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Modeling of Desalination Concentrate Storage Options for Future Recovery and Use

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Modeling of Desalination Concentrate Storage Options for Future Recovery and Use

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Abstract. Cd. Juárez, Chihuahua, a rapidly growing city across the Rio Grande from El Paso, Texas with a 2005 population in excess of 1.2 million, relies exclusively on ground water from an aquifer known as the Hueco Bolson. The aquifer's fresh water is being depleted and it is degrading in quality due to the lateral inflow of brackish water. Although the Hueco Bolson's fresh water is diminishing, it still contains a considerable quantity of brackish water. This paper defines the feasibility of using desalination technology in conjunction with concentrate storage to extend the 'life' of the Juárez portion of the Hueco Bolson.

Well injection of the concentrate was analyzed based on the premise that the cones of depression created by well pumping could provide a storage area for the concentrate. So doing would enable the brackish concentrate to be 'stored' for future use when advances in desalination technology will render the stored concentrate into an economically recoverable resource , unlike evaporation ponds that result in the permanent loss of water due to vaporization. The research team used a combination of three software systems for this portion of the analysis: a ground water modeling software, a mass transport extension to the ground water modeling software, and GIS software to facilitate the visualization of model outputs. The technical report on which this paper is based was authored by Turner and Hamlyn (2004).

Background. Concentrate management is a significant concern in the development and operation a desalination facility. The concentrate outflow from a desalination plant is very brackish. The minerals dissolved in the concentrate have too little market value to make any kind of selective crystallization and recovery scheme practical. Based on contemporary technological options and economics, a means of concentrate management is essential if desalination is to be pursued.

Management of concentrate requires either its deep well injection, export, or the solidification and land filling of the salt. Another alternative is the underground storage of the concentrate until such time when technology makes its recovery and use economically feasible. Inland desalination plants such as the one under construction in El Paso will use deep well injection of the concentrate which greatly increases the cost. For Cd. Juárez, direct discharge options are precluded as the concentrate cannot be released into irrigation drains or the Rio Grande/Río Bravo, as doing so will salinate soils, degrade surface water quality, impact riparian and aquatic ecosystems, and potentially contaminate the shallow aquifer. Thus, the options that remain are either to solidify and landfill the salt, or to inject the brackish concentrate into a suitable underground formation.

An alternative to deep well injection is to inject and store the concentrate in "shallow" underground formations. This alternative has benefit of 'storing' the brackish concentrate as a potential water resource for future generations. Ground water disposal of concentrate usually implies deep well injection. For purposes of this study, an alternative approach was studied, namely that of injecting concentrate at relatively shallow depths allowing it to fill the "pockets" formed by cones-of-depression in portions of the well field where wells have had to be taken out of production. A ground water model was used to evaluate this approach in terms of storage capacity and in terms of the potential impair the nearby high quality ground water.

Analysis Procedure. Initially, a copy of the Hueco Bolsón ground water model was obtained from El Paso Water Utilities. This model, fortuitously released in the fall of 2002, was developed through a collaborative effort of the U.S. Geologic Survey (USGS) and hydrologists working at El Paso Water Utilities and the U.S. Army – Fort Bliss. The model is based on ground water program called MODFLOW, the source code of which had been modified to incorporate a multi-aquifer package (water wells that extracting water from more than one strata) to account for the conditions prevalent in well fields that exploit the Hueco Bolsón. The model was developed based on a horizontal grid, the densest part of which defines cells based on a 500 m by 500 m network. Vertically, the model defines ten different layers. The uppermost layer varies in thickness based on ground surface elevations, and averages 30 m in depth in the vicinity of the Rio Grande/Río Bravo alluvium. The subsequent eight layers are a uniform 30 m depth each, and the final, tenth layer is again non-uniform based on the variable depth of the underlying igneous and sedimentary bedrock, and varies in thickness from 0 to 276 m.

Overall, the Hueco Bolsón model encompasses an area of 5,303 km^2 and is shown in Figure 1.

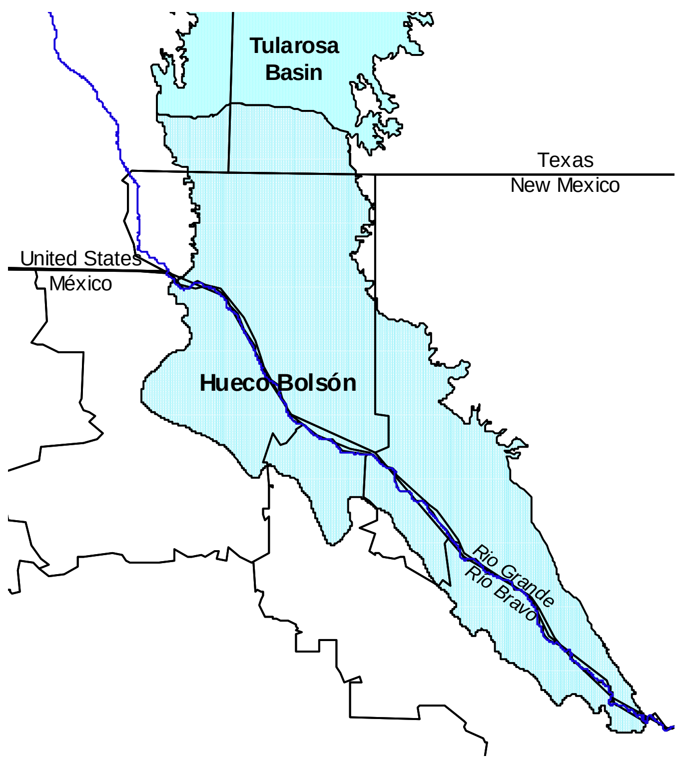

Figure 1. Rio Grande / Rio Bravo showing the Hueco Bolson / Aquifer.

The model encompasses the totality of the well fields of both El Paso Water Utilities and the Junta Municipal de Aguas y Saneamiento (UACJ). The UACJ well field is shown in Figure 2.

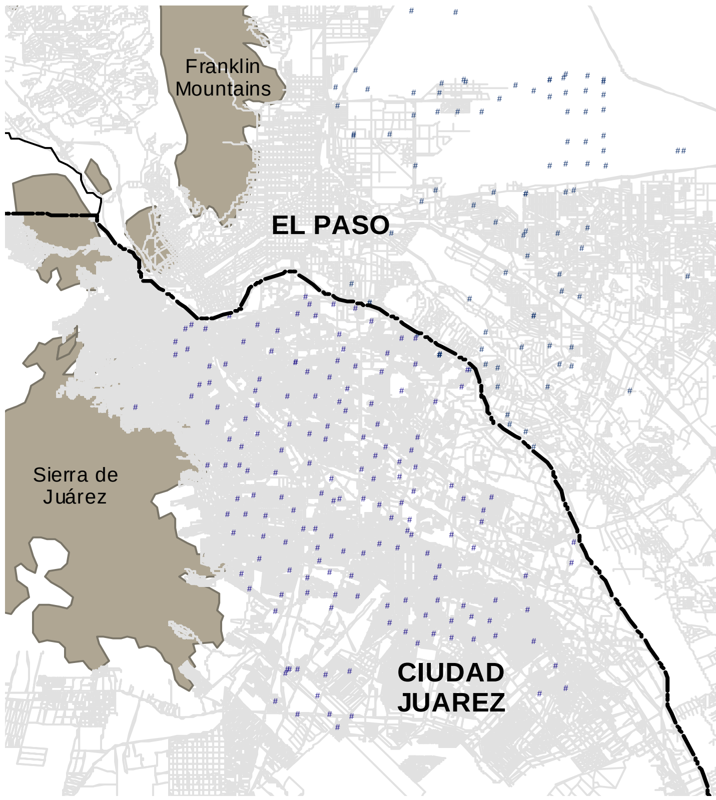

Figure 2. JMAS well field in Ciudad Juarez

The model's boundary conditions include surrounding impervious areas or pervious alluvium outside of the bounds of the model area, and inflow parameters including infiltration from the Rio Grande, the region's unlined irrigation canals, irrigated fields, and previously identified mountainous areas that provide a source of natural recharge. The horizontal grid spacing has 165 rows and 100 columns, (based on a map aligned with north at the top of the sheet). The dimensions of the grid vary, with the central, densest portion having a grid 500 m per side. (Note: Because this is the highest resolution of the model, it should be understood to be a generalized, regional model. A 'tighter' grid would be required for assessing smaller-scale ground water movement.) The area selected for study using this model is shown in Figure 3.

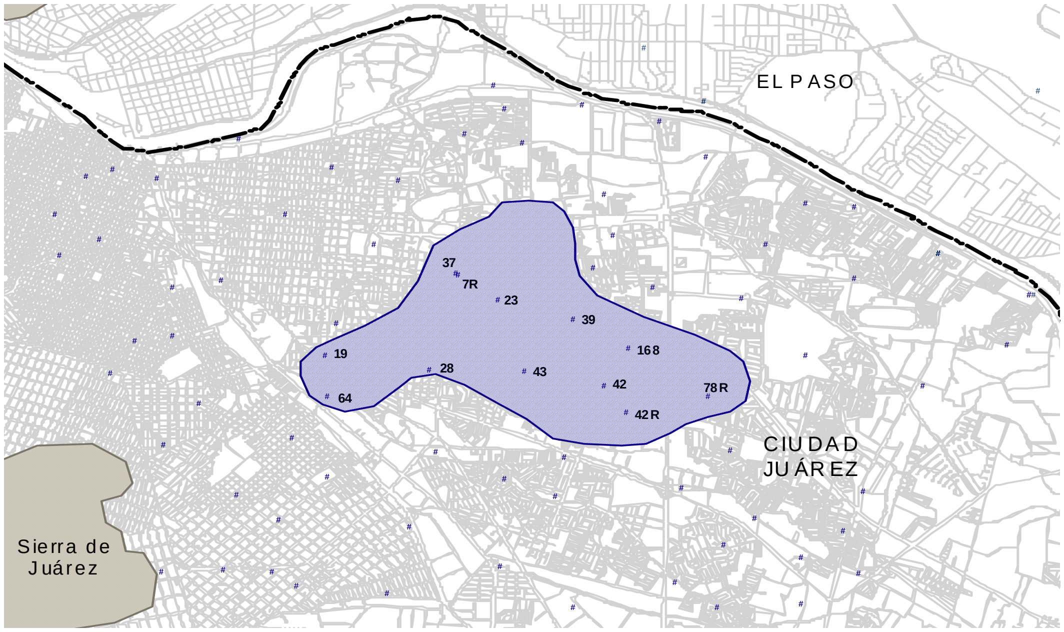

Figure 3. Area of highest TDS in JMAS well field.

Calibration of the model was based on calculation of varying head pressures on an annual basis for the years from 1909 through 1968 (66 time increments), and monthly thereafter from 1969 through 2002 (a total of 408 time increments). Thus, the full duration of the model covers the time period from the inception of deep ground water pumping to contemporary conditions. The model has been peer reviewed and it was deemed to provide an adequate simulation of the dynamics of the ground water system, (Bredehoeft et al. 2004). The Hueco Bolsón model assigns a uniform lateral (horizontal) hydraulic conductivity of 10m/day; the vertical hydraulic conductivity was assigned at 2 x 10^{-2} m/day for all layers except the deepest layer, which as assigned a value of 6 x 10^{-3} m/day. While these uniform values suggest an unrealistic homogeneity in the sediment strata, the values were deemed acceptable for purposes of this generalized, relatively low-resolution model. Although the hydraulic conductivity parameters were established based on the best available information, in the future, as better geo-stratigraphic information becomes available, the parameters may be modified.

Analyses of the potential impact of concentrate injection were undertaken based on the Hueco Bolsón model coupled with computer software called Groundwater Vistas® version 3.0. This modeling software was chosen, in part, due to its being used by hydrogeologists at El Paso Water Utilities, as this facilitated communication between the research team staff and the Utility professionals that were currently using the Hueco Bolsón model. The core of the Hueco Bolsón model was built on MODFLOW-2000, a public-domain software developed by the USGS. MODFLOW-2000 is a three-dimensional, finite-difference ground water flow model. It can simulate both steady-state and transient-state flow, and its modular structure is adaptable for complex geological conditions such as confined versus unconfined aquifer conditions. The original version of MODFLOW was published in 1984 and it has been revised and upgraded several times since then, and now contains program extensions that can be used to evaluate solute transport. Groundwater Vistas® provides a graphic user interface to facilitate data entry and to enable the results of different analyses to be visualized by means of velocity vectors and in a cross-sectional display aligned with the modular grid. Also within Groundwater Vistas® is a program extension called MT-3D99 that is designed to compute cell-by-cell mass flux and mass storage terms, to evaluate the transport of soluble contaminants for ground water risk assessment. Each individual 'run' of the MODFLOW and MT-3D99 programs in Groundwater Vistas® generates a suite of four different files, the extensions of which are: .hds, .cbc, .mt3, and .out. The .hds file controls the 'head' pressure calculations; the .cbc file tracks cell-by-cell interaction; the .mt3 file tracks solute transport; and the .out file is the general output file.

Stress periods, as employed in the model simulations, are five-year periods. The stress periods define the intervals at which the modeling software generates an output file. The model itself recalculates head on a monthly basis. The duration of a full simulation run was set at 30 years, representing six, five-year stress periods. After several preliminary simulations were made to familiarize the researchers with the program, a series of simulations were run at varying locations. In almost all cases, two different simulations were made at each location: the first simulation was based on a constant injection rate for all six stress periods (30 years); the second simulation was based on constant injection for two stress periods only (10 years), though the full six stress periods were simulated to enable an assessment of the concentrate movement after injection ceased.

For all simulations, the research team chose a single cell location, representing a potential injection well injecting concentrate into a specific layer, or strata, of the Bolsón, to receive 9,464 m^3d^{-1} of concentrate, this corresponding with the full volume of concentrate produced by the proposed desalination plant. The total dissolved solids concentration of the well for 1999 is shown in Figure 4.

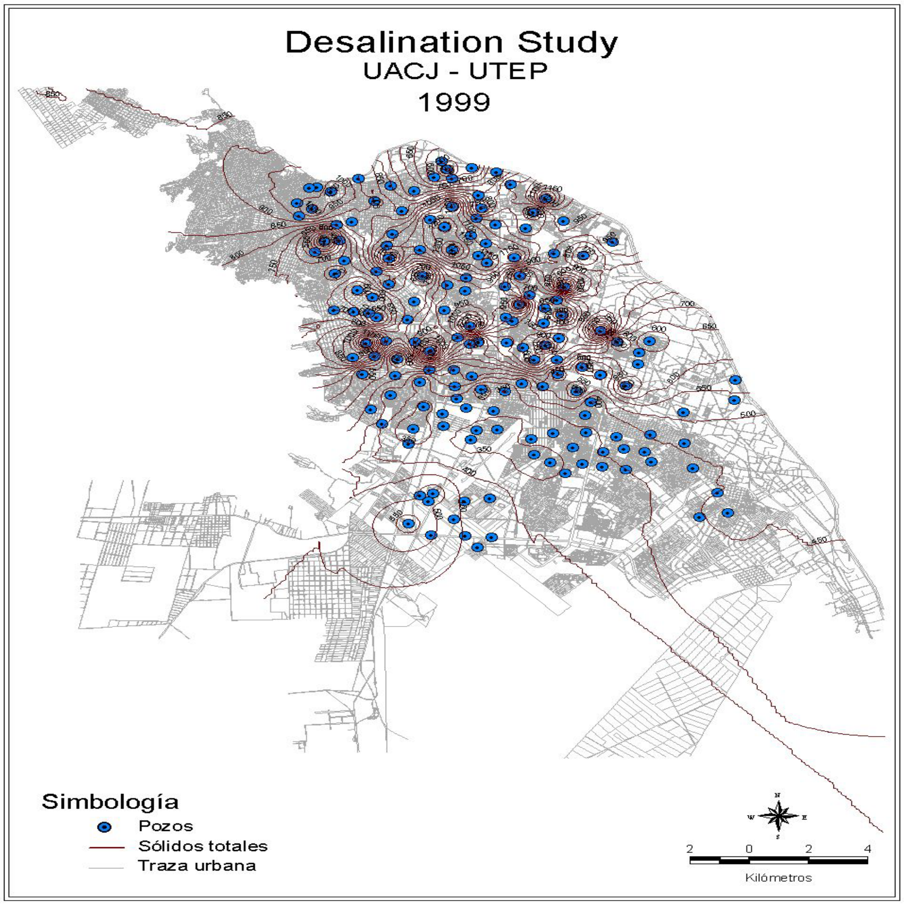

Figure 4. Total dissolved solids concentration in JMAS well field.

For the model, a value of '10,000' was used in defining the concentrate injection. This value did not represent TDS; rather, it was used as a 'marker' to simplify subsequent calculations. Once the simulations were completed using Groundwater Vistas®, the output file was exported to ArcView®. This enabled the display the output data relative to other physical and cultural features, such as roads, boundaries and water well locations. The concentration values generated by the simulations were converted to TDS concentrations by taking a weighted average between the 'marker' number (10,000) and the background value (0). TDS values were subsequently assigned using a concentrate value of 4,000 mg/l and a value of 500 mg/l for the native ground water. This latter value was based on an approximate mean value of water quality from wells on the periphery of the JMAS well field. Results were mapped in ArcView® using increments that highlighted the migration of concentrate based on seven ranges of concentration varying from initial indications of concentrate spread to severe impairments of water quality.

A number of simulation runs were attempted for varying sites and depths proximate to the portion of the JMAS well field experiencing the most severe diminution in water quality. This area also coincides with the deepest drawdown of the water table, thus taking advantage of the storage potential created by the cones-of-depression, based on the initial research hypothesis. Locations were also tested in sites near to impermeable outcrops that form the 'boundaries' of the ground water model. As noted previously, experiments were performed with continuous injection over a six time-step (30-year) period, and with injection for shorter time-steps (either 5-year or 10-year periods), but still allowing the model to run for a full six time-step (30-year) cycle to observe any movement or spread of the concentrate. The trial injection sites were deliberately chosen to 'bracket' the range of possible outcomes. Exam ples of simulations of injection runs are included in Figures 5, 6, 7 and 8. Both scenarios shown below involve the injection of concentrate in that portion of the JMAS well field that has experienced the greatest water table decline and the most marked diminution in water quality. Two alternatives were investigated: continuous injection of concentrate (Figures 5 & 7), and a limited, 5-year injection (Figures 6 & 8) after which the migration of concentrate was observed.

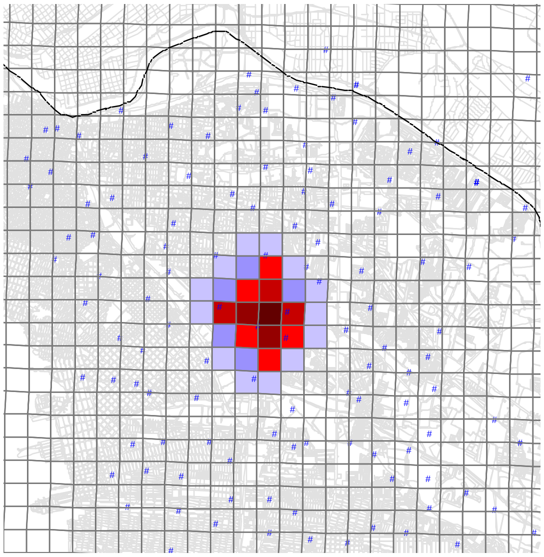

Figure 5. After five years of continuous injection, cells up to 1.5 km distance show elevated TDS, and several cells within 1 km have TDS >1,000.

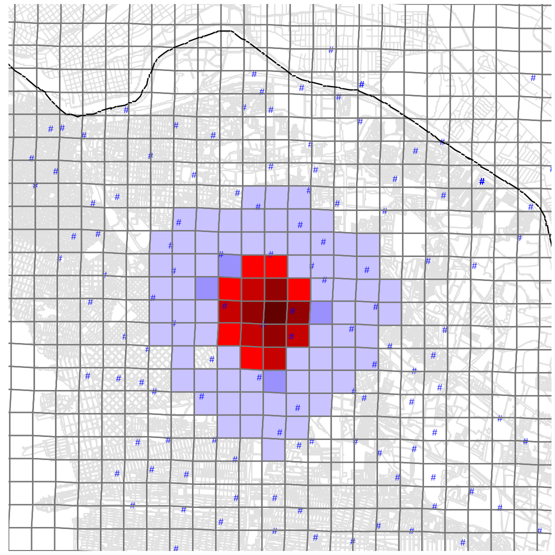

Figure 6. This alternative ceased injecting concentrate after the initial 5 years. This image shows year 10, (5 years after injection stopped). Note the continuing spread of concentrate.

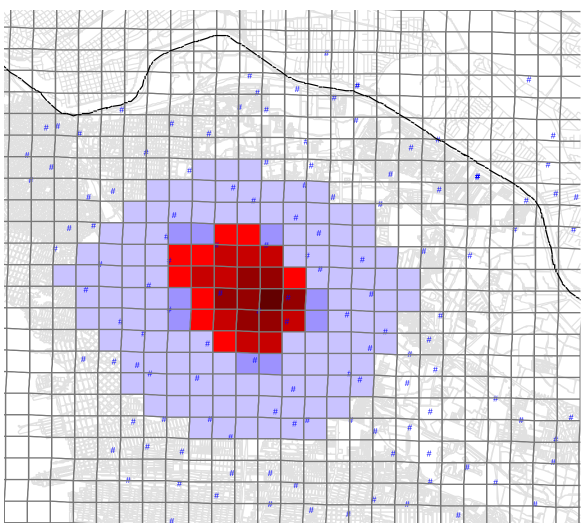

Figure 7 . After 25 years of continuous injection, cells up to 4.5 km distance show elevated TDS, and cells as far as 2 km have TDS >1,000 mg/l

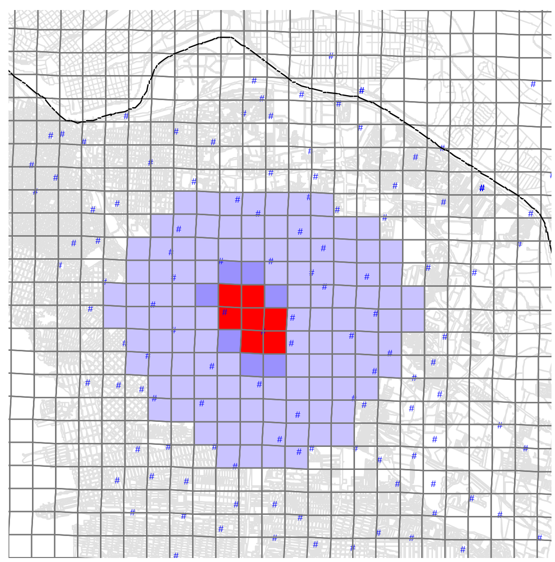

Figure 8. Year 25, (20 years after injection stopped), cells 3.5 km distance show elevated TDS, but the injection site itself shows signs of dilution.

Ground Water Management. Deteriorating water quality of in the JMAS central well field is an ongoing event. If it is due to a lateral intrusion of brackish water, rather than up-coning, then a series of strategically positioned (both in terms of horizontal spacing and depth) wells could provide the feed water for the desalination plant while 'shielding' the wells in the existing well field from brackish water intrusion. By this means, a desalination system would both expand the city's water supplies and protect its fresh ground water. Adopting this kind of integrated approach will influence the siting of the desalination plant, as it should be reasonably proximate to its brackish supply wells as well as its concentrate management site.

Until relatively recently, hydrologists in the U.S. believed that the declining well water quality in the U.S. portion of the Hueco Bolsón was due to 'up-coning' of underlying brackish water. More recent evidence suggests that much of the impairment of water quality is due instead to the lateral inflow of brackish water. This different understanding has led El Paso Water Utilities (EPWU) to propose positioning brackish water wells in a linear pattern to intercept brackish inflow that, under current head pressures, is moving from the northeast and east and contaminating the fresh water of the Hueco Bolsón, (Hutchison, Pease and Hess 2003). The line of brackish water wells will supply feed water for the proposed EPWU/Fort Bliss desalination plant. That kind of strategic approach may be appropriate for the JMAS.

Ground Water Modeling. The Hueco Bolsón ground water model represents a significant information management resource to the region. A further enhancement of this model is currently under development by EPWU. Both the current and the enhanced model incorporate the Juárez portion of the Bolsón. The evident level of complexity of the Juárez portion, however, does not appear to be as detailed as the U.S. portion. Specifically, the uniform horizontal and vertical hydraulic conductivity rates imply an unrealistic degree of homogeneity in the aquifer.

Saline Water Management. The approach to concentrate injection used in this study was limited to modeling the effects of alternative injection sites. Clearly, injection in the active well field is not advisable, as the spread of concentrate will impact existing production wells. A slightly modified approach might yield a different conclusion. It may be possible to use a combination of concentrate injection and *fresh* water injection to contain the injected concentrate water. Such an approach is commonly used to counteract saline water intrusion in sea coast locations, and this management system might be adapted to inland locations as part of concentrate management strategies.

Modeling a strategy that combines concentrate injection with fresh water injection for containment purposes will require a higher-resolution model than that developed for the Hueco Bolsón ground water model. This could be developed as a 'nested' model, enabling a 'tighter' grid in areas for detailed modeling, while still accepting information from, and transferring information to, the larger, regional model. Future enhancements of area ground water models should take this research focus into consideration.

Conclusion. Cd. Juárez faces major challenges in meeting its future water needs. Continued reliance on the fresh water of the Hueco Bolsón as a sole source of water supply, is not a prudent strategy. In the short-term, this will minimize costs and allow the JMAS to maintain affordable water rates. Ultimately, regardless how well the JMAS manages ground water pumping, the city will be forced to make use of brackish ground water for drinking water purposes. From this perspective, it is wise to begin planning for desalination now.

Given the magnitude of the water supply problems of Cd. Juárez, desalination as a means of supplementing the city's water supplies can and should be considered as so doing will reduce pumping stress on the fresh water aquifer. Desalination does not represent a 'solution' to the city's water supply problems, but taken together with water conservation programs, growth management initiatives, strategies to make use of surface water, wastewater reuse options, and water importation from the nearby Conejos Médanos aquifer and the outlying Bismark Mine, desalination can become part of a holistic water supply and ground water management strategy.

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