Global Journal of Engineering and Technology Advances, 2020, 05(02), 063–070

Global Journal of Engineering and Technology Advances

Cross Ref DOI: 10.30574/gjeta

Journal homepage: http://www.gjeta.com

(RESEARCH ARTICLE)

Factors to predict success of ASR systems

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Publication history: Received on 28 September 2020; revised on 08 November 2020; accepted on 13 November 2020

Article DOI: https://doi.org/10.30574/gjeta.2020.5.2.0081

Abstract

A 2019 inventory of ASR projects indicates that there are a total of 233 ASR sites in the US. Of this number, 127 had sufficient information and sufficient longevity to evaluate their success. A logistic model was run using the reduced variable set, and (1) Injection Capacity, (2) Withdrawal Capacity, and (3) Ratio of Planned Pumping In/Out had slight positive effects on the odds of success; (4) Estimated start date and (5) Well Depth did not have any effect on the odds of success. All other variables reduced the odds of ASR success (the uses for the water, limestone and carbonate formations). The area's geological formation may be the most useful parameter to predict future ASR success, but further study is required. Data on well construction is not indicative of success because wells construction accounts for the subsurface formations. Information on water quality in the formation and confinement layers was missing for many ASR sites, but both are likely to have predictive value for ASR project success.

Keywords: Aquifer Storage and Recovery; ASR; Aquifer Recharge; Success

1. Introduction

Around the world, treated or treatable water is pumped below ground and stored to preserve current water resources, prepare for future droughts, protect water resources, recharge wellfields, and store water for use at a later time to sustain development (AWWA, 2015). Aquifer storage and recovery (ASR) is one approach to groundwater recharge that is generally accepted as viable for managing both potable and non-potable water supplies in areas with unreliable supplies and water shortages (AWWA, 2002, 2014, 2015, Bloetscher et al 2014, 2015). ASR systems are those that pump water, treated or not, down a well into an aquifer, and the water injected into that aquifer is recovered later from the same well for some intended purpose. ASR as defined here excludes other types of managed aquifer recharge programs like infiltration basins, spreader basins, trenches, and other means to recharge aquifers from the surface. By leveraging unused treatment plant capacity to treat excess or available water and store it in an aquifer for later withdrawal, ASR programs can augment future water supplies which can help utilities avoid the costs required to build in extra water treatment capacity (AWWA, 2014, 2015, Bloetscher et al 2014, 2015).

In 2013, a dataset on ASR systems in the United States was collected from USEPA, state environmental agencies, on line, peer reviewed and conference literature and through telephone interviews with specific water utilities. This effort yielded 204 sites that included over 700 wells. The ASR projects in this inventory used water sources that included raw surface (64%), ground water (21%), and reclaimed wastewater (14%). Storage periods ranged from multiple months to years depending on the goal which included storing water to meet the next high demand period, supplementing supply during an emergency such as a severe drought, and provide water during an interruption of supplies resulting from equipment breakdown. Approximately 37% of the ASR sites were considered to be operational, while 25% of the sites were not active (Bloetscher et al 2014), with the rest in various stages of testing or feasibility studies. In the fall of

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2019, the authors researched online sources, state agency databases, and knowledge of new regulatory measures to update the 2013 compiled by Bloetscher, et al (2014, 2015), and apply statistical tools in the manner of Bloetscher (2018) to reveal insights into the criteria associated with the development of ASR systems and to highlight those characteristics that might lead to a higher rate of success for new sites. For this study, the 2013 dataset was expanded based on data availability and working knowledge of ASR programs, with the intention to account for operational issues, construction approaches, and local differences. Some of the earlier ASR systems contained inconsistencies or missing data that was not required.

2. Methodology

A review of EPA's, state and other regional, current, publicly available regulatory databases with respect to ASR system was undertaken to identify changes in the ASR inventory since 2013. Per the prior effort (Bloetscher et al 2014, 2015), 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 inactive; the number of individual ASR wells on a site to accommodate the designed injection capacity; and the number of individual ASR wells not in service. Data on the operations that was queried included: the 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; the number of storage cycles (estimated), which may be indicative of age of the system; the injection rate per well and the 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, 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. Items that were difficult to find included; injection zone transmissivity; water quality in the injection horizon (total dissolved solids), the type of confinement (formation type) and the number of monitoring wells.

The focus was on new sites and sites where the status changed since 2013 (through October 2019). Several findings came out of this effort (Bloetscher et al 2020):

"Georgia had decided not to permit ASR systems,

The Texas State Water Plan included ASR as a part of the water resources portfolio (at a total of 1% of the total water use), which has spawned 20 proposed ASR project site for investigation over the next 10 years,

Florida and EPA entered into an agreement to address arsenic in recovered water from ASR systems in limestone formations, which may have fostered some renewed interest in ASR in Florida.

Washington has undertaken ASR feasibility studies in all aquifers in the state, while Cheyenne, WY had ceased pursuing its ASR project

Two projects undertaken by the Army Corps of Engineers for the South Florida Water Management District completed testing, with no further activities.

Utah continues to evaluate ASR and surface reservoirs in high growth areas of the state, but surface reservoirs are chosen most frequently."

While there are nearly 30 new systems, few of the new systems had data available in the literature as most are in the study or conceptual stage.

For this study, ASR sites with incomplete data were not used in associated statistical analyses. In addition, sites that are not either in operation or inactive were excluded from the analysis as the goal was to identify those factors that contribute to success of ASR programs. Study and recently initiated project do not have sufficient information to identify the potential for success. After removing sites with incomplete data, 127 sites were included in the analysis. Linear regression and logistic regression models were run on the complete dataset using XLSTAT® for the linear regression and SPSS® for the logistic regression, to help determine which variables may lead to the success or failure of an ASR program.

Linear regression is a probabilistic statistical technique that models a relationship between one or more explanatory variables (or independent variables) of observed data to predict a condition. In this case, the critical query was whether the ASR system was operational or not. Because so many of the variable were categorical, logistic regression was used as well and compared 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. Logistic regression better uses categorical variables. The critical query was whether the ASR system was operational (1) or not in operation (0) as the dichotomous dependent variable in both cases.

3. Results and discussion

The updated database added 29 new sites to the previous inventory of ASR sites in the US. The state with the most ASR sites remains Florida, with California and Texas next in line. ASR is being proposed in Nebraska, the only new state to investigate the program. The greatest increase of ASR projects is in Texas, although many of these involved in studies, i.e., no wells have been drilled yet. It should be noted that the presence of ASR sites is not necessarily an indicator for future ASR projects; taking Florida for example, over half its sites are inactive or have wells that are no longer used due to recovery issues; metals were a previous concern. While an agreement was reached with EPA to resolve the metals mobilization issues associated with arsenic in recovered water, few Florida programs have restarted.

In California, the major reason that sites were drilled, but are currently inactive is that many sites lack reliable water sources. At one point, the Metropolitan Water District of Southern California was going to deliver surface water supplies to ASR sites, but changes to water supply reservoirs management and construction of new reservoirs in the last decade altered this effort.

In the current data set, approximately 29% of the ASR sites were considered to be operational, while 33% of the sites were inactive. The remaining are in test and study modes (including most of the new Texas sites). In the aggregate, there are more inactive sites in 2019 when compared to those in 2013, but most of this can be explained by test or study efforts that were discontinued. The change has reduced the number of active sites from 74 (in 2013) to 68 (in 2019). The growth in the number of new sites initiated since 2010 has slowed compared to the previous decades. In part, the issues with water supply, regulations, and weather/droughts have all affected decisions to evaluate and invest in ASR projects.

The majority of sites are storing surface water, and virtually all the new sites propose to use surface water. Groundwater and reclaimed water make up the balance. The use of the withdrawn water is primarily for potable water supplies with via raw (untreated) and or in some cases as direct connections to drinking water supplies (although chlorine, and pH adjustments are normal). Other uses include irrigation, reuse, canal recharge, industrial, and fire department. All new ASR systems proposed to withdraw water from surface waters and store it for later treatment for potable water use.

As reported in Bloetscher et al (2020), other things noted include:

Most ASR wells are less than 15 inches, with 15-20 being the second most common size.

The casings remain primarily steel

The casing depths are primarily less than 750 ft below land surface

The main storage units are limestone and alluvial formations

ASR wells often face challenges including high arsenic levels, clogging, recovery percentages, water supply availability, and in some cases, the lack of recovery. The absence of water sources has led to inactivity of ASR projects, but many of these projects could be restarted if conditions change. The largest ASR project stored over 10 billion gallons, but the majority were less than a billion gallons. However, because so many systems are in test, study, or inactive stages, it’s not surprising that over half the systems have had less than 10 cycles

Of critical note, the injection and withdrawal rates tend to be around 1 MGD, which is a threshold that indicates whether high volume ASR wells are unlikely, which has been confirmed on several projects like the Collier County project in 1started in 1995. From the current database, 40% of injection rates were less than 1.0 MGD and 36% were in the range of 1 to 1.5 MGD. Likewise, 31% of withdrawal rates were less than 1.0 MGD and 26% were in the range of 1 to 1.5 MGD.

As shown in Bloetscher (2018), when ASR wells were grouped into regions of the US, significant correlations exist for:

Sand/sandstone formations in the east

Unconfined alluvial formations in the west/southwest; and

Confined limestone formations in Florida

None of these are useful for predicting success outside of regional efforts so this project was designed to probe more data to provide preliminary estimates for ASR project success. The resulting model provided good predictions of success, but it included many redundant factors that are indicative of success (number of wells, injection/withdrawal cycles, water stored, etc.). Independent variables that contributed to predicting success (with positive coefficients) were:

Number of active wells

Water supply sources

Attributes or variables that indicated project failure included:

Low number of cycles (<20)

Limestone formations

Use of water

A linear regression coefficient matrix, which identified the number of sites that were correctly classified and those that were not, yielded a correct prediction 79 percent of the time. Figure 1 shows the factor loadings for the linear regression model. Variables that had a strong influence on increasing the odds of success were:

Number of wells and number of active wells (which makes sense because that is what is being tested for)

Water Supply (all sources)

Number of Cycles

Injection Formation

Injection Capacity (MGD)

All other variables - except start date, number of wells, and depth of wells which had little or no effect - reduced the odds of ASR success. Again, contact the authors for model-specific details.

Some variables such as the number of wells, storage cycles, and amount of water stored are inherently measures of ASR success, but this data isn't valuable to predict success at sites with no injection data. Therefore, to determine the influence of the other variables in the analysis, the influence of number of wells, storage cycles, and amount of water stored variables, which are variables that correlate highly with successful projects, were removed. Reducing these redundant factors if shown in Figure 2. Based on the remaining variables in the model, positive influence was exerted by (1) Water Supply and (2) Injection Formations – Except Limestone; negative influence was found in the variables (3) Use of Water and (4) Injection Formation – limestone; using this approach, the model predicted the correct status 64.8% of the time.

A logistic model was run using the reduced variable set, and (1) Injection Capacity, (2) Withdrawal Capacity, and (3) Ratio of Planned Pumping In/Out had slight positive effects on the odds of success; (4) Estimated start date and (5) Well

Depth did not have any effect on the odds of success. All other variables reduced the odds of ASR success (the uses for the water, limestone and carbonate formations). The logistic model correctly predicted the ASR site status 68% of the time. Both the linear regression and the logistic regression were close in this case, but only as an initial estimate of ASR project success.

Table 1 Results of Logistic Regression – all Variables

	Logistic Regression Results Full Dataset			
Variables	B	S.E.	Sig.	Exp(B)
Est_Start_Date	***0.046***	0.126	0.713	***1.048***
Number_wells	***0.197***	0.117	0.092	***1.218***
Number_Active_wells	***8.963***	3.295	0.007	***7810.515***
Depth_of_well	0.000	0.002	0.853	1.000
injection_Cap_MGD	***0.992***	1.481	0.503	***2.696***
Withdr_Cap_MGD	-1.410	0.927	0.128	0.244
Ratio_in_out	-7.025	3.839	0.067	0.001
Supply_Potable	***11.982***	35203.914	1.000	***159912.106***
Supply_Surface	***11.134***	35203.914	1.000	***68442.123***
Supply_Grround	***10.071***	35203.915	1.000	***23658.085***
Supply_Reclaimed	-6.217	30518.450	1.000	0.002
Use_for_Raw	-115.921	35204.819	0.997	0.000
Use_for_PWS_direct	-114.819	35204.820	0.997	0.000
use_for_Cooling	-114.831	41509.032	0.998	0.000
Use_for_Suface_Augmentation	-114.976	35204.823	0.997	0.000
use_for_Irrigation	-98.957	30519.498	0.997	0.000
Inj_Form_Sand	***4.314***	2.897	0.136	***74.751***
Inj_Form_Limestone	***3.272***	3.360	0.330	***26.364***
Inj_Form_Basalt	***7.302***	3.563	0.040	***1483.231***
Inj_Form_Carbonate	***8.789***	4.235	0.038	***6564.916***
Less_than_3_cycles	***7.239***	8.764	0.409	***1393.236***
Three_to_20_cycles	***10.609***	5.229	0.042	***40515.228***

Table 2 Results of Logistic Regression – Reduced Variables

Variables	B	S.E.	Sig.	Exp(B)
Est_Start_Date	0.030	0.121	0.803	***1.031***
Numb_Wells	0.176	0.115	0.126	***1.192***
Numb_Active_Wells	8.489	3.099	0.006	***4862.431***
Supply_Potable_Water	18.347	17552.895	0.999	***92889739.897***
Supply_Surface	17.519	17552.895	0.999	***40604183.809***
Supply_Grround	16.574	17552.895	0.999	***15770496.574***
Use_for_Raw	-16.754	17552.895	0.999	0.000
Use_for_PWS_direct	-16.340	17552.895	0.999	0.000
use_for_Cooling	-15.153	27922.397	1.000	0.000
Use_for_Suface_Augmentation	-15.780	17552.898	0.999	0.000
Inj_Form_Sand	-3.529	4.226	0.404	0.029
Inj_Form_Limestone	-4.886	4.191	0.244	0.008
Inj_Form_Basalt	-1.514	4.092	0.711	0.220
Inj_Form_Alluvial	-7.798	4.177	0.062	0.000
Depth_of_well	0.000	0.002	0.874	1.000
Less_than_3_cycles	6.052	8.000	0.449	***424.801***
Three_20_Cycles	9.825	4.895	0.045	***18497.657***
injection_Cap_MGD	0.728	1.488	0.624	***2.071***
Withdr_Capacity_MGD	-1.218	0.900	0.176	0.296
Ratio_in_out	-5.952	3.770	0.114	0.003
Constant	-64.904	238.108	0.785	0.000

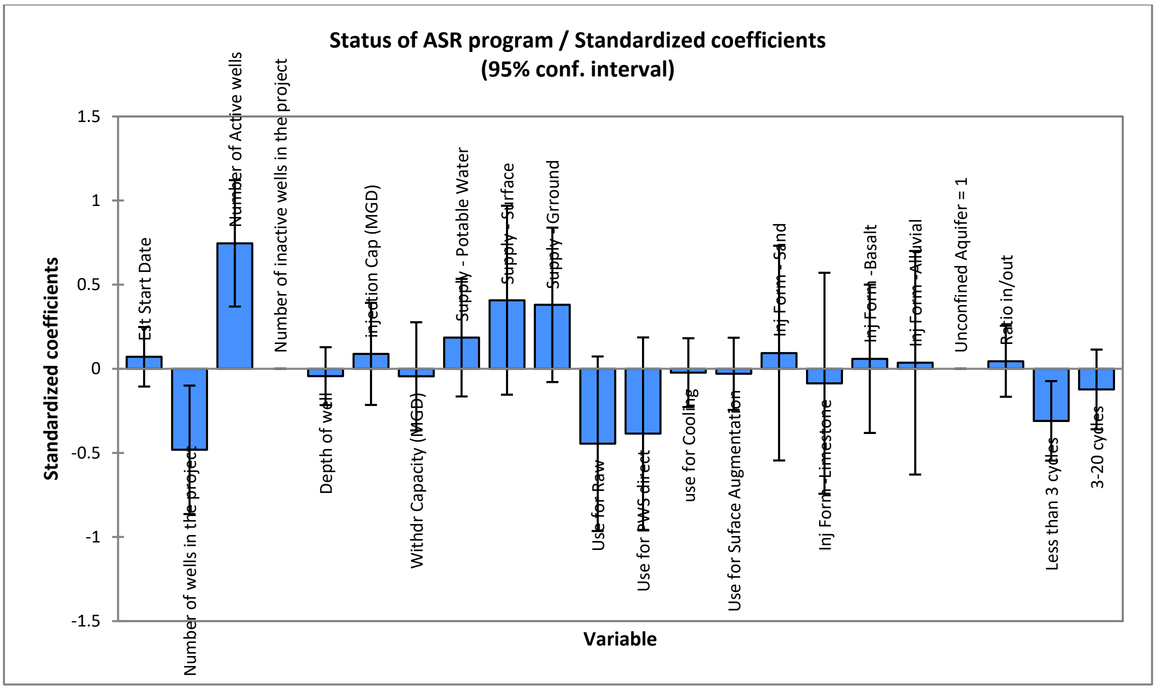

Figure 1 Linear Regression Factors - larger bars indicate greater impact

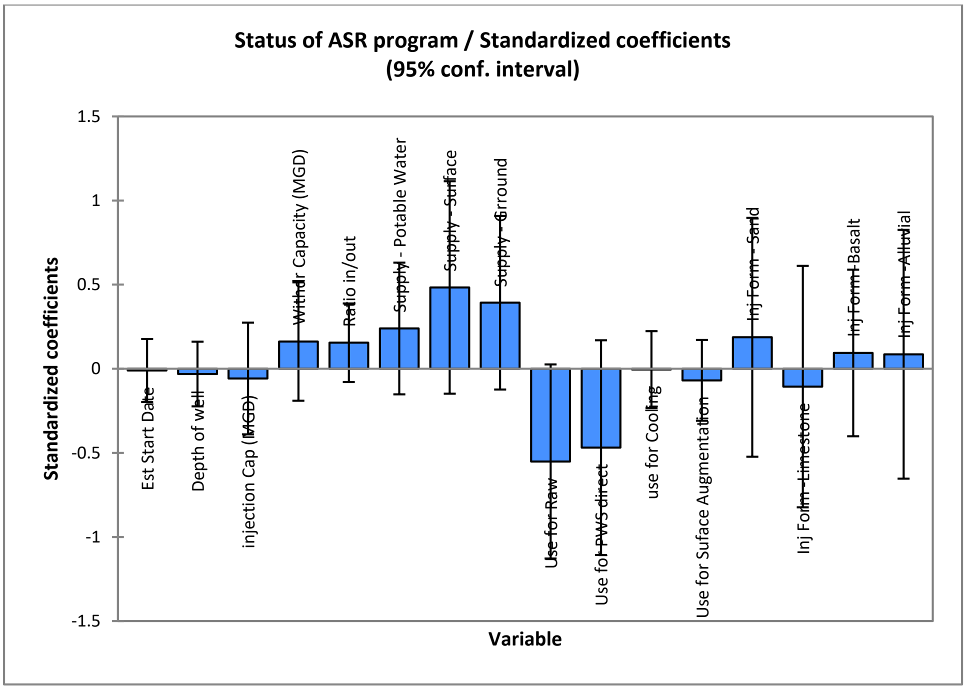

Figure 2 Linear Regression Factors with reduced variables - larger bars indicate greater impact

4. Conclusion

Of the 233 total ASR sites in the updated US inventory, 127 collected data that was sufficient to evaluate their success or failure. In the end, an area's geological formation may be the most useful parameter to predict future ASR success, but further study is required. Data on well construction is not indicative of success because wells construction accounts for the subsurface formations onsite. Information on water quality in the formation and confinement layers was missing for many ASR sites, but both are likely to have predictive value for ASR project success. As more utilities across the North America explore ASR and more projects come online it's hopeful that more complete information will improve our ability to predict where ASR systems will find success.

Compliance with ethical standards

Acknowledgments

The authors undertook this information on their own.

Disclosure of conflict of interest

The authors have no conflicts of interest.

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