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# The economics of aquifer storage recovery technology

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ABSTRACT

Aquifer storage recovery (ASR) technology is increasingly being utilized around the world for storing water underground through one or more wells during wet months and other times when water is available for storage. The water is then recovered from the same wells when needed to meet a growing variety of water supply objectives. The economics of ASR constitute the principal reason for its increasing utilization. ASR unit capital costs are typically less than half those of other water supply and water storage alternatives. Unit operating costs are usually only slightly greater than for conventional production well-fields. Marginal costs for ASR storage and recovery provide a powerful tool for making more efficient use of existing infrastructure, providing water supply sustainability and reliability at relatively low cost. The opportunity exists for a careful analysis of the net present value of ASR well-fields, addressing not only the associated capital and operating costs but also the value of the benefits achieved for each of the water supply objectives at each site.

Key words: aquifer storage recovery, capital costs, operating costs, marginal costs, net present value.

## *Costes de la técnica de almacenamiento con recuperación en acuíferos*

*RESUMEN*

*La tecnología de almacenamiento con recuperación en acuíferos se utiliza cada vez más en todo el mundo para el almacenamiento de agua en el subsuelo a través de uno o más pozos en los meses húmedos y en los momentos en los cuales hay agua excedentaria para ser almacenada. El agua se recupera después, a partir de los mismos pozos cuando es necesaria. Los costes de esta técnica son una de las razones por las cuales cada vez se utiliza más. Los costes unitarios de capital son menores de la mitad de los de cualquier otro método de suministro y almacenamiento de agua alternativos. Los costes unitarios de operación son por lo general sólo ligeramente mayores que los correspondientes a los campos de pozos de producción convencionales. Los costes marginales constituyen una poderosa herramienta para conseguir un uso más eficiente de la infraestructura existente, proporcionando sostenibilidad y fiabilidad en el abastecimiento de agua a un coste relativamente bajo. Hay una gran oportunidad para realizar estudios detallados sobre el valor actual neto de los campos de pozos ASR, abordando no sólo el capital asociado y los costes de operación, sino también el valor de los beneficios obtenidos por cada uno de los objetivos de abastecimiento de agua en cada lugar.*

*Palabras clave: almacenamiento con recuperación de acuíferos, costes de capital, costes de operación, costes marginales, valor actual de red.*

## *VERSIÓN ABREVIADA EN CASTELLANO*

### ***Introducción***

*La tecnología de recuperación de almacenamiento de acuíferos (ASR) se utiliza en muchos países para el almacenamiento de agua subterránea en momentos en que las lluvias son abundantes y la demanda de agua se reduce . El agua se almacena en uno o más pozos en un acuífero que presenta características adecuadas, y se recupera a partir de los mismos pozos cuando sea necesario. En los Estados Unidos de América (EE.UU.) se* *estima que más de 134 campos de pozos ASR están en funcionamiento, con más de 544 pozos ASR, situados en 22 estados del país.*

*ASR es una de las técnicas de la recarga artificial de acuíferos (MAR). Normalmente, la recarga en superficie suele ser más rentable que el ASR, aunque si lo que se persigue es almacenar el agua en el suelo para recuperarla posteriormente, el ASR puede ser más rentable.*

*Las capacidades de almacenamiento de los pozos abarcan desde 600 000 m$^3$/día (Las Vegas Valley Water District, Nevada) hasta sólo 1000 m3/día (Isla de Vancouver, Canadá, en el desarrollo).*

*Hasta la fecha, se han identificado 27 diferentes aplicaciones de la tecnología ASR.*

*Los acuíferos utilizados para el almacenamiento de ASR se encuentran a diferentes profundidades, y su litología abarca una gran variedad: arena, arenisc, grava, piedra caliza, dolomita, depósitos glaciales, basaltos, conglomerados y esquistos fracturados. La mayoría se encuentran en acuíferos confinados y semi - confinados, sin embargo, muchos campos de pozos ASR se encuentran en acuíferos profundos no confinados.*

*La razón principal por la cual la aplicación de la tecnología ASR se ha expandido rápidamente en los últimos treinta años es la rentabilidad. En casi todas las situaciones en que existe la necesidad de buscar fuentes de suministro de agua alternativas, la técnica de ASR puede proporcionar el agua a menos de la mitad del coste de otras fuentes. Los costes de operación no son bien conocidos; sin embargo, se cree que son similares o quizás un poco más alto que los costos de operación de los campos de extracción de pozos. El éxito demostrado del ASR en un número creciente de lugares también ha contribuido a la aceptación de esta tecnología por parte de los gestores del agua. Los grupos ecologistas, en general, prefieren buscar la solución definitiva a las necesidades de gestión del agua en el ahorro del mismo, sin embargo, si la elección real es entre ASR y un nuevo embalse de superficie, o una instalación de tratamiento de agua que necesita elevados consumos de, por lo general prefieren el almacenamiento de agua potable subterránea en los pozos, puesto que el ASR no tiene impactos ambientales adversos.*

### *Costes de capital*

*Los costes de capital incluyen los costos de construcción de las instalaciones como los de redacción de los proyectos de ingeniería vinculados, los gastos legales y los de otros tipos asociados a los proyectos de construcción. Los costes de capital se evalúan en los EE.UU. en función de la relación coste-capacidad de la instalación. Las instalaciones incluyen: uno o más pozos ASR, la instalación del equipamiento de los mismos con bombas, motores, tuberías y válvulas de boca de pozo, y por lo general una pequeña estructura de carcasa eléctrica, la desinfección de las instalaciones y, a veces también la tubería de cabeza de pozo; tuberías para el campo de pozos, desinfección del agua recuperada de los pozos de ASR y, a veces, la generación de energía de emergencia. Los costes no incluidos comprenden los de transporte del agua a larga distancia hacia y desde campos de pozos ASR, ya que casi todos ellos se construyen cerca de los lugares en donde se necesita el agua, ni los costes de tratamiento de agua, tales como los que requieran las normativas locales para el abastecimiento de agua para el uso que sea: agrícolas, industriales o urbano, excepto los costes necesarios para el pre - o post- tratamiento de agua específicos para su inyección en los pozos de ASR. La necesidad de tratamiento previo del agua no es común, pero puede incluir filtración, ajuste del pH, desoxigenación, decloración u otros ajustes químicos. Los tratamientos del agua recuperada comúnmente incluyen la adición de cloro, cloramina u otro desinfectante antes de enviar el agua al sistema de abastecimiento público y, ocasionalmente también un ajuste del pH.*

*Como ejemplo, cabe citar el caso de un campo de 11 pozos de ASR (South Florida Water Management District, 2006), en donde el coste es de 1.00 USD ($) por galón por día de capacidad de recuperación, con un rango de variación de 0.50 a 2.00 USD (0.26 USD por m$^3$/día de capacidad de recuperación). Los datos del tercer mayor campo de pozos ASR en los EE.UU., de San Antonio Water System, Texas, que fue construido entre 2004 y 2006, indican un coste de 1.13 USD por galón por día de capacidad de recuperación (0.30 USD por m$^3$/día de capacidad) (Texas Water Development Board, 2011). Más recientemente, en Carolina del Norte y Carolina del Sur, campos de pozos puestos en funcionamiento entre 2012 y 2013 indican un coste promedio de 1.02 USD por galón por día de capacidad de recuperación (0.27 USD por m$^3$/día). Para la planificación futura, una estimación razonable y conservadora para los costes de capital está en el rango de 1.00 a 1.25 USD m$^3$/día por galón por día de capacidad de recuperación (0.26 a $ 0.33 USD por m$^3$/día).*

### *Costes unitarios de operación*

*Estos costes incluyen: la energía de operación, productos químicos para el tratamiento del agua, mantenimiento y rehabilitación periódica de los pozos, equipamiento de bombeos y su mantenimiento y reparaciones; contralavado periódico de los pozos para evitar su colmatación, costes de mantenimiento y control de los pozos, sistemas de control y desinfección, gastos de mano de obra y gastos generales.*

*Una estimación de estos costes en EE.UU. son 25.000 USD al año por MGD de capacidad de recuperación (6.61USD/año/m3/dia de capacidad).*

*Los costes de operación a veces se comparan en términos de coste por unidad de volumen de agua recuperada, aunque en ocasiones, este enfoque puede ser engañoso, en función del uso que se vaya a dar al agua recuperada.*

***Costes marginales***

*El coste marginal es el coste de producir una unidad de volumen adicional de agua en un momento dado, cuando las operaciones ya están en marcha . El coste marginal de producir un metro cúbico de agua adicional durante los meses de invierno es muy pequeño. Por lo general incluye sólo la electricidad, productos químicos y los gastos de retirada de los residuos. En los EE.UU. el coste en esos momentos se encuentra en el rango de 0.15 a 0.35 USD por 1000 galones (0.04 a 0.09 USD por metro cúbico) . Esto puede ser de aproximadamente una cuarta parte del coste promedio anual de producción de agua, lo que incluiría los costos de mano de obra, costo de amortización de capital, y muchos otros factores. El negocio para que una empresa de suministro de agua sería ofrecer este agua durante los meses de invierno a mitad de precio, pues podría aumentar sus ingresos anuales con un coste adicional relativamente pequeño. El comprador del agua podría lograr un ahorro significativo y almacenar el agua en pozos ASR para su posterior recuperación durante los meses de verano. El potencial de ahorro de costes puede ser suficiente para pagar la inversión en instalaciones de ASR con bastante rapidez.*

*El valor marginal del agua durante las horas pico puede ser muy alto, ya que, si todas las instalaciones de suministro están operando a su máxima capacidad para satisfacer esa demanda pico, en teoría el siguiente metro cúbico que fuese necesario suministrar requeriría la construcción y operación de nuevas instalaciones, que pueden ser muy costosos. Por eso, la recuperación de agua almacenada en los acuíferos se covierte en una alternativa de suministro relativamente barata.*

***ASR Costos y beneficios del ciclo de vida***

*Para evaluar correctamente los costes del ciclo de vida y beneficios de la ASR, y su valor actual neto, es necesario, comprender bien en particular, el coste y el valor asociado con cada uno de los diversos usos de la ASR campo de pozos. Los sistemas de compra de derechos de agua (water banking) tienen costes todos los años, pero sus beneficios solamente son tangibles durante los años de sequía o en momentos de emergencia, que es cuando se recupera el agua . Si se utilizan también las mismas instalaciones para operaciones normales de almacenamiento mediante ASR estacional, no habría ningún aumento en el coste de capital y sólo un pequeño aumento en el coste de funcionamiento anual; sin embargo los beneficios anuales se acumularían y tendrían un valor actualizado. Si las mismas instalaciones también ofrecen beneficios adicionales, su valor debe ser incorporado en el análisis del valor actual neto.*

***Conclusiones***

*El almacenamiento de agua en los pozos ASR es rentable, sobre todo si se compara con otras alternativas de abastecimiento y almacenamiento de agua. La tecnología ASR se utiliza cada vez más a nivel mundial con muy diversos objetivos.*

## Introduction

Aquifer storage recovery (ASR) technology is utilized in many countries for storing water underground during times when rainfall is plentiful and water demand is reduced. The water is stored in one or more wells in a suitable aquifer, and is recovered from the same wells when needed. The concept is very simple, and was used hundreds of years ago by the Mayan civilization in Central America and also by the Bedouins of the Kara Kum Plain in what is now Turkmenistan. The application of modern technology has enabled more widespread and efficient use of this water management concept. In the United States of America (USA) it is estimated that more than 134 ASR well-fields are operational, with over 544 ASR wells, located in 22 states nationwide. Other countries with known operational ASR well-fields include England, Australia, The Netherlands, Namibia, South Africa, United Arab Emirates, India, Canada, Israel and probably other countries. ASR projects are being developed in several additional countries.

ASR is a subset of managed aquifer recharge (MAR). MAR includes all forms of recharge, including wells and also ponds, recharge basins, in-stream levees and other means of storing water underground.

Where the hydrogeology is suitable, surface recharge is usually more cost-effective than ASR for getting water into the ground. However, if the intention is to store and to subsequently recover the stored water from a well, ASR may be more cost-effective. In many areas the hydrogeology is unsuitable for surface recharge. Land costs may be too high; contamination of shallow aquifers may be a significant constraint, or water table levels may be high. In these areas ASR in deeper aquifers may be more appropriate. At a few locations, two or three aquifers are utilized for ASR storage. This is called "stacking," which uses a relatively small area for storing a lot of water in different aquifers through separate wells that may be relatively close to each other.

ASR well-field capacities include a broad range from 600,000 $m^3$/day (Las Vegas Valley Water District, Nevada) to 1,000 $m^3$/day (Vancouver Island, Canada, in development). Larger ASR well-field capacities are in planning stages, up to 1,300,000 $m^3$/day, addressing regional and national water storage needs. Individual well capacities range from about 800 $m^3$/day to 30,000 $m^3$/day.

To date, 27 different applications of ASR technology have been identified, meeting a wide variety of water storage needs for public, industrial and agricultural water supply; augmentation of low streamflows to meet environmental goals; water management objectives such as salt water intrusion prevention and subsidence control; storage of hot or cold water to meet process needs, and many others. Principal applications are for seasonal, emergency, and long-term storage, such as from wet, cold winter months to hot, dry summer months, or from wet years to drought years. The storage volumes available underground are usually much greater than the storage volumes required to meet project needs. One of the principal constraints upon more rapid expansion of ASR globally is the limited awareness of the range of potential applications of this technology. For most ASR well-fields there is a primary objective, such as long-term or emergency storage, and one or more secondary objectives such as seasonal storage, disinfection by-product reduction, or maintaining distribution system flows and/or pressures. Careful initial selection and ranking of ASR objectives affects estimates of target storage volumes, selection of storage aquifers, and location of ASR wells.

Aquifers utilized for ASR storage are at depths as shallow as about 30m and as deep as 900 m. Lithologies of these aquifers include sand, sandstone, gravel, limestone, dolomite, glacial deposits, basalts, conglomerates, and fractured schists. A majority are in confined and semi-confined aquifers, however many ASR well-fields are in deep, unconfined aquifers. Ambient water quality in these aquifers ranges from fresh to brackish to saline, with total dissolved solids (TDS) concentrations ranging from 30 mg/l to 37,000 mg/l. Most ASR well-fields are in aquifers with TDS concentrations below 7,000 mg/l. Almost all storage aquifers contain ambient groundwater with at least one constituent that is not desired in the water recovered from ASR storage. For brackish aquifers this could be elevated concentrations of total dissolved solids. For fresh aquifers this could include iron, manganese, hydrogen sulfide, fluoride or other constituents.

The principal reason why the application of ASR technology has expanded rapidly during the past thirty years is cost-effectiveness. In almost all situations where the need exists for supplemental water supplies, ASR wells can provide this water at less than half the capital cost of alternative water sources. Operating costs are not well known however they are believed to be similar to, and perhaps slightly higher than, typical production well-field operating costs. Other factors contributing to ASR implementation in recent years include the ability to phase construction, if necessary adding one well at a time. This is a lot easier than having to construct a surface reservoir or a major water treatment plant expansion. The demonstrated success of ASR at a growing number of locations has also contributed to the acceptance of this technology by water managers. Environmental constituencies generally prefer water conservation as the ultimate solution to meet water management needs, however if the real choice is between ASR and a new surface reservoir, or an energy-intensive water treatment facility, they usually prefer storing drinking water underground in ASR wells where it has no significant adverse environmental impacts.

Water utilized for ASR storage comes from multiple sources. Most common is storage of drinking water, whether from surface sources or from wells. Usually this water has been treated, at least for disinfection and often for removal of other constituents such as iron, manganese, hydrogen sulfide, turbidity, suspended solids, color, etc. One of the most rapidly growing applications of ASR is for storage of high quality reclaimed water which, for many water-short areas, is the most reliable supply of water for aquifer recharge. Seasonally available storm water is utilized for ASR storage, in conjunction with bank filtration treatment or with filtration through other means such as gravity sand filters, pressure filters and disinfection. Groundwater is also utilized for ASR storage at several locations, transferring water from an overlying or underlying aquifer that is fresh to a different aquifer that contains poor ambient water quality. Alternatively, groundwater may be transferred from a portion of an aquifer that is fresh to another, perhaps coastal, portion of the same aquifer that is brackish or saline.

## ASR Unit Capital Costs

Capital costs include both facilities construction costs and associated engineering, legal and other overhead costs usually associated with construction projects. Unit capital costs have been evaluated for many ASR well-fields in the USA, relating capital costs to facilities capacity. The facilities include construction of one or more ASR wells and monitor wells; equipping the wells with pumps, motors, wellhead piping and valves, and usually a small structure for housing electrical, control and disinfection facilities and sometimes also the wellhead piping; well-field piping, disinfection of the water recovered from ASR storage, instrumentation and control systems, and sometimes standby emergency power generation. These may also include well-field mitigation costs, which sometimes are needed at the beginning of well-field operations to modify other wells and wellhead facilities in the surrounding areas that may otherwise be adversely affected by higher and lower water levels resulting from ASR well-field operations.

ASR is a water storage option. Facilities considered for inclusion in ASR unit capital cost calculations do not include long distance transmission of water to and from ASR well-fields since almost all ASR wells are located close to where the water is needed during recovery. Transmission piping and pumping of water over long distances is very expensive and can easily double water costs, or more. Including transmission costs in ASR cost estimates can complicate comparison of ASR unit capital costs between ASR well-fields. It is usually more cost-effective to store water where it is needed during recovery, even if the hydrogeologic conditions may be less than ideal, rather than pay the substantial additional cost to store water at an alternate, distant location with more favorable hydrogeologic conditions.

Facilities also do not include water treatment costs, such as may be required for normal public, agricultural or industrial water supplies, unless additional pre- or post-treatment costs are required specifically for recharge into the ASR wells, or for treatment of water recovered from the ASR wells, other than disinfection. The need for supplemental pretreatment of water for ASR storage is not common but can include filtration, pH adjustment, deoxygenation, dechlorination or other chemical adjustments. Post-treatment of water recovered from ASR storage commonly includes addition of chlorine, chloramine or other disinfection prior to putting this water into a public water supply system. Occasionally post-treatment also requires pH adjustment.

With this understanding of the definition of the capital cost items utilized for comparison between ASR well-fields, investigations have been conducted during the past few years to determine typical unit capital costs. A Florida survey of 11 ASR well-fields (South Florida Water Management District, 2006) indicated an average cost of US$1.00 per gallon per day of recovery capacity, within a range of US$0.50 to US$2.00 (average: US$0.26 per m$^3$/day of recovery capacity). Data from the third largest ASR well-field in the USA, for San Antonio Water System, Texas, which was constructed between 2004 and 2006, indicates a unit capital cost of US$1.13 per gpd capacity (US$0.30 per m$^3$/day capacity) (Texas Water Development Board, 2011). That well-field has a recovery capacity of 60 MGD (227,000 m$^3$/day) although currently its operation is limited by transmission capacity to 40 MGD (151,000 m$^3$/day). More recent experience with ASR well-fields brought on line in North Carolina and South Carolina between 2012 and 2013 indicates an average of US1.02 per gpd recovery capacity, within a range of US$0.77 to US$1.55 (average US$0.27 perm$^3$/day). For future planning purposes, a reasonable and conservative estimate for ASR unit capital costs is in the range of US$1.00 to US$1.25 per gpd of recovery capacity (US$0.26 to US$0.33 per m$^3$/day).

Individual well productivity is the largest factor influencing the unit capital cost. Higher capacity wells have lower unit costs and lower capacity wells tend to have higher unit costs. Deeper wells, and single well projects, tend to have higher unit costs. Shallower wells, and multiple wells, tend to have lower unit costs.

Perhaps the greatest significance of these ASR unit capital costs is their comparison to comparable unit capital costs for other water supply, treatment and storage alternatives providing the same increase in yield and the same level of reliability. Typically these might include desalination costs, including brackish or saline water supply, treatment and concentrate disposal; surface reservoir construction costs, including treatment; and transmission pipelines to distant water sources, with associated treatment. In most cases these are at least two times the capital cost of ASR.

## Unit Operating Costs

These costs are less well known. In general they should be similar, and perhaps slightly greater, than for conventional well-field operating costs. These would include power; chemicals; residuals disposal from any treatment processes; well maintenance and periodic rehabilitation; pump and motor maintenance and repairs; periodic back flushing to reverse well clogging; operation and maintenance of controls, instrumentation systems and disinfection; and a reasonable allocation of associated labor and overhead expenses. Since these costs are often lumped together with water supply, treatment and transmission costs in water utility accounting systems, it can be difficult to separate the ASR well-field operation costs.

A reasonable best estimate based on limited available data is that unit operation costs are about US$25,000 per year per MGD of recovery capacity (US$6.61/yr/m$^3$/day of capacity). This is probably within a broad range of maybe 40% to 400% of these unit costs, depending upon power costs, chemical costs, monitoring costs, lab analytical costs, reporting requirements to regulatory agencies, etc. (Pyne, 2005). Operating costs are typically higher during the first year or two due to typical startup costs, then decline to a long-term approximate equilibrium that is variable depending upon volumes recharged and recovered each year.

Instead of cost/unit of recovery capacity, operating costs are sometimes compared or measured in terms of cost/unit volume of water recovered. This approach can be deceptive when applied to ASR well-fields. Some locations require relatively small volumes in storage in order to meet short-term peak demands, such as a holiday weekend at a beach resort, or emergency demands. Unit costs expressed in cost/unit volume may then be very high, even though the ASR alternative may be very cost-effective relative to other options to meet the same, short-term peak. Other locations may utilize ASR primarily for long-term water banking, storing large volumes of water in wet years and recovering it several years later during drought years while utilizing a small volume each year for seasonal storage and recovery. For these projects annual operating costs may vary substantially, depending upon the balance of recharge, storage and recovery operations in any given year.

## Marginal Cost Water Pricing

Ownership and operation of an ASR well-field opens up the opportunity for a powerful new economics tool for water management purposes, namely marginal cost water pricing. The marginal cost is the cost for producing an additional unit volume of water at any given time when operations are already underway. The marginal cost of producing an additional cubic meter of water during winter months when river flows are high and water demands are low is very small. It typically includes only electricity, chemicals and residuals disposal. In the USA a typical marginal cost for water at such times is in the range of US$0.15 to US$0.35 per 1,000 gallons (US$0.04 to US$0.09/cubic meter). This may be approximately one-fourth of the annual average cost for water production, which would include labor costs, capital cost amortization, and many other factors. The opportunity for a water supply company would be to offer to sell such water during winter months at half price. The water supply company would increase its annual revenues at very little additional cost. The purchaser of the water would achieve significant cost savings, and would store the water in ASR wells for recovery during summer months. The potential cost savings may be sufficient to pay for the investment in ASR facilities quite rapidly. Alternatively, the water supply company would construct and operate the ASR wells, storing inexpensive water during winter months and selling the water during summer months at peak rates, supplementing water supply capacity during peak summer demand periods.

The marginal value of water during peak periods can be quite high. If all facilities are operating at maximum capacity to meet peak demands, theoretically the next cubic meter of water would require construction and operation of new facilities, which can be very expensive. Recovery of water stored underground would then be relatively inexpensive as an alternative. Marginal cost pricing of water is a relatively new concept that, in conjunction with ASR, offers great potential to the water supply industry. Two good examples of this in the USA include a water supply agreement between Beaufort Jasper Water and Sewer Authority and Hilton Head Public Service District, in South Carolina; and also an agreement between New Jersey American Water Company and its wholesale customers, which include several cities in southern New Jersey, each of which has constructed ASR wells and well-fields, the cost of which has been long since paid by the annual savings in water purchase costs.

## ASR Life Cycle Costs and Benefits

The opportunity exists for evaluation of the life cycle costs and benefits of ASR, and their net present value. To do this properly will require not only an understanding of economics but also an understanding of ASR operations and, in particular, the cost and value associated with each of the various uses of the ASR well-field. Long term water banking operations will have operating costs each year, but tangible benefits only during drought years or emergencies when water is being recovered. If the same facilities are also utilized for normal seasonal storage operations, there would be no increase in capital cost and only a small increase in annual operating cost, however annual benefits would accrue and would have present value. If the same facilities also provide additional benefits, their value should be incorporated into the net present value analysis.

For example, a common water treatment issue for many communities in the north-central USA is high concentrations of nitrates in the river water during the spring thaw, often exceeding drinking water standards. This results from snowmelt and runoff from agricultural operations in the watershed. Denitrification of drinking water supplies may be required for 30 to 45 days each year and is very expensive. At such times water could instead be recovered from ASR storage, with no additional capital investment. The volume stored would be slightly increased in the same well-field facilities. The increase in operating cost for ASR facilities would be very small, however the savings in treatment costs for denitrification would be very large. The resultant net savings would then accrue to any determination of net present value for the investment in ASR well-field facilities.

## Conclusions

Water storage in ASR wells is cost-effective, particularly when compared to other water supply and water storage alternatives. ASR technology is increasingly utilized globally to meet a variety of objectives. Most ASR well-fields are designed and operated to achieve a primary objective and several secondary objectives. Any analysis of net present value will need to carefully evaluate water-company accounting records and allocate capital and operating costs in a manner appropriate for separate consideration of ASR operations. This is a worthy challenge, the results of which would be of great interest to many engineers, hydrogeologists, economists, water managers and others around the world with a common interest in ASR and managed aquifer recharge. In the meantime, capital investment decisions will continue to be made based upon estimation of unit capital costs, unit operating costs and marginal costs, as discussed in this paper. They will also reflect many other considerations that are more difficult to quantify in an economic analysis.

## References

South Florida Water Management District, 2006. Economic Analysis of Water Supply Alternatives. Chapter on ASR prepared by ASR Systems LLC and ASRus LLC

Pyne, RDG, 2005. Aquifer Storage Recovery: A Guide to Groundwater Recharge Through Wells (Second Edition). ASR Press (www.asrforum.com). 608 pp.

Texas Water Development Board, 2011. An Assessment of Aquifer Storage and Recovery in Texas. Report No. 0904830940, prepared by Malcolm-Pirnie Inc., ASR Systems LLC, and Jackson, Sjoberg, McCarthy and Wilson, LLP (Chapter 3.1).

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