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Managed Aquifer Recharge (MAR) and Design and Construction of Hydraulic Barriers against Seawater Intrusion: the California Case

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ABSTRACT

Managed aquifer recharge (MAR) has been practiced in California for over a century, using a range of artificial recharge methods, including surface spreading basins, injection wells and aquifer storage and recovery (ASR) wells. Intense municipal and industrial development of coastal regions, particularly in southern California, during and following World War II, led to overdraft of coastal groundwater basins, where groundwater levels were drawn down below sea level, resulting in seawater intrusion into freshwater aquifers. Surface water is imported from the Colorado River and later northern California to satisfy water demands of a growing population. This imported water is also a water supply used for injection into to injection wells constructed in the 1960s along the coastline to repel seawater from intruding into coastal aquifers. Since the 1960s, these seawater intrusion barriers have evolved in terms of water supplied for injection and in their construction and operation details. Imported water supplies are being completely replaced with highly treated wastewater and the injection wells are being constructed so that they are more automated to reduce operational costs. The West Coast Basin of southern California is provided as a case study of the evolution of hydraulic barriers used for protection against seawater intrusion into coastal aquifers.

Key words: coastal aquifers, injection wells, managed aquifer recharge seawater intrusion.

Gestión de la Recarga a los Acuíferos (MAR) y diseño y construcción de barreras hidráulicas contra la intrusión marina: el caso de California

RESUMEN

La Gestión de la Recarga a los Acuíferos (MAR) se lleva practicando en California más de un siglo, utilizando varios métodos de recarga artificial, que incluyen balsas de infiltración superficial, pozos de inyección y pozos de almacenamiento y recuperación de acuíferos (ASR). El intenso desarrollo municipal e industrial de las zonas costeras, sobre todo en el sur de California, durante y despúes de la Segunda Guerra Mundial, condujo a la sobreexplotación de los acuíferos costeros, en los cuales el nivel freático descendió por debajo del nivel del mar, dando lugar a la intrusión marina en los mismos. Se importa agua superficial desde el Río Colorado y desde el norte de California para poder satisfacer las demandas de agua de esta creciente población. Este agua importada se utiliza también como fuente de agua para la inyección en los pozos construidos en la década de 1960 a lo largo de la costa para frenar la intrusión marina en los acuíferos costeros. Desde la década de 1960, estas barreras contra la intrusión han evolucionado mucho, tanto en términos cuantitativos, de agua inyectada, como en la tecnología de su construcción y en la forma de operación de las mismas. El agua importada se está sustituyendo completamente por agua residual altamente tratada, y los pozos de inyección se construyen cada vez de una forma más automatizada, para reducir los costes operativos. En este artículo, se presenta el caso de la cuenca costera del suroeste de California como un caso de estudio de la evolución del diseño, construcción y operación de las barreras hidráulicas que se utilizan para la protección contra la intrusión marina en los acuíferos costeros.

Palabras clave: acuíferos costeros, intrusión marina, MAR, pozos de inyección, recarga artificial.

VERSIÓN RESUMIDA EN CASTELLANO

Introducción

La gestión de la Recarga a los Acuíferos (MAR) se lleva practicando en California más de un siglo, utilizando diversos métodos que van desde balsas superficiales, pozos de inyección o sistemas ASR (Almacenamiento y Recuperación de Acuíferos). El intenso desarrollo municipal e industrial de las zonas costeras, particularmente en el Sur de California, durante y después de la Segunda Guerra Mundial, condujo a una sobreexplotación de los acuíferos costeros, en los cuales el nivel freático descendió por debajo del nivel del mar, originando intrusión marina en los mismos. El agua superficial se importa desde el río Colorado, y también desde el Norte de California, para satisfacer la demanda de una población creciente. Esta agua importada se utiliza también como fuente para su inyección en pozos construidos en los años 60 del pasado siglo a lo largo de la línea de costa, para repeler el agua del mar y evitar su intrusión en los acuíferos costeros.

La satisfacción de la demanda de agua continúa siendo un reto para las empresas suministradoras en California. Este artículo resume algunas de las líneas seguidas para continuar y mejorar las prácticas de la recarga artificial de acuíferos, ejemplos de métodos de recarga puestos en marcha en California, y hace hincapié en la evolución de las barreas hidráulicas de control de la intrusión en los acuíferos costeros del Sur de California. Desde la década de 1960, el uso de estas barreras ha evolucionado, tanto en lo referente a los volúmenes inyectados como a las técnicas de construcción y operación. Los recursos de agua importada utilizados en las barreras están siendo completamente reemplazados por agua residual altamente tratada, y los nuevos pozos de inyección se están construyendo de manera que se automaticen al máximo para reducir costes de operación. La cuenca de la West Coast, en el Sur de California, se muestra como el caso típico de utilización de barreras hidráulicas como protección frente a la intrusión marina en los acuíferos costeros.

Técnicas de recarga artificial utilizadas en California

La recarga artificial se ha utilizado en California desde hace más de un siglo. Técnicas de tipo superficial, como los canales dentro de cauces, o balsas fuera de cauces, son típicas, como se ve en la figura 2. También la recarga "por sustitución" se emplea mucho, en cuencas que han sido puestas bajo control judicial, por tener un balance deficitario, y cuyas extracciones están bajo severo control. Se sustituye agua subterránea que se hubiese tenido que bombear por agua procedente de una fuente superficial, lo que estaría generando una recarga "artificial" por evitar una extracción, de ahí su denominación. Por último, la recarga artificial a través de pozos se utiliza cada vez más, en parte por la carestía del terreno necesario para las instalaciones de tipo superficial, pero también porque ha aumentado la capacidad para el tratamiento de recursos disponibles fuera de épocas de gran demanda, así como para utilizar agua residual altamente tratada.

El proyecto de Las Posas

Es el mayor proyecto de ASR de California. Lo gestiona el municipio de Callegas, a unos 80 km al norte de Los Ángeles. Se utiliza para complementar el suministro urbano para más de medio millón de personas, complementando un antiguo embalse, de 12,3 hm^3 de capacidad, y vulnerable a sequías y otras incertidumbres, con un sistema de ASR, compuesto por un campo de 19 pozos de profundidades entre 240 y 370 metros, y capacidad de infiltración entre 0,08 y 0,11 m^3/s. Este campo de pozos aumenta la fiabilidad del sistema de suministro de agua a Calleguas.

La barrera contra la intrusión marina de la costa oeste de California

La costa oeste se ubica al suroeste del centro de Los Ángeles, California (Figura 7). Los acuíferos situados en ella sufren intrusión marina desde los primeros años del siglo XX, por lo cual se han construido dos barreras de inyección para intentar frenar este problema: el Proyecto de la Cuenca de la Costa Oeste, en el oeste y el Proyecto Dominguez Gap en el sur. En la década de 1950, el ritmo de avance de la cuña salina hacia el interior era de 335 m/año. El agua de mar se extendió 2,4 km tierra adentro en el oeste y 3,2 km en el sur, de modo que unos 493 hm^3 de agua de mar habían invadido la cuenca de la década de 1960 .

Se construyó un conjunto de pozos de inyección experimentales cerca de la costa, en la década de 1950, cuyo objetivo fue elevar los niveles de agua subterránea hasta alcanzar el equilibrio con el agua de mar.

Las barreras de inyección se realizaron principalmente en la década de 1960 para evitar una mayor intrusión de agua de mar por el oeste y el sur. Hay más de 153 pozos de inyección separados aproximadamente 150 m unos de otros, abarcando 14,5 km a lo largo de la costa (véase la Figura 7) . La profundidad de los pozos de inyección se extiende hasta unos 300 m. Hasta 1996, se utilizó agua importada para la inyección en los pozos de barrera de inyección, momento en el que el West Basin Municipal Water District empezó a inyectar

agua reciclada. Actualmente, se inyecta una mezcla al 50% de agua reciclada y agua superficial importada, con planes de llegar al 100% de agua reciclada en un futuro próximo.

En 1997, el Departamento de Obras Públicas del Condado de Los Ángeles, en colaboración con el Bureau y el Distrito de Reabastecimiento de Agua del Sur de California, inició un estudio para examinar las causas de la disminución de la capacidad de los pozos de inyección y las posibles soluciones para mantener el rendimiento de los mismos. Se estudiaron tres mecanismos de colmatación: física (arrastre de aire y/o sólidos en suspensión); geoquímica (precipitación de minerales), y biológica (crecimientos bacterianos). Tras el estudio, se concluyó que los fenómenos presentes reponsables de la pérdida de rendimiento de los sondeos de inyección eran una combinación de mecanismos físicos y biológicos predominantemente. Para la corrección de este problema, es necesario hacer un nuevo desarrollo de los pozos cada tres años, con un coste de más de $ 4.000.000 por año.

La puesta en marcha de la barrera del proyecto Dominguez Gap en 2005 permitió mejorar el diseño y la operación de los pozos de inyección. El objetivo de este proyecto era triple: 1) establecer un sistema de inyección y contra-lavado completamente automático, 2) un pozo dedicado a contralavado, y 3) un sistema de reutilización del agua utilizada en el contralavado y de eliminación de sólidos presentes en el mismo. Se espera que este nuevo sistema diseñado la barrera del Proyecto Dominguez Gap sea un prototipo para el diseño de la futuras barreras de inyección contra la intrusión de agua de mar. En este proyecto, la fuente de agua está también en transición hacia el 100 por cien reciclado de aguas residuales.

Conclusiones

La recarga artificial de acuíferos (MAR) se lleva practicando en California más de un siglo. En sus inicios, los objetivos de la aplicación de esta técnica se dirigían a la captura de agua de lluvia para su posterior infiltración, con el fin de aumentar la recarga de aguas subterráneas. Con el tiempo, los objetivos se han dirigido a responder a multitud de problemas, como las sequías, el envejecimiento de las infraestructuras de abastecimiento, el crecimiento de la población, el cambio en la economía, el cambio climático, la modificación de la reglamentación vigente en cada momento, la política de personal laboral y la sostenibilidad. Los proyectos actuales de recarga incluyen instalaciones superficiales, tanto dentro como fuera de cauces, e instalaciones subterráneas, como los pozos de inyección, tanto en la zona saturada como en la no saturada, y pozos ASR. Los pozos de inyección se utilizan cada vez más como consecuencia de la carestía y escasa disponibilidad de suelo.

Para luchar contra la intrusión marina, se han puesto en marcha barreras de inyección desde 1960 en la costa oeste. Estas barreras han tenido éxito en el control de la intrusión de agua de mar tratada usando agua superficial importada. El uso de agua importada está siendo reemplazado paulatinamente con agua reciclada, con el objetivo de utilizar únicamente ésta en un futuro próximo. La capacidad específica de inyección de los pozos de la barrera ha disminuido con el tiempo, debido a su colmatación tanto física como biológica. Para la lucha contra este problema, cada 3 años se hace un nuevo desarrollo de los pozos, con un coste de más de $ 4.000.000 por año.

Introduction

Managed aquifer recharge (MAR) has been practiced in California for over a century, using a range of artificial recharge methods, including surface spreading basins, injection wells, and aquifer storage and recovery (ASR) methods. Intense municipal and industrial development of coastal regions, particularly in southern California, during and following World War II, led to overdraft of coastal groundwater basins, where groundwater levels were drawn down below sea level, resulting in seawater intrusion into freshwater aquifers. Surface water is imported from the Colorado River and later northern California to satisfy water demands of a growing population. This imported water is also a water supply used for injection into to injection wells constructed in the 1960s along the coastline to repel seawater from intruding into coastal aquifers.

Meeting water supply requirements continues to be a challenge for water suppliers in California. This paper summarizes some of the drivers for continued creativity to MAR practices, examples of types of recharge practiced in California, an example of a large ASR project in southern California, and a focus on the evolution of hydraulic barriers used to control seawater intrusion into coastal aquifers in southern California. Since the 1960s, use of seawater intrusion barriers have evolved in terms of water supplied for injection and in their construction and operation details. Imported water supplies are being completely replaced with highly treated wastewater and the injection wells are being constructed so that they are more automated to reduce operational costs. The West Coast Basin of southern California is provided as a case study of the evolution of hydraulic barriers used for protection against seawater intrusion into coastal aquifers.

Drivers for creative water supply management

Water supply management in the 21st century goes beyond just matching water supply to water demands as was the case in the past. Figure 1 shows the range of drivers for creative water supply management not only in California, but for many areas of the southwestern United States, as well as many parts of the world in general. These drivers include typical drivers such as droughts, ageing infrastructure, growing populations, and economics. However, new drivers such as climate change, regulations, politics, workforce staffing and sustainability are becoming more controlling factors that go beyond those more traditional drivers. Climate change is expected to result in more frequent and severe dry periods in the southwestern US. The United States Bureau of Reclamation (USBR, 2012) just released a report on the water supply and demand in the Colorado River Basin which identifies significant imbalances in supplies and demands, along with potential mitigation strategies to address those imbalances. However, one of the most recent causes of reduction in water supplies in California was not due to hydrological conditions but to regulations regarding maintaining flows in the Sacramento and San Joaquin Bay Delta, for which the term "regulatory drought" was coined. Such regulatory droughts are expected to drive greater uncertainty in water supplies as competing water needs between human consumption and environmental sustainability are resolved. These regulatory droughts will impact the timing and quantity of water available for use; therefore, conjunctive use of surface water and groundwater supplies, and thus MAR operations, will need to adapt to these changing conditions.

Artificial recharge techniques used in california

Artificial recharge techniques have been used in California for over a century. These techniques include surface recharge techniques such as use of stream channels and off-stream basins as shown in Figure 2.

The source of water can include local surface water, treated wastewater, and imported water (water from distant watersheds). Another popular recharge technique in California is "in lieu recharge." In lieu recharge is often used where a groundwater basin has been adjudicated (under the control of a court of law), where the water budget of the basin has been carefully determined and continuously monitored and where pumping is restricted to specified levels to maintain a balance in the water budget of the basin. So, in lieu recharge occurs where a surface water supply is delivered in lieu of pumping, such that the groundwater that would have been pumped would be left in the basin, and therefore indirectly replenished, for later withdrawal (e.g., during a drought, so that twice as much groundwater could be pumped at that later time period because the allowed quantity of groundwater was not pumped when it was allowed to be pumped earlier). Surface recharge techniques are typically simple to operate and relatively low cost operations. However, these methods require large tracts of land in areas that are located in zones that are conducive to the recharge of basin aquifers, which are nearly impossible to find in highly urbanized areas today.

Figure 3 shows well recharge techniques that are growing in popularity in California due to, 1) lack of availability of land for surface recharge methods, 2)

Figure 1. Range of drivers for creative water supply management not only in California.
Figura 1. *Esquema de condicionantes a la hora de buscar fuentes de suministro de agua, no solamente en California.*

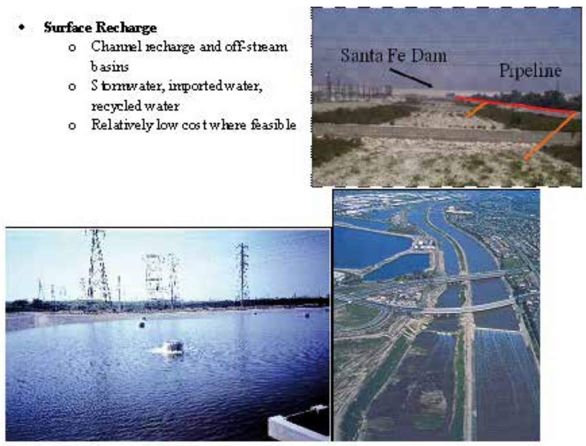

Figure 2. Artificial recharge using surface spreading techniques in California.
Figura 2. *Recarga artificial mediante la utilización de técncias de tipo superficial en California.*

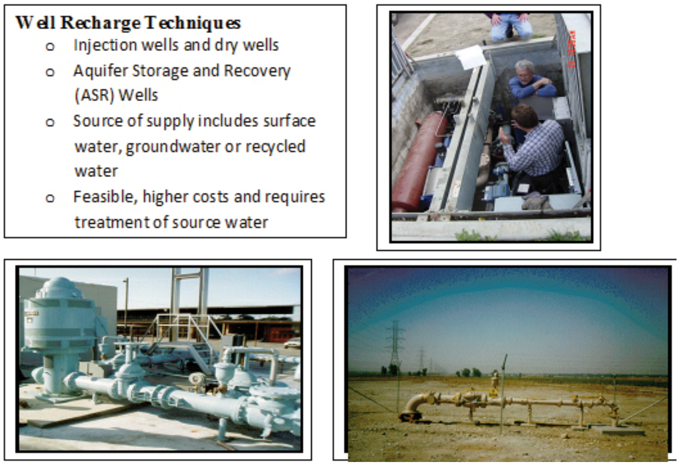

Figure 3. Well-recharge techniques in California.
Figura 3. *Técnicas de recarga a través de pozos en California.*

surplus treatment capacity during off-peak demands of surface water supplies and, 3) increased use of highly treated wastewater for recharge. Highly treated wastewater (also commonly referred to as recycled or repurified water) is replacing the use of imported water supplies for groundwater recharge for two principal reasons: 1) demand for imported surface water (including development of more surface storage reservoirs) has increased so that there is less surplus supply available for groundwater recharge and, 2) indirect use of recycled water (through groundwater recharge) is more acceptable to the public than more direct uses (e.g., such as potable water supply augmentation through discharge of recycled water to surface water reservoirs). Figure 4 shows the extent of ASR development in California, with most of this development occurring in the last two decades, and the benefits associated with this development.

Las posas basin asr project example

the largest ASR project in California is implemented by the Calleguas Municipal Water District (Calleguas), located approximately 80 kilometers northwest of Los Angeles, California (Figure 5). Calleguas serves supplemental imported water to eastern Ventura County, including 22 agencies and 550,000 people. Calleguas has one source of water supply that is vulnerable to interruptions due to drought, earthquakes, regulations and other uncertainties. The only system storage was a 12.3 million cubic meters (m^3) surface water reservoir. Any disruption of imported water supplies would result in major curtailments to water deliveries and water uses.

Calleguas initiated their ASR project with the conversion of an agricultural supply well in 1991. This ASR well was used to demonstrate that ASR is feasible in the Las Posas Basin and to provide a basis for future expansion of the concept. Today, the ASR well-field has been expanded to 19 wells. These wells range in depth from 240 to 370 meters deep. The capacity of the wells ranges from .08 to .11 m^3 per second (m^3/s) for a total well-field capacity of approximately 2 m^3/s. Figure 6 shows typically ASR well facilities and the setting of the well-field.

The Las Posas ASR well-field greatly increases the reliability of the Calleguas' water supply. Approximately one third of the Calleguas water demands can be met from the well-field in an emergency for a sustained period of time.

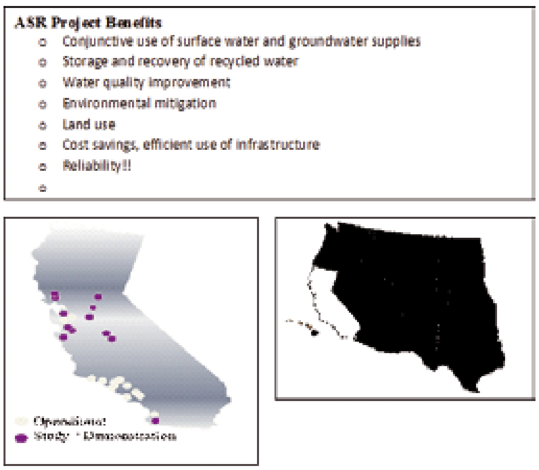

Figure 4. Extent of ASR development in California.
Figura 4. *Desarrollo de la técnica ASR en California.*

Figure 5. ASR project in California is implemented by the Calleguas Municipal Water District.
Figure 5. *Proyecto ASR en California puesto en marcha por el "Calleguas Municipal Water District".*

Figure 6. ASR well facilities and the setting of the well.
Figura 6. *Instalaciones de ASR y trabajo en elcampo.*

West coast basin seawater intrusion barrier case study

The West Coast Basin is a 473 square kilometer (km^2) area, located southwest of downtown Los Angeles, California as shown in Figure 7. The aquifers of the basin are exposed to seawater intrusion from the Pacific Ocean to the west and south. Two injection well barriers have been constructed to control seawater intrusion: the West Coast Basin Barrier Project in the west and the Dominguez Gap Barrier Project in the south. High chloride levels were detected inland of the coast as early as 1912. By 1950, as much as 61.7 million m^3 of brackish water was intruding per year at an advancing rate of 335 m per year. Seawater extended inland by 2.4 km to the west and 3.2 km to the south, such that about 493.4 million m^3 of seawater had intruded into the basin by the 1960s.

A set of experimental injection wells were constructed near the coast in the 1950s. The concept behind the injection wells was to raise groundwater levels near the cost to be in equilibrium with the seawater. The Ghyben-Herzberg theory was used to determine the protective elevations as shown in Figure 8.

The West Coast Basin consists of several aquifers separated by aquitards as shown in Figures 9 and 10. The principal aquifer used for municipal and industrial supply is the Silverado Aquifer, which is the lowermost aquifer. There are two lesser aquifers above this aquifer and partially separated by confining units that are used for supply as well; therefore, injection wells are required for each aquifer to ensure protection against seawater intrusion.

The injection barriers were largely completed in the 1960s to prevent further seawater intrusion from the west and south. There are over 153 injection wells located approximately 152 m apart, extending over 14.5 km along the coast (see Figure 7). The depth of injec-

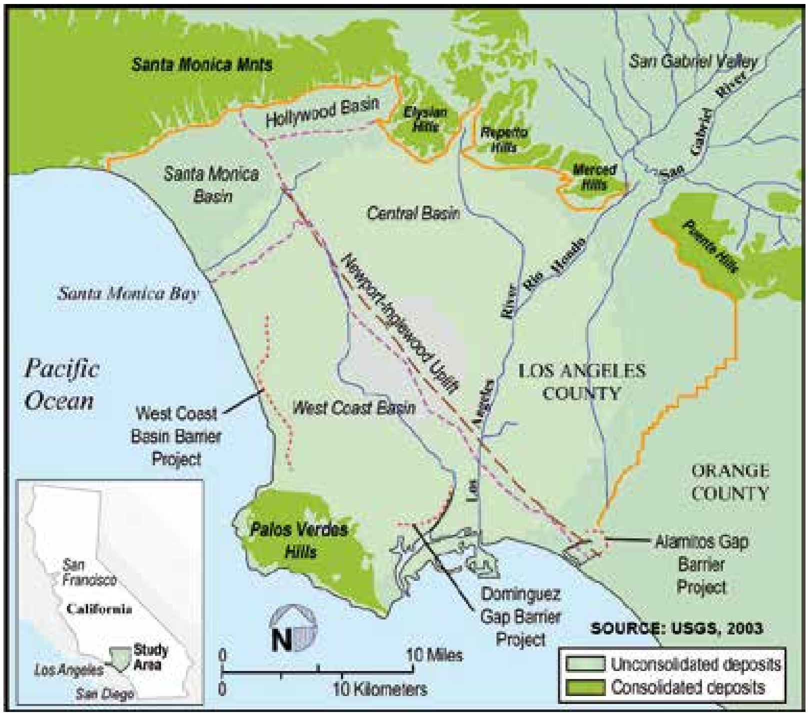

Figure 7. The West Coast Basin.
Figura 7. *La cuenca de la costa oeste de California.*

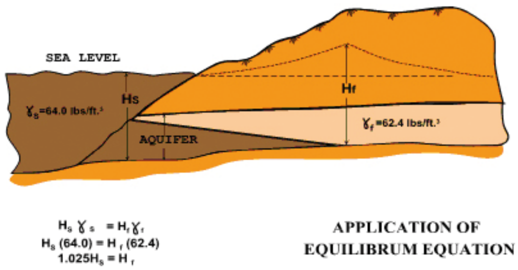

Figure 8. The Ghyben-Herzberg theory.
Figura 8. *Teoría de Ghyben-Herzberg.*

Figure 9. The west coast basic hydrogeological scheme.
Figura 9. *Esquema hidrogeológico de la cuenca de la costa oeste.*

tion wells ranges up to approximately 300 m. Figure 11 shows typical injection-well construction, which includes single and multiple completions (targeting one or more aquifer with a single injection well). Injection rates are controlled by manually adjusting valves at the wellhead in response to weekly water level measurements in nearby monitoring wells, which are monitored weekly. Until 1996, imported water was used for injection into the injection barrier wells, at which time recycled water was introduced by the West Basin Municipal Water District for injection. Currently, a 50/50 blend of recycled water and imported surface water is injected to the barrier, with plans to go to 100 percent recycled water in the near future.

In 1997, the Los Angeles County Department of Public Works, in collaboration with the USBR and the Water Replenishment District of Southern California, initiated a study to examine the causes of decline in well-injection capacity and potential solutions to maintain well performance. Figure 12 shows a typical pattern of well performance decline as measured by specific capacity of injection. It is interesting to note that prior to 1984, treated imported water used for injection contained a free chlorine disinfection residual, which was changed to chloramines after 1984. So, it appears that this change in disinfection process somewhat accelerated the decline in injection-well performance as measured by the specific capacity of injection shown in Figure 12.

Three clogging mechanisms were studied to examine which mechanisms were likely to contribute to deterioration of well-injection capacity: physical, such as air entrainment and/or suspended solids; geochemical, such as precipitation of minerals; and biological from bacterial growths. Based on extensive sampling of water and solid materials, laboratory testing, including x-ray diffraction to identify the mineral contents of the solids, and water chemistry and biological characterization, it was concluded that a combination of physical and biological mechanisms

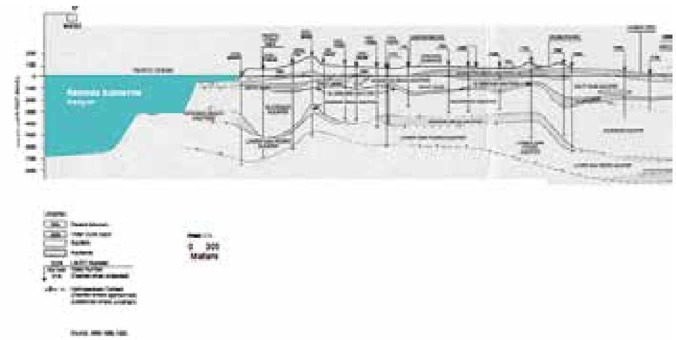

Figure 10. The west coast basic hydrogeological scheme.
Figura 10. *Esquema hidrogeológico de la cuenca de la costa oeste.*

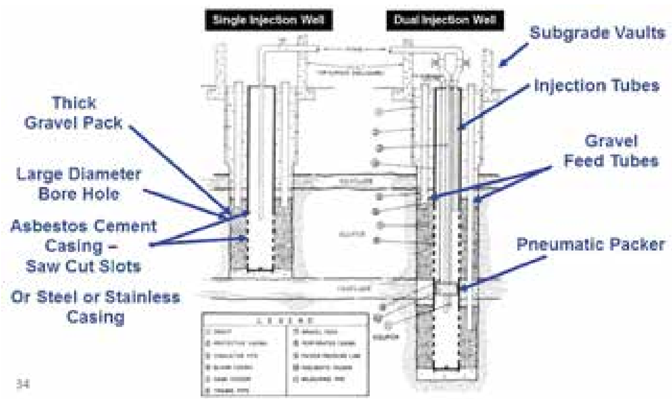

Figure 11. Typical injection-well construction.
Figura 11. *Construcción tipo de los pozos de inyección.*

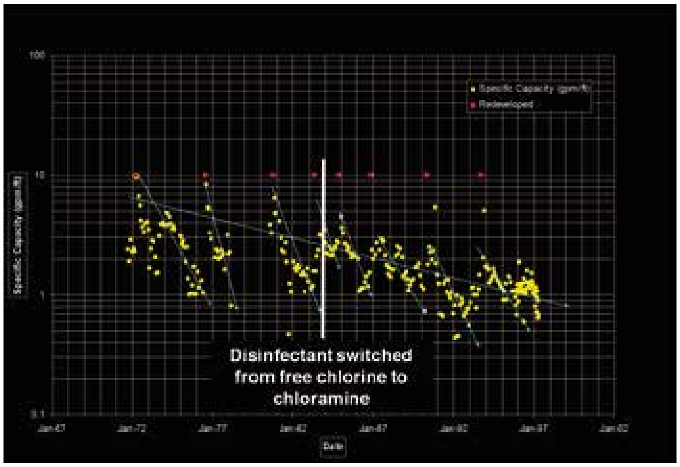

Figure 12. Specific capacity depending on the disinfectant used.
Figura 12. *Capacidad específica en función del desinfectante utilizado.*

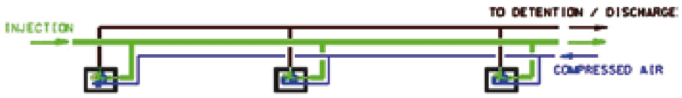

Figure 13. Typical injection wells and associated water supply, air, and back-flush collection lines.
Figura 13. *Pozo de inyección tipo con sus instalaciones asociadas.*

were the predominant clogging mechanisms of the injection wells. Redevelopment of injection wells is required approximately once every three years at a cost of over $4,000,000 per year. Alternative methods for redevelopment were examined for reducing costs, but these methods could not be easily implemented because of the design of existing wells.

Expansion of the Dominguez Gap Barrier Project in 2005 created an opportunity to improve the design and operation of the seawater barrier injection wells. The expansion of the barrier included 2,135 m of injection barrier water supply line, 2,135 m of well redevelopment waste disposal line, 17 injection well sites, an online redevelopment system, 15 new monitoring wells, and connection to a barrier telemetry system (BTS). The design intent of the barrier extension was to: 1) provide for a fully automatic injection and back-flushing operation, 2) a dedicated back-flush well operation using air juttering, and 3) a dedicated back-flush collection and reuse system for reuse of back-flush water and disposal of collected solids. Figure 13 shows a typical injection well and associated, water supply, air, and back-flush collection lines. Injection wells were completed so that injection was focused into single targeted zones, but with multiple wells at a single location. Design features of injection wells are shown in Figure 14. All wells are completed below grade in vaults, as shown in Figure 15. These vaults are located in pedestrian sidewalks where the injection alignment runs through city streets. Figure 16 shows a screen shot of a computer screen of the BTS. The wells can be operated and monitored remotely, including taking the well off-line and redeveloping it as necessary, based on a decline in injection specific capacity.

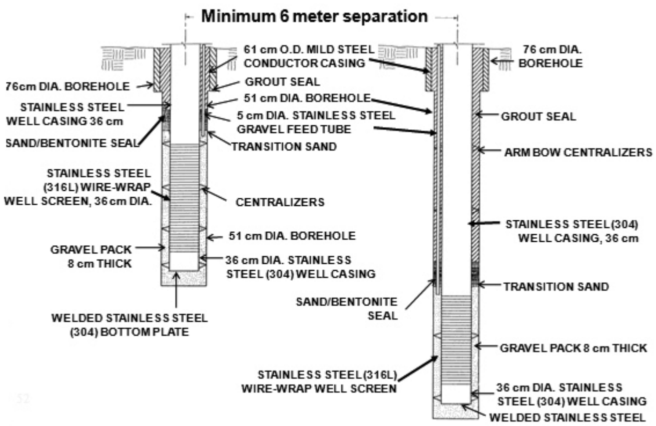

Figure 14. Design features of injection wells.
Figura 14. *Esquema de diseño de los pozos de inyección.*

Figure 15. The process of completing the wells.
Figura 15. *Proceso de terminado de los pozos.*

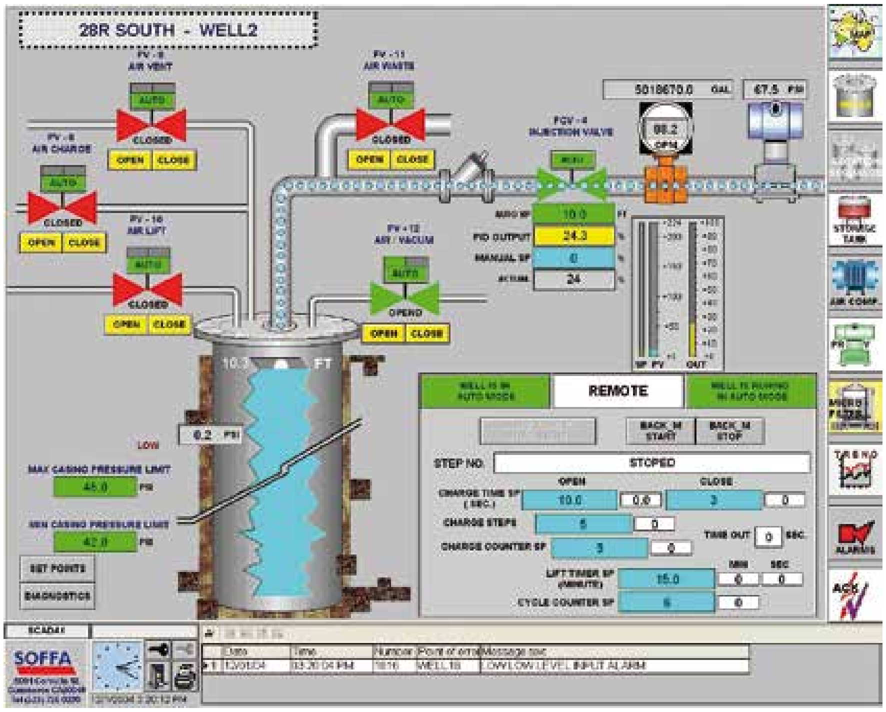

Figure 16. *Screen shot of a computer screen of the BTS.*
Figura 16*. Captura de pantalla del sistema automático de control de los pozos.*

The injection well system designed for the expansion of the Dominguez Gap Barrier Project is expected to be a prototype for design of future seawater intrusion injection well barriers. Similar to the West Coast Basin Barrier Project, the source of water is transitioning to 100 percent recycled wastewater in the near future.

Conclusions

MAR has been practiced in California for over a century. Initial MAR practices involved capturing local storm water in surface recharge facilities to augment groundwater recharge. MAR practices have evolved to more creative solutions to respond to a multitude of diverse drivers including droughts, ageing infrastructure, growing populations, economics, climate change, regulations, politics, workforce staffing and sustainability. Recharge techniques include surface recharge facilities, both in-stream and off-stream basins, and injection wells, including vadose zone injection wells, saturated zone injection wells, and ASR wells. Injection wells are becoming more common as land located in favorable areas for surface recharge becomes less available and as more recycled water is used for recharge. Calleguas has implemented the Las Posas Basin ASR project as a means of increasing its water reliability under increasing uncertainties of its imported water supply.

Injection well barriers to create a hydraulic barrier to seawater intrusion have been operated in the West Coast Basin since the 1960s. These barriers have been successful in controlling seawater intrusion using treated imported surface water. Use of imported water is being replaced with recycled water so that 100 percent of the source of supply will soon be recycled water. Injection specific capacity of barrier injection wells has declined over time, largely due to physical and biological clogging. Redevelopment of these wells occurs on a regular basis (approximately every three years), which is labor intensive and costs about $4 000 000 per year. An innovative design was used for the expansion of the Dominguez Gap Barrier Project, which incorporates an automated back-flushing scheme which is expected to result in more sustained injection rates for less cost. This barrier expansion will be monitored for future comparison to the other barrier operations and maintenance, including costs.

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