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Large-Scale Aquifer Replenishment and Seawater Intrusion Control Using Recycled Water in Southern California

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ABSTRACT

In 2008, eighteen years after determining that its Talbert Seawater Barrier required expansion, the Orange County Water District started up the world's largest indirect potable reuse facility, the Groundwater Replenishment System (GWR System). The GWR System provides a reliable potable-quality water supply to the Talbert Barrier, which consists of 109 multi-depth injection wells. The Talbert Barrier began operation in 1976 with the completion of Water Factory 21, the first project in California permitted to inject recycled water into a potable-supply aquifer. By 1990, as groundwater pumping increased, it was evident that the barrier's original injection wells were incapable of maintaining protective groundwater elevations to prevent seawater intrusion. Ten years of technical planning and public outreach culminated in the decision to demolish the undersized Water Factory 21 and build a state-of-the-art advanced recycled water treatment system and expanded barrier. Barrier expansion entailed construction of over 20 new injection wells in key areas where seawater intrusion was observed. Flow modeling indicated that average barrier injection needed to be doubled to 80 m^3/min (30 mgal/day). Based on seasonal groundwater pumping patterns, model simulations indicated that the barrier should inject up to 107 m^3/min (40 mgal/day) in the summer/fall months and one-half that rate in winter/spring months to maintain a protective hydraulic barrier. With a capacity of 187 m^3/min (70 mgd), the GWR System provides all of the high-quality water that the barrier requires, with the remainder conveyed to OCWD's infiltration basins in the city of Anaheim. Five years after start-up, the expanded seawater barrier has met all expectations in terms of capacity and groundwater elevation maintenance using a reliable locally-produced water supply.

Key words: Artificial recharge, California, hydraulic barrier, seawater intrusion.

Recarga artificial de acuíferos y control de intrusión de agua de mar a gran escala utilizando agua reciclada en el sur de California

RESUMEN

En 2008, dieciocho años después de llegar a la conclusión de que la Barrera Talbert contra la intrusión necesitaba una ampliación, el Orange County Water District puso en marcha la instalación más grande del mundo para la reutilización indirecta de agua potable, el GWR System. Este sistema proporciona un suministro fiable de agua de calidad casi potable a la barrera Talbert, que consta de 109 pozos de inyección de diferentes profundidades. La barrera Talbert comenzó a funcionar en 1976 con la realización de "Water Factory 21", el primer proyecto en California que posibilitó la inyección de agua reciclada en un acuífero que era utilizado para suministro de agua potable.. En 1990, como el bombeo de agua subterránea aumentó, se hizo evidente que los pozos de inyección originales de la barrera eran incapaces de mantener la protección contra la intrusión del agua del mar. Diez años de planificación técnica y la difusión pública culminaron en la decisión de demoler la fábrica "Water Factory 21", cuyo tamaño estaba infradimensionado, y construir un sistema técnicamente avanzado de tratamiento de agua reciclada, así como de ampliar la barrera hidráulica contra la intrusión. Esta ampliación implicaba la construcción de más de 20 nuevos pozos de inyección en áreas clave en las que se observó un mayor avance de la intrusión marina. Un modelo de flujo indicó que la capacidad de inyección de la barrera debía duplicarse hasta alcanzar un caudal de inyección de 80 m^3/min. Basado en los patrones de *bombeos estacionales de las aguas subterráneas, el modelos indica que la barrera debería inyectar hasta 107 m^3/min en los meses de verano / otoño y la mitad en invierno / primavera de meses para mantener su capacidad de protección contra la intrusión marina. Con una capacidad de 187 m^3/min, el Sistema GWR proporciona toda el agua de alta calidad que requiere la barrera, y el resto es enviado hacia unas balsas de recarga situadas en la ciudad de Anaheim. Cinco años después de su puesta en marcha, la nueva barrera hidráulica ha cumplido todas las expectativas en términos de capacidad y de mantenimiento de los niveles de las aguas subterráneas utilizando una fuente de agua fiable y producida en la misma zona geográfica.*

Palabras clave: Barrera hidráulica, California, intrusión marina, recarga artificial.

VERSIÓN RESUMIDA EN CASTELLANO

Introducción

La costa sur de California depende en gran medida de agua que se transporta (o "importa") desde varios cientos de millas a través d eacuductos desde el norte del estado y desde el río Colorado (figura 1). Esta agua supone aproximadamente la mitad de las necesidades totales para satisfacer la demanda de una población de 20 millones de personas en una región semi-árida. Las aguas subterráneas, las superficiales y las recicladas suministran la otra mitad de las necesidades. En los últimos 10 años, la normativa medioambiental en el norte de California y la reducción de la aportación del río Colorado han ocasionado una disminución de la disponibilidad de esta agua importadas, en una cuantía cifrada entre el 20 y el 25%.

Para hacer frente a estas reducciones sustanciales en las fuentes de suministro de agua tradicionales, las agencias de agua del sur de California han tratado de fortalecer y diversificar sus carteras de agua, aumentando la captura de aguas de tormenta, aguas residuales recicladas, la eficiencia en el uso del agua y la desalación de agua de mar. Afortunadamente, una parte significativa del sur de California están ubicada sobre grandes cuencas de agua subterránea. El objetivo de las agencias regionales de agua es la gestión sostenible de estas aguas subterráneas maximizando su producción y evitando su sobreexplotación a largo plazo, así como la degradación de la calidad del agua, la intrusión de agua de mar y la subsidencia.

El range County Water District (OCWD) administra los recursos de agua subterránea en el norte del Condado de Orange mediante actuaciones y programas que incluyen la recarga de acuíferos, el control de intrusión de agua de mar, la protección de la calidad del agua, el reciclado del agua y la conservación del agua de lluvia. OCWD cubre un área aproximada de 900 km^2 y tiene una población de 2,4 millones (Figura 2).

Abastecimiento con agua subterránea y gestión de la cuenca

El agua subterránea proporciona dos tercios de la demanda de agua en el área de servicio de OCWD, y el tercio restante se obtiene a través del agua importada. El costa de la utilización del agua subterránea es de aproximadamente la mitad del costo del agua importada.

La principal fuente de agua de recarga de la cuenca subterránea del Condado de Orange es el río Santa Ana, cuyos caudales se componen generalmente de aguas residuales tratadas descargadas de plantas de tratamiento de aguas residuales situadas aguas arriba del condado, y de caudales estacionales ligados a tormentas. En promedio, OCWD puede detraer y recargar aproximadamente 185 hm^3 del río cada año. El distrito también recarga aproximadamente 86 hm^3 por año de agua reciclada procedente del Sistema de Recarga de Agua Subterránea (GWR System), que se describe más adelante. Por último, los acuíferos reciben un promedio de 74 hm^3 por año de recarga natural procedente de la precipitación y la infiltración del agua de riego. En ocasiones, OCWD agua importada comprándola como fuente adicional de agua para recargar los acuíferos. El agua subterránea se bombea desde aproximadamente 200 pozos de gran capacidad, que son propiedad y son operados por las agencias locales que suministran el agua directamente a los usuarios (Figura 3).

Como su principal objetivo, OCWD se ha esforzado por aumentar la utilización de los acuíferos mediante la ampliación de la capacidad de recarga de los mismos (Figura 4). Como históricamente se han sucedido períodos de sequía e inundación, la cuenca se ha operado como un depósito para retirar o almacenar agua (Figura 5).

Características hidrogeológicas

La cuenca de agua subterránea del Condado de Orange es una estructura sinclinal, con sedimentos que contienen agua dulce que alcanzan profundidades de hasta 1.200 m. Cerca de la costa, una zona de falla ha creado una barrera local contra la intrusión marina. Los acuíferos de la cuenca forman una compleja serie depósitos *de arena y grava interconectados y con intercalaciones de arcillas y limos. En las zonas del interior, las capas de arcillas y limos se vuelven más delgadas y más discontinuas, lo que permite un mayor flujo de agua entre los acuíferos someros y los más profundos. Tres sistemas acuíferos más importantes de la cuenca están hidráulicamente conectados, de froma que las aguas subterráneas pueden fluir entre ellos a través goteo procedente de los acuitardos intermedios o de discontinuidades dentro de los mismos (Figura 6).*

Control de la intrusión marina

La entrada de agua salada en los acuíferos costeros del Condado de Orange se conoce desde 1930 y ha constituido el factor clave para la explotación de los acuíferos. Cuatro barreras de intrusión de agua de mar operan en el sur de California y consisten en una serie de pozos que inyectan agua dulce para crear un domo hidráulico o "cresta" que impide el flujo hacia el interior de las aguas subterráneas salinizadas.

La barrera Talbert, del OCWD, lleva en funcionamiento desde 1976 y originalmente el agua que se inyectaba era una mezcla de aguas subterráneas profundas y agua reciclada procedente de Water Factory 21, que fue el primer proyecto en California con autorización para inyectar aguas residuales tratadas en un acuífero con agua potable para suministro (Figura 7). La barrera inicial estaba formada por 23 pozos de inyección de diferentes profundidades ,con una capacidad de alrededor de 40 m^3/min. El agua de mar puede intruir en acuíferos profundos plegados, como consecuencia de que los mismos poseen conexión hidráulica con el acuífero superior, el Talbert, que está en contacto directo con el Océano Pacífico. Los acuíferos más profundos son fuertemente explotados mediante los pozos de producción situados hacia el interior, creando así fuertes gradientes hidráulicos hacia los pozos (Figura 8).

En los años de la década de 1990, el aumento de bombeo superó la capacidad del acuífero Talbert para hacer frente a la intrusión de agua de mar, como se indica por las concentraciones de cloruro que progresan hacia el interior (Figura 9). Basándose en estas observaciones, OCWD comenzó investigaciones para ampliar el sistema así inyección. Se desarrolló y calibró un modelo numérico de flujo, que posteriormente fue utilizado para determinar las ubicaciones y las tasas de inyección de los pozos de inyección adicionales. Los resultados mostraron que se necesitaría doblar la tasa media de inyección de la barrera hidráulica, alcanzando 80 m^3/min (30 Ml / día). Para lograr esa capacidad de inyección deseada, se construyeron nuevos pozos de inyección en 13 nuevas ubicaciones que se muestran en la Figura 9. Los pozos de Inyección fueron desarrollados nuevamente, y actualmente se sigue haciendo lo mismo para eliminar los materiales finos acumulados en las rejillas, que rodean el empaque de grava anular. Con estas operaciones se consigue restaurar la capacidad de la inyección (Figura 10).

Agua reciclada – una fuente local de agua fiable

El suministro de agua a la barrera Talbert fue el impulso para el desarrollo y puesta en funcionamiento de instalaciones para el reciclado de agua en el condado de Orange a finales de 1960 y principios de 1970. En ese momento, el acceso al agua importada para los futuros pozos de inyección habría requerido la construcción de un acueducto costoso para conectarse a la tubería principal de alimentación de agua importada más cercana y habría creado una dependencia a largo plazo de las fuentes de agua que se encuentran a cientos de kilómetros de distancia. Teniendo en cuenta estas cuestiones, OCWD decidió proseguir el tratamiento avanzado de aguas residuales procedentes del Orange County Sanitation District (OCSD) que eran descargadas al mar. mediante la construcción de la infraestructura "Water Factory 21".

Más de 25 años de experiencia operacional con Water Factory 21 y la barrera de Talbert sentaron las bases para planificar una instalación de reciclado de agua mucho mayor y la expansión de la barrera hidráulica contra la intrusión. En un maravilloso ejemplo de la colaboración interinstitucional, OCWD y OCSD encontraron una solución común a sus respectivas necesidades: el Sistema GWR. El Sistema GWR se diseñó inicialmente para producir 187 m^3/min de agua reciclada con un tratamiento avanzado. Esto fue suficiente para abastecer a toda la barrera hidráulica de inyección, entregar otros de 107 m^3/min para las balsas de infiltración de OCWD, y posponer la necesidad de OCSD para construir un emisario marino más grande (Figura 11). La microfiltración fue seleccionado como método rentable de pre-tratamiento previo a la ósmosis inversa. Después de la ósmosis inversa, el agua es tratada por oxidación avanzada mediante luz ultravioleta y peróxido de hidrógeno. Estos procesos purifican el agua hasta aportarle una calidad casi igual a la del agua destilada. Debido a que la ósmosis inversa elimina casi todos los minerales del agua, es necesario añadir cal para estabilizar el agua antes de su transporte a las instalaciones de recarga (Figura 12). El agua producto final tiene una concentración de sólidos disueltos totales de aproximadamente 45 mg/L y supera todas las demás normas para el agua potable del estado y federal, otorgándole la máxima calidad del agua de recarga disponible.

Un paso importante para llevar al Sistema GWR a buen puerto fue la obtención de la aceptación y apoyo públicos. Se hicieron más de 1.000 presentaciones ante las organizaciones comunitarias, funcionarios electos, agencias reguladoras, grupos empresariales, científicos y académicos, profesionales de la salud, educadores, y los grupos ecologistas. Además, el proyecto está supervisado por un panel asesor independiente *que proporciona una continua revisión científica periódica de las operaciones y el desarrollo del proyecto. El resultado de esta campaña educativa multianual fue un abrumador apoyo público al Sistema GWR. Ahora en su sexto año de funcionamiento, el GWR ha producido y recargado más de 370 hm^3 de agua. El coste de producción es menor que la del agua importada, lo que demuestra la viabilidad económica del proyecto.*

Conclusions

Los acuíferos costeros del sur de California han sido amenazados por la intrusión de agua de mar desde el comienzo de su utilización hace más de 100 años. Barreras hidráulicas contra la intrusión marina requieren un suministro continuo de agua cuya calidad esté próxima a la de potable. Como el agua importada se ha convertido en una fuente de agua no segura y más cara, las agencias locales han desarrollado sus propias fuentes de agua, utilizando agua reciclada altamente tratada. El sistema GWR, de OCWD, garantiza para el Condado de Orange un suministro fiable, resistente a la sequía, y controlado localmente, de agua de la más alta calidad, y ha revolucionado la forma que los consumidores tienen de percibir las aguas residuales - como un recurso valioso que se debe cuidar y reutilizar.

Introduction

Coastal southern California is highly dependent on water transported (or "imported") hundreds of miles through aqueducts from northern California and the Colorado River (Figure 1). Imported water accounts for approximately one-half the total supplies to meet the needs of a population of 20 million in this semi-arid region. Local groundwater, surface water, and an increasing amount of recycled water comprise the other half of the water supply. In the last ten years, environmental regulations in northern California and supply reductions on the Colorado River have decreased the volume of imported water delivered to southern California by 20 to 25 percent.

Facing substantial reductions in their traditional water supplies, southern California water agencies have sought to strengthen and diversify their water portfolios by increasing the amount of captured local storm water, increasing the use of recycled wastewater, increasing water use efficiency, and exploring seawater desalination. Fortunately, significant portions of southern California are underlain by large groundwater basins comprised of alluvial and marine deposits of gravels, sands, silts, and clays. These groundwater basins contain large quantities of potable-quality water; however, their long-term groundwater production yield depends on the supply of replenishment water. The objective of regional water agencies is to sustainably manage these groundwater basins by maximizing

Figure 1. Coastal southern California has a population of 20 million and receives 50 percent of its water supply from northern California and the Colorado River via aqueducts.
Figura 1. *La costa sur de California tiene una población de 20 millones de habitantes, y recibe el 50% de su suministro de agua desde el norte de California y el río Colorado a través de acueductos.*

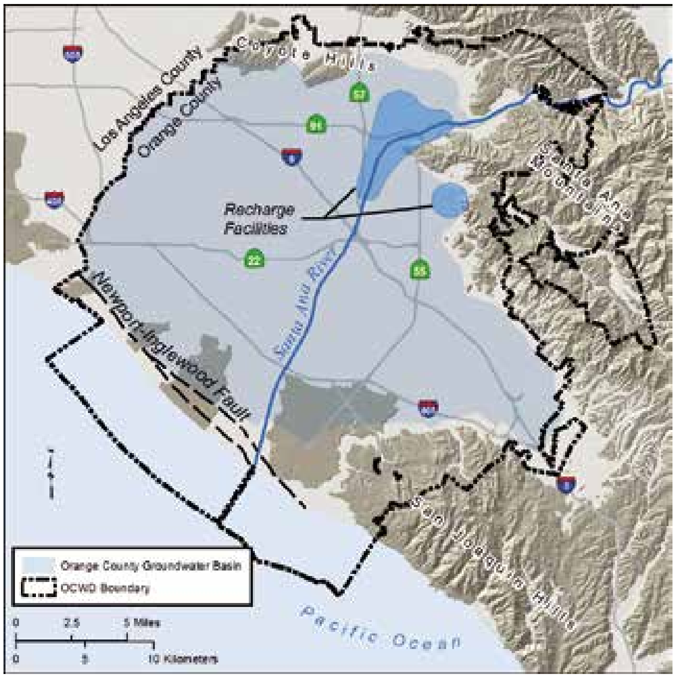

Figure 2. The Orange County Water District recharges the basin with Santa Ana River water and recycled water at 400 hectares (1,000 acres) of infiltration ponds.
Figura 2. *El Orange County Water District realiza recarga artificial mediante balsas de 400 ha de superficie utilizando agua procedente del río Santa Ana y agua reciclada.*

groundwater production while avoiding long-term overdraft, water quality degradation, seawater intrusion, and land subsidence.

This paper discusses some of the programs and projects that have been implemented by the Orange County Water District (OCWD or District) to improve water supply reliability and protect against seawater intrusion in a highly urbanized coastal groundwater basin in southern California.

Institutional Setting and Climate

OCWD is a special governmental water agency that was created by the state of California in 1933 to manage the surface water and groundwater resources in northern Orange County for the benefit of the public within the District. District programs include aquifer replenishment or recharge, seawater intrusion control, water quality protection and improvement, water recycling, and storm water conservation (OCWD, 2009). OCWD is governed by a board of directors, seven of whom are publicly elected and three of whom are appointed by three cities. Employees number approximately 220, including engineers, hydrogeologists, water system operations and maintenance staff, public affairs specialists, chemists, biologists, accountants, and water quality specialists. Most revenue for OCWD comes from an assessment that it charges on groundwater pumped and a lesser amount from property taxes.

OCWD covers an area of approximately 900 km^2 (350 mi^2) and has a population of 2.4 million (Figure 2). The Mediterranean-type climate in Orange County is generally mild, with annual rainfall of approximately 350 mm (14 in), and average monthly temperatures ranging from 14 to 24^o C (58 to 75^o F). Most of the rainfall occurs in the months of December through March.

Groundwater Supply and Basin Operation

Groundwater supplies approximately two-thirds of the total water demand within OCWD's service area. Most of the remaining water demand is met by imported water. The cost of using groundwater is about one-half the cost of imported water (OCWD, 2012). Thus, the residents and businesses that overlie the Orange County groundwater basin enjoy a tremendous economic savings in water cost as compared to areas, such as the city of San Diego, that are largely dependent on imported water due to the absence of a prolific groundwater basin.

The primary source of recharge water to the Orange County groundwater basin is the Santa Ana River, the longest river in southern California. The Santa Ana River flows that arrive in Orange County are generally composed of treated wastewater discharged from upstream sewage treatment plants and seasonal storm flows. On average, the combined amount of river flows that OCWD is able to capture and recharge in its infiltration basins is approximately 185 million m^3

(150,000 acre-ft) each year. During periods of heavy rainfall, high volumes of storm flow in the river may greatly exceed the District's recharge capacity and discharge to the Pacific Ocean. The District also recharges approximately 86 million m^3 (70,000 acre-ft) per year of advanced treated recycled water from a landmark project known as the Groundwater Replenishment System that is described later. Lastly, the groundwater basin receives an average of 74 million m^3 (60,000 acre-ft) per year of natural recharge from precipitation and infiltration of irrigation water. Occasionally, OCWD purchases imported water as an additional source of water to recharge the groundwater basin.

Groundwater is pumped from approximately 200 large-capacity wells owned and operated by cities, local water districts, and water companies that provide water directly to the water users (Figure 3). Water users are primarily residences, industries, parks, and golf courses, as very little agricultural land remains in Orange County. A "typical" production well within OCWD is 330 m (1,100 ft) deep, has an operating rate of 8 m^3/min (2,110 gal/min), and today would cost at least $3 million to construct and equip with pump and motor. Considering the cost differential between groundwater and imported water, the cost of investing in a new well can be recovered in a short time period.

As its primary goal, OCWD has strived to increase the utilization of the groundwater basin by expanding recharge capacity. Since the 1950s, groundwater production from the basin has increased by more than 50 percent (Figure 4). As periods of drought or deluge have occurred historically, the basin has been operated as a reservoir to withdraw or store water. OCWD established a basin operating range based on historical experience and observations, e.g., seawater intrusion or shallow groundwater levels, such that if groundwater storage approaches the low end of the range, OCWD has the authority to provide financial incentives to well operators to reduce groundwater pumping and shift more of their supply to imported water. Alternatively, as the volume of groundwater in storage approaches the high end of the range, OCWD can allow groundwater pumping to increase (Sovich and Herndon, 2007). Figure 5 illustrates the cycles over the last 40+ years of increasing and decreasing the volume of groundwater stored in the basin, depending on water availability, e.g., drought.

Hydrogeologic Setting

The Orange County groundwater basin formed in a synclinal, northwest-trending trough that deepens as it continues beyond the Orange-Los Angeles county line. The Newport-Inglewood fault zone, San Joaquin Hills, Coyote Hills, and Santa Ana Mountains form the uplifted margins of the syncline. The total thickness of sedimentary rocks in the basin surpasses 6,000 m (20,000 ft), of which only the upper 600 to 1,200 m (2,000 to 4,000 ft) contain fresh water. In the southeastern area underlying the city of Irvine and along the

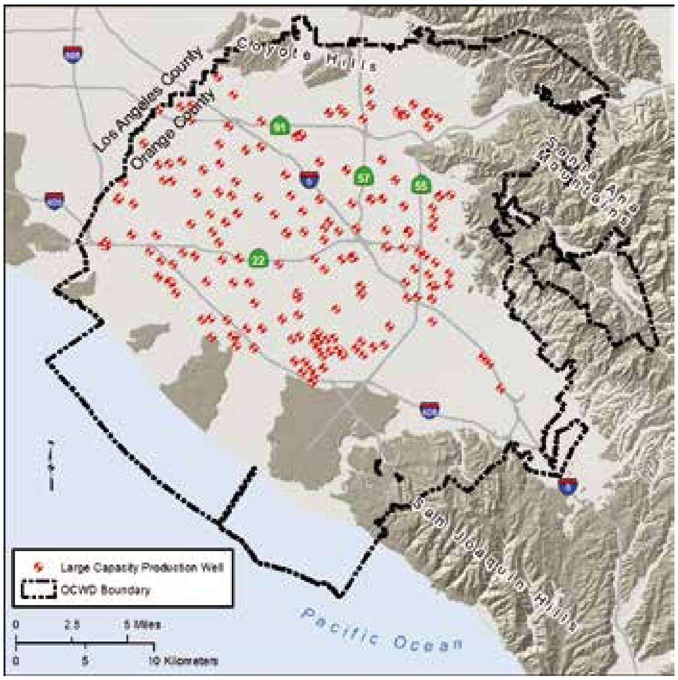

Figure 3. Groundwater accounts for two-thirds of the total water needs within OCWD and is supplied by 200 production wells.

Figura 3*. El agua subterránea aporta las dos terceras partes de la demanda del OCWD, y es suministrada mediante 200 pozos de bombeo.*

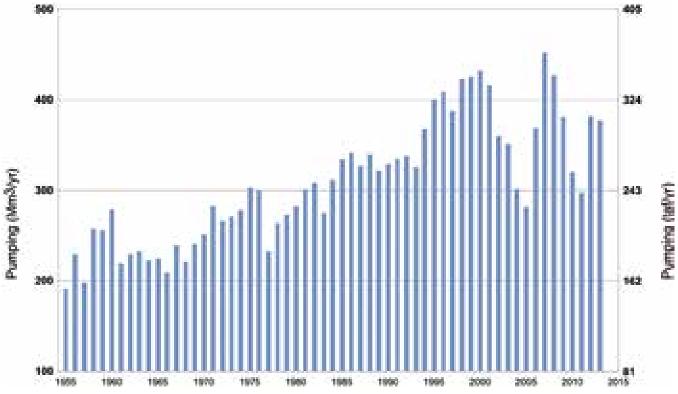

Figure 4. Groundwater production has increased since the 1950s with the expansion of OCWD's recharge facilities and increased recharge water supplies.
Figura 4*. La producción de agua subterránea se ha incrementado desde la década de 1950 gracias al mayor número de instalaciones de recarga del OCWD, así como a un mayor volúmen de agua recargada.*

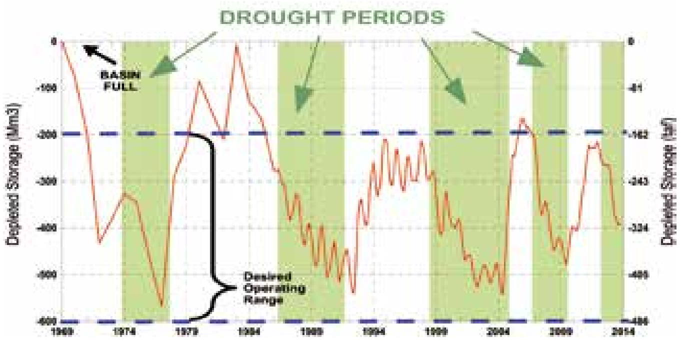

Figure 5. Groundwater storage varies depending on water supply availability and precipitation, but is maintained within an acceptable operating range.
Figura 5*. El almacenamiento de agua subterránea varía dependiendo de la disponibilidad de agua y de la precipitación, pero se mantiene dentro de un rango de operación aceptable.*

basin margins, the thickness of fresh water-bearing sediments is less than 300 m (1,000 ft) (Herndon and Bonsangue, 2006).

Structural folding and faulting along the basin margins, together with downwarping and deposition within the basin have occurred since Oligocene time. The Newport-Inglewood fault zone, comprising the most significant structural feature in the basin from a hydrogeologic standpoint, consists of a series of faulted blocks which are generally up thrown on the southwest side. Folding and faulting along the Newport-Inglewood fault zone have created a natural restriction to seawater intrusion into the groundwater basin (Herndon and Bonsangue, 2006).

Pleistocene or younger aquifers within the basin form a complex series of interconnected sand and gravel deposits. In coastal and central portions of the basin, these deposits are extensively separated by lower-permeability clay and silt deposits or aquitards. In the inland areas, the clay and silt deposits become thinner and more discontinuous, allowing larger quantities of groundwater to flow more easily between shallow and deeper aquifers (California Department of Water Resources, 1967).

OCWD subdivided the groundwater basin into three major aquifer systems based on vertical potentiometric head differences measured regionally at over 50 multi-depth monitoring wells. The three aquifer systems, known as the Shallow, Principal, and Deep, are hydraulically connected, as groundwater is able to flow between them via leakage through the intervening aquitards or discontinuities in the aquitards (Figure 6). Over 90 percent of groundwater production occurs from wells that are screened within the Principal aquifer system at depths between 60 and 400 m (200 and 1,300 ft).

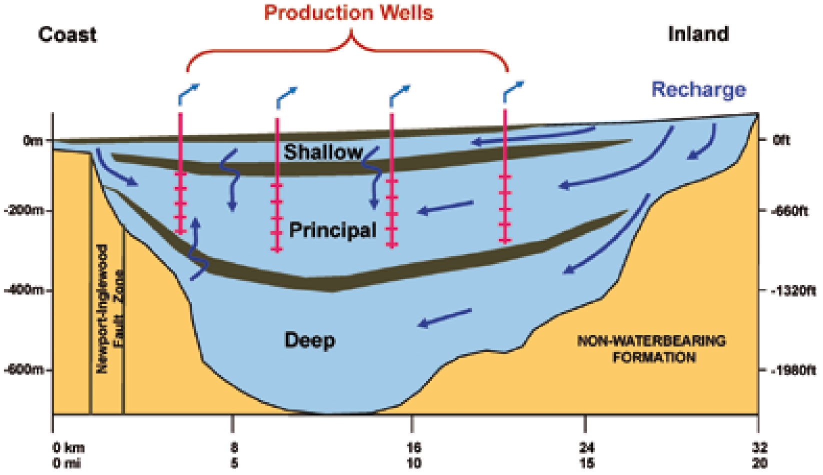

Figure 6. Three hydraulically-connected major aquifer systems form the conceptual hydrogeologic model of the Orange County groundwater basin.
Figura 6*. El modelo hidrogeológico conceptual de la cuenca subterránea del Condado de Orange lo forman 3 acuíferos principales conectados hidráulicamente.*

Seawater Intrusion Control

Incursion of saline ocean waters into Orange County coastal aquifers has been documented since the 1930s, several decades after the first groundwater production wells were constructed for agricultural irrigation (Poland and Sinnott, 1959; California Department of Water Resources,1966). Because of its detrimental impacts to groundwater quality, seawater intrusion has been a major factor governing the amount of groundwater that can be reliably pumped from the Orange County groundwater basin.

Between 1953 and 1975, four seawater intrusion barriers were constructed along coastal southern California in Los Angeles and Orange counties. These barriers consist of a series of wells that inject fresh water to create a pressurized subsurface hydraulic "mound" or "ridge" that prevents the inland flow of saline groundwater within the affected aquifers. All four barriers are currently supplied by at least 50 percent advanced treated recycled water, the remaining portion supplied by imported water.

OCWD's Talbert Seawater Barrier has been in operation since 1976 and was originally supplied with a blend of deep groundwater and recycled water from Water Factory 21, which was the first project in California that was permitted to inject highly-treated wastewater into a potable-supply aquifer (Figure 7). The original barrier consisted of 23 multi-depth injection well sites with 81 individual casings ranging in depth from approximately 30 to 120 m (100 to 400 ft) and had a total operating capacity of about 40 m^3/min (15 mgal/day). Hydrogeologic studies found that seawater is able to intrude into folded deeper aquifers due to their hydraulic connection with the younger, overlying Talbert Aquifer that is in direct contact with the Pacific Ocean. The areas of hydraulic connection are referred to as "aquifer mergence zones" (California Department of Water Resources, 1966). The deeper aquifers are heavily pumped by inland production wells, thereby creating strong lateral and vertical hydraulic gradients toward the wells (Figure 8). The Main Aquifer is protected against seawater intrusion, because it is hydraulically separated from the Talbert Aquifer and is offset by the Newport-Inglewood fault zone, which largely acts as an effective hydraulic barrier, based on the lack of evidence of increasing salinity in the Main Aquifer.

By the 1990s, increased production of groundwater caused coastal aquifer groundwater elevations to decline below sea level, thus exceeding the Talbert Barrier's ability to prevent seawater intrusion. Chloride concentrations in groundwater, an excellent indicator of saline intrusion, also showed increases progressing inland and beginning to "flank" around both ends of the barrier (Figure 9). Based on these observations, OCWD began investigations to expand the seawater barrier injection well system to reverse the seawater intrusion. A numerical groundwater flow model was developed, calibrated, and used to determine the locations and flow rates of additional injection wells (Camp Dresser & McKee, 2000). Ultimately, using assumptions of anticipated future groundwater production, it was determined that the average barrier injec-

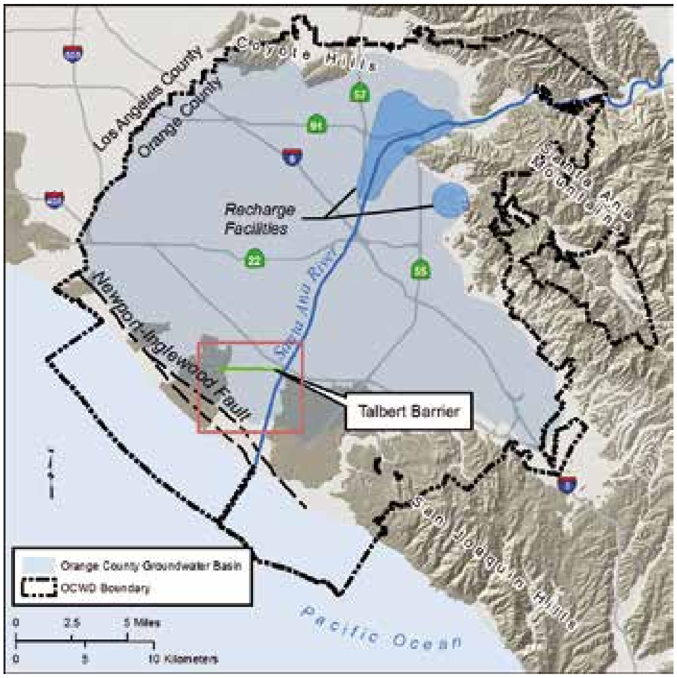

Figure 7. OCWD's Talbert Seawater Barrier injects 42 million m^3/yr (34,000 acre-ft/yr) of recycled water, most of which flows inland to replenish the groundwater basin.

Figura 7. *La barrera Tablbert contra la intrusión, del OCWD, inyecta 42 hm^3/año de agua reciclada, la mayor parte de la cual se mueve hacia el interior y recarga la cuenca subterránea.*

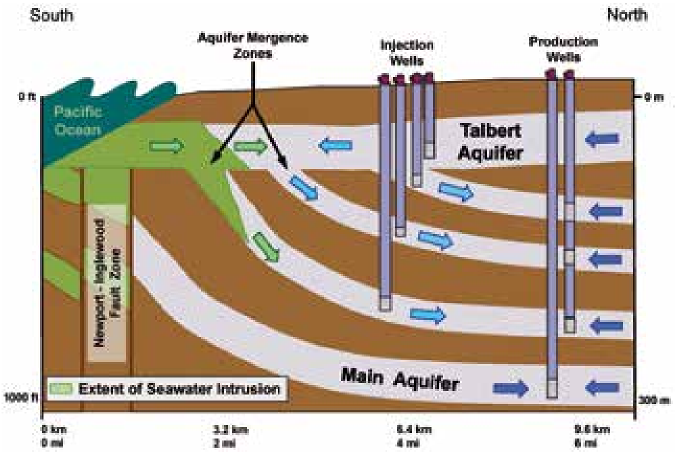

Figure 8. Injection wells maintain a "pressure mound" in multiple aquifers to counteract the hydraulic gradient that drives seawater intrusion toward production wells.
Figura 8. *Los pozos de inyección mantienen la "presión en el domo de recarga" en múltiples acuíferos, para contrarrestar el gradiente hidráulico en función del cual la intrusión marina penetra en el acuífero.*

tion rate would need to double to 80 m^3/min (30 mgal/day). Observed cyclical groundwater level changes based on seasonal pumping patterns dictated the need for higher injection in the summer/fall months of heaviest pumping and significantly less injection in the winter/spring months of lowest pumping. Based on these seasonal patterns, the model simulations indicated that the barrier should inject up to 107 m^3/min (40 mgal/day) during the summer/fall months and only one-half that rate in the winter/spring months. The model simulation results turned out to be amazingly accurate based on subsequent operational experience.

To increase injection capacity, 13 new injection well sites, comprising 28 individual multi-depth casings, were constructed between 1998 and 2006 at the west and east ends of the original barrier as well as to the south (Figure 9). As with the original injection wells, the new wells were screened in several aquifers that are susceptible to seawater intrusion; however, eight of the new wells were constructed into the deeper Main Aquifer for the sole purpose of aquifer recharge, as it was explained previously that this aquifer is not impacted by seawater intrusion. Each well casing was installed in a separate borehole with a cement-bentonite annular seal above the well screen to reduce the potential for leakage of pressurized injection water within the annulus. Specifications for the new injection wells included 30.5-cm (12-in) diameter Type 316L stainless steel casing and wire-wrapped screen. Each new well is equipped with pressure-reducing valves and flow meters at the wellhead, down-hole

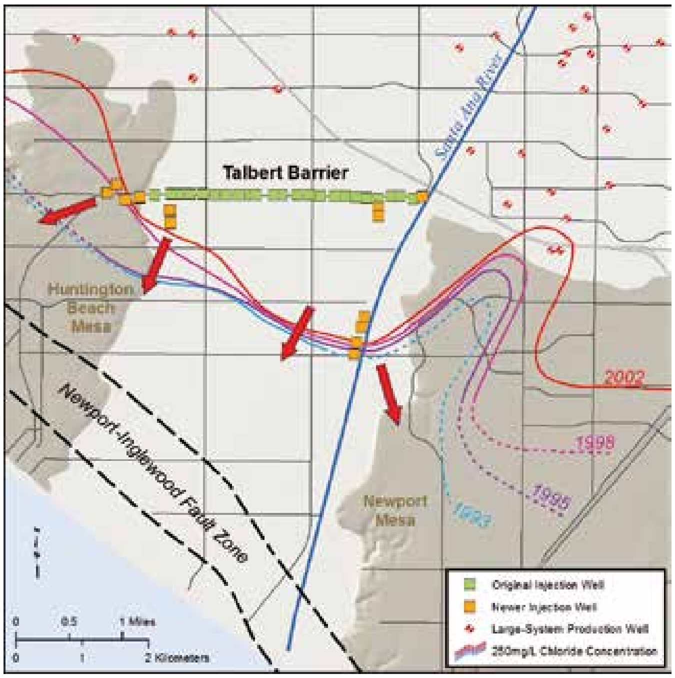

Figure 9. OCWD doubled the capacity of the Talbert Seawater Barrier by constructing 28 new injection wells to reverse inland migration of saline groundwater.
Figura 9. *OCWD ha doblado la capacidad de la barrera contra la intrusión Talbert construyendo 28 nuevos sondeos de inyección cuyo objetivo es revertir la entrada de agua del mar hacia el interior del acuífero.*

pneumatic flow-control valves to maintain a full column of water (prevents injection of air if well is turned off and put back on-line), and telemetry. The telemetry system monitors and transmits water level/pressure and flow data to the central operations data management system for performance tracking.

Typical operational flow rates of the older, original injection well casings range from 0.2 to 1.1 m^3/min (50 to 300 gal/min). Typical flow rates of the newer injection wells range from 0.8 to 4.5 m^3/min (200 to 1,200 gal/min). The difference in the flow rates between older and newer wells is likely a function of the age, smaller diameter (15 cm/6 in), and shorter screen length of the older wells relative to the newer wells.

Injection well redevelopment and back-flushing are performed periodically to remove accumulated fine particulate materials from the well screens and surrounding annular gravel pack and thereby restore injection capacity (Burris, 2012). Redevelopment of the older injection wells is typically performed every other year and consists of air-lift pumping and surging, which requires the disassembly and reassembly of the wellhead piping. More frequent redevelopment of the older injection wells would be preferable; however, the labor and mobilization of well development equipment is time-consuming and costly and, thus, must be considered when determining an acceptable frequency (Figure 10). The newer injection wells are equipped with 10-cm (4-in) diameter "sounding" tubes that join the blank well casing above the screen. OCWD staff use a mobile air compressor to air-lift pump the injection wells through the sounding tubes on an approximate monthly basis. No wellhead disassembly is required, so this process can be accomplished quickly and more frequently to maximize injection well performance by minimizing the effects of clogging.

Recycled Water – A Reliable Local Water Supply

Supplying water to the Talbert Seawater Barrier was the original impetus for the development of recycled water treatment facilities in Orange County in the late 1960s and early 1970s. At that time, access to imported water to the future injection wells would have required the construction of a costly pipeline to connect to the nearest major imported water feeder pipeline. In addition, the use of imported water for barrier injection would have created a long-term dependency on water sources that are hundreds of miles away. Considering these issues, OCWD made the bold and innovative decision to pursue advanced treatment of secondary-treated effluent from the Orange County Sanitation District (OCSD) that was being discharged to the ocean. California's Department of Public Health and Regional Water Quality Control Board permitted Water Factory 21 as the first research and demonstration project to treat and inject wastewater into a drinking water aquifer. Water Factory 21's treatment processes included lime clarification, multimedia filtration, and either carbon adsorption and chlorination or reverse osmosis. The recycled product water was blended with deep aquifer water and/or imported water so that the wastewater component never exceeded two-thirds of the total blend prior to injection. To make way for the expanded recycled water treatment facility, Water Factory 21 was demolished in 2004.

The successes and lessons learned from over 25 years of operation of Water Factory 21 and the Talbert

Figure 10. Redevelopment of the older injection wells requires heavy equipment and more time (left photo), whereas air-lift pumping of the newer injection wells can be done quickly using a mobile air compressor and dedicated sounding tubes (right photo).
Figure 10. *El re-desarrollo de los viejos sondeos de inyección requiere equipos pesados y más tiempo (foto de la izquierda), mientras que el bombeo mediante air-lift en los sondeos nuevos se puede hacer rápidamente utilizando un compresor de aire comprimido portátil y tubos (foto derecha).*

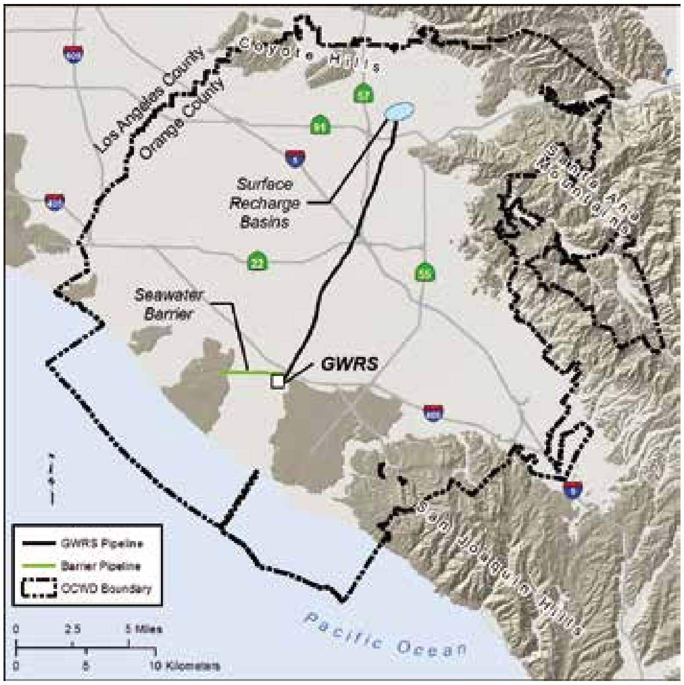

Figure 11. The GWR System provides approximately one-fourth of the total recharge to the Orange County groundwater basin. The highly-treated recycled water is recharged via seawater barrier injection wells and surface infiltration basins.
Figura 11*. El sistema GWR aporta aproximadamente una cuarta parte del total de agua que se recarga en la cuenca subterránea del Condado de Orange. El agua reciclada, con un alto grado de tratamiento, se recarga a través de la barrera contra la intrusión y también mediante balsas.*

Barrier laid the foundation for planning of a much larger advanced treated water recycling facility to supply the expanded seawater barrier as well as infiltration basins 13 miles inland. As OCWD was considering the need for a larger water supply to the expanded seawater barrier, OCSD (a separate governmental agency responsible for the collection, treatment, and disposal of sewage) was facing the prospect of constructing a larger ocean outfall pipe to accommodate larger volumes of treated sewage disposal resulting from projected population growth. The ocean outfall pipe would have cost approximately $200 million and would have been subject to substantial environmental review and potential opposition by coastal environmental groups. In a wonderful example of interagency partnership, OCWD and OCSD found a common solution to their respective needs – the Groundwater Replenishment System (GWR System). A joint funding agreement was signed in 1997, wherein OCSD agreed to supply secondary-treated effluent to OCWD, and the $481 million in total project construction costs would be shared between the two agencies.

The GWR System was initially sized to produce 187 m^3/min (70 mgal/day) of advanced treated recycled water. This rate of production was sufficient to supply all of the seawater barrier injection water, deliver an additional 107 m^3/min (40 mgal/day) to OCWD's infiltration basins, and postpone OCSD's need to construct a larger ocean outfall pipe (Figure 11). Early in the project design, microfiltration was identified as a cost-effective alternative to lime clarification and conventional filtration pre-treatment prior to reverse osmosis. Several microfiltration systems were pilot tested by OCWD for several years beginning in 1995. After microfiltration, the next step in the treatment process is reverse osmosis, followed by advanced oxidation consisting of ultraviolet light and hydrogen peroxide. Pilot testing of these processes together demonstrated that this technology could purify wastewater to near-distilled quality. Because the treatment process, reverse osmosis in particular, removes nearly all minerals from the water, lime is added back to the product water in order to stabilize it prior to conveyance to the recharge facilities (Figure 12). The final product water has a total dissolved solids (TDS) concentration of approximately 45 mg/L (Burris, 2012). This compares favorably to the TDS concentrations of imported water and Santa Ana River water, approximately 500 and 600 mg/L, respectively. The GWR System water also exceeds all other state and federal drinking water standards, making it the highest quality recharge water available.

One of the biggest potential challenges in bringing the GWR System to fruition was obtaining public acceptance and support. Although OCWD had an established track record of performance over 25 years with Water Factory 21, implementation of a recycled water recharge project on such an unprecedented scale warranted an aggressive public outreach program. Over 1,000 presentations were made to dozens of community organizations, elected officials, regulatory agencies, business groups, scientists and academicians, health care professionals, educators, and environmental groups. In addition, the project is overseen by an independent advisory panel that provides on-going periodic scientific peer review of the project operations and performance. The result of this concerted, multi-year educational campaign was overwhelming public support for the GWR System, including over $92 million in local, state, and federal grant funding as well as $85 million in operational subsidies from the Metropolitan Water District of Southern California because the project reduces dependence on imported water supplies.

Now in its sixth year of operation, the GWR System has produced and recharged over 370 million m^3 (300,000 acre-ft) of high-quality water, which is equal to the annual amount of groundwater pumped from the basin. In 2009-10, the unit cost of producing water from the GWR System, including amortized capital and operation and maintenance costs, was $0.72/$m^3$ ($887/acre-ft) excluding all subsidies. This cost is less than that of imported water, demonstrating the project's economic viability.

A key issue that OCWD faced soon after project start-up was the need to modify the facility operation to account for diurnal fluctuations in the supply of secondary effluent from OCSD. The GWR System had to be run at higher flows during the day and lower flows at night to coincide with effluent availability. This operation was not anticipated during project design, but it was accommodated successfully by OCWD operations staff. The facility is operated such that the demand of the seawater barrier injection wells is met first, and the remainder of the product water is conveyed to the infiltration basins. This procedure is followed because it is difficult to constantly raise and lower flows to a series of highly-metered and controlled injection wells which are best operated at a generally constant pressure.

Another finding after operating the project for several months is that the injection wells continue to clog and require regular redevelopment. By installing and visually monitoring cartridge filters at different locations along the barrier injection system, OCWD staff discovered that very fine particulates were being conveyed and deposited on the filters, which also meant that these particulates were being delivered to the injection well screens and surrounding gravel pack. Staff analyzed the particles and found that they are predominantly composed of calcium carbonate, iron oxide, and aluminum silicate. Current hypotheses for the sources of these particles are: 1) undissolved lime that is added after the treatment processes, 2) impurities in the lime, and 3) dissolution or erosion of the mortar lining of the barrier supply pipeline. While OCWD staff continues to investigate these issues, it has found that regular redevelopment and back-flushing are successful in removing particulate matter and restoring and maintaining injection well capacity.

Building upon the successful first phase implementation of the GWR System, OCWD has embarked upon an expansion of the project to add 80 m^3/min (30 mgal/day) of treatment capacity. The expansion will cost approximately $143 million and provide enough additional recharge water to the groundwater basin to meet the needs of 250,000 Orange County residents each year. In order to utilize nearly all remaining available secondary effluent from OCSD, the expansion includes the construction of two large reservoirs to store and balance the diurnal effluent flows from OCSD. Construction is scheduled to be completed in 2015. Further details of the GWR System and its on-going expansion can be found at: http://www.gwrsystem.com/about-gwrs.html

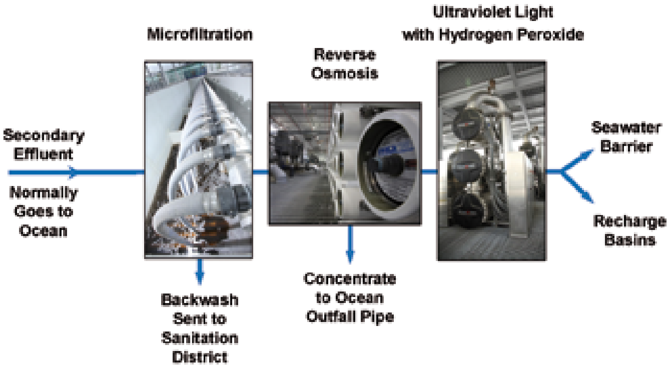

Figure 12. The GWR System's state-of-the-art multi-stage treatment process removes or destroys pathogens, nutrients, metals, pharmaceuticals, and trace organic compounds such as 1,4-dioxane and N-nitrosodimethylamine.

Figura 12. *El estado del arte del tratamiento multiproceso que se lleva a cabo en el sistema GWR muestra la desaparición o destrucción de patógenos, nutrientes, metales, productos farmacéuticos y compuestos orgánicos traza, como el 1,4-dioxano y el N-nitrosodiometilamina.*

Conclusions

Coastal groundwater basins in southern California have been threatened by seawater intrusion since they began to be heavily utilized over 100 years ago. Seawater intrusion barriers, consisting of injection wells, have protected the coastal basins; however they require a continuous supply of potable-quality water. As imported water, the traditional supply to the barriers, has become a threatened and more expensive source of water, water management agencies such as OCWD have developed their own sources of highly-treated recycled water. Following in the footsteps of Water Factory 21, OCWD's GWR System guarantees Orange County a reliable, drought-resistant, locally-controlled supply of water of the highest quality, and reduces southern California's reliance on water supplies from northern California and the Colorado River. Additionally, producing GWR System water costs less than and uses one-half the energy of imported water. Prior to the GWR System, water/wastewater agencies treated wastewater to tertiary levels for non-potable uses such as landscape and agriculture. In an era of distrust in government, OCWD and OCSD successfully partnered to build a potentially controversial water project that garnered overwhelming public support and overcame the "toilet to tap" misperception. The GWR System has revolutionized how consumers look at wastewater – as a valuable resource they should take care of and reuse.

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