. Among the wells that are inactive, 10 wells were affected by water quality issues. Five of those are related to arsenic in Florida [4] [5], and four are associated with arsenic, manganese, iron or a combination of metals (e.g., in Wisconsin [6]). Two additional wells are related to radon in the west [7] [8]. The arsenic releases are all from limestone aquifers, and are associated with a range of injected water quality. Nevertheless, change in the geochemistry induced by injected water may lead to the release of arsenic from the geologic formations. Among the wells that are still active but not operational, a total of 6 wells in Florida are all releasing arsenic from limestone formations. One of these wells (*i.e.*, Bradenton), is actively looking at deploying ion exchange as a means to deal with arsenic in the recovered water. Recently, U.S. EPA and the state of Florida have entered into a memorandum of understanding on permitting issues associated with arsenic in recovered water [9].

Clogging is another ongoing problem at many sites. Eleven sites were identified as being abandoned as a result of clogging. Although 18 other sites are still active, they are associated with ongoing clogging issues. Among the inactive wells, 9 of them are injecting surface water into alluvial formations. The mechanism for clogging was not explicitly identified in these cases, but biofouling, particulates and geochemistry are all potential factors because of the organics in the water sources. Gin [10] [11] and Walker [12] reported that the clogging of the Phoenix wells (one using surface water and two injecting reclaimed water) got so bad that clearing the wells was required every three days, which led to the abandonment of the systems. Clogging is an issue at 18 active sites for which 13 of them are alluvial formations with a majority of them injecting surface water. Most of these sites are located in the west and they all have steel casings which may contribute to the potential for biofouling [13].

Low recovery of injected water has derailed ASR programs at 17 sites. The majority of these sites are in Colorado or Florida. Boomgaard [14] indicated that recovery was low in the abandoned Colorado wells. In addition, it was easier and cheaper to obtain new water rights from west of the Continental divide than to keep the ASR program going.

As for the Florida sites that are no longer active, low recovery is mostly associated with sites that attempted to inject potable water into limestone formations containing brackish groundwater. Many are in southeast Florida where only the Boynton Beach wells have been successful to date [5]. Bloetscher and Muniz [15] suggest that the percent recovery would improve with lesser recovery from the well, but the clients were discouraged by the low recovery and hence abandoned the project. The CERP projects partially fall into this category of low recovery (although arsenic was a bigger issue). The Dalton, Georgia well was a private project that injected into granite [16] [17]. It is the only granite well and relies of fissure for success. Given north Georgia is known for its tight geologic formations and limited fissures, it is not surprising that the project was abandoned due to a lack of recovery.

Table 6 and Table 7 indicate that well problems leading to inactivity or abandonment can be broken into three groups: 1) physical and chemical clogging or biological fouling, 2) inability to adequately recover injected water, 3) water quality changes which include arsenic, metals mobilization and trihalomethanes [5] [6] [18]. Each of these issues are outlined in the following sections.

3.1. Well Clogging

Well clogging was reported as one of the major operational problems with ASR wells [19]. Clogging was mentioned as a problem at 29 inactive sites of the 204 ASR sites, including 11 as the main reason for why the wells

Table 6. Characteristics of wells that are no longer active sorted by reason inactive.

State	Project/Location	Est Start Date	Number of abandoned wells in the project	Reason To Abandon	Injection Cap	Formation Type	Casing Material	Source of Water
FL	Punta Gorda-Shell Creek	1996/2002	4	Arsenic	1.4	Limestone	S	Drinking Water
FL	Lee County, Olga WTP	2001	1	Arsenic	1	Limestone		GW
FL	CERP St Lucie	2001	1	Arsenic	5	Limestone	PVC	Raw GW
FL	Collier County North	2006	1	Arsenic	1	Limestone	FG	Reclaimed
FL	CERP Taylor Creek SFWMD (Cl 61k)	1989	1	Arsenic	0.3 - 0.5	Limestone	S	Surface
FL	NW Hillsborough (WQ deter)	2003	1	WQ Deterioration	2	Limestone	S	Reclaimed
SC	Myrtle Beach	1987	1	WQ Deterioration	0.5	Limestone	S	Surface Water
WI	Oak Creek	1998	2	Metals Mobilizatin	1	Sandstone	S	Surface
WI	Green Bay Utlility	1998	1	Metals Mobilizatin	1	Sandstone/Limestone	S	Surface
TN	Memphis Light Gas and Water	1995	1	WQ Deterioration	0.8	Sand	S/SS	Ground
OR	Clackamas River Water (radon)	2000	1	Radon	0.5	Basallt	S	Surface
WA	Seattle Public Utilities Highline	1989	3	Radon	1	Alluvial	SS SC	Surface
NY	Bay Park (clog)	1968	1	Clogging	0.3	Alluvial	S	PWS
AZ	Phoenix 1-Salt River Project	1995	8	Clogging	1	Alluvial	PVC	Raw Surface
AZ	Phoenix 2-Tormanto	2004	2	Clogging	2.5	Alluvial	PVC	Raw Surface
AZ	North Scottsdale	2006	2	Clogging	0.5	Alluvial	S	Raw Surface
AZ	Peoria-Stone Street	1963	1	Clogging	1.6	Alluvial	S	Raw Surface
AZ	Phoenix 3-Cave Creek	2007	2	Clogging	1.5	Alluvial	PVC	Reclaimed
NY	East Meado Reclaimed Water (Clog)	2000	5	Clogging	0.5	Sand		Reclaimed
UT	Salt Lake City/High Plains	2003	40	Clogging	0.6	Alluvial		Surface
OR	Portland Water Bureau (Shore)	2003	2	Clogging	1.1 To 4	Alluvial/Sandstone	S	Surface
FL	Ft. Myers Winkler	1998	1	Clogging	1	Limestone		Surface
FL	Lee County, North Reservoir	2000	1	Clogging	1	Limestone		Surface
FL	Marathon	1990	1	Recovery	0.25	Limestone	S	PWS GW
FL	Sunrise Springtree	2002	1	Recovery	1	Limestone	S	PWS GW

Continued

FL	Miami Beach	1998	1	Recovery		Sandstone	S	PWS GW	
FL	Deerfield Beach, City of	2001	1	Recovery	1.3	Limestone	S/PVC	PWS GW	
FL	Lee County, Corkscrew	1996	6	Recovery	0.65	Limestone	S	PWS GW	
FL	Delray Beach	1996	1	Recovery	0.4	Sandstone	S	PWS GW	
FL	Broward County	1998	1	Recovery	0.8 - 1.6	Limestone	S	Raw GW	
FL	Fort Lauderdale Fiveash	1999	1	Recovery	0.5	Limestone	S	Raw GW	
FL	Miami-Dade Water & Sewer Dept. NW	1998	3	Recovery	5	Limestone	S	Raw GW	
FL	SFWMD Jupiter	1974	1	Recovery	5	Limestone	S	Raw GW	
CO	East Cherry Creek Valley Water District and Sanitation/Willows Water District acq 2001	1990	4	Recovery		Limestone	S	Surface	
FL	West Palm Beach	1997	1	Recovery	3	Limestone	S	Surface	
CO	Castle Pines North AR4	1999	1	Recovery	0.5	Sandstone	S	Surface	
CO	Parker Water and Sanitation District	1996	1	Recovery		Sandstone	S	Surface	
CO	Colorado Springs Utilitie Park Forest/Donata	2004	2	Recovery	0.7, 0.1	Sandstone	S	Surface	
TX	Laredo	1996	4	Recovery	0.2	Sandstone	S	Surface	
CA	Camarillo	1979	2	Recovery	0			Surface	
NM	Alamogordo	1996	1	Study Only	0.8	Limestone	S	Ground	

Table 7. Characteristics of wells that are still active, but reported issues sorted by reason inactive.

State	Project/ Location	Est Start Date	In Development	Number of abandoned wells in the project	Reason to abandon	injection Cap	Formation type	Casing Material	Source of water
FL	Bonita Springs San Carlos	2000	Study-Ab	1	Arsenic	1	Limestone	S	Drinking Water
FL	Sanford	2008	Test	0	Arsenic	1	Limestone	S	PW
FL	Englewood	1998	Op	1	Arsenic	2.2	Carbonate	S	Reclaimed
FL	CERP Hillsboro Basin	2001	Study	1	Arsenic	5	Limestone	Pvc	Surface
FL	Bradenton-Reservoir	2007	Hold	1	Arsenic	3	Limestone		Surface
FL	CERP Lake Okeechobee	2004	Test	1	Arsenic	9.4	Limestone	S	Surface Water
CA	Antelope Valley Los Angeles PWD	1994	Op	2	Clogging	1	Alluvial	S	Ground

Continued

UT	Cachw/Leamington Town Culinary Water Well	2008	Study Ex Well	1	Clogging	1.3	Limestone	S	Ground
NJ	Evesham Township Municipal Utilities Authority (They are abandoning 1 well and drilling another 50 ft away)	1996	Op	1	Clogging	0.5	Sand/Clay	S	Ground
AZ	Gilbert	2005	Op	1	Clogging	2	Alluvial	S	Reclaimed
AZ	Chandler Intel	2005	Op	3	Clogging		Alluvial		River Wa-ter
CA	Victorville (Victor Valley Water District)	2006	Op	4	Clogging	0.8	Alluvial	Epoxy Ss	Surface
CA	Valley Water Company Foothills/Monk Hill Basin	1994	Op	0	Clogging	1	Alluvial	S	Surface
NV	Washoe County (Truckee) gravity flow	2008	Op	2	Clogging	0.2	Alluvial	S	Surface
UT	Jordan Valley Water District (retro wells)	1994	Op	18	Clogging	0.7	Alluvial	S	Surface
OK	Okahoma City, Blaine Recharge Demo Project	1972	Pilot	5	Clogging	1	Alluvial	S	Surface
CA	Elsinore Valley Municipal Water District	2005	Op	0	Clogging	2 to 3	Alluvial	S W Screen	Surface
CA	Pleasanton, Zone 7 Livermore	1998	Op	4	Clogging	1.7	Alluvial	Ss	Surface
CA	Tracy, City of	2004	Test	1	Clogging	1.5	Alluvial	Ss	Surface
CA	Oxnard, City of	2003	Test/Ab	5	Clogging	9	Alluvial	Ss	Surface
OR	Baker City, City of	2004	Op	0	Clogging	1.1		S	Surface
OR	Pendleton, City of	2003	Test	2	Clogging	1.7	Basallt	S	Surface Via Rbf
NV	N Las Vegas	1989	Op	6	Clogging	1	Alluvial	S	Varies, Inc Reuse
ID	Boise, United Water	1991	Op	1	Clogging	0.3	Basalt	S	
CA	Sonoma County Water Agency-Santa Rosa ASR 1 aband to std wll	2004	Test	1	Conv To Well	0.8	Alluvial	S	Surface
CA	East Bay MUD	1997	Test	1	Mn, Thm	3759 m^3/d		S	Surface
CA	Pasadena, City of (thm)	1992	Op	3	Thm	1.2	Alluvial	S	Surface
WA	Yakima	2002	Test	1	Thm	1.7	Basalt		PWS
GA	Dalton (carpet industry-small test wells only-no formation)	2007	Test	5	Recovery		Granite		Raw GW
FL	PBC 3	1998	Test	1	Recovery	1	Sandstone	S	Raw GW
FL	PBC System 9 Hillsboro	2003	Test	1	Recovery	5	Limestone	S	Surface

are no longer active. All these wells were constructed with steel casings and most of them were using surface water as their source water, which makes particulate clogging and biofouling prime suspects of operational problems. As mentioned earlier, there are three types of clogging: particulate (or mechanical), chemical, and biological, along with combinations thereof. Mechanical clogging problems result from suspended solids clogging the pores of the receiving formation, well screens, and/or gravel packs. The Total Suspended Solid (TSS) concentration of the injected water, often characterized by turbidity, represents the most influential factor in determining the potential for this form of clogging, even when other factors may contribute to well clogging. Pyne *et al.* [20] reported that it is rare to find an ASR well that will not clog if the injected water has high TSS. Pitt and Magenheimer [21] suggested that TSS concentrations at 0.5 mg/L to 1.0 mg/L can already cause clogging of a porous-media formation (e.g., an alluvial formation). Pyne [22] indicated that significant loss in recharge rates for most wells when the injected water are associated with TSS concentrations as low as 2.0 mg/L. Despite the best efforts of operations, periodic clogging of the injection well is expected, as suspended solids reduce permeability and transmissivity of the formation in the zone surrounding the well.

If the injected water has low TSS, but the injection rate is high, silt particles and clay colloids in receiving alluvial formations can be disturbed and clog the pores of the injection zone. Note that sites with alluvial formations are the most common to report clogging in the survey. Mechanical clogging problems also include air entrainment and formation particle jamming [21].

It should be noted that the pores of aquifers are typically too small to permit movement of the suspended particles for any distance beyond the borehole. Plugging caused by suspended solids can be mitigated by frequent re-development of the well during injection operation. Brown *et al.* [23] reported that well clogging issues have been managed successfully through the use of a regular back flushing programs. When the water flow is reversed, the particles are removed from the well screen, gravel, and/or borehole wall, along with the tightening of the gravel pack.

Re-development of the wells often entails discontinuing injection for a brief period, and reversing the well pump to remove solids accumulating around the wellbore. Periodic re-development should be expected but constant re-development hinders the goal of operations. For example, the City of Phoenix (AZ) had to backflush every few days, so the projects were finally abandoned [10] [11]. A number of the California systems have also reported clogging and two noted that re-development was required every 3 to 5 days to maintain well performance [24].

Chemical clogging is a geochemical issue. High conductivity water generally indicates the presence of chlorides and dissolved metals in the water. High TDS in itself is unlikely to create clogging problems, but it may contribute to chemcial clogging problems by bringing ions into the formation that can create various chemical reactions. When injected water with high cation concentrations replaces the more stable native water, geochemical equilibrium would need to be re-stablished through chemical reaction between the injected water and native fluid/aquifer matrix. In some cases, geochemical inequilibrium may result in the release of metals from the formation. Injection waters containing high sodium concentrations may also exacerbate clogging by hydrating and swelling of clays. Chemistry induced clogging is not unusual and may be treated with acidization of the well and re-development. For example, for the Wildwood, NJ system, the oldest ASR system in the US, acidization has been deployed every three months for each of its 4 ASR wells to combat clogging [25].

Microbiological fouling is generally interrelated with physical and chemical processes, and is particularly common with steel casings [13]. Microbiological fouling issues with ASR wells are similar to those encountered by water supply wells in that microorganisms can incrust or corrode the wells, and thus enhancing physical and chemical deterioration of the wells. Microbiological fouling encourages changes in the electrical potential and structure of the well material by creating anodes on metallic surfaces. Biofilms can form that eventually clog screens. The bacteria absorb nutrients and minerals such as iron, manganese, arsenic, nitrogen, and oxygen within the biofilm matrix, leading to the formation of tubercles and films that reduce capacity of the pumps and casings. The typical symptoms of microbiological fouling problems are [1]:

- Decrease in the water quality;
- Reduced specific capacity;
- Change in the amount of iron or manganese in the water supply;
- Increases in microbiological densities such as an observance of slimes or staining from the raw water.

Biological growth can be controlled by maintaining a chlorine residual in the injected water, but this can lead to disinfection by-products (DBPs) issues.

3.2. Metals Leaching/Water Quality

A second problem observed among some of the ASR projects is water quality issues. Seventeen sites reported issues associated with water quality changes, particularly metals mobilization. Arsenic mobilization in limestone was reported in 11 Florida wells and two Wisconsin wells [4]-[6]. The metals leaching is most common with Florida and limestone, because virtually all the Florida wells use the same Floridan formation that contains pyrite in the limestone matrix. With respect to the Florida arsenic issues, Arthur *et al.* [4] reported that

"… examples of natural arsenic mobilization mechanisms and associated mineral phases include: 1) oxidation of sulfide minerals such as pyrite, which may contain trace elements as lattice substitutes, impurities or in solid solution (e.g., nickel, copper, cobalt, lead, arsenic, zinc and manganese), 2) desorption or dissolution of iron and manganese hydroxides (including grain or fracture coatings), 3) oxidation-reduction of organic material, which can mobilize organically complexed arsenic, and 4) biological transformations."

The study suggests that

"… [f]rom the whole rock geochemistry data, many trace metals… showed high concentrations, when compared to global averages for limestones, especially arsenic in arsenian pyrite or organic materials" [4].

The results of their investigation indicated that geologists should assess chemical (including isotopic) variability within ground water and the aquifer system in light of the quality of the water to be injected. Of particular concern is the injection of oxygen-rich surface waters into an aquifer which can cause the release of trace metals into the injected water because of chemical in-equilibrium and reactions.

Brown *et al.* [23] reported that several ASR project sites in Oregon and Washington with naturally occurring radon in the recovered water. Eastern Municipal Water District in California had manganese issues when they started their program [26]. The ASR site located in Monmouth County, New Jersey had high iron in the recovered waters as a result of oxidation of minerals within the aquifer by oxygen in the recharge water [27]. As the iron concentrations in the recovered water increased considerably above the secondary drinking water standard of 0.3 mg/L, the increases oxygen was suggested as a cause [27]. When the acidification treatment failed to correct the problems in Monmouth County, the iron concentration was reduced in the recovered water by elevating the pH of the recharge water [28]. The Foothill Municipal Water District ASR site in California reported elevated mercury levels that exceed historical levels in both the recharge water and the recovered native groundwater [27]. They used imported water sources for blending to bring the concentration down in the finished water to resolve the problem.

Geochemistry is a difficult and complex issue to work with among ASR wells. For successful ASR operations, the injection water must be compatible with the native groundwater and the aquifer material. Pyne [27] suggested pH differences between the recharge and groundwater can cause reactions that lead to clogging problems or the release of constituents (such as arsenic) from the aquifer matrix which may require removal upon recovery of the water. As noted in **Table 6** and **Table 7**, surface waters were more likely to be associated with metals leaching problems (when compared with the use of groundwater, with the exception of Florida). It is suggested that this maybe because the dissolved oxygen content of surface waters is higher than native groundwater.

Chemical leaching issues can be solved using treatment techniques prior to injection and upon withdrawal. Overcoming geochemical problems may require modifications to the injected water—e.g., additional chemicals can be used to make the quality of injected water "match" more closely with that of the native groundwater.

3.3. Disinfection Byproducts

Potable and reclaimed water sources often contain chlorine that is used as a disinfectant. In the presence of organics, disinfection by-products (DBPs) such as haloacetic acids (HAAs) and trihalomethanes (THMs) would be generated. The presence of HAAs and THMs in the injection formation may be considered by regulatory agencies as introduced contaminants. The presence of DBPs (in the injection water) has led to stoppage of several projects in Washington and California. This issue was also raised in Florida and Colorado. Willows Water District in Denver, Colorado, Las Vegas, Nevada and Lancaster, California have all been studied in detail with regard to DBP issues [17] [29]-[31]. These studies and others demonstrated that microbial processes can attenuate HAA and THM during storage in the aquifer [17] [32]-[34] Pavelic *et al.* [35] reported that "three orders of magnitude difference in total THM attenuation rates occurred between the smallest half-lives at Charleston (less

than 1 day) and the greatest half-lives at East Bay (120 to 550 days) and Las Vegas (greater than 120 days). There has been little evidence to suggest that the formation of DBPs continues in aquifers during ASR, apart from studies by Singer *et al.* [32] and Fram *et al.* [36] that were designed specifically to observe the kinetics involved with DBP formations. Other than those studies designed to deliberately create DBPs, only the Foothill Municipal Water District in California has observed an *increase* in THMs [37], which may likely be related to organic content in the injection horizon.

3.4. Operational Issues

Parsing through the data did indicate several trends:
- ASR sites with problems generally have a smaller number of injection wells. There were 2.4 wells per site with failure issues versus 4.4 at active sites. More successful sites tended to have more wells, for example, Grand Strand in South Carolina has 20 wells. This was not a surprise, but confirmed the expectations of the investigators.
- Sites with high injection or withdrawal rates tended to be less successful. The typical ASR wells injected or withdrew 1.5 MGD.
- The formation did not seem to matter much although the more common limestone and alluvial formations had issues with metal mobilization and clogging, respectively.
- The amount of water stored was lower for the inactive sites, which was not unexpected.

There are no big surprises in this data, but there may be an underlying anecdotal pattern that may worth investigating further. Newer projects were more likely to be stopped than older projects and thus the time period of inactive sites is generally shorter. The inactive southeast Florida wells that had recovery issues were all stopped within a three years of effort. Having evaluated numerous ASR projects and on the basis of discussion with project clients, the stoppage after a short time period may be related to client expectations on the ability to recover injected water (*i.e.*, the willingness to inject a lot of water that might not be recovered and the willingness to spend money on a "risky" venture and anticipated treatment needs).

The inability to recover sufficient quantities of injected water was listed as a reason to abandon ASR efforts at 20 sites, primarily in Colorado and Florida. For recovery success, finding a confining layer immediately above the injection horizon is necessary so the buoyancy of the injected water does not cause the injected water to move away from the ASR well as shown to occur in two sites [38]. Another challenge associated with recovered water is the need to treat the water upon withdrawal, which is an issue with all the sites with arsenic problems. If the project client is unwilling to treat the recovered water, the project will not be a success. To deal with these issues, appropriate stratigraphy is required and a series of injection and recovery cycles must be undertaken to determine quality of the recovered water, the amount of water that might be successfully recovered and any needed treatment to meet compliance requirements. In order not to waste water, injection and recovery cycles usually start with small amount of water (e.g., under 10 million gallons) and then increase to 30 - 50 million gallons. To date, many of the systems have over 100 million gallons invested in injection cycles. Given most of the wells are designed to inject 1 MGD, 100 million gallons would take 100 days of injection. Recovery, however, may be more or less than the 1 MGD—one of the unknown and uncertain variables [2] [3] [36]. A 5 cycle test program might take 2 or 3 years on top of the permit and construction period. Such a program cost could cost $1 - $1.5 million. On the other hand, a client may expect that a well will be operational in a matter of a year or less, which is rarely attainable.

The use of ASR technology in brackish aquifer systems presents different challenges that are related to the mixing of the injected "fresh" water with the native brackish water. Where a brackish aquifer is used, the density difference between the treated freshwater and saline source would cause a "bubble" of freshwater to form. A large mixing area may also form as a result, depending on the formation, but with adequate quantities of injected water and the right aquifer properties, the bubble would remain fresh for a sufficiently long time period to be available for water supply augmentation. The quantity of water to be stored can be as extensive as the localized aquifer system allows, and can be continuously pumped into the aquifer system until needed. However, the initially mixed water may not be recoverable unless treatment is deployed to remove impurities such as elevated levels of chlorides (salinity). In many cases, the transition zone between native an fresh water may be over 500 million gallons for a single well [2] [36], after which the ASR system may derive 70 percent recovery of the water injected, depending on aquifer characteristics.

An ongoing current issue in Texas, among others is tied to ultimate management of the waters recharged. While no utility has noted that this as a barrier, several states are in the process of, or have had to revise, water-rights laws identifying who owns the water recharged in an ASR system. Those rules are ongoing and state specific. If a utility cannot recover the water it injects because of water-rights issues, the incentive to pursue ASR is lost.

4. Conclusions

This paper results from a nationwide analysis of ASR systems through a data gathering effort as of July 1, 2013. Unlike the previous efforts, every utility that was identified as having investigated ASR was contacted, whether they proceeded with the development of ASR projects or not, and whether the system was still active or not. Nine months of data collection, literature reviews, online searches, phone calls, emails, file searches and permit collection yielded information on operations of the ASR systems, stratigraphy, ASR challenges and information were gathered and compiled for every system we knew of in the U.S. Copies of reports and rules have been posted at www.h2o-pe.com. One of the issues that arise from the inventory of the 204 systems in the U.S. is that 26% percent of the ASR projects have been functionally abandoned.

This paper focuses on the causes of failures associated with ASR projects and provides solutions to avoid some of the common pitfalls. While the wells at over 50 sites were technically abandoned, only one (Broward County) was reported as permanently plugged and abandoned, and three systems in California were converted to potable supply wells, which was not surprising because many of the California ASR wells started as supply wells. Geochemistry, clogging and recovery are the most common issues associated with failed efforts. Both physical and chemical properties of the injected water may change after injection as a function of chemical reactions between injected water and the native groundwater/aquifer matrix. The stored water has the potential to change as a result of increased aquifer pressure, temperature (increases or decreases), and the potential for micro-organisms activities. The changes in water and the formation are directly related to recovery potential.

The combined challenges of meeting requirements for drinking water storage, groundwater injection, water quality and disinfection byproducts rose in several states. The need to establish ownership of the stored water in several states has created additional challenges that must be addressed by the regulatory agencies within those states where ASR is used and water rights are at issue.

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