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TECHNICAL ARTICLE

A Deep, Non-potable Water Supply for the Ochoa Sulphate of Potash (SOP) Mine Project, New Mexico, USA

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Abstract Competing with communities, agriculture, and industry for potable-water resources can pose great challenges for mining companies seeking public and regulatory support for proposed projects. In semi-arid and arid regions of the world where freshwater resources are limited, using potable resources to supply water to mining operations often faces opposition from existing water users or is subject to lengthy regulatory reviews. Here we describe how Intercontinental Potash Corp. (USA) developed a deep, non-potable water supply from the Capitan aquifer for its Ochoa SOP Mine Project (Ochoa Project) in southeastern New Mexico (USA) that safeguards the limited freshwater resources. Through a program of exploratory well drilling, aquifer testing, and groundwater flow modeling, we find that the Capitan aquifer can sustain the proposed pumping rate of 252 L/s for a 50 year period, and that drawdown is predicted to be up to 200 m in the area of the proposed well field. We also find that depletions from the Pecos River, a connected stream subject to interstate compact agreements for water deliveries, are predicted to be at a rate of up to 1.10 L/s. We attribute the minimal impacts of the proposed pumping on the Pecos River largely to a zone of low hydraulic conductivity (1.5×10^{-3} m/day) near the county line that separates the aquifer where pumping is proposed in Lea County, New Mexico, from the area where the aquifer is connected to the Pecos River in Eddy County, New Mexico.

Keywords Capitan aquifer · Desalination · Fertilizer · Saline water

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Introduction

Fundamental to the successful development and operation of most mines is securing a sufficient, long-term supply of process water required for routine functioning. In locations where water supplies are short, including the southwestern United States of America, clashes between mining companies and competing water users can cause delays in development schedules and, in turn, losses in revenue. A company that competes for limited freshwater resources risks losing public and regulatory agency support for its projects. In contrast, a company that considers non-potable options can avoid pitting its interests against those of other water users, thereby increasing the probability that it will secure critical support required to advance development and operational goals. Central to the strategy for developing the Ochoa SOP Project in southeastern New Mexico was the use of a non-potable water supply in a region that contains the largest potash reserve in the USA (Barker and Austin 1993), but is relatively water-short.

The Ochoa Project is located 100 km east of Carlsbad, New Mexico, and less than 35 km from the New Mexico-Texas state line (Fig. 1). Operations will include a conventional underground polyhalite mine and processing facility that will produce SOP and sulphate of potash magnesia (SOPM). The processing of polyhalite, mining, and administrative needs on-site require a total water consumption of about 190 L/s.

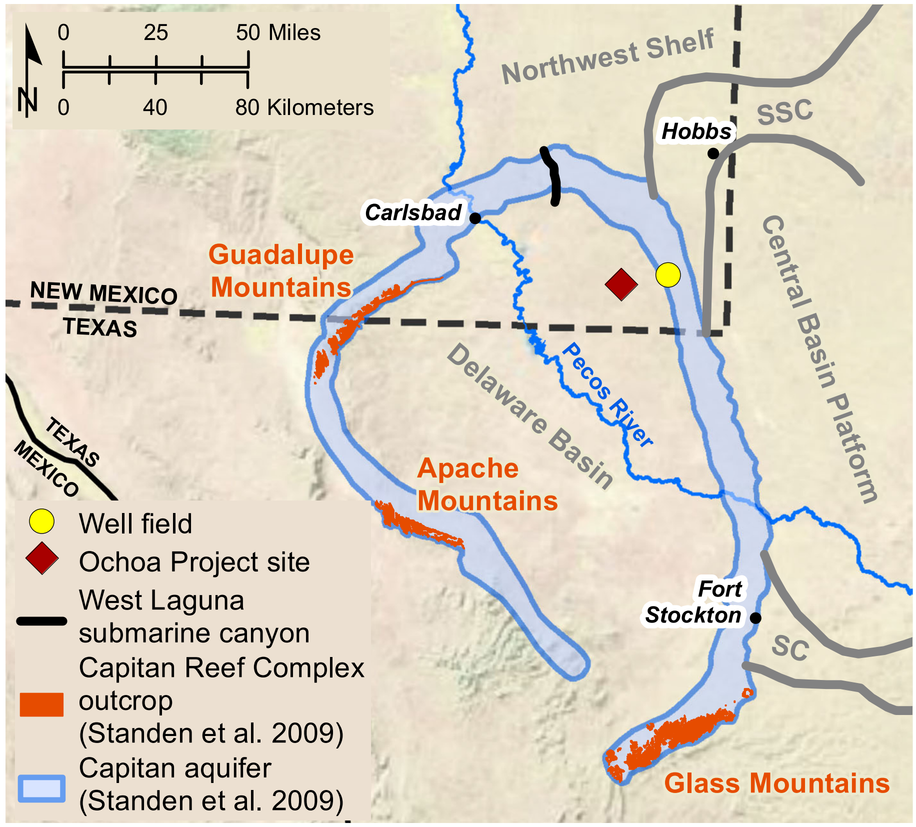

Fig. 1 Location of Ochoa Project near Texas/New Mexico state line, Capitan aquifer (*light blue*), West Laguna submarine canyon (Hiss 1975), and the Pecos River. Large-scale, subsurface features delineated by Ward et al. (1986) and Hiss (1975) include the Delaware Basin, Sheffield Channel (SC) and San Simon Channel (SSC), Central Basin Platform, and Northwest Shelf

A variety of water-supply options were considered for the Ochoa Project, including purchasing or leasing potable water from nearby municipalities, purchasing or leasing existing water rights, purchasing an out-of-state source of water, applying to the State of New Mexico for a new appropriation of water, or developing a deep, non-potable resource. Of these many options, the development of a non-potable resource from the Capitan aquifer was selected to supply water to the Ochoa Project because: (1) the Capitan aquifer is recognized by the U.S. Geological Survey (Hood and Kister 1962) and state agencies (e.g. Texas Water Development Board 2010) as a significant brackish water resource with a proven history of industrial use for oil and gas development during the 1960s and 1970s; (2) the New Mexico Office of the State Engineer, the state agency responsible for regulating water use throughout the state, and the U.S. Bureau of Land Management, the federal agency regulating the construction and operation of the mine, were both supportive of the use of the Capitan aquifer for mining and industrial purposes; (3) no permit was required to pump the deep, non-potable water for mining purposes because the aquifer meets several basic criteria that allow development without a lengthy permitting process; and (4) developing the aquifer did not directly compete with other water users in the area.

Capitan Aquifer

The Capitan aquifer (Fig. 1) was formed by the youngest of the Permian shelf-margin reef complexes that developed around the Delaware Basin (Harris and Saller 1999). Hiss (1975) describes the Capitan aquifer as a lithosome that includes the Capitan and Goat Seep formations and most of the Carlsbad carbonate facies of the Artesia Group from northern Pecos County, Texas, around to the Guadalupe Mountains and the Gilliam and Word formations in southern Pecos County (Glass Mountains). Within Lea County, New Mexico, the Capitan aquifer ranges from 240 to 670 m thick, and is approximately 20 km wide near the Eddy/Lea County line and 10 km wide directly east of the Ochoa Project (Leedshill-Herkenhoff Inc. et al. 2000). In the area of the Ochoa well field (Fig. 1), the top of the aquifer is about 1,344 m below ground surface (bgs), the bottom is about 1,642 m bgs, and water level is about 210 m bgs.

The hydraulic conductivity of the Capitan aquifer is highly variable. West of the Pecos River, the hydraulic conductivity is extremely high due to caves and caverns resulting from groundwater dissolution of carbonate rocks (Hiss 1975). For example, Barroll et al. (2004) used an estimated hydraulic conductivity of 229 m/day for the Capitan aquifer in the area extending west from the Pecos

River for several kilometers to the Guadalupe Mountains (Fig. 1) for a flow model of the Capitan aquifer for the Carlsbad area. This part of the Capitan aquifer west of the Pecos River is an important source of water for the City of Carlsbad and other water users in the area. East of the Pecos River, both hydraulic conductivity and water quality drop quickly. Measurements of hydraulic conductivity east of the Pecos River down to the Glass Mountains in Texas range from 0.3 to 7.6 m/day and average 1.5 m/day (Hiss 1975).

Near the Eddy/Lea County line, there is a zone of low hydraulic conductivity associated with a constriction in the Capitan aquifer that divides the aquifer into two distinct limbs and creates a groundwater divide between two separate hydraulic regimes. The constriction in the aquifer is attributed to submarine canyons that incised into the shelf carbonates that compose the aquifer (Hiss 1975; Hill 1996). Hiss (1975) described these submarine canyons as a series of basinward-trending, deep-sea channels that extend for many tens of kilometers into the basin. Electrical logs suggest that the submarine canyons are almost completely filled with a mixture of carbonate debris, sandstones, and siltstones resembling the basin facies near the shelf margin (Hiss 1975). The most prominent of the submarine canyons is the West Laguna submarine canyon (Fig. 1), which is believed responsible for the groundwater divide.

The Capitan aquifer is confined above by the Salado Formation and both laterally and beneath by the Delaware Mountain and Artesia Groups. The hydraulic conductivity of the overlying halite and anhydrite intervals of the Salado Formation are extremely low compared to other rock types, interpreted to be on the order of 1.2×10^{-9} to 3.5×10^{-6} m/day by Beauheim et al. (1991). Except in the Glass Mountains in Texas where the Capitan Reef Complex crops out (Fig. 1) and where the Pecos River has eroded the Salado Formation in the area of Carlsbad, New Mexico, the Capitan aquifer is not in communication with overlying aquifers. In the area of the Pecos River, however, the Capitan aquifer is well connected to the Pecos River and the associated alluvial aquifer. Historically, the Capitan aquifer discharged into the Pecos River at Carlsbad Spring near Carlsbad, New Mexico. However, groundwater pumping for municipal, industrial, and irrigation use intercepts most of the water that would have discharged to the river.

Recharge from the basin to the Capitan aquifer is restricted laterally by the Castile Formation, a halite deposit that acts as a barrier to groundwater flow (Mercer 1983). Underlying the Castile Formation and the Capitan aquifer is the Delaware Mountain Group. With a hydraulic conductivity several orders of magnitude lower than that of the Capitan aquifer, along with very low, naturally occurring hydraulic gradients, a relatively small quantity of water would be expected to flow from the Delaware Mountain Group into the Capitan aquifer under natural-gradient conditions (Mercer 1983). Along the back reef, shelf carbonates and sandstones of the Artesia Group grade into evaporites with distance from the aquifer, as discussed by Ward et al. (1986). The aquifer is largely constrained by these evaporites and the associated low hydraulic conductivity. However, hydraulic communication increases between the Capitan aquifer and the relatively permeable rocks of the San Andres Formation (Hiss 1980), in places such as the San Simon Channel and Sheffield Channel (Fig. 1), which have hydraulic conductivities up to ten times that of the adjacent back-reef facies (Ward et al. 1986).

Methods

Two exploratory wells were drilled to characterize the hydraulic properties of the Capitan aquifer in the area of the proposed water-supply well field. The wells were spaced 457 m from one another and fully penetrated the thickness of the Capitan aquifer to provide sufficient data for modeling and water-treatment testing. The wells, each drilled to approximately 1,642 m bgs, produce from a 22.2 cm diameter open hole over the 320 m thickness of the Capitan aquifer. Step-drawdown tests were completed to characterize the specific capacity of the wells in support of engineering and design of the well field.

Following well construction and testing, an aquifer test was completed to characterize bulk aquifer properties and inform a groundwater flow model developed in support of the mine permitting process. The pumping well was pumped at a constant rate of 31 L/s for 7 days, followed by a recovery period of 23 days. Water levels were monitored in the pumping and observation wells before commencing the test, during the pumping phase, and during the recovery phase. The data were analyzed to estimate transmissivity, hydraulic conductivity, and storativity.

Both conceptual and numerical groundwater models were developed to support the mine permitting effort for the Ochoa Project. The conceptual groundwater model provided the basis for development of a numerical groundwater flow model of the Capitan aquifer. The numerical groundwater flow model provided quantification of potential impacts of pumping deep, saline groundwater from the ICP wells on existing wells and springs producing from, and surface water bodies in contact with, the aquifer in New Mexico and Texas. The aquifer was modeled using MODFLOW-2000 (Harbaugh et al. 2000) using a uniform grid spacing of 609 m by 609 m.

The portion of the aquifer included in the model domain extends east and south from near Carlsbad, New Mexico, to

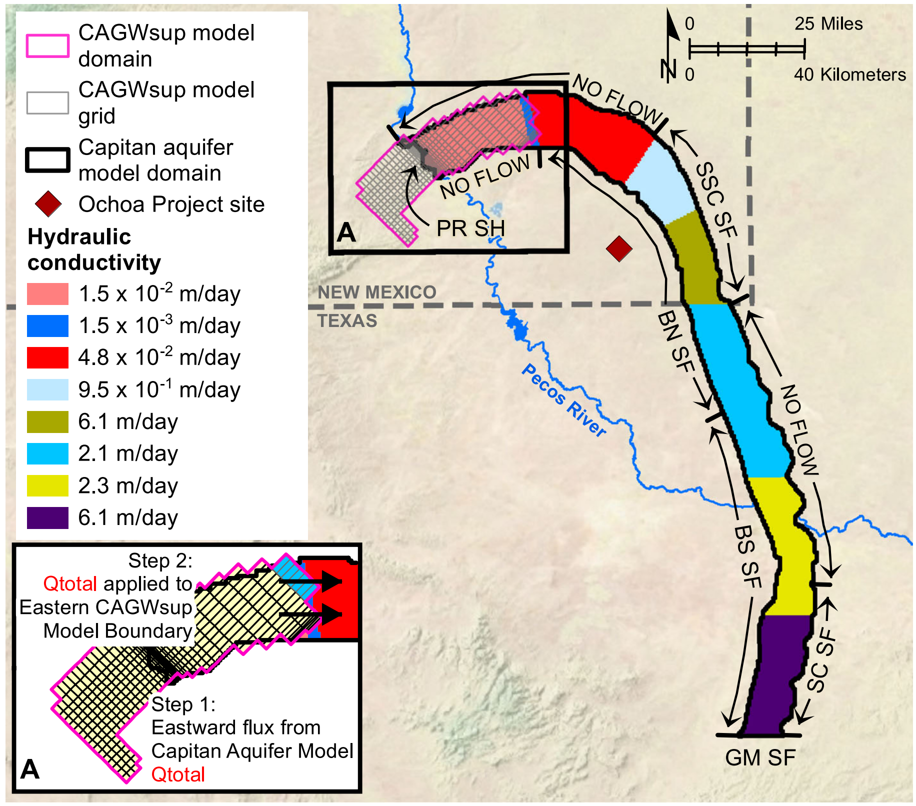

Fig. 2 Model domain with zones of hydraulic conductivity and method of linking CAGWsup model and Capitan aquifer model to assess impacts on the Pecos River (Panel A). Boundary conditions of calibration and predictive models are as follows: Pecos River specified head (PR SH), no flow, San Simon Channel specified flux (SSC SF), Sheffield Channel specified flux (SC SF), Glass Mountains specified flux (GM SF), Basin-South specified flux (BS SF), and Basin-North specified flux (BN SF). One dimensional models were used to represent flux across the BN SF, BS SF, SSC SF, and SC SF boundaries

the Glass Mountains in Texas (Fig. 2). Recharge from the Glass Mountains was initially estimated to be 173 L/s using a method adapted from Beach et al. (2004). This method takes into account the precipitation, topographic, geologic, and soil characteristics of the study area, and then calculates the potential recharge and runoff, thereby determining the groundwater recharge for the area of interest. Glass Mountain recharge was subsequently reduced to 70 L/s during model calibration. Aquifer thickness and depth were identified using logs from the large number of oil and gas wells in the region. These logs, as well as other data sources, and the subsequent development of a database containing information about the formation tops, were key components for delineating the hydrostratigraphic units to be included in the numerical groundwater flow model. In addition to the use of pre-existing data, aquifer test data from the two ICP water wells provided site-specific information on the Capitan aquifer.

Four models were developed to support the permitting processes: a no-action model, a calibration model, and two predictive models representing the ICP water-supply pumping and recovery scenarios. The no-action model was developed to provide results for a simulation without groundwater pumping. The calibration model represents historical flows from 1967 through 1972, the period during which data were available for hydraulic heads and stresses on the system. Hydraulic conductivity was the only parameter adjusted during the calibration process, which was completed using the code PEST (Watermark Numerical Computing 2005). Using the overall structure and flow parameters of the calibration model, along with the results of the no-action model that defined the initial model heads and pre-pumping outflows from the Capitan aquifer, the predictive pumping model simulated a 50 year pumping scenario at 252 L/s, a rate larger than the water demand of 190 L/s to accommodate loss in the water treatment process. The recovery model was used to evaluate rebound of groundwater levels after Ochoa supply wells were shut off.

Because accurate estimates of flow rates between the Capitan aquifer and adjacent aquifers were unknown and a physically based model of the system was required, lateral flow exchanges between the Capitan aquifer and the Delaware Mountain Group (the aquifer on the Delaware Basin side of the Capitan aquifer, or basin aquifer) and the back-reef aquifers were determined using one-dimensional MODFLOW models linked to different sections of the Capitan aquifer boundary (Fig. 3). Each one-dimensional model had a thickness of 304 m based on Hiss (1975), a domain of 153 km, and a storativity conservatively set to 5×10^{-4}, which is about twice the storage associated with the compressibility of water in a 304 m thick unit of 5 % porosity. The standard domain of 153 km is representative of the San Simon Channel and Sheffield Channel, based on the delineation of zero porosity in back-reef formations by

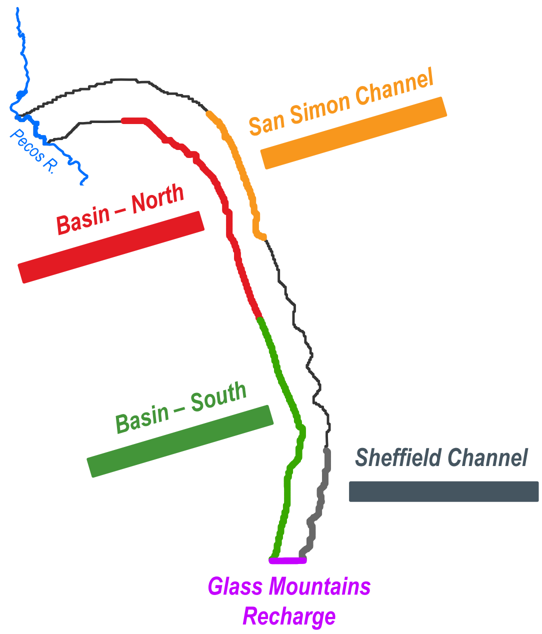

Fig. 3 Flow into and out of the Capitan aquifer model boundaries were represented by flux across each model boundary reach using one-dimensional models for the Basin-North, Basin-South, San Simon Channel, and Sheffield Channel. Fluxes determined from one-dimensional models were then multiplied by the length of each model boundary reach to obtain the total flux. Reach lengths are 120 km each for the Basin-North (*red*) and Basin-South (*green*), 77 km for the San Simon Channel (*orange*), and 58 km for the Sheffield Channel (*grey*)

Ward et al. (1986). The initial condition for the one-dimensional models was a uniform, static water level. For the basin aquifer, one-dimensional models with hydraulic conductivity set to 3.0×10^{-3} m/day were used to represent the flux across the boundary in both the north and the south of the basin. For the back-reef aquifers, one-dimensional models with hydraulic conductivity each set to 5.2×10^{-2} m/day were linked to the Capitan aquifer model in the San Simon Channel and Sheffield Channel area.

Potential impacts to groundwater in the vicinity of the Pecos River near Carlsbad, New Mexico, were based on reduced groundwater discharge to the Pecos River. An extensive and detailed evaluation of the groundwater flow system was conducted by Barroll et al. (2004) in support of the State of New Mexico's efforts to manage water in the Carlsbad area. This work included the development of the Carlsbad Area Groundwater (CAGW) model, which is a numerical model of the flow system used to assess potential impacts in that area. A superposition model of the CAGW model (CAGWsup) was further developed as a tool for evaluating impacts on river flows due to additional withdrawals from the aquifer in that area (Papadopulos 2008). The CAGWsup model was used to evaluate the induced leakage from the Pecos River (Fig. 2) from proposed pumping. A sensitivity analysis in accordance with ASTM (2008) was performed to evaluate the sensitivity of the calibrated groundwater model with respect to various parameters and boundary conditions.

Results

Pump testing indicated that the supply wells can sustain pumping rates of 31 L/s or greater for extended periods. The specific capacity of the well is summarized in Table 1. Rapid rebound was observed following cessation of pumping in the pumping well during the step test; the water level returned to 100 % of the pre-test level within 1 h. As expected, the specific capacity decreased with an increase in the pumping rate. The maximum estimated storativity value from the 7 day pumping test was 1.5×10^{-4}. Transmissivity of the Capitan aquifer was estimated to be 650 m^2/day, yielding an estimated horizontal hydraulic conductivity of 2.1 m/day, applying a 304 m thickness for the open-hole producing zone.

Model calibration statistics indicate that the model is well-calibrated (Table 2). The mean head residual of 0.36 m indicates little bias (i.e. simulated heads are not too high or too low, on average). The RMSE was 2.59 m and the range in heads was 203 m, leading to a normalized RMSE of 1.3 %, indicating that the model accurately reproduces the observed heads.

Predictive simulations indicate that drawdown will be greater east of the groundwater divide created by the submarine canyons near the Eddy/Lea County line (Fig. 4). Results of the sensitivity analysis showed that induced

Table 1 Results of specific capacity testing at three pumping rates (steps) used for well testing

Step no.	Flow rate (L/s)	Water level drawdown (m)	Specific capacity (L/s/m)
1	20	56.1	0.36
2	28	90.5	0.31
3	37	140.8	0.26

Table 2 Results of model calibration statistics

Calibration statistic	Result
Mean error (m)	0.36
Residual standard deviation (m)	2.56
Root mean squared error (RMSE; m)	2.59
Minimum residual (m)	−7.53
Maximum residual (m)	11.03
Range of observations	203
Normalized RMSE	0.013
Number of observations	272

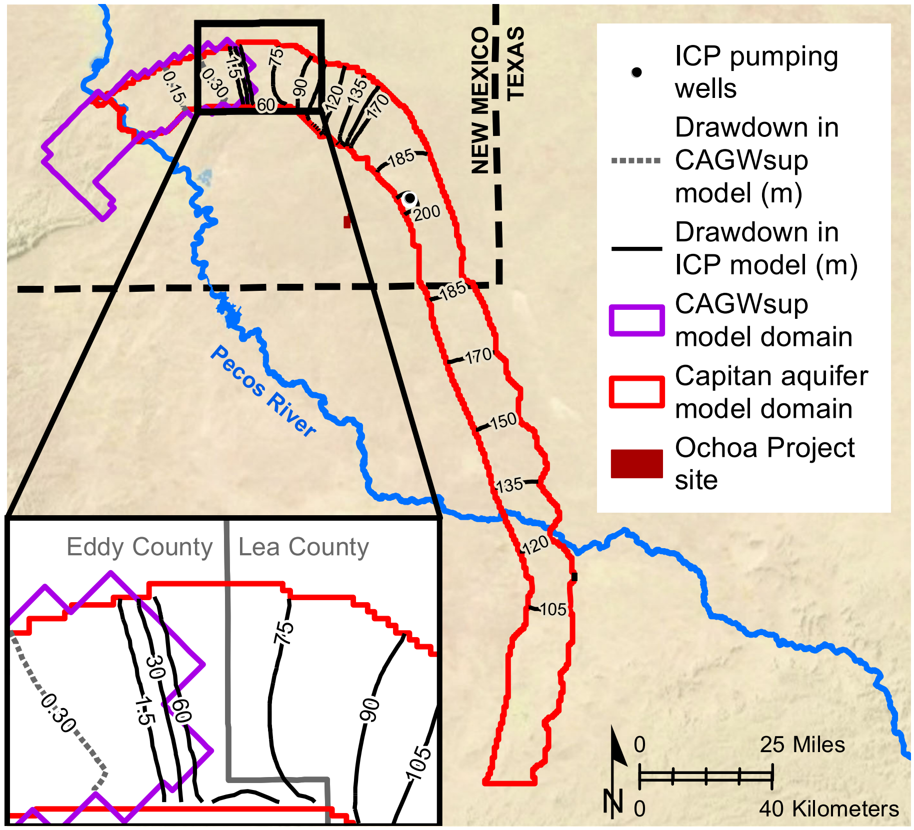

Fig. 4 Drawdown in the Capitan aquifer after 50 years of pumping at 252 L/s. Area enlarged shows Eddy/Lea County line in the vicinity of the West Laguna submarine canyon that restricts flow in the Capitan aquifer

leakage from the Pecos River was in the range of 1.00–1.25 L/s for a significant portion of the simulations (Fig. 5). The mean value for induced leakage was 1.10 L/s, and the standard deviation of the data was 0.61 L/s. After 50 years of pumping of the Ochoa well field, the wells were shut off in the model and the water levels in the Capitan aquifer were allowed to rebound. At the end of 500 years, the water level near the ICP pumping wells had rebounded to 87 % of its original no-action level.

Discussion

The testing and modeling results show that the Capitan aquifer will be capable of providing a long-term supply of water to the Ochoa Project. Well and aquifer testing confirmed the desired well yield and that the hydraulic character of the Capitan aquifer was suitable for the desired supply. Maximum simulated drawdown of 200 m after 50 years of pumping will not change the confined nature of the aquifer because the present water level is approximately 210 m bgs and the top of the aquifer is at 1,344 m bgs. The hydraulic conductivity of 2.1 m/day estimated from testing was above the average measurement of 1.5 m/day reported by Hiss (1975) for the entire Capitan aquifer, but within the reported range of 0.3–7.6 m/day. The transmissivity of 650 m^2/day estimated from testing is comparable to the value of 929 m^2/day reported by Hiss (1975) for areas of the aquifer outside of the submarine canyons. Though the storativity value of 1.5×10^{-4} was on the lower end of the scale for hard rock aquifers, adopting this value for use in the model resulted in a more conservative evaluation of potential impacts.

Simulated drawdown demonstrates the importance of the thinning of the Capitan aquifer at the West Laguna submarine canyon near the Eddy/Lea County line and its effect on limiting the impact of pumping at the Ochoa well field on groundwater discharge to the Pecos River. For example, drawdown decreases sharply from 30 m immediately east of the West Laguna submarine canyon to 1.5 m within a few kilometers west of the hydraulic divide (Fig. 4). Relative to modeled hydraulic conductivities for most of the aquifer, the modeled value of 1.5×10^{-3} m/day for the constriction zone is significantly less. However, compared to an estimated hydraulic conductivity of $<7.3 \times 10^{-4}$ m/day, which is based on permeability measurements of drill core from the lower section of the Capitan Reef Complex in a research borehole a few kilometers west of the constriction (Garber et al. 1989), the modeled value is relatively conservative. As a result, simulated impacts of pumping the Ochoa well field on induced leakage from the Pecos River are both reasonable and conservative.

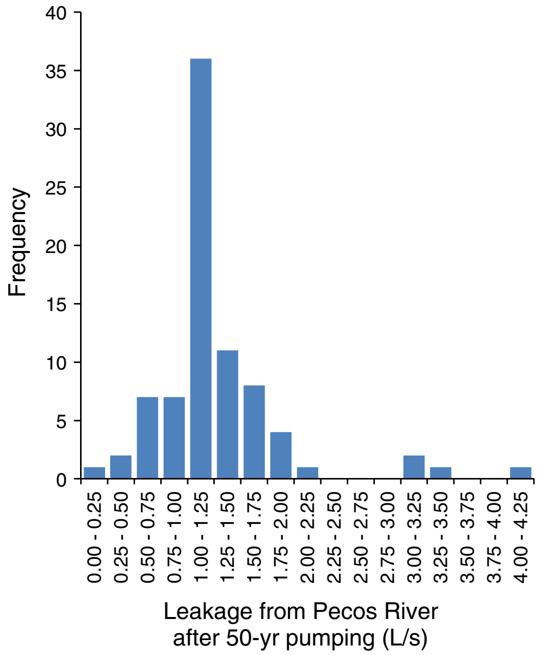

Fig. 5 Distribution of estimated impacts of pumping on the Pecos River from the sensitivity analysis

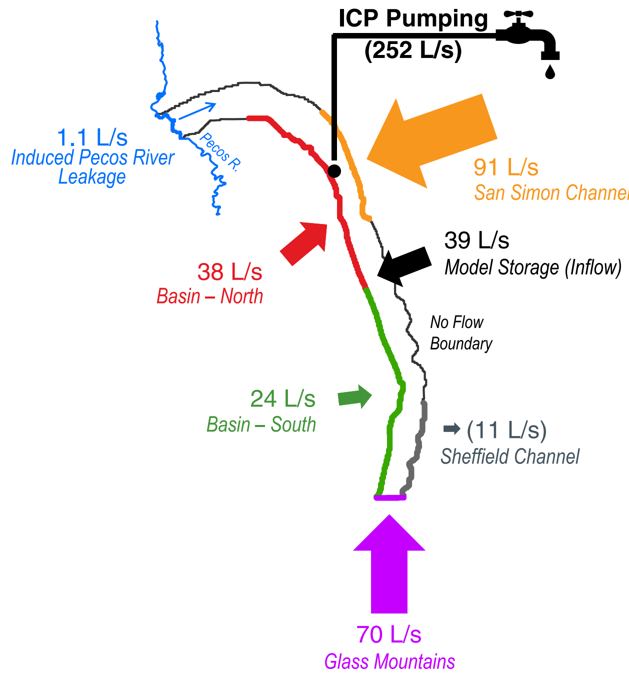

Fig. 6 Water balance after pumping 252 L/s for 50 years from the Ochoa Project well field. *Size of arrow* corresponds to size of contributing recharge or discharge

The water balance after 50 years of pumping 252 L/s at the Ochoa well field highlights the importance of hydraulic communication between the Capitan aquifer and both the basin aquifer and the San Simon Channel (Fig. 6). For example, the flux after 50 years of pumping was 62 L/s from the basin aquifers and 80 L/s from the San Simon and Sheffield Channels. Though the hydraulic conductivity of the basin aquifer is several orders of magnitude less than that of the Capitan aquifer (Mercer 1983), when applied over a combined length of 240 km where the aquifers are in communication, the total contribution is substantial. The contributions from basin and back-reef aquifers total 142 L/s, which is more than the combined amount of 109 L/s contributed from aquifer storage (39 L/s) and recharge from the Glass Mountains (70 L/s). Comparing the mean for induced leakage of 1.10 L/s from the Pecos River to 1,625 L/s, the average rate of groundwater discharge to the River over the period of 1965 to 2001 (Barroll et al. 2004), groundwater discharge from the aquifer to the river would be reduced by only 0.07 %.

Conclusions

By supplying the Ochoa Project with deep, non-potable water from the Capitan aquifer, ICP avoided a relatively complicated process for developing fresh water, and instead safeguarded its use for other purposes that are essential to the surrounding community. Where regulatory frameworks encourage or permit the use of non-potable resources, developing these resources can help project owners overcome barriers to doing business in regions that have limited drinking water resources. Though sourcing water from deep, non-potable aquifers may require deeper wells and desalination, making the commitment to safeguard limited freshwater resources can add value to a project through public and regulatory support received when proposals do not include a new and competing use of freshwater. As freshwater resources become more limited, companies that choose to adopt conventional drilling and treatment technologies to develop non-potable resources may also realize value in the support received for such proposals.

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References

ASTM (2008) D5611-94: standard guide for conducting a sensitivity analysis for a groundwater flow model application. Annual book of ASTM standards, vol 04.08. ASTM International, West Conshohocken. doi:10.1520/D5981-96R08

Barker JM, Austin GS (1993) Economic Geology of the Carlsbad Potash District, New Mexico. New Mexico Geological Soc Guidebook, 44th Field Conf, Carlsbad Region, New Mexico and West Texas, pp 283–291

Barroll P, Jordan D, Ruskauff G (2004) The Carlsbad area groundwater flow model. Consultant's report prepared by INTERA Inc and submitted to the New Mexico Interstate Stream Commission

Beach JA, Ashworth JB, Finch ST, Chastain-Howley A, Calhoun K, Urbanczyk KM, Sharp JM, Olson J (2004) Groundwater availability model for the igneous and parts of the West Texas Bolsons (Wild Horse Flat, Michigan Flat, Ryan Flat and Lobo Flat) aquifers. Prepared for the Texas Water Development Board

Beauheim RL, Saulnier GJ, Avis JD (1991) Interpretation of brine-permeability tests of the Salado formation at the waste isolation pilot plant site: first interim report, SAND90-0083. Sandia National Laboratories, Albuquerque

Garber RA, Grover GA, Harris PM (1989) Geology of the Capitan shelf margin-subsurface data from the Northern Delaware Basin. In: Harris PM, Grover GA (eds) Subsurface and outcrop examination of the Capitan shelf margin—a core workshop, soc of economic paleontologists and mineralogists core workshop 13, p 3-269

Harbaugh AW, Banta ER, Hill MC, Mcdonald MG (2000) MODFLOW-2000, the U.S. Geological Survey modular ground-water model—user guide to modularization concepts and the groundwater flow process. USGS OFR 00-92, Washington DC, USA

Harris PM, Saller AH (1999) Subsurface expression of the Capitan depositional system and implications for hydrocarbon reservoirs, northeastern Delaware Basin. In: Saller AH, Harris PM, Kirkland BL, Mazzullo SJ (eds) Geologic framework of the Capitan reef, soc for sedimentary geology (SEPM) special Publ no 65, Univ of California Press, Berkeley, CA, USA, ISBN: 1565760638, 9781565760639

Hill CA (1996) Geology of the Delaware Basin Guadalupe, Apache, and Glass Mountains, New Mexico and Texas. Permian Basin Section-SEPM Pub No. 96-39. Univ of California Press, Berkeley, CA, USA

Hiss WL (1975) Stratigraphy and groundwater hydrology of the Capitan aquifer, Southeastern New Mexico and Western Texas. Unpubl Ph. Diss, Univ of Colorado, Boulder, CO, USA

Hiss WL (1980) Movement of ground water in Permian Guadalupian aquifer systems, southeastern New Mexico and western Texas. In: Dickerson PW, Hotter JM (eds) New Mexico Geological Society Guidebook, 31st field conference. Trans-Pecos Region, p 289–294

Hood JW, Kister LR (1962) Saline-water resources of New Mexico. USGS water supply paper 1601. http://pubs.usgs.gov/wsp/1601/report.pdf

Leedshill-Herkenhoff, Inc, John Shomaker & Assoc, Inc, Montgomery & Andrews, PA (2000) Final report, Lea County regional water plan. Prepared for Lea County water users assoc. http://www.ose.state.nm.us/Planning/RWP/region_16.php

Mercer JW (1983) Geohydrology of the proposed waste isolation pilot plant site, Los Medaños area, Southeastern New Mexico. USGS water-resources investigations report 83-4016, Washington DC, USA

Papadopulos (SS Papadopulos and Assoc) (2008) Carlsbad area groundwater model, superposition version GUI. Prepared for the State of New Mexico/Interstate Stream Commission, Santa Fe, NM, USA

Standen A, Finch S, Williams R, Lee-Brand B, Kirby P (2009) Capitan reef complex structure and stratigraphy. Prepared for the Texas Water Development Board, Austin, TX, USA

Texas Water Development Board (2010) Aquifers of West Texas. In: Mace RE, Mullican WF, Angle ES (eds) Texas Water Development Board Report 356, Austin, TX, USA

Ward RF, Kendall CG, Harris PM (1986) Upper Permian (Guadalupian) facies and their associations with hydrocarbons—Permian Basin, West Texas and New Mexico. Am Assoc Petr Geol B 70(3):239–262

Watermark Numerical Computing (2005) PEST, model independent parameter estimation. User manual, 5th edn