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Successful implementation of ASR in basalt-hosted aquifers in the Pacific Northwest of the United States

L. Eaton, RG, LHG[1], J. Melady, RG, CWRE[1] and T. Tolan, RG, LHG[2]

[Note: RG = registered geologist, LHG = licensed hydrogeologist, CWRE = certified water rights examiner.]

(1) GSI Water Solutions, Inc., 55 SW Yamhill St., Suite 400, Portland, OR, USA 97204
leaton@gsiwatersolutions.com and jmelady@gsiwatersolutions.com
(2) GSI Water Solutions, Inc., 1020 North Center Parkway, Suite F, Kennewick, WA, USA 99336
ttolan@gsiwatersolutions.com

ABSTRACT

Despite the Pacific Northwest's reputation for being "wet," many cities west and east of the Cascade Range in the United States of America find it increasingly difficult to meet peak water supply demand during the dry summer months. Aquifers in the east side of Oregon and Washington are the primary water supply sources for a vast agriculture industry, and they have experienced significant declines prompting regulatory restrictions. For these reasons, municipalities west and east of the Cascade Range, as well as agricultural interests have opted to implement aquifer storage and recovery (ASR) projects as a unique water management technique to help meet peak summer water demands. Unique to the Pacific Northwest are the Miocene-age continental flood-basalt flows of the Columbia River Basalt Group (CRBG), which consists of a thick, areally extensive series of extraordinarily huge lava flows. The CRBG plays host to an extensive regional aquifer system in eastern Washington, eastern Oregon, and western Oregon. The two ASR projects discussed in this paper, the City of Beaverton and Madison Farms, use CRBG aquifers to host their ASR projects. Since 1999, the City of Beaverton (City), Oregon, population 85,500, has installed three ASR wells hosted in the CRBG aquifer. Currently, the City stores approximately 1,703,000 cubic meters of treated drinking water annually with its ASR wells. The three wells can provide up to about 22,700 cubic meters per day of peaking capacity, which is equivalent to 35 percent of the City's summer peak day demand. Favorable hydrogeologic response and significant economic savings have made the City's ASR system immensely successful. Since 2006, Madison Farms, a 71-square-kilometer farm near Echo, Oregon, has been using ASR to increase summer pumping capacity from the CRBG. Unlike the City of Beaverton, which uses treated river water to recharge the CRBG aquifer, Madison Farms uses untreated shallow alluvial groundwater to recharge the CRBG aquifer. Nitrate is the only constituent of concern for the Madison Farms ASR system and is monitored continuously to ensure recharge water does not have nitrate concentrations greater than the project-specific regulatory threshold of 7 milligrams per liter (mg/L). A nitrate analyzer is connected to the downhole control valve in the injection well that stops injection when the 7 mg/L threshold is met. The economics of Madison Farms' ASR system also are very favorable compared to the alternative of piping surface water from the Columbia River more than 22 kilometers to meet irrigation demands. Key lessons learned at each ASR project include: storage in basalt is highly successful; understanding well and aquifer hydraulics in CRBG aquifers, however, is challenging because of their unique geologic characteristics (e.g., tabular interflows and compartmentalization); aquifer clogging by air entrainment is a concern, but can be managed with the installation of a downhole control valve; recharge well design is important; radon dissolves quickly into stored water; natural filtration of shallow groundwater shows that it can be used to recharge deeper aquifers; surface water and shallow groundwater have proven to be geochemically compatible with native CRBG groundwater; continuous monitoring of recharge linked to a downhole control valve has proven to be successful; and ASR has proven to be a cost-effective peak water management technique.

Keywords: aquifer storage and recovery (ASR), Columbia River Basalt Group (CRBG), downhole control valve, nitrate, water storage

Implementación con éxito de la ASR en acuíferos basálticos en el Noroeste de los Estados Unidos

RESUMEN

A pesar de la reputación de húmeda de la zona Noroeste del Pacífico, muchas ciudades tanto al este como al oeste de la cordillera de las Cascadas, en Estados Unidos, están encontrando cada vez más dificultades para satisfacer las demandas puntuales de agua durante el verano. Los acuíferos situados al este de Oregon y Washington son la principal fuente de abastecimiento de una enorme industria agrícola, y han sufrido importantes descensos piezométricos, que han llevado al establecimiento de normas de explotación restrictivas. Por estas razones, tanto los municipios como la industria agrícola han optado por poner en marcha sistemas de almacenamiento y recuperación de acuíferos (ASR) como técnica de gestión unificada, para permitir satisfacer las demandas pico que se producen en verano. Característica exclusiva del Pacífico Noroeste es la presencia de grandes flujos basálticos de edad Mioceno que forman el Grupo Basáltico del Río Columbia (CRBG), el cual consiste en una potente y extensa capa de flujos de lava extraordinariamente grandes. Esta formación CRBG forma un extenso acuífero regional que se desarrolla entre el este del estado de Wahsington, y el este y el oeste del estado de Oregon. Los dos proyectos de ASR presentados en el presente artículo, en la ciudad de Beaverton y en las granjas de Madison, utilizan estos acuíferos par almacenar y recuperar el agua. Desde 1999, la ciudad de Beaverton, Oregon, con una población de 85.000 personas, ha instalado 3 pozos de ASR. Actualmente, se almacenan 1.700.000 m^3 de agua potable tratada en los sondeos. Estos 3 pozos pueden pro-

porcionar hasta 22,700 m³/día de capacidad máxima, lo que equivale al 35% de la demanda pico de la ciudad en verano. La óptima respuesta del acuífero desde el punto de vista hidrogeológico, así como un importante ahorro económico, han hecho del sistema de ASR de la ciudad de Beaverton un enorme éxito. Desde 2006, las granjas Madison, localizadas cerca de Echo, Oregón, y con una superficie de 71 km² han estado utilizando el ASR para incrementar la capacidad de bombeo desde el acuífero CRBG. Sin embargo, mientras que la ciudad de Beaverton utiliza agua tratada del río para recargar el acuífero, las granjas Madison utilizan agua subterránea procedente de un acuífero aluvial muy poco profundo. El único elemento de preocupación para el sistema ASR de las granjas Madison es el nitrato, y por ello se hace una medida continua del mismo para evitar que el agua de recarga exceda de concentraciones mayores de 7 mg/l. Un medidor de nitrato está conectado a la válvula de control, instalada en el fondo del sondeo de inyección, de manera que la misma se interrumpe cuando el agua de recarga alcanza el umbral de los 7 mg/l. Los indicadores económicos de este sistema de ASR son también muy favorables si se les compara con la alternativa de traer agua para el riego a través de un sistema de tuberías desde el río Columbia desde una distancia de 22 km. Las lecciones más importantes aprendidas durante cada uno de los proyectos de ASR son las siguientes: el almacenamiento en basaltos ha tenido un éxito considerable; la mejora en el conocimiento de la hidrodinámica de los pozos y del acuífero CRBG, aunque es complicada debido a sus características geológicas únicas (interflujos tabulares, compartimentación); la colmatación por aire es un problema, pero se puede paliar mediante la instalación de válvulas de control en el fondo de los sondeos de inyección; el diseño del pozo de recarga es importante; el radón se disuelve rápidamente dentro del agua almacenada; la recarga natural de los acuíferos someros puede utilizarse para recarga acuíferos más profundos; tanto el agua superficial como el procedente de estos acuíferos superficiales han demostrado ser compatibles con el agua nativa del acuífero CRBG desde el punto de vista geoquímico; el control continuo de la recarga, junto con las válvulas de control en el fondo de los sondeos proporcionan muy buenos resultados; y el ASR ha demostrado ser una técnica de gestión de las demandas pico rentable.

Palabras clave: almacenamiento y recuperación de acuíferos, almacenamiento de agua, ASR, CRBG, formación basáltica del río Columbia, nitrato, válvula de control en el fondo del sondeo

Introduction

The Pacific Northwest of the United States of America, consisting of the states of Washington, Oregon, and western Idaho, are geographically divided by the north-south trending Cascade Range into the west and east sides. The west side is considered "wet," with average rainfall of approximately 1,015 millimeters (mm)/year occurring mainly between October and June as storms from the Pacific Ocean roll across the states. East of the Cascade Range, it is much drier because of the rain shadow effect of the mountain range, with rainfall averaging less than 380 mm/year. The major municipalities in the Pacific Northwest are located on the "wet" side and include the Cities of Seattle, Washington, and Portland, Oregon (see Figure 1). Each of these cities has experienced growth and it is increasingly difficult for them, and their outlying communities, to meet peak water supply demands during the dry summer months. The main reasons: minimum stream flow requirements driven by fish habitat protection, difficulty in finding suitable aboveground reservoir sites in an increasingly urbanized environment, over-drafting of aquifers, state regulatory designation of "critical groundwater areas," and an increasing influx of new residents and businesses. Each of these elements has added to increased pressures on peak demand for many key west-side municipalities in Oregon and Washington. Figure 2 illustrates the low rainfall during the summer months in the Portland area; note it has less rain in July than the desert city of Phoenix, Arizona (195 mm/year). For the reasons stated, many cities on the west side have turned to aquifer storage and recovery (ASR) as an innovative water management technique to better meet peak demands. The ASR systems also provide a critical water supply facility centrally located in the cities that can be used during an emergency, such as a failure of the main water transmission line as the result of an earthquake.

East of the Cascade Range, smaller communities also have experienced rapid growth and have peak demand water supply pressures similar to those encountered by major west-side cities. In addition, groundwater is the primary water supply source east of the Cascade Range, and because of extensive agriculture and limited recharge by rainfall, aquifers on the east side have experienced significant impacts. Critical or limited groundwater areas have been designated by state agencies in Washington, Oregon, and Idaho in an effort to restrict and/or limit further groundwater withdrawal because of declining groundwater levels. These factors, combined with urban and rural growth pressures, have led select east-side cities, as well as agricultural interests, to explore and implement ASR.

Unique to the Pacific Northwest are the Miocene-age continental flood-basalt flows of the Columbia River Basalt Group (CRBG), which consists of a thick, areally extensive (Figure 3) series of extraordinarily huge lava flows. The vast size and rapid eruption rate for CRBG flows resulted in their emplacement as sheet flows and not as compound flows that typify most basaltic flow fields. Because CRBG flows were emplaced as sheet flows, and not compound flows,

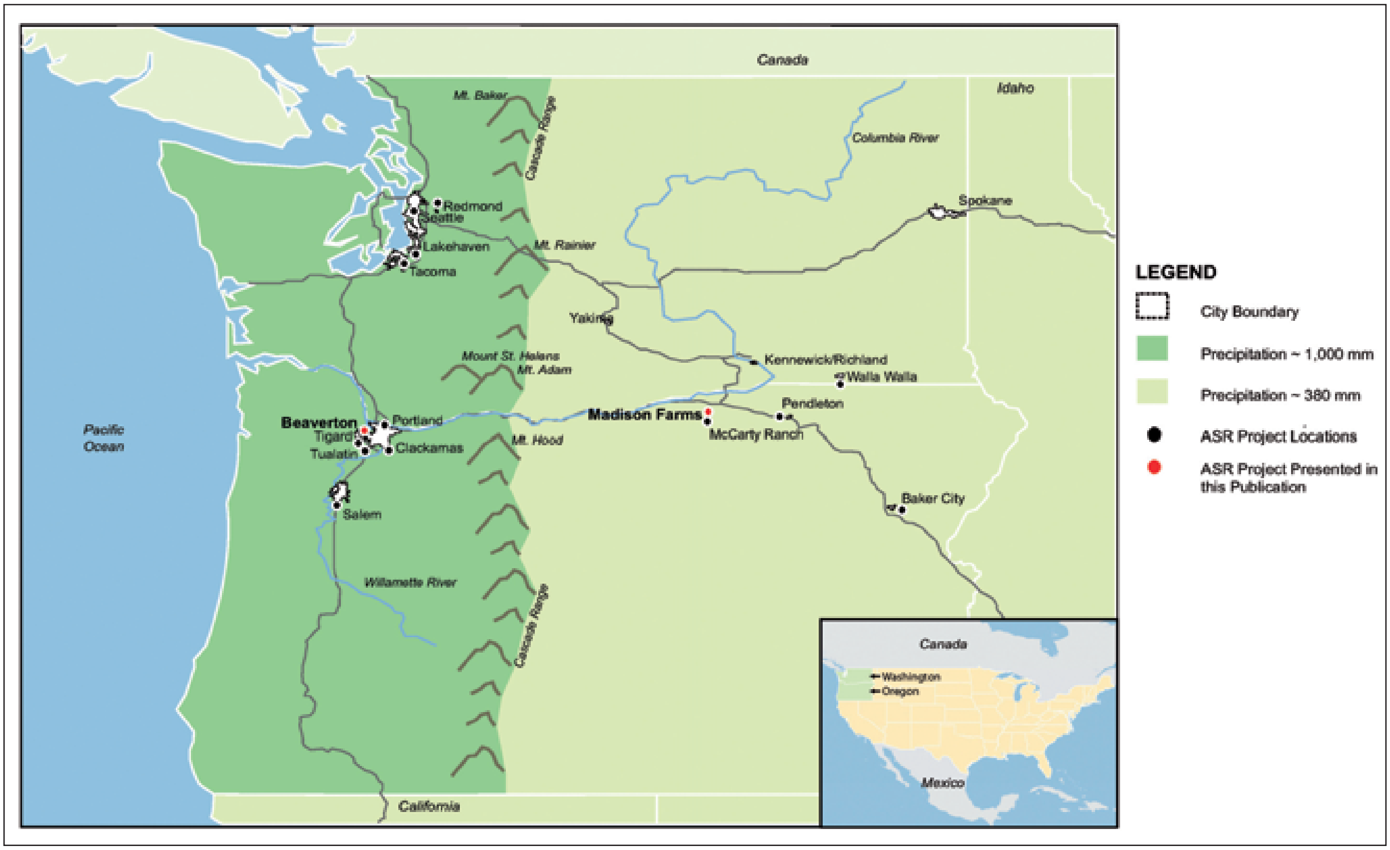

Figure 1. Aquifer storage and recovery (ASR) projects in the Pacific Northwest
Figura 1. Proyectos de ASR en el Pacífico Noroeste

this fact has profound ramifications regarding how groundwater behaves within a CRBG section. The CRBG typically consists of a series of individual, confined aquifers, which is in direct contrast to aquifers hosted by compound flows that can behave much differently because there is no clear hydraulic separation between flows (see subsequent section).

The CRBG plays host to an extensive regional aquifer system in western Idaho, eastern Washington, eastern Oregon, and western Oregon. The two ASR projects discussed in this paper, City of Beaverton, Oregon, and Madison Farms, near Echo, Oregon, use CRBG aquifers and these CRBG aquifers have proven to be successful at hosting ASR systems (see Figure 1) for many communities, east and west of the Cascade Range, allowing them to better meet peak demand periods during dry summer months. Specifically, the ASR systems presented allow the communities and/or entities to store water during times when it is more readily available (winter months) and recover it during high demand periods (summer months). For these case studies, ASR has proven to be a successful water management technique.

The objective of this paper is to provide a basic understanding of the geology and hydrogeology of the CRBG aquifer system and how it has been used successfully to host two ASR systems. The paper presents detailed economics of two ASR case studies, the City of Beaverton and Madison Farms, to illustrate the cost-benefits of implementing ASR.

Geology and Hydrogeology of the Columbia River Basalt Group

General

The CRBG consists of a thick sequence of more than 300 continental tholeiitic flood-basalt flows that covers portions of western Idaho, Oregon, and Washington (Figure 3). The CRBG covers more than

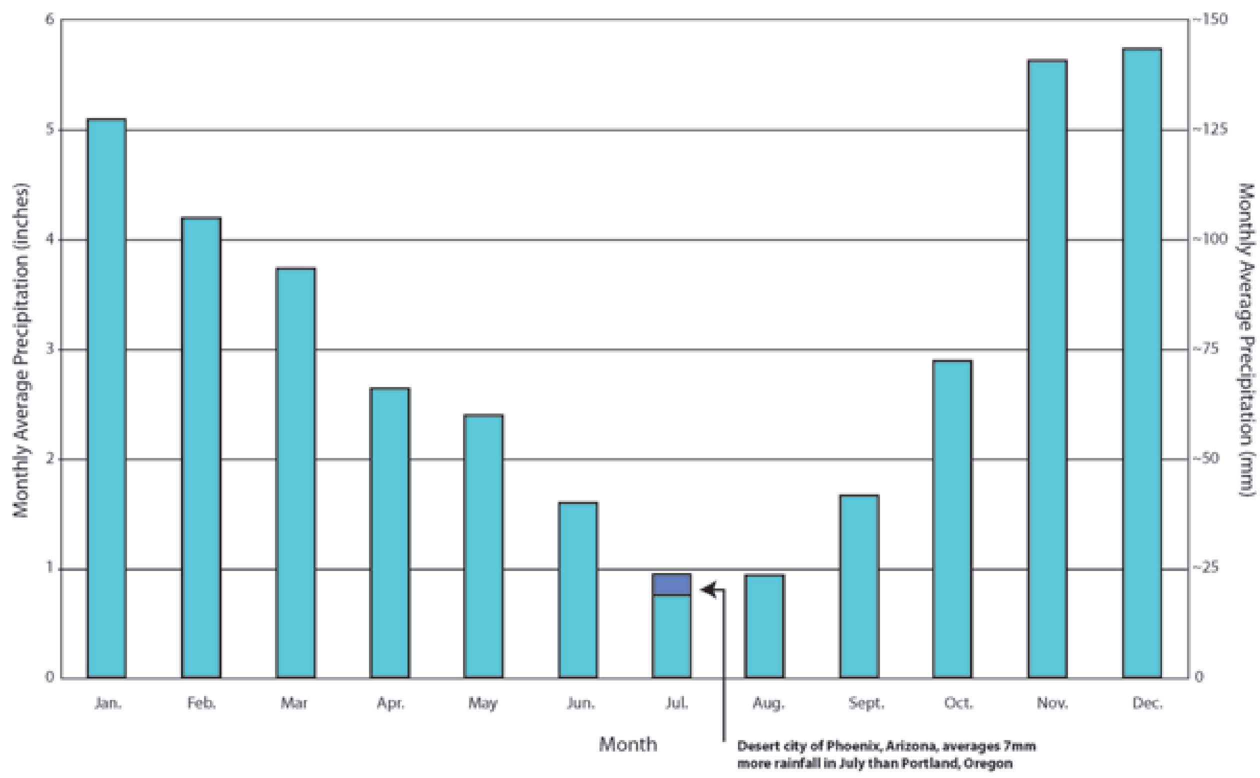

Figure 2. Beaverton-Portland, Oregon, monthly precipitation
Figura 2. Precipitación mensual en Beaverton-Portland, Oregón

164,000 square kilometers (km^2) and has a total estimated volume of more than 174,000 cubic kilometers (km^3) (Tolan et al., 1989), and has a maximum thickness of more than 3.2 kilometers near Pasco, Washington (Reidel et al., 1982, 1989a). CRBG flows were erupted during a period from about 17 to 6 Ma from long (10 to >112 kilometer-long, north-northwest-trending linear fissure systems located in eastern Washington, northeastern Oregon, and western Idaho. No vents or feeder dikes for CRBG flows have been identified in western Oregon or Washington (Swanson et al., 1981; Beeson et al., 1979, 1989).

Although CRBG eruptive activity spanned an 11-million-year period, most (>96 volume-percent) of the CRBG flows were emplaced during a 2.5-million-year period from 17 to 14.5 Ma (Figures 3A and 4; Swanson et al., 1979a; Tolan et al., 1989). During this intense period of CRBG volcanism, most of the flows emplaced were of extraordinary size, commonly exceeding 1,000 km^3 in volume (some exceeding 2,000 km^3), traveled hundreds of kilometers from their fissure systems, and covered many thousands of square kilometers (Tolan et al., 1989; Reidel et al., 1989b). These gigantic CRBG flows are hundreds to thousands of times larger than any lava flow erupted during recorded human history. CRBG flows represent the largest individual lava flows known on the earth (Tolan et al., 1989).

The flowage of lava away from the vent systems was directed by major tectonic features (i.e., Palouse Slope, Columbia Basin, Columbia Trans-Arc Lowland) and continued regional subsidence (Reidel et al., 1994; Beeson et al., 1989; Reidel and Tolan, 1992) that combined to produce a westward, regional down-gradient pathway (Figure 5). Of these features, it was the Columbia Trans-Arc Lowland that provided the CRBG flows with a lowland route across the Miocene Cascade Range to the Pacific Ocean (Beeson et al., 1989; Beeson and Tolan, 1990). Without the presence of the Columbia Trans-Arc Lowland, and the continued subsidence that maintained its viability as a pathway, CRBG flows would have ponded against the eastern slope of the Miocene Cascade Range.

Regional studies and mapping of the CRBG have

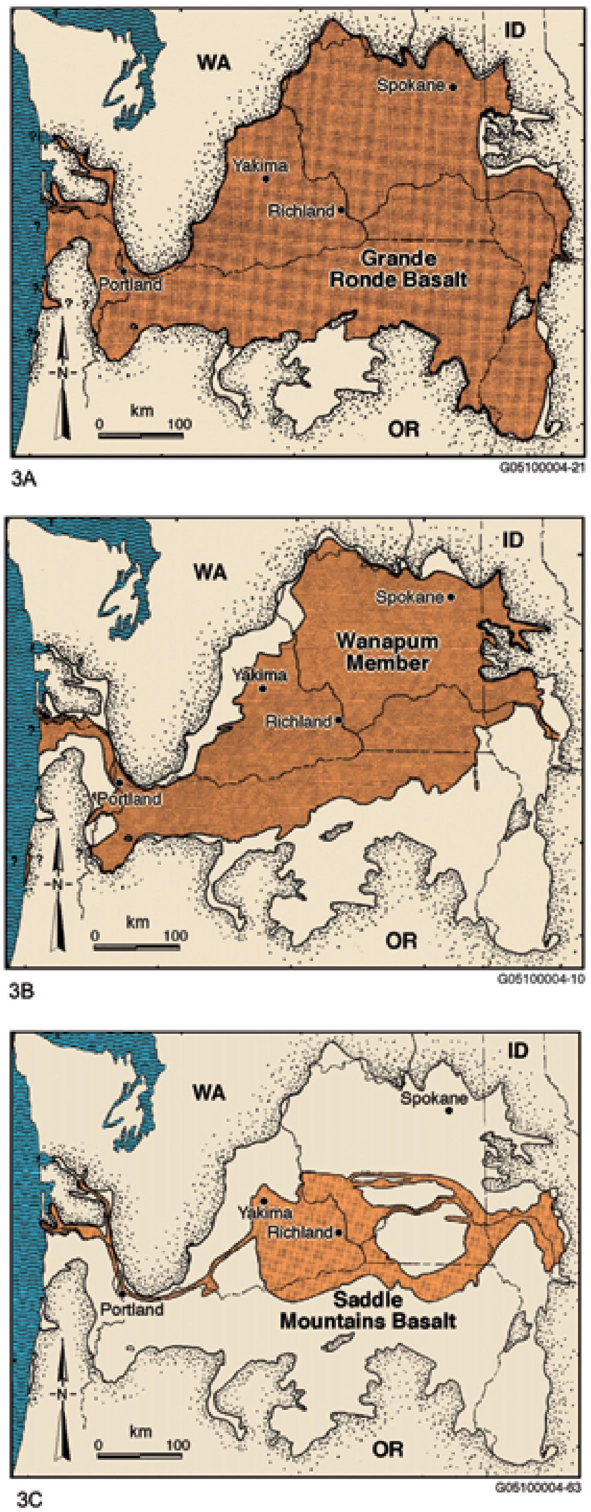

Figure 3. Columbia River Basalt Group (CRBG) areal extent of distinct flows [modified from Tolan et al. (1989)]. 3A. Grande Ronde Basalt. 3B. Wanapum Basalt. 3C. Saddle Mountains Basalt

Figura 3. Grupo basáltico del Río Columbia (CRBG). Extensión de los distintos flujos (modificado de Tolan et al.,1989). 3A Basalto de Grande Ronde. 3C Basalto Wanapum. 3C Basaltos de las montañas Saddle

demonstrated that there are consistent and systematic variations in lithology, geochemical compositions, and paleomagnetic polarity among flows and groups of flows. These differences have allowed for the establishment of stratigraphic units within the CRBG (Figure 4) that can be reliably identified and mapped on a regional basis (e.g., Swanson et al., 1979a, 1981; Beeson et al., 1985; Reidel et al., 1989b; Reidel, 2005). Aquifers hosted by units of the Grande Ronde Basalt primarily are used in the ASR projects that are discussed in the following sections. Waning CRBG volcanism produced the volumetrically smaller Wanapum Basalt (about 15.5 to 14.5 Ma; Figure 3B) and the Saddle Mountains Basalt (about 14 to 6 Ma; Figure 3C) (Swanson et al., 1979a; Beeson et al., 1985).

Physical Characteristics of CRBG Flows

As mention above, the rather unique physical character of CRBG flows plays an important role in controlling the location, hydraulic characteristics, and behavior of groundwater within the CRBG. The purpose of this section is to provide a brief review of the physical characteristics of CRBG flows that have an effect on the hydraulic properties of these rocks.

Mode of Emplacement

Rate/volume of lava erupted, lava composition/temperature (rheology), vent geometry, topography, and environmental conditions are believed to be of central importance in the eruption, emplacement, and overall geometry of individual basalt lava flows or flow fields (Shaw and Swanson, 1970; Reidel and Tolan, 1992; Reidel et al., 1994; Beeson et al., 1989; Self et al., 1997; Beeson and Tolan, 1996).

There are two basic types of flow geometries, compound and sheet (Figure 6). A compound flow develops when the flow advances away from its vent in a series of distinct and separate lobes of flowing lava. Each lobe is subsequently covered by later lava lobes as the eruption continues. As the lava cools, this results in the accumulation of elongated bodies of basalt rock with numerous, local, discontinuous, thin layers of dense basalt (Figure 6). In comparison, a sheet flow results when erupted lava flows away from a fissure system largely as a single, uniform, moving sheet of lava. As the sheet of lava cools, a relatively extensive layer (or "sheet") of dense basalt will form. Each successive sheet flow will create a similar layer or sheet flow geometry, with the flow

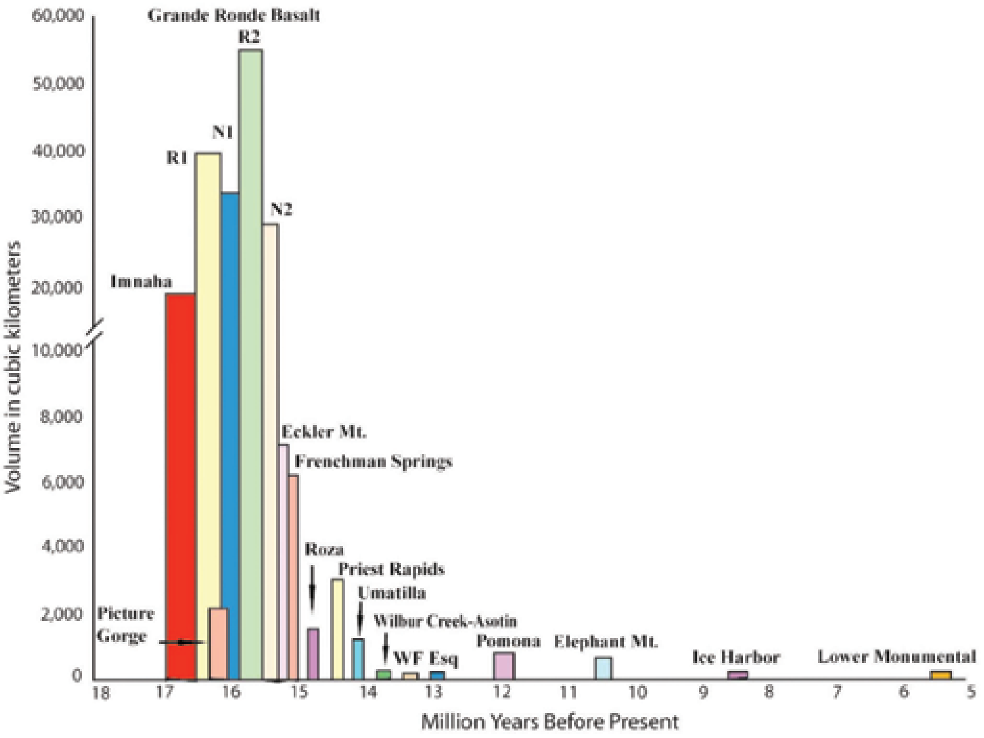

Figure 4. CRBG eruptive activity [modified from Tolan et al. (1989)]
Figura 4. Actividad eruptiva en el CRBG (modificado de Tola et al., 1989)

boundaries being delineated by distinct vesicular flow tops and bottoms.

Individual, large-volume CRBG flows (especially Grande Ronde and Wanapum Basalts) are voluminous, thick (commonly more than 30 meters thick), and generally do not display a complex flow lobe structure, but instead display the characteristics of sheet flows (Swanson et al., 1979a, 1979b; Tolan et al., 1989; Reidel et al., 1989a, 1989b, 1994; Reidel and Tolan, 1992; Beeson et al., 1985, 1989; Beeson and Tolan, 1990, 1996; Reidel, 1998). Generally, areally extensive CRBG flows only exhibit physical features and characteristics expected of sheet flows, with the complex internal features associated with compound flows found only at flow margins (Beeson et al., 1989; Reidel and Tolan, 1992; Reidel et al., 1994; Beeson and Tolan, 1996; Reidel, 1998).

Intraflow Structures

Vertical exposures through CRBG flows reveal that they all exhibit the same basic three-part internal arrangement of geologic features (Figure 7). These intraflow structures originated during the emplacement and cooling of the lava flow and are referred to as the flow top, flow interior, and flow bottom. The combination of a flow top of one flow and the flow bottom of the overlying flow is commonly referred to as the "interflow zone."

The flow top is the crust that formed on the top of a molten lava flow. Flow tops commonly consist of glassy to very fine-grained basalt that is riddled with numerous spherical and elongate voids (vesicles), giving this portion of the flow the appearance of a sponge. Vesicles represent gas bubbles that were trapped (frozen) as the flow cooled and solidified. These gasses were originally dissolved within the lava (magma) when it was deep underground, but the reduction in pressure (and subsequent decrease in temperature) as the magma reached the surface allowed these gasses to come out of solution and create bubbles within the lava. CRBG flow tops can display a wide range of variation in both their physical character and thickness (U.S. DOE, 1988). The physical character of a flow top falls between two

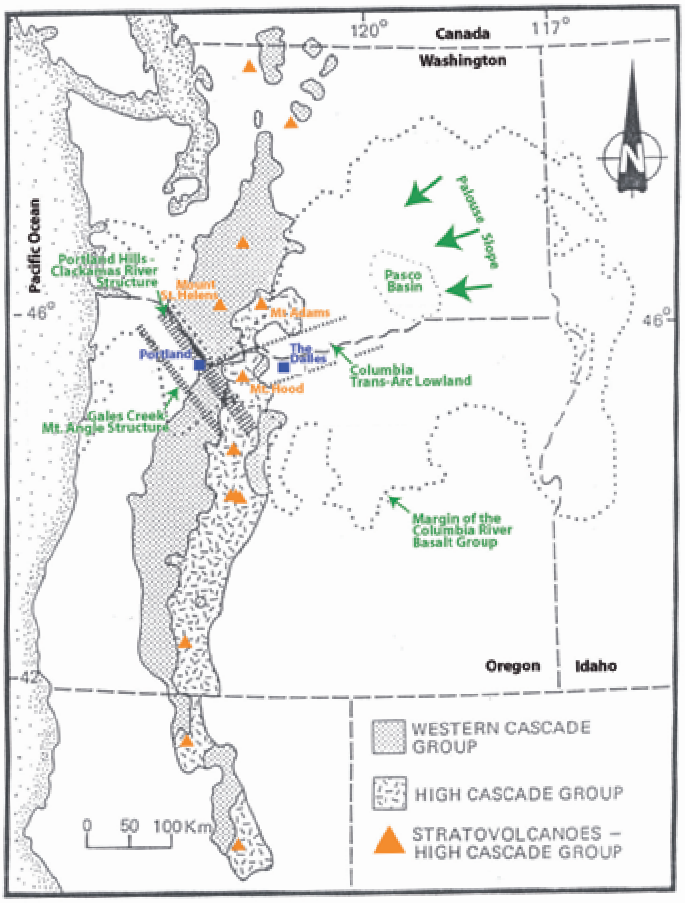

Figure 5. Structural and topographic control of CRBG
Figura 5. Control estructural y topográfico del CRBG

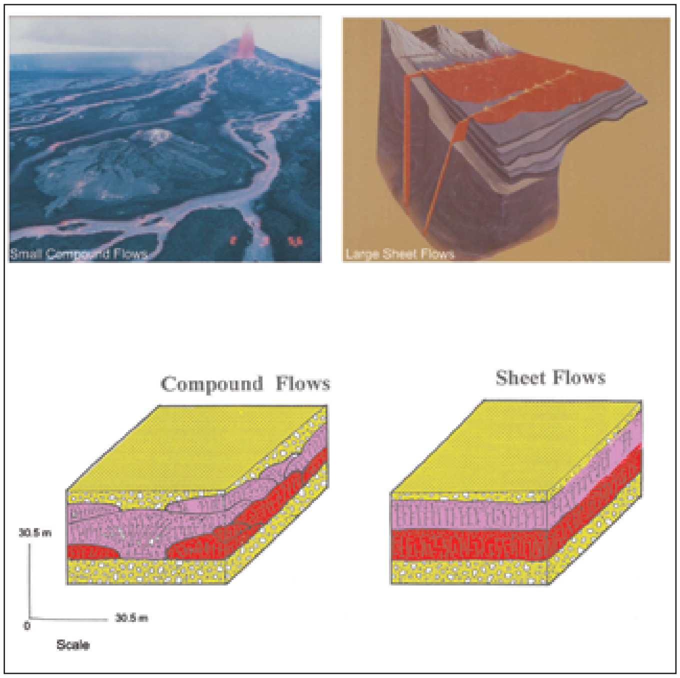

Figure 6. Compound versus sheet basalt flows
Figura 6. Flujos basálticos compuestos frente a laminares

basic end-members, a simple vesicular flow top and a flow top breccia (Figure 7).

A simple vesicular flow top (Figure 7) commonly consists of glassy to fine-grained basalt that displays a rapid increase in the density of vesicles near the top of the flow (U.S. DOE, 1988; McMillan et al., 1989). Vesicles may be isolated or interconnected, resulting respectively in lower and higher permeability and porosity (U.S. DOE, 1988). Tension cooling joints, related to flow top formation/flow emplacement, augment the permeability and porosity of the flow top. Simple vesicular flow tops typically will comprise 5 to 10 percent of the total thickness of the flow.

A flow top breccia (Figure 7) consists of angular, scoriaceous to vesicular fragments of basaltic rubble that lie above a zone of non-fragmented, vesicular basalt. Flow top breccias can be very thick (in some cases comprise half the entire thickness of the flow, more than 30 meters in thickness) and are laterally very extensive (U.S. DOE, 1988). There are two models for the origin of CRBG flow top breccias: (1) an autobrecciation process like that which creates 'aa' flows, as observed in Hawaii, and (2) rafted scoria originally produced along the vent system and subsequently rafted away on top of the flowing lava. In either case, laterally extensive flow top breccias can have a high degree of interconnected pore space resulting in formation of widespread and highly permeable aquifers at the tops of individual basalt flows (Newcomb, 1969; U.S. DOE, 1988).

CRBG flow interiors typically consist of dense, non-vesicular, glassy to crystalline basalt that contains numerous cooling joints that formed when the lava shrank as it solidified. CRBG cooling joints often form regular patterns or styles, with the two most common being entablature-colonnade and columnar-blocky jointing (Figure 7). A columnar-blocky jointed basalt flow (Figure 7) typically consists of mostly vertically oriented, relatively well formed to poorly formed, polygonal columns that can range from 0.3 to more than 3 meters in diameter. The vertical columns often are cut by horizontal to sub-horizontal joints. Entablature-colonnade jointed basalt flows (Figure 7) display a more complex pattern. Most such flows display a pattern of numerous, irregular jointed small columns to apparently random oriented joints, called the entablature. This entablature generally overlies a

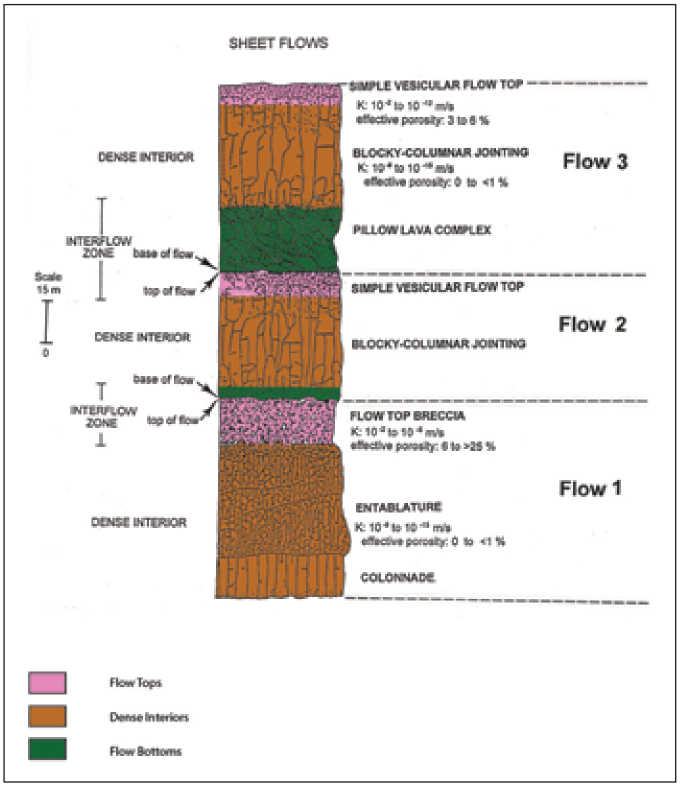

Figure 7. CRBG geomorphology and hydraulic properties [from Tolan et al. (2000)]
Figura 7. Propiedades hidráulicas y geomorfológicas del CRBG (de Tolan et al., 2000)

Figure 8. Beaverton's source water, Scoggins Reservoir, at 12 percent fill capacity in October 2001
Figura 8. El embalse de Scoggins, frente de agua para Beaverton, al 12 % de su capacidad en octubre de 2009

thinner zone displaying well-developed columnar jointing and is called the colonnade. The transition zone between the two is very narrow, commonly less than an centimeter in width. Another characteristic of entablature is that the basalt comprising it contains a high percentage of glass (more than 70 percent) in contrast to the colonnade (Long and Wood, 1986; U.S. DOE, 1988). The entablature portion of the flow typically is thicker than its basal colonnade.

Studies on the nature and characteristics of cooling joints within the CRBG (U.S. DOE, 1988; Lindberg, 1989) have found that undisturbed joints are narrow, averaging 0.23 millimeter wide, and that there is no difference in joint widths between entablature and columnar-blocky jointing despite the extreme difference in their appearance.

The physical characteristics of CRBG flow bottoms are largely dependent on the environmental conditions the molten lava encountered as it flowed across the Earth's surface. If the lava flow encountered relatively dry ground conditions, the flow bottom typically consists of a narrow (less than 1 meter-thick) zone of sparsely vesicular, glassy to very fine-grained basalt. This type of flow bottom structure is very common within the CRBG. If advancing flows encountered lakes, rivers, and areas of water-saturated, unconsolidated sediments, more complex flow bottom structures (e.g., pillow lava complexes, hyaloclastites, peperites, and spiracles) may form (Mackin, 1961; Grolier and Bingham, 1978; Swanson et al., 1979a, 1979b; U.S. DOE, 1988; Beeson et al., 1989). Flow bottom structures can be either highly localized or widespread.

CRBG Hydrogeology

General

Numerous studies of CRBG aquifers have been conducted within this flood-basalt province to better understand their hydraulic characteristics and to develop a model of how various factors (e.g., CRBG flow physical characteristic/properties, tectonic features/properties, erosional features, climate, etc.) interact to create and govern this confined groundwater system (e.g., Hogenson, 1964; Newcomb, 1961, 1969; Brown, 1978, 1979; Gephart et al., 1979; Oberlander and Miller, 1981; Livesay, 1986; Drost and Whiteman, 1986; Lite and Grondin, 1988; Davies-Smith et al., 1988; U.S. DOE, 1988; Burt, 1989; Johnson et al., 1993; Hansen et al., 1994; Spane and

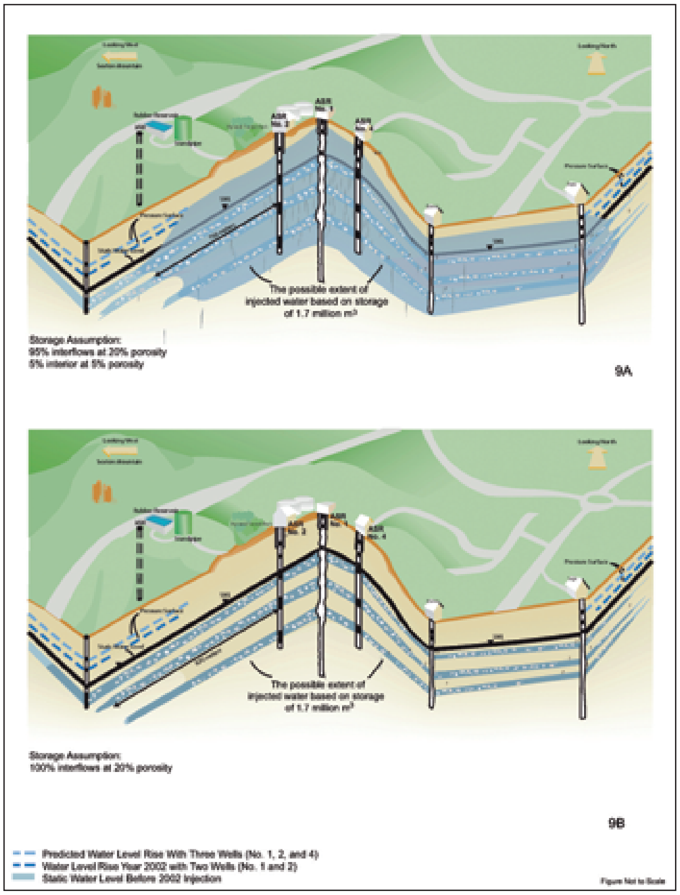

Figure 9. Conceptual hydrogeological model of the Beaverton ASR system

Figura 9. Modelo hidrogeológico conceptual del sistema ASR de Beaverton

Webber, 1995; Wozniak, 1995; Steinkampf and Hearn, 1996; Packard et al., 1996). One of the overall significant findings that have come out of these studies is the general similarity of the hydrogeologic characteristics, properties, and behavior of these aquifers across this entire region. Therefore much of the general knowledge that has been learned about the characteristics and behavior of the CRBG aquifers is readily applicable to CRBG aquifers in other areas.

Hydraulic Characteristics of CRBG Flows

This section will present a brief review and discussion of the principal hydraulic characteristics of CRBG flows derived by both indirect (qualitative) and direct (quantitative) means. Having an accurate understanding of these characteristics is a critical component in developing an understanding of the CRBG aquifer system.

It is widely agreed that within CRBG aquifers, given the typical distribution and physical characteristics of CRBG intraflow structures, groundwater primarily resides within the interflow zones (Newcomb, 1969; Oberlander and Miller, 1981; Lite and Grondin, 1988; U.S. DOE, 1988; Davies-Smith et al., 1988; Wozniak, 1995; Tolan and Lindsey, 2000). As discussed above, an interflow zone (Figure 7) is defined as the flow top of one flow and the flow bottom of the overlying flow (plus any interbedded sediment). CRBG interflow zones are stratiform, tabular, laterally extensive bodies, which clearly have physical properties conducive to forming an aquifer. The presence of interbedded sediments can either enhance (e.g., sandstone and conglomerate) or inhibit (e.g., mudstone and paleosols) groundwater storage and movement within this zone. Another critical aspect with regards to interflow zones, that is not commonly recognized, is their potential lateral variability. For example, thick flow top breccias are known to abruptly end with a much thinner normal flow top taking its place. The same is true for flow bottom features (e.g., pillow lava complexes) that can abruptly end or transition to a more simple flow bottom. These intraflow structure "facies changes" can result in radically changing the hydraulic properties and behavior of individual CRBG aquifers.

The physical properties of undisturbed, laterally extensive, dense interiors of CRBG flows (Figure 7) make this portion of the flow essentially an impermeable layer for all practical purposes (Newcomb, 1969; Oberlander and Miller, 1981; Lite and Grondin, 1988; U.S. DOE, 1988; Davies-Smith et al., 1988; Lindberg, 1989; Wozniak, 1995). While the dense interior portion of a CRBG flow is replete with cooling joints, in their undisturbed state these joints have been found to be typically 77 to +99 percent filled with secondary minerals (clay, silica, zeolite) and void spaces that occur are typically not interconnected (U.S. DOE, 1988; Lindberg, 1989). The fact that CRBG dense flow interiors typically act as aquitards accounts for the confined behavior exhibited by most all CRBG aquifers. In many areas around the flood-basalt province, artesian (flowing) conditions within the CRBG aquifer system have been encountered by well drillers.

Various methods have been used to calculate CRBG interflow and dense interior hydraulic properties. These methods range from laboratory testing of core, to in situ single borehole testing, to multiple well tests (e.g., LaSala and Doty, 1971; Shannon & Wilson, Inc., 1972, 1973a, 1973b; Gephart et al., 1979;

Oberlander and Miller, 1981; Strait and Mercer 1987; Lite and Grondin, 1988; U.S. DOE, 1988; Davies-Smith et al., 1988; Wozniak, 1995). The overall applicability of hydraulic properties determined by laboratory testing of core samples (e.g., LaSala and Doty, 1971) has been questioned because of significant disagreement between laboratory results and field results (Gephart et al., 1979; U.S. DOE, 1988). It is believed that the coring process inherently "disturbs" the sample and small-scale heterogeneities within the small-volume sample combine to produce non-representative results (U.S. DOE, 1988).

Hydraulic properties can be measured by drilling into the zone of interest, isolating it, and performing various injection and extraction (or pumping) tests. This type of testing has been conducted at the U.S. DOE Hanford Site (south-central Washington) and the results are summarized in U.S. DOE (1988). These investigations at the Hanford Site were conducted from about 1975 to 1988 and used 19 boreholes that were drilled using "drill and test" methods (U.S. DOE, 1988). This technique typically involved drilling down to the target test zone, isolating the zone with packers, and development pumping for hydrologic tests and groundwater sampling. After completing a test, the zone was sealed (grouted with cement to prevent aquifer intermixing) before drilling to the next lower test zone. This sequence was repeated until the deepest test was completed. Representative hydraulic properties for CRBG intraflow structures derived from these investigations are summarized in Figure 7.

Secondary Controls on CRBG Hydraulic Characteristics

There are several processes that can modify the specific, and overall, hydraulic behavior of CRBG aquifers and aquitards. These include tectonic fracturing forming faults/tectonic joints, folding, secondary mineralization, and construction of uncased water wells through multiple CRBG aquifers. The potential effect and impact of these various processes on CRBG groundwater systems can range from benign to profound. Understanding their impact on CRBG aquifers is critically important to accurately interpret the behavior of CRBG groundwater systems.

Groundwater investigations in the Columbia Plateau area have determined that faults can affect the occurrence and movement of groundwater through CRBG aquifers (e.g., Newcomb 1959, 1961, 1969; Gephart et al., 1979; Oberlander and Miller, 1981; Lite and Grondin, 1988; U.S. DOE, 1988; Burt, 1989; Johnson et al., 1993; Packard et al., 1996). Impacts to the CRBG aquifer system from faults include:

- Forming barriers to the lateral and vertical movement of groundwater; a series of faults can create hydrologically isolated areas or compartments.
- Providing a vertical pathway (of varying length) for groundwater movement allowing otherwise confined CRBG aquifers to be in direct hydraulic communication.
- Exposing interflow zones creating local opportunities for aquifer recharge and/or discharge.

The ability of faults to affect the CRBG aquifer system in a variety of ways reflects the potential for both lateral and vertical heterogeneities in the physical characteristics of fault zones. For example, the degree of secondary alteration and mineralization along a fault zone may vary. Complete alteration and/or mineralization of fault shatter breccias and gouge zones would "heal" these features and produce rock of very low permeability. Variations in the completeness of this process would produce hydrologic heterogeneities along the trace of the fault. Even if a fault zone is completely healed by secondary alteration and mineralization, renewed movement (displacement) on the fault could produce new permeability within the healed shatter breccia (e.g., U.S. DOE, 1988; Johnson et al., 1993).

Several groundwater investigations in the Columbia Plateau area have noted that folds (primarily anticlinal and monoclinal folds) affect the occurrence and movement of groundwater through the CRBG aquifer system (e.g., Newcomb 1961, 1969; Gephart et al., 1979; Oberlander and Miller, 1981; Lite and Grondin, 1988; U.S. DOE, 1988; Burt, 1989; Packard et al., 1996). In many cases, folds have been identified as groundwater barriers or impediments that either block or restrict lateral groundwater movement through the CRBG aquifer system (e.g., Newcomb, 1969; Oberlander and Miller, 1981; U.S. DOE, 1988). Because most of the folds in this region have genetically related faults, one would initially suspect that the observed impacts of folds on the CRBG groundwater system are caused by related faults. However, the process of folding CRBG can affect the hydraulic characteristics of interflow zones.

During the process of folding, slippage parallel to the layers (CRBG flows) will occur, in part, to accommodate structural shortening. An analogy for this process is seen when a deck of playing cards is flexed and the individual cards slip past one another to accommodate the flexure: The tighter the flexure of the cards, the greater the "intercard" slippage. In folds, this type of flexural slip typically occurs within CRBG interflow zones (Newcomb, 1969; Price, 1982;

Anderson, 1987), which are the mechanically weakest layers in the CRBG. The effects of this flexural slip on the CRBG interflow zone range from minor shearing to nearly complete destruction (production of fault shatter breccia/gouge material) and are directly related to the intensity and magnitude of deformation (Price, 1982; Anderson, 1987). This process also affects the original hydraulic characteristics of interflow zones, reducing or even destroying the permeability of these features (Newcomb, 1969). In contrast, recent faulting and/or folding, where the fractures have not had time to heal, actually can enhance permeability of the interflows and possibly the interiors of the basalt sections.

A number of different secondary processes also can change the physical characteristics of CRBG interflow zones, which, consequently, alter the hydraulic properties of these features. The common aspect to all of these secondary processes is that they fundamentally change the original physical (and hydraulic) characteristics of CRBG flow tops and flow bottoms. The two most important of the natural processes are:

- Paleosol development. If a sufficiently long hiatus occurred between emplacement of CRBG flows (more than 50,000 to 100,000 years), weathering and chemical breakdown of the glassy vesicular flow top will occur and lead to soil formation. This process alters the original physical texture of the flow top and decreases its original permeability. The extent of the flow top involved, and degree to which these paleosols are developed, varies tremendously. Factors controlling their development are thought to be duration of interval before flow top is covered by the next CRBG flow, absence of sediment cover, and environmental conditions (e.g., climate, vegetation, paleogeography, etc.).
- Secondary mineralization. After the emplacement and burial of the CRBG flows, secondary minerals (e.g., silica, cryptocrystalline quartz, calcite, zeolite, pyrite, clay minerals, etc.) can partially to completely fill existing voids within interflow zones. Processes by which precipitation of these minerals occurs can be very complex and are dependent on a host of variables including groundwater hydrochemistry, groundwater mobility/mixing rates, groundwater residence time, and local geothermal regime (U.S. DOE, 1988). The net effect of secondary mineralization on CRBG interflow zones is a reduction, ranging from slight to total, in the per-

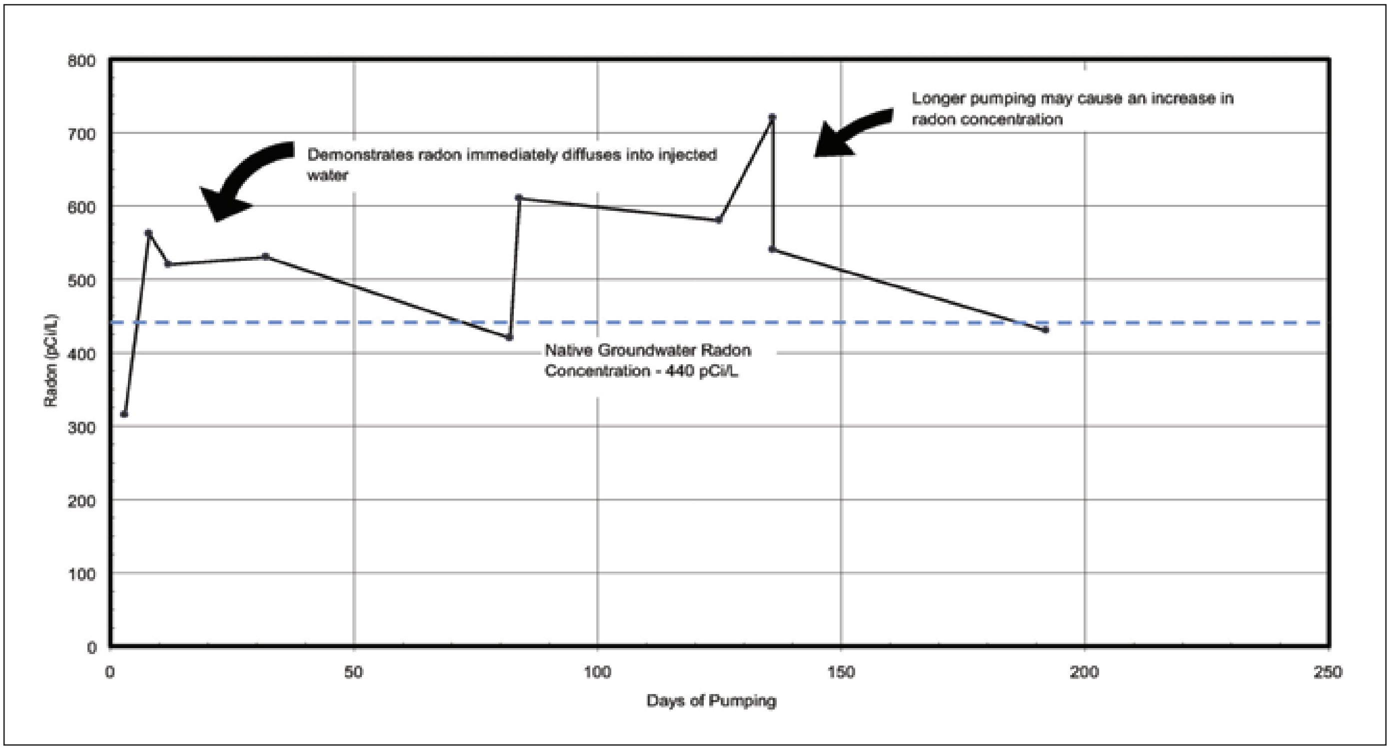

Figure 10. Radon concentration in recovered water
Figura 10. Concentración de radón en el agua recuperada

meability of these zones. This process also is important in sealing cooling fractures in dense flow interiors.

Finally one of the most extensive impacts to the CRBG aquifer system is that caused by construction of water wells that are open to more than one CRBG interflow zone. Throughout the flood-basalt province, many tens of thousands of water wells have been drilled and completed in the past 100 years. Except in the past few years, most of these wells have been completed with very minimal lengths of sealed casing to maximize the amount of open borehole interval. This well construction practice has been traditionally favored because it was believed that the more interval open to the CRBG, the greater the potential for water production. This is a result of the fact that the CRBG has been generally treated as a single aquifer instead of a multiple-aquifer system. This practice is changing because of regulatory rules that have been instituted during the last 30 years in Washington, Oregon, and Idaho. However, the tens of thousands of existing wells create manmade vertical pathways, which potentially allow groundwater to migrate between individual CRBG aquifers having different hydraulic heads (U.S. DOE, 1988; Wozniak, 1995). Therefore in regions where groundwater within the CRBG is the primary source of domestic, agricultural, and/or industrial water, the CRBG aquifer system can have a significant degree of vertical connectivity because of water wells. Where this is the case, characterization of individual CRBG aquifer hydrologic properties, using data derived from the various types of "open-well" hydrologic tests and observations, can tend to bias the data to reflect higher transmissivities because multiple interflows are contributing to the well, thus making interpretation of hydraulic test data more difficult to evaluate.

Case Studies

This section presents ASR case studies hosted in CRBG aquifer systems that the authors have been involved with during the past 8 years. The case studies included are the City of Beaverton, located near Portland, Oregon, on the "wet side" of the Cascade Range, and Madison Farms, located in drier eastern Oregon. The latter is an example of an agricultural application of CRBG ASR technology. Economic data for the various ASR projects also are presented. The purpose of presenting the case studies is to provide the reader with examples of "real world" applications of ASR systems developed in CRBG aquifers.

City of Beaverton

The City of Beaverton (City/Beaverton), located southwest of Portland, is on the "wet" side of the State of Oregon (see Figure 1). Beaverton, like many growing cities west of the Cascade Range, faced continued growth and pressure to meet peak summer-time water demands. Beaverton recognized these supply hurdles in the early 1990s and opted to evaluate and test ASR to help offset peaking demands.

Beaverton's ASR program involves injecting treated drinking water from the Joint Water Commission (JWC) water treatment plant into a basalt aquifer that is closed to native groundwater withdrawals. The JWC receives its water from the Trask and Tualatin Rivers via Henry Hagg Lake (also known as Scoggins Reservoir; see Figure 8) and Barney Reservoir (coastal impoundments operated by the U.S. Bureau of Reclamation). Specifically, stored water is released on the basis of Beaverton's daily needs during the summer peak season to maintain stream flows in the Trask and Tualatin Rivers, where it is eventually pumped to the JWC treatment plant to produce finished drinking water before it is piped to Beaverton. The City has water rights ownership in the reservoirs. During drought years, the amount of water available from the reservoirs is uncertain. In addition, Beaverton's transmission line capacity from the JWC treatment plant is limited to 53,000 cubic meters per day (m^3/day). Upsizing the transmission line would be costly. For these primary reasons, the City developed ASR as a way to help meet peak demands, and, in part, to help offset water supply issues.

This section will briefly describe the hydrogeologic setting, the City's current ASR system, and lessons learned during development and operation of the system during the past 8 years, and will present a brief summary of a cost/benefit analysis the City completed to evaluate the City's ASR system against more conventional options to meet peak water demand.

Hydrogeology of Beaverton's ASR System

The Beaverton ASR wells at the Sorrento Water Works facility (Sorrento facility) are completed in units of the Grande Ronde Basalt of the CRBG. At the Sorrento facility (ASR No. 1, ASR No. 2, and ASR No. 4), three Grande Ronde interflow zones are believed to host the primary aquifers used for ASR. These three Grande Ronde interflow zones range in thickness from 3 to 12 meters. In Beaverton, these Grande Ronde aquifers collectively exhibit a confined to semiconfined behavior and have an average transmissivity of about 1,000 square meters per day (m^2/day) based on late-time data and a storage coefficient of 1 x 10^{-4}. In the Sorrento area, it is believed that structural deformation (horst structure) has produced secondary fracturing that transects the Grande Ronde flows that may have locally increased the hydraulic connection between individual Grande Ronde interflow zones. Faults are present in the area and either act as no-flow boundaries or leaky boundaries.

For example, the Mattel site, located approximately 2.5 kilometers east of the ASR site, has a network of monitoring wells installed within the Grande Ronde Basalt aquifer system (same units as penetrated by the Beaverton ASR well network) to track groundwater contamination. The Mattel site is a state-regulated cleanup site with groundwater affected by chlorinated solvents. No response has been observed in the Mattel monitoring wells since the start of the Beaverton ASR operation. In contrast, a measurable response from Beaverton's ASR activities at the Sorrento facility is observed at an historic seep more than 2 kilometers northwest of the site and at a future City ASR well (ASR No. 3) located more than 4 kilometers south of the site. In addition, a state observation well has shown a response to ASR activities more than 2.5 kilometers south of the site. The latter well is unique in that it is completed in basin sediments (overlying the Grande Ronde Basalt section). However, these younger basin sediments are juxtaposed against the older Grande Ronde Basalt section by faulting, which likely allows for a direct hydraulic connection between the units.

Generally, it is believed that many of the faults in the CRBG beneath Beaverton are leaky, which, in part, is displayed in pump test data because the drawdown and recovery curves do not match an expected theoretical confined aquifer (Theis) response. Specifically, the response is less than that predicted by the Theis-type curve in early-time data (1,000 minutes or less) and the response is greater than the Theis-type curve in late-time aquifer test data. Alternatively, there could be a combination of leaky faults and lateral changes in the transmissivity of the interflow zones (lateral hetrogeneities) that results in non-Theis-type curve responses. Figures 9A and 9B present two conceptual generalized hydrogeologic cross sections through the Sorrento facility, host to the City's three ASR wells. The first section, Figure 9A, shows that the interflow zones are interconnected because of secondary fracturing related to the horst structure in the area, thus injected water also is stored in the interior of the basalt section. The alternative model, Figure 9B, is that all, or at least the majority of, the stored water injected is stored in the three primary interflow zones. The source water bubble (i.e., treated drinking water that displaces native groundwater) may extend approximately 800 meters laterally from the site. This estimate is based on theoretical calculations using an assumed porosity for the basalt interflows and interiors, and further assuming that the injected water is banked in the interflows (Figure 9B) or is banked in a combination of the interflows and the interiors of the basalt flows (Figures 9A).

Overall, the increase in CRBG aquifers potentiometric head associated with ASR injection has not resulted in a loss of water from the natural system. The regional CRBG aquifer system in the Beaverton area has shown a positive water level response for the following reasons: (1) small amounts of injected water often are left in the aquifer annually as a result of ASR, (2) precipitation trends have been normal for the past several years, (3) ASR has reduced the City's dependency on native groundwater, and (4) many domestic and irrigation wells have been abandoned because of urbanization of the area. One historic seep in the region began to flow again, in part, because of ASR activities. This seep was mitigated with an infiltration gallery and stormwater catchment system.

ASR source water from the JWC and native groundwater are geochemically compatible based on mixing studies (as demonstrated by PHREEQC geochemical models), as well as operational water quality testing data that has shown no adverse reactions are occurring. During recovery, low-level concentrations of iron, manganese, and disinfection by-products (DBP) were observed, but at concentrations well below regulatory screening levels. DBPs are present because source water is chlorinated at the JWC treatment plant before being transmitted to Beaverton. Total haloacetic acids (HAA) were reduced to non-detectable levels, while the total trihalomethanes (THM) appear to have been reduced as a result of mixing patterns. HAAs may have been reduced because of biodegradation at the Beaverton site (LJHB Partners, in press). Chloroform, a THM, on the other hand, is the most persistent DBP found in recovered water; however, its detected concentrations are still well below the regulatory screening criteria. Native groundwater at Beaverton has very low levels of organic carbon, thus the mechanism for the formation and persistence of chloroform is unknown at this time. Chloroform exhibits a similar response at other basalt-hosted ASR systems that are being monitored by the authors. Overall, water quality data during Beaverton's ASR operation show a mixing pattern between source water and native groundwater. Radon, the only constituent to show a unique pattern, is present in native groundwater in the CRBG in the

Beaverton area at concentrations ranging from 100 to 900 picocurries per liter (pCi/L). Radon typically is not present in basalts because it is a decay product of Uranium 238, and thus the source may be from the underlying, older marine sediments. Work by Richard Glanzman (2006) supports that the older marine sediments are the sources of the radon because the ratio of daughter products does not match what would be expected if the CRBG were the radon source. Regardless of the source, radon has been shown to dissolve quickly into source water and is the only constituent to be found at concentrations in early-time recovered water at levels similar to what is found in native groundwater (see Figure 10). Specifically, all other constituents monitored (cations and anions) do not approach native groundwater concentrations in recovered water until after 100 to 150 days of pumping, whereas radon is detected in recovered water at native groundwater concentrations within 2 weeks of pumping. These data show that radon diffuses quickly from the native groundwater to source water. Depending on future radon regulations, treatment for radon may be needed at the Beaverton ASR facility as well as at other ASR systems in the Portland area.

Beaverton's ASR System at a Glance

Beaverton's current average daily demand is approximately 34,000 m^3/day, with peak water demands approaching nearly 68,100 m^3/day (see Figure 11). Annually, drinking water supplied by the City is approaching nearly 13.2 million m^3 per year. Demand for water continues as the City grows, and by 2020, the average daily demand is expected to be about 45,400 m^3/day, with peak water demands expected to reach 90,850 m^3/day, even after taking into account aggressive conservation and water management measures. As presented, Beaverton's current transmission capacity from the JWC is limited to 53,000 m^3/day.

Beaverton's current ASR system consists of three operational ASR wells: ASR No. 1, ASR No. 2, and ASR No. 4, with a total peak delivery capacity of 22,700 m^3/day. ASR No. 3, which is located in the southern part of the City, is expected to be online in 2011, and will add 2,850 m^3/day of peak capacity. The City is exploring additional sites to expand its ASR system, both in terms of peak delivery and storage volume. The three primary ASR wells are located in the central part of the City's distribution system (Sorrento facility) and were developed around an existing infrastructure system that includes source piping, storage reservoirs, and pump-to-waste capacity. Figure 11 illustrates how ASR is allowing the City to meet peak demands that are beyond its supply transmission capacity of 53,000 m^3/day and shows how ASR is "shaving off" peak summer-time demands.

Figure 12 shows the relative position of the City's ASR wells within the City's distribution system and Figure 13 shows the three primary ASR wells at the Sorrento facility in Beaverton. As shown in Figure 13, the ASR wells were developed in a highly urbanized environment on City land with existing infrastructure, initially built in the mid-1940s and consisting of one groundwater supply well, reservoirs, a pump station, and a water softening facility. Although the ASR wells are located in close proximity to each other, the hydrogeologic conditions at the site support the large injection and recovery rates, as discussed in the next section.

Overall, the ASR wellfield at the Sorrento facility was developed in steps, beginning with development of ASR No. 1 in 1998 and bringing ASR No. 1 online in 1999 (see Figure 11). Feasibility and design studies were undertaken and included evaluation of groundwater users in the area, hydraulic design, hydrogeologic assessments, aquifer performance testing, and water quality compatibility studies, followed by pilot testing of the well(s). Initial work also included developing a numeric groundwater model of the site to support a wellhead protection plan for the site. Preliminary work at ASR No. 1 included rehabilitating and retrofitting the original well that was drilled in 1945, most likely using cable tool techniques. Because of well bore alignment issues and diameter constraints, it was not possible to install a well liner or a downhole control valve in ASR No. 1 even though static water level in ASR No. 1 is nearly 61 meters below ground surface (bgs). Additionally, because of size constraints within the existing building for ASR No. 1, the injection and recovery piping from the well occurs through the same pipe using a bi-directional clay-valve.

Based on successful pilot testing of ASR No. 1, installation of a second ASR well at the site was evaluated and determined to be feasible. ASR No. 2 was drilled using reverse circulation drilling techniques; lined with stainless steel and low carbon steel casing and well screens; and equipped with a more robust telemetry system, including a downhole control valve and a variable-frequency-drive turbine pump. ASR No. 2 was brought online in 2001. The ASR No. 2 well house was acoustically upgraded after its completion because of noise generated by the variable-frequency-drive motor control, which was a nuisance to the neighbors. Even though ASR No. 2 penetrated the same primary interflow zones present in ASR No. 1, its yield is about 7,600 m^3/day, whereas the yield for ASR No. 1 is about 3,800-m^3/day. In addition, ASR No. 1 has to be routinely back-flushed to control head buildup, whereas ASR No. 2 requires much less maintenance. The difference in production between the ASR wells could be related in part to differences in drilling the wells, how they were completed (lined verses unlined), the difference in diameters, and, lastly, the downhole control valve installed in ASR No. 2 also may help in maintaining higher production rates at ASR No. 2 by limiting air entrainment during injection, which can reduce well yield over time.

Favorable ASR pilot testing results at ASR No. 1 and ASR No. 2 led to the development of a third ASR well (called ASR No. 4) at the Sorrento facility. ASR No. 4 became operational in late 2007. Overall, the plan is to use ASR No. 1 and ASR No. 2 to recharge the aquifer, and to use ASR No. 1, ASR No. 2, and ASR No. 4 to recover stored water. However, ASR No. 4 also is equipped to inject source water and, like ASR No. 2, it also was completed with a downhole control valve to limit the potential for air entrainment and to provide operational flexibility during recharge events. Lessons learned at ASR No. 1 and ASR No. 2 also resulted in design changes to ASR No. 4 that included installing a variable frequency drive (VFD) submersible pump, as compared to VFD line-shaft turbine pump. The latter pump results in motor noise that is a nuisance to nearby houses, whereas a submersible pump is much quieter. ASR No. 4 also was upgraded to pump at about 11,400 m^3/day because aquifer testing showed that the well was capable of this yield for a short period of time. All of the ASR wells are connected to the City's supervisory control and data acquisition (SCADA) system.

Since initial testing started in 1999, more than 7.9 million m^3 of source water have been injected and

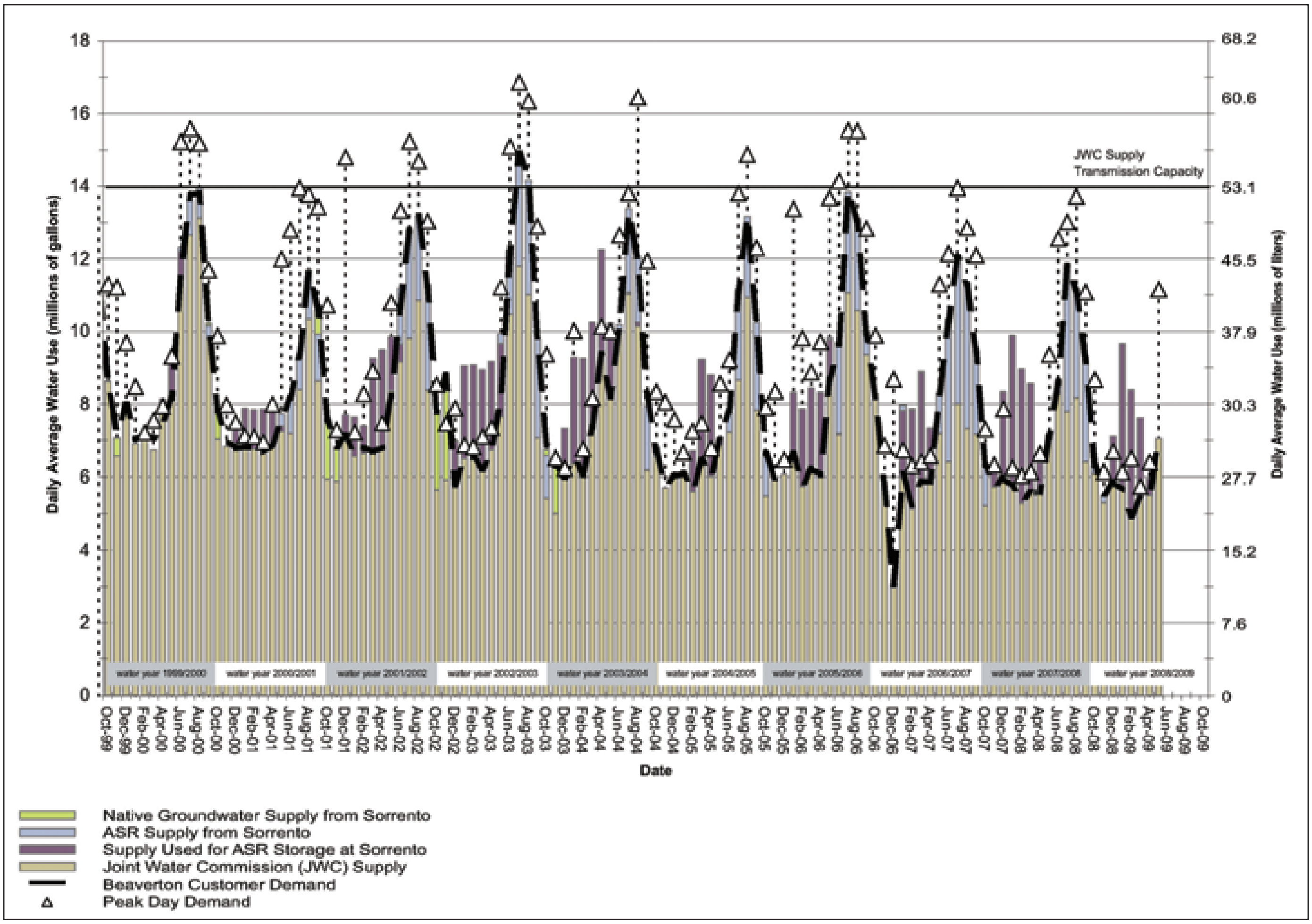

Figure 11. Beaverton's historical water use showing how ASR shaves off peak demand periods
Figura 11. Uso histórico del agua en Beaverton. Se observa cómo el ASR recorta las demandas pico

recovered using the existing ASR wells. In addition, because the City has native groundwater rights, the ASR wells also have been used to pump native groundwater (more than 1.49 million m^3 to date) after the ASR storage account is depleted. In addition, the Beaverton area has been closed to any new groundwater rights since early 1974, when it was designated by the State of Oregon as a Critical Groundwater Area, which is another key factor that makes ASR attractive in this area.

The City's ASR wells are operated under a permit ("ASR limited license") issued by the Oregon Water Resources Department (OWRD) as the lead agency, with support from the Oregon Department of Environmental Quality and the Oregon Department of Human Services, Drinking Water Program. The City's ASR limited license was based on a 5-year testing period with the option to renew, which the City has done. After testing is complete, the City can apply to the OWRD for a full-scale operational permit. The key regulatory point that has helped spur the interest in ASR in Oregon is that State of Oregon rules allow an exemption to the antidegradation regulations for ASR and permit chlorinated water to be injected and recovered. Specifically, ASR rules in Oregon allow DBPs in source water and recovered water up to the federal maximum contaminant level (MCL), and other constituents, as regulated by the federal Safe Drinking Water Act, are allowed at concentrations up to 50 percent of the federal MCLs. The DBP allowance in the ASR rules reduces the need to dechlorinate the source water, which helps reduce ASR capital costs, as well as, operation and maintenance costs. Water recovered from the wells can be debited against the ASR account and, in part, can be considered "native groundwater," based on the City's existing native groundwater rights. Overall, ASR has permanently transformed Beaverton's utilization of the JWC supply system resulting in a dramatic flattening of previous peaks and valleys of water supply from the JWC.

The Economics of Beaverton's ASR System

[Note: this section is presented in English units followed by SI units in brackets, where appropriate.]

To evaluate ASR, the City completed a cost/benefit analysis comparing ASR to more conventional source water upgrades to meet demands. ASR projects, we believe, have to meet three components to be successful: (1) the hydrogeology and geochemistry have to be favorable, (2) infrastructure must be compatible with an ASR system, and (3) the project needs to be cost effective. As previously discussed in this paper, the hydrogeology and geochemistry are suitable for ASR, and the Sorrento facility, where the City's ASR system was developed, has a robust infrastructure system that supports ASR development. As discussed in this section, the project also is cost effective.

Table 1 (Parts A and B) compares the relative cost of ASR per cubic meters (million gallons [MG]) of storage to the cost of conventional storage (i.e., reservoirs) in the Beaverton area. From a storage perspective, ASR is cost effective. However, this type of comparison, in our opinion, is an oversimplification of the "true" cost comparison between ASR and conventional water supply options. To complete a more rigorous cost/benefit analysis, the following parameters were used to evaluate the cost to meet future demands using ASR or conventional water supply upgrades (e.g., increasing transmission size capacity, reservoir upgrades, treatment capacity upgrades, and operation and maintenance costs):

- An increase of 500 MG (1.9 million m^3) of storage capacity
- An increase of 5 mgd (about 19,000 m^3/day) of supply
- Annualization of capital costs
- Life cycle of the systems
- Depreciation and return on investment
- Annual operation and maintenance (O&M) costs

Using capital costs to develop the City's existing ASR system, the cost to develop a new 5-mgd (19,000-m^3/day) ASR source is about $2,950,000 per mgd ($800 per m^3/day). In comparison, the capital cost to develop an additional 5 mgd (19,000 m^3/day) of capacity for Beaverton, assuming a conventional source, is about $6,000,000 per mgd ($1,600 per m^3/day). These options take into account raw water storage costs, water treatment capacity upgrades (from JWC), finished water storage costs, and transmission capacity upgrades. ASR O&M costs are higher than conventional source water O&M costs. Annualizing the capital costs shows that ASR has a benefit/cost ratio of 1.26 over a conventional source (see Table 2). Specifically, the cost per ccf (100 cubic feet of water or 748 gallons), which is the typical unit of measurement used by municipalities, demonstrates that ASR is $0.94 per ccf compared to $1.18 per ccf for a conventional supply, assuming 5 mgd (19,000 m^3/day) of flow and 500 MG (1.9 million m^3) of storage capacity. Overall, ASR is more cost effective when compared to conventional water supply alternatives.

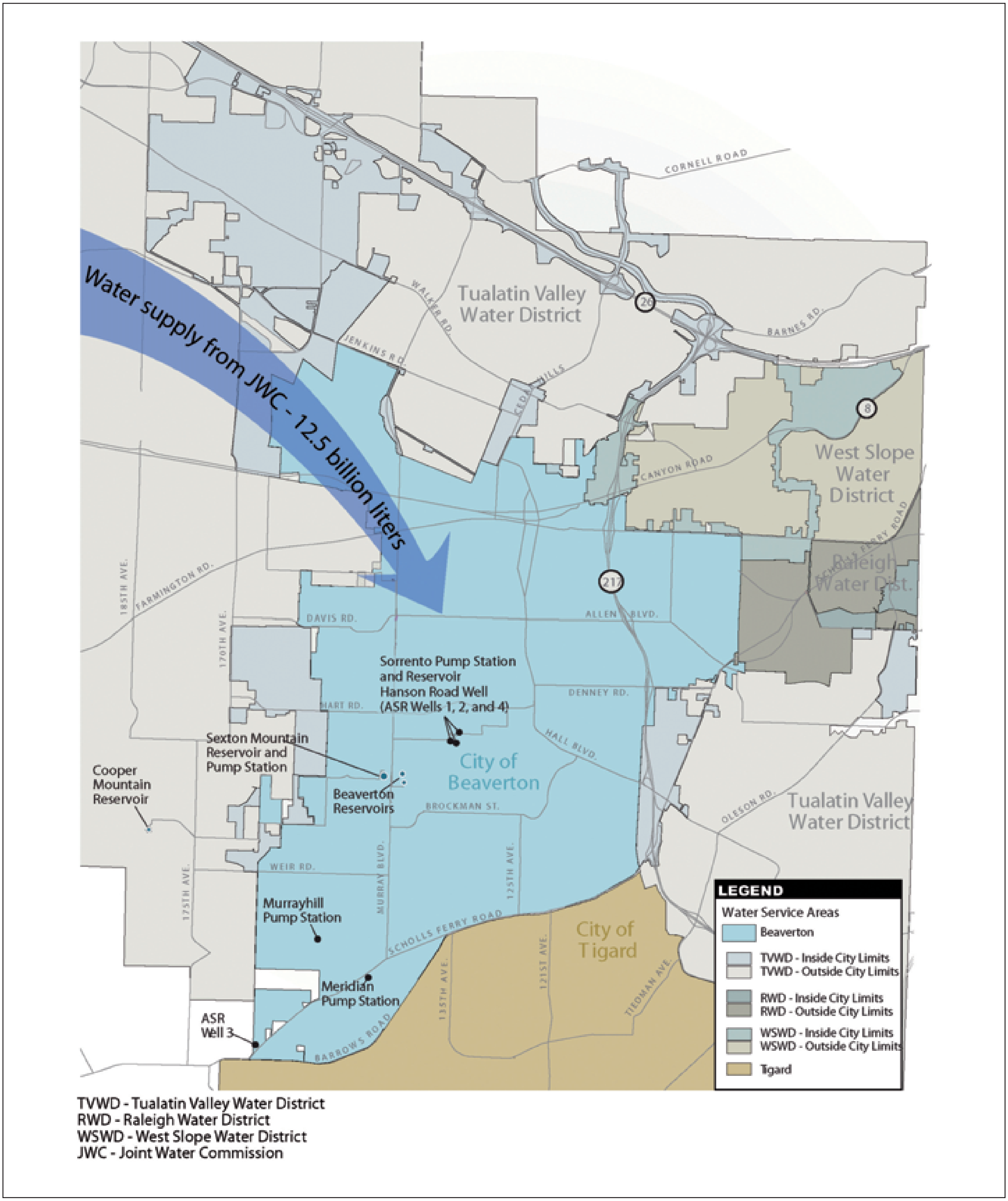

Figure 12. Beaverton's service area
Figura 12. Área de suministro de Beaverton

Part A. English Units

Facility	Year of Cost	Cost (original)	2006 Cost	Storage Volume (MG)	Cost/MG
ASR Wells					
ASR No. 1	1997	$724,320	$924,051	100	$9,241
ASR No. 2	2001	$1,228,881	$1,428,291	150	$9,522
ASR No. 3	2001	$1,032,504	$1,199,259	50	$23,985
ASR No. 4	2004-2006	$2,159,833	$2,273,511	200	$11,368
Conventional Storage Option					
Sexton Mountain	1995	$7,289,000	$10,596,284	15	$706,419
JWC No. 2 + Piping	2005-2006	$25,210,247	$25,210,247	20	$1,260,512

Part B. SI Units

Facility	Year of Cost	Cost (original)	2006 Cost	Storage Volume (m^3)	Cost/ m^3
ASR Wells					
ASR No. 1	1997	$724,320	$924,051	378,541	$2.44
ASR No. 2	2001	$1,228,881	$1,428,291	567,812	$2.52
ASR No. 3	2001	$1,032,504	$1,199,259	189,271	$6.34
ASR No. 4	2004-2006	$2,159,833	$2,273,511	757,082	$3.00
Conventional Storage Option					
Sexton Mountain	1995	$7,289,000	$10,596,284	56,781	$186.62
JWC No. 2 + Piping	2005-2006	$25,210,247	$25,210,247	75,708	$332.99

Note: All costs presented are in U.S. dollars.
ASR = aquifer storage and recovery
JWC = Joint Water Commission
MG = million gallons
m^3 = cubic meters

Table 1. Storage Cost Comparison – ASR vs. Conventional Storage Option. [Note: Part A of this table is presented in English units. Part B is presented in SI units.]
Tabla 1. Comparación entre costes de los sistemas ASR y convencional (Nota: La parte A está en unidades inglesas, la parte B en unidades SI)

Madison Farms

Madison Farms is a 71-km^2 farm located on the east side of the Cascade Range near Echo, Oregon (see Figure 1), producing crops including corn, canola, potatoes, alfalfa, ryegrass, bluegrass, fescue grass, and wheat. In eastern Oregon, a rain shadow effect is produced by the Cascade Range, resulting in a dry climate relative to the west side of Oregon. Annual precipitation in Echo, Oregon, is 225 mm, a majority of which falls during the winter, outside of the summer growing season (June to October) when moisture is needed for agriculture. Regionally, this area supports approximately 2,600 km^2 of irrigated agricultural land, which historically was irrigated by surface water, followed by aggressive development of groundwater from wells completed in CRBG aquifers. The intense groundwater development and limited aquifer storage in the basalt resulted in significant overdrafting of the aquifers, causing groundwater levels to decline in some areas up to 150 meters. As a result of these declines, the OWRD declared the basin a "Critical Groundwater Area" in 1986, which restricted additional appropriation of groundwater in the CRBG aquifers and limited existing groundwater users to small allocations on the basis of seniority. The OWRD determined that only a relatively small volume could be sustainably pumped from the basalt aquifers on an annual basis and many farms in the basin, including Madison Farms, no longer were able to irrigate their crops using groundwater from the basalt aquifers.

The Critical Groundwater Area declaration by the

ASR Supply	ASR Annualized Cost of 500 MG	Total ASR Unit Cost ($/CCF)
Total ASR Annualized Capital Cost	$209.749	$0.314
Total ASR O&M	$417,303	$0.624
Total	**$627,051**	**$0.94**

JWC Conventional Supply	Annualized Cost of 500 MG	Total JWC Unit Cost ($/CCF)
Total JWC Annualized Capital Cost	$565,516	$0.846
Total JWC O&M	$224,635	$0.336
Total	**$790,151**	**$1.18**

Note: All costs presented are in U.S. dollars.
ASR = aquifer storage and recovery
ccf = 100 cubic feet
JWC = Joint Water Commission
MG = million gallons
O&M = operations and maintenance
m^3 = cubic meters

Table 2. Overall Cost Comparison for 5 mgd (19,000 m^3/day) of Flow Capacity and 500 Million Gallons (1.9 million m^3) of Storage [Note: this table is presented in English units followed by SI units in brackets, where appropriate]
Tabla 2. Coste total comparado para las opciones de 19.000 m³/día y 1,9 Mm³ de capacidad de almacenamiento total (Nota: esta tabla se presenta en unidades inglesas seguidas por unidades SI entre paréntesis cuando es necesario)

OWRD resulted in eliminating Madison Farms' ability to appropriate up to 740,000 m^3 per year of groundwater from the CRBG aquifer, which provided irrigation for 200 acres of cropland. As a result, Madison Farms began using ASR to divert shallow alluvial groundwater (recharged by flood irrigation and a small, ephemeral creek) and store it in the CRBG aquifer during the winter. Stored water is pumped out of the CRBG aquifer for irrigation during the summer growing season (Figure 14).

Hydrogeology of Madison Farms' ASR System

Source water for Madison Farms' ASR system is from the shallow alluvial aquifer overlying the CRBG aquifer. Shallow alluvial groundwater is pumped from a 122-centimeter-diameter, 5.8-meter-deep collector well and is piped 1 kilometer to a 30.5-centimeter-diameter, 211-meter-deep ASR well used to inject source water into the local CRBG aquifer (Figure 14). Detailed stratigraphy of the CRBG at the Madison Farms ASR well is not known. Based on known CRBG stratigraphy in several nearby wells, it appears that the Madison Farms ASR well is completed in the Wanapum and Grande Ronde Formations. Based on well driller's logs, the well intersects seven interflow zones within the CRBG with an average thickness of 3.4 meters each. Aquifer transmissivity is 810 m^2/day based on late-time, multi-day aquifer testing. A suitable observation well was not available to evaluate aquifer storativity during aquifer testing, but testing at nearby CRBG wells indicates aquifer storativity is approximately 2×10^{-4}.

Water quality of the source water and native groundwater is generally good, with the exception of periodically elevated nitrate in the source water. Oregon ASR rules restrict injection of water that exceeds drinking water standards, generally requiring water quality of source water to not exceed half of any the federal and/or state drinking water quality standard. Because Madison Farms' ASR source water is appropriated from a shallow groundwater well in close proximity to surface water (within 1,600 meters), Microscopic Particulate Analysis (MPA) of the source water from the collector well was completed to evaluate the degree of connection with surface water. MPA results indicate the alluvial sediment provides adequate filtration of microorganisms and viruses present in surface water to meet state and federal drinking water standards, eliminating the need for cost-prohibitive water treatment systems. Madison Farms' ASR limited license from OWRD allows injection of ASR source water at nitrate concentrations up to 7 mg/L, which is slightly higher than the typical ASR standard for nitrate of 5 mg/L (half of the federal/state drinking water quality standard of 10 mg/L). A higher nitrate water quality standard was allowed for Madison Farms because no other viable ASR source water was available. Moreover, the 7

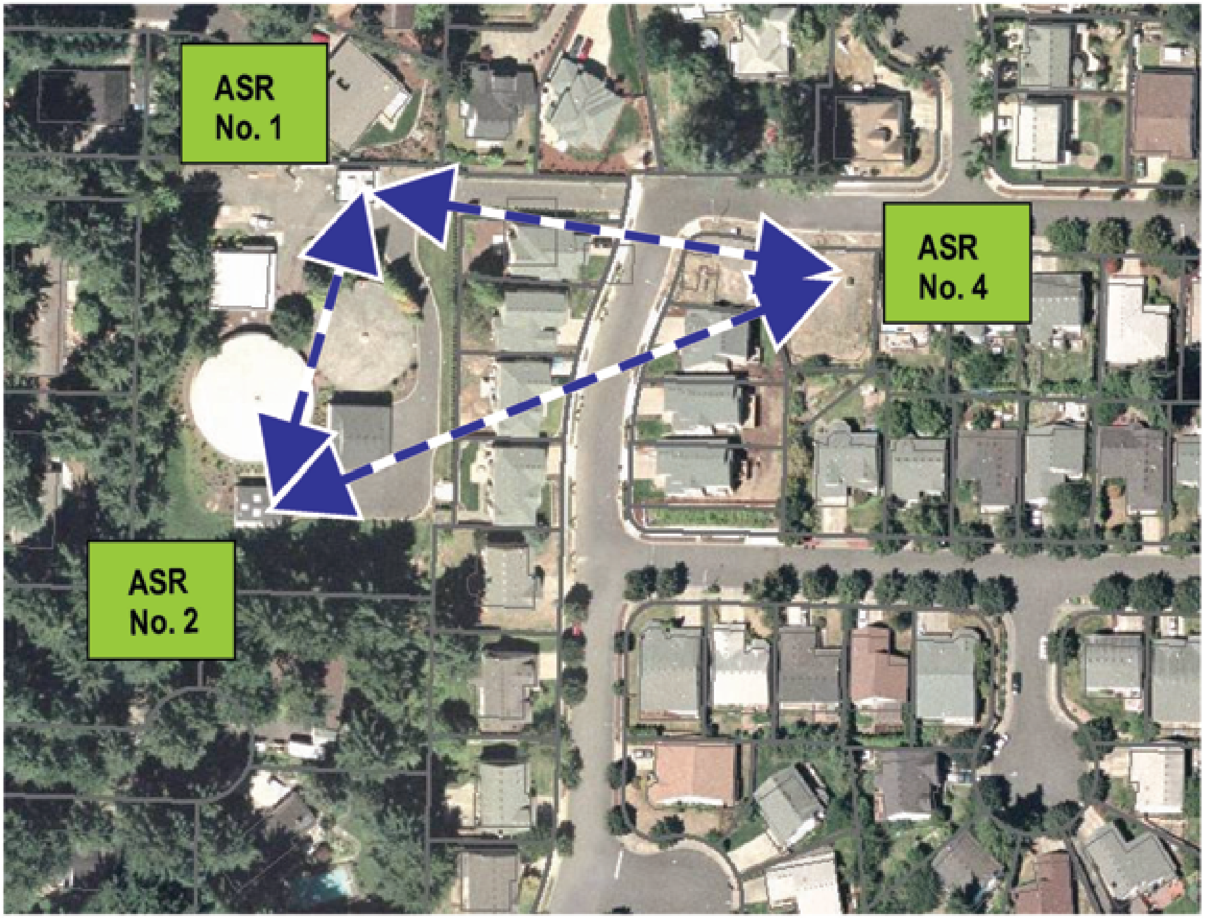

Figure 13. ASR wells – Sorrento Water Works facility, Beaverton
Figura 13. Pozos ASR en las instalaciones de Sorrento, Beaverton

mg/L standard set for Madison Farms' ASR system is still below the federal and state drinking water standards for nitrate of 10 mg/L. As a condition to Madison Farms' ASR limited license, an in-line nitrate analyzer was required to continuously monitor nitrate concentrations during injection to ensure that no water exceeding the 7 mg/L standard is injected into the basalt aquifer. This nitrate analyzer is connected to an electronically actuated valve (3R Valve is discussed later) that will stop ASR injection when the nitrate concentration of the source water exceeds 7 mg/L. Evaluation of data from the nitrate analyzer indicates that nitrate concentrations at the Madison Farms collector well range from 5 mg/L to 10 mg/L, which means that the ASR system is shut down periodically when values exceed 7 mg/L. Nitrate concentrations generally increase between February and May each year, which coincides with up-basin flood irrigation and leaching of excess nutrients into the shallow groundwater system used by the Madison Farms' source water collector well. Interestingly, following injection into the deep CRBG aquifer, recovered water nitrate concentrations quickly reduced to below analytical non-detection limits after a few days of storage. This reduction in nitrate concentration most likely is related to microbiological denitrification because the CRBG aquifer is suboxic, which thermodynamically favors an environment for denitrifying bacteria.

Since initiation of ASR at Madison Farms in 2006, more than 550,000 m^3 of water have been injected into the CRBG aquifer. Madison Farms typically begins injection of shallow alluvial groundwater into the CRBG aquifer in February at a rate of approximately 4,440 m^3/day and continues injection until June. The target for annual injection volume is

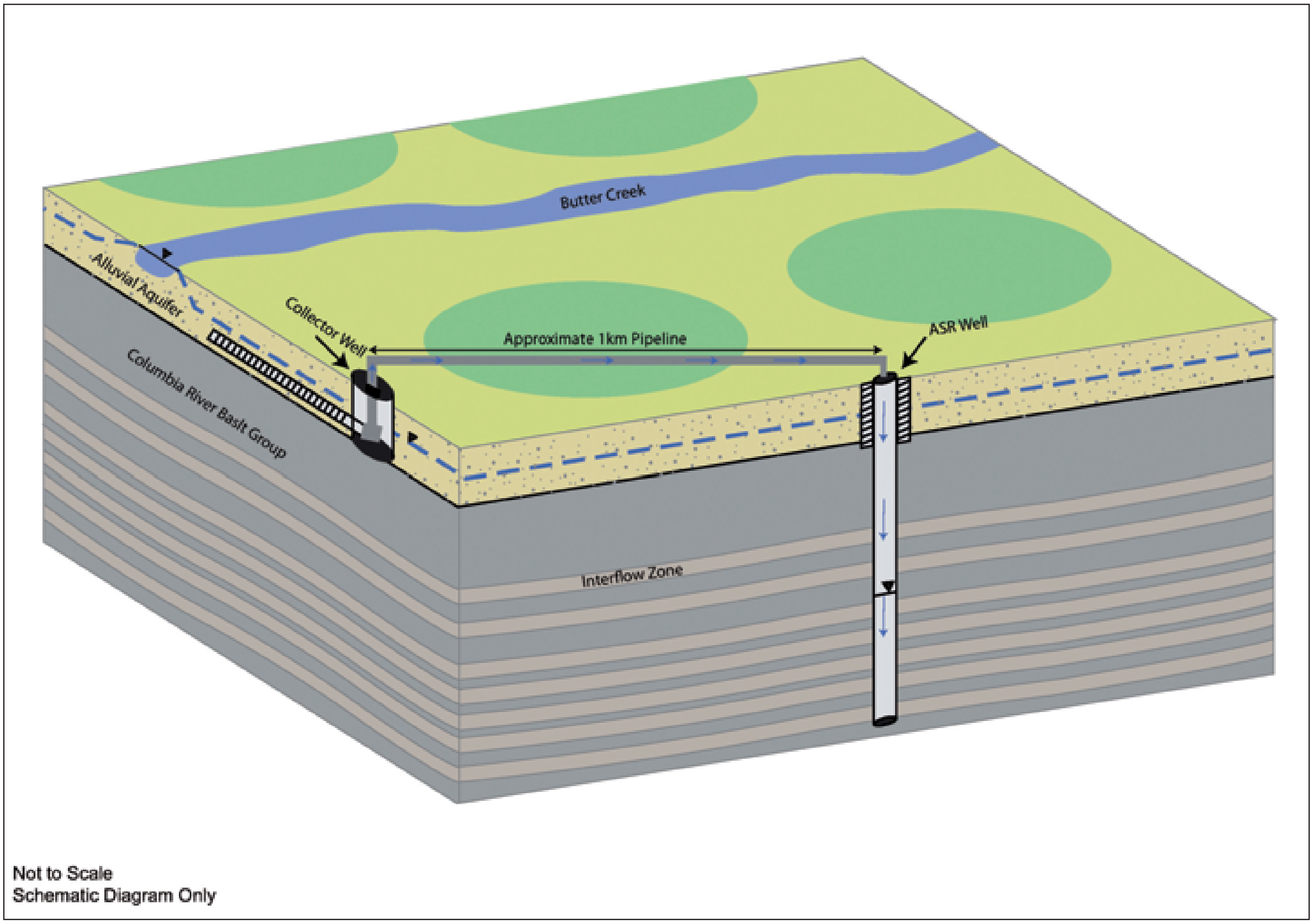

Figure 14. Madison Farms ASR system
Figura 14. Sistema ASR en Madison Farms

758,000 m^3 of shallow groundwater. To date, this annual target injection volume has not been reached because of the limited availability of the shallow alluvial groundwater system used to supply recharge water to the ASR system. Specifically, the groundwater level in the alluvial groundwater system fluctuates significantly during the winter and spring and can drop below the bottom depth of the collector well, precluding the ability to pump source water for ASR injection. Recovery of the stored water starts in June or July, at a rate of 4,440 m^3/day, and continues until 98 percent of the injected volume is pumped, which is typically in September. Retaining 2 to 5 percent of the water volume injected in the aquifer initially was required by the State of Oregon as a buffer to the potential loss of stored water from the CRBG system. Analysis of water quality and water level data is completed annually, and if a loss of stored water is not occurring, then Madison Farms can recover up to 100 percent of the stored water.

One unique characteristic of the Madison Farms ASR system is integration of a custom downhole control valve (called the 3R Valve), developed by Kent Madison, owner and operator of Madison Farms. An ASR downhole control valve allows for precise control of ASR injection rate and minimizes the possibility of entraining air into the aquifer because air trapped at the start of recharge in the pump column is allowed to evacuate before starting injection. Air entrained in source water can air-bind the aquifer and reduce its permeability and hence the well yield during injection and recovery. The 3R Valve currently is being used by a neighboring agricultural ASR system near Madison Farms and also is being used on City of Tigard's municipal ASR system near Portland, Oregon.

ASR Costs	
Capital Expenditures Required to Initiate ASR	
Retrofit of existing well for ASR	$25,000
ASR downhole control valve	$35,000
ASR wellhead piping	$8,000
Nitrate water quality meter	$13,500
Consulting/Engineering	$60,000
TOTAL ASR CAPITAL COSTS	$141,500
Annual Operation and Maintenance for ASR	
Electric cost for collector well	$9,200
Electric cost for ASR well	$27,500
Chlorination of ASR water	$3,000
Consulting and laboratory fees	$20,000
Miscellaneous costs	$1,200
TOTAL ANNUAL ASR COSTS	$60,900
Alternative Water Supply - Columbia River	
Estimated Capital Expenditures Required to Use Columbia River	
Conveyance piping	$8,000,000
New pump station on Columbia River	$200,000
Consulting/Engineering	$1,000,000
TOTAL ALTERNATIVE CAPITAL COST	$9,200,000
Estimated Annual Operation and Maintenance for Columbia River Diversion	
Raw water purchase cost	$61,300
Electric cost for Columbia River pump	$25,000
TOTAL ANNUAL COLUMBIA RIVER COST	$86,300
Gross Annual Profit for 200 Acres (0.8 Square Kilometer) of Irrigated Crop	$122,600

Note: All costs presented are in U.S. dollars.

Table 3. Costs Associated with Supply Options. [Note: this table is presented in English units followed by SI units in brackets, where appropriate]
Tabla 3. Costes asociados para cada opción de suministro (Nota: la tabla se presenta en unidades inglesas, seguidas por las unidades SI entre paréntesis cuando es necesario)

The Economics of Madison Farms' ASR System

ASR is not only economically favorable for Madison Farms, it is a necessity. Following local regulation of groundwater use by the State of Oregon, options for supplying irrigation water were severely limited. Madison Farms' use of ASR to store shallow alluvial groundwater in the CRBG aquifer is the most economically feasible alternative to supply water during the summer irrigation season. The only other alternative to supply irrigation water to Madison Farms would be to purchase and divert water from the Columbia River, nearly 22 kilometers away. Table 3 presents the economics of ASR and an alternative water supply option for Madison Farms.

As indicated in Table 3, ASR capital costs are significantly lower (99 percent lower) and the annual cost is moderately lower (30 percent lower) relative to the Columbia River water supply alternative for Madison Farms. The amount of time required for capital cost recovery for the expense of connection to the Columbia River makes this option economically infeasible. This results in ASR being the only economically viable alternative to grow irrigated crops.

Conclusions

Based on more than 8 years of ASR testing and operational data from the City of Beaverton and Madison

Farms ASR projects in CRBG aquifers, the following conclusions are presented:

CRBG aquifers are good hosts for ASR. Specifically, the basalt interflow zones are very permeable and many of the faults act as leaky boundaries rather than no-flow boundaries, which facilitates storing substantial quantities of source water.

- Because of the unique geologic characteristics of the CRBG, understanding the aquifer and well hydraulics is challenging. For example, because the aquifers are tabular, changes in lateral transmissivity are common, and basalts often are compartmentalized.
- It has been shown that proper design of ASR wells in CRBG aquifers is important. Downhole control valves reduce the likelihood of introducing entrained air into the interflow zones, given the depth to the static water level, and provide operational flexibility during ASR injection.
- To track the dynamic response of the CRBG aquifers caused by ASR activities, a network of monitoring wells is critical. This information has been helpful in assessing ASR expansion and evaluating the potential for development of seeps as a result of ASR activities.
- Overall, the increase in CRBG aquifers potentiometric head associated with ASR injection has not resulted in a loss of water from the natural system. In fact, the regional CRBG aquifer system in the Beaverton area has shown a positive water level response because: (1) small amounts of injected water often are left in the aquifer annually as a result of ASR, (2) precipitation trends have been normal for the past several years, (3) ASR has reduced the City's dependency on native groundwater, and (4) many domestic and irrigation wells have been abandoned because of urbanization of the area.
- The pressure response in the CRBG aquifers resulting from ASR activities propagates radially for a distance of several kilometers (miles) from the ASR wells. If a preferential pathway exists, seeps can be generated or reactivated.
- Radon, which typically is not present in CRBG aquifers, is present in the groundwater in the Beaverton area. The source of radon most likely is the underlying older marine sediments. Analysis of recovered water indicates that radon dissolves quickly into stored water.
- Surface water and shallow groundwater have been shown to be geochemically compatible with native groundwater in the CRBG aquifers. However, each ASR system is unique and before making ASR capital investments, geochemical compatibility studies are strongly encouraged to evaluate the mixing of source water and native groundwater to ensure that clogging of the well is not likely. Geochemical compatibility studies were completed for the Beaverton and Madison Farms ASR projects before making large ASR capital expenses (drilling new wells, retrofitting existing wells).
- For the Madison Farms ASR project, it has been shown that natural filtration of shallow groundwater has made it suitable for recharging deeper CRBG aquifers. Continuous monitoring of nitrate, which is the only water quality constituent of concern, can be accomplished easily with an in-line analyzer tied to the recharge system (downhole control valve).
- Overall, the City of Beaverton has not received any customer complaints regarding water aesthetics since the start of ASR. In the past, the City received numerous complaints whenever native groundwater was used.
- Finally, the City of Beaverton and Madison Farms case studies have shown that ASR is a cost-effective alternative to meet peak demands when compared to conventional water supply alternatives, such as increasing aboveground storage and/or increasing transmission capacity.

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