Groundwater Resources Management for the City of Monterrey, NE-Mexico: The Buenos Aires Wellfield in the Huasteca Canyon

Dirk Masuch Oesterreich, Jose Juan Medina Aleman
Autonomous University of Nuevo Leon, Earth Science Faculty, Laboratory for Geographic Information Systems, A.P. 104, Hacienda Guadalupe,
Carretera a Cerro Prieto km. 8, Linares NL, C.P. 67700, Mexico.
Tel.: +52 821 2122013, Fax: +52 821 2124326,
Email: dmasucho@prodigy.net.mx, dmasuch@ccr.dsi.uanl.mx, JJMA@yifan.net

Jesus Martinez de la Cerda
Water Supply Authority of Monterrey, Matamoros No. 1717 Pte., Colonia Obispado,
Monterrey NL, C.P. 64010, Mexico. Tel.: +52 818 3483818,
Email: jesús.martinez@sadm.gob.mx

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Summary

The main (deep) aquifer of the Buenos Aires wellfield consists of Upper Cretacious limestones of the Aurora and Cupido formation and has a maximum thickness of up to 900 meters. Before groundwater extraction began the aquifer was under artesian conditions. A high number of unproductive wells (44 %) was drilled close to the axis of two synclines formerly thought to be the productive areas. Although these wells are located in fractured zones the fractures seem to be closed and do not permit groundwater circulation. Piezometric levels suggest a groundwater flow in the flanks where the most productive wells are found, explaining the vicinity of unproductive and highly productive wells. The flanks consist of the aquifer limestone itself and represent the areas of recharge and trespassing of groundwater within the fold belt. Although a significant drop in dynamic levels was observed in some of the wells the aquifer is not considered at risk of long term depletion. Rainfall is scarce and uneven, however, the occurrence of major precipitation events (hurricanes) in NE-Mexico is factored into the hydrologic balance. In fact, hurricanes Gilbert (1988) and Keith (2000) brought the Buenos Aires deep aquifer back to artesian conditions, indicating a complete recharge. Within a time frame of 10-12 years operation at present or even slightly higher discharge is considered an appropriate means of managing the aquifer.

Introduction

Monterrey, the capital of the state of Nuevo Leon, Mexico, is situated approximately in the center of the State located in NE-Mexico close to the Texas border with a latitude of $25^o 45´$ N and longitude of $100^o 15´$ W. It has a semi-arid climate with a mean temperature of $24\,^o$ C. However, most of the times temperatures are either hot ($>28^o$) or cold ($<14^o$). Monterrey is the center of large industries, commercial and financial activities and represents the second largest manufacturing city in the Republic. A basic condition for wealthy development of major cities similar to Monterrey around the world is the availability of drinking water. Shortage of drinking water is in most cases due to a dramatic population growth in such a short time that even a well planned strategy for urban development can fail. In 1920 the Metropolitan Area of Monterrey had a population of 103,000 inhabitants and because of severe droughts, floods and revolution by 1940 the population had increased only to 350,000. By 1980 the population had increased to

2,300,000. Severe water shortage with availability of water only around three or four hours daily was common. Twenty years later its population grew to 3,500,000 but due to the construction of two new dams, water culture programs, reusable water from wastewater treatment plants and rehabilitation of groundwater wells inhabitants can enjoy 24 hours of water availability. Although this is very important in order to sustain the existing population it is not enough for the rhythm of growth and development. Recent statistics show that our mean drinking water consumption is 10,400 liter per second (lps) with lows in winter of 9,300 lps and high peaks in summer of 12,100 lps. Basic problems encountered in a semi-arid region with surface water are scarce rainfall and high temperatures stimulating high amounts of loss through evaporation. In the largest dam (El Cuchillo) water evaporation is equal to the amount extracted for drinking water at least five months of the year due to a large water surface and low depth of the reservoir. Before 1985 engineers believed that surface water would be sufficient to sustain the Metropolitan Area of Monterrey. However, due to a severe drought that begun in 1986 most of the dams have been at only 25% of their capacity even though 64% of the drinking water comes from surface water. The advantage of surface water is that the levels can be measured with facility and strategy for a water contingency plan can be conducted with greater accuracy.

The remaining drinking water is obtained by man-made tunnels and natural springs (3.20%); shallow and deep boreholes located in the "Metropolitan Area of Monterey Wellfield", "Buenos Aires Wellfield" and "Mina Wellfield" which contribute 33% of the total water consumption. The "Buenos Aires Wellfield" is the most important one and contributes with 46% of the groundwater extracted (~ 1.5 m^3/s). It is located in the mountainous area of the "Huasteca Canyon" close to the city. The wellfield provides water of high quality with low cost of treatment. Water distribution is easy because of its relatively higher altitude to the city.

Fig. 1: Situation of Monterrey (blue outline) and the Buenos Aires wellfield (red outline) within the Huasteca Canyon in the "Curvatura de Monterrey" fold belt, Sierra Madre Oriental (Landsat ETM image from 4.1.2002, UNITED STATES GEOLOGICAL SURVEY, EROS Data Center).

Another advantage of this aquifer is that in severe droughts depletion of dynamic well levels is only approximately 0.30 m per week compared to the Mina wellfield with a depletion of 1.0 m or 2.0 m per week The disadvantage of the groundwater is the complexity to determine the amount of available water for a well contingency plan and the possibility of contamination by natural or human activities. A survey taking into consideration the recharge area, lithology, and a calculation of aquifer reserves needed to be carried out in order to establish a good contingency plan to use the "Buenos Aires Wellfield" in a sustainable manner and at the same time determine if we can explore new boreholes in the same aquifer or explore new aquifers within this region. Fig. 1 shows the location of the City of Monterrey and its surroundings. The Buenos Aires wellfield is highlighted in red color. The image demonstrates the "Curvatura de Monterrey" fold belt, in which the Huasteca Canyon and the wellfield are located.

Problem definition

Of 41 mostly deep wells drilled in the 1970's, down to a depth of 1,940 m in the deepest well, 18 never produced water or were depleted soon after operation began. The operating wells show a significant variation in discharge, varying from 10 lps to 187 lps mean discharge. In some of the wells dynamic levels have dropped close to 100 meters. In order to develop a sustainable groundwater management plan for the Buenos Aires wellfield, the Monterrey Water Authority needed to know:

1. An explanation for the "dry" wells and the differences in discharge of neighboring wells
2. The amount of water safely exploitable from the aquifer, and
3. Recommendations for the location of new wells.

At the center of discussion for several of the past years was the question whether the aquifer system in the Huasteca Canyon is overexploited, and if so, to what degree. This problem most urgently needed to be addressed in order to come up with recommendations for the management of the aquifer system and its catchment area.

Hydrology of the Buenos Aires Basin

The hydrological basin that contributes to the wellfield was delineated using Digital Elevation Models supplied by the INEGI (Instituto de Geografía, Estadística e Informática) that have a resolution of 50 x 50 meters. A total of 9 DEM´s covering almost the entire "Curvatura de Monterrey" was merged into one dataset and analyzed with the hydrological modeling functions of the Arc/Info GIS. The resulting grid was checked for inconsistencies (such as data errors, sinks that have no outlet, water bodies) and subsequently watersheds and drainage patterns were derived from the new hydrologically corrected surface model (Fig. 2). The principal drainage of the fold belt is the Santa Catarina River. Its basin was found to cover an area of 1,793 km^2, 1,131 km^2 of which contributes to the Buenos Aires wellfield. The major hydrological basin is divided into three minor basins. Recharge areas, accumulated surface flow, and direction of surface flow were calculated for any given point within the basin. Assuming a medium annual precipitation of 538 mm/year within the wellfield´s catchment area, groundwater reserves were calculated at ~51 x 10^6 m^3/a (PLANIMEX 1975). This equals a total well discharge of ~1,600 lps that can safely be exploited at any given time. In 1998, the wellfield was operated at a mean discharge of 1,535 lps. However, due to higher extraction during most of the last 25 years, dynamic levels in some of the wells have been observed to drop almost 100 meters over a period of several years, apparently indicating overexploitation.

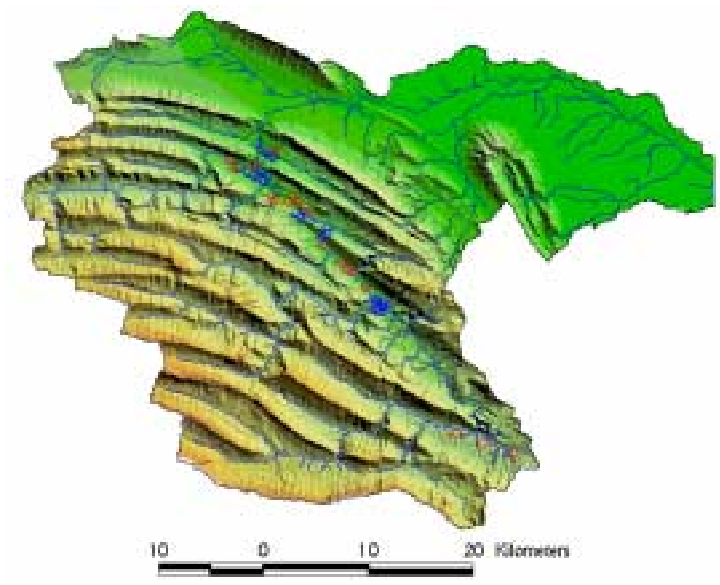

Fig. 2: Hydrological basin and drainage pattern of the Santa Catarina River. The wells of the Buenos Aires system are marked in blue (productive) and red (non-productive) color.

There are several aspects in the water balance that deserve a closer look. Climatic conditions within the “Curvatura de Monterrey” fold belt are subject to dramatic changes both in time and place. Furthermore, precipitation greatly depends on morphological features. The high slopes of the mountain ranges generally receive higher and more frequent precipitation as the intramountainous valleys and the foreland of the Sierra Madre Oriental. The occurrence of short but heavy precipitation events is a common climatic feature in this region. Torrential rainfalls, and even hurricanes (Gilbert, 1988; Keith, 2000), hit the region rather frequently and contribute significantly to aquifer recharge. Hurricane Keith in some parts of the Sierra Madre Oriental southeast of Monterrey dropped some 250 mm of rain within less than a day, equaling almost half of the mean annual precipitation. Although a great part of the precipitation is subject to surface runoff a significant amount infiltrates into the highly permeable alluvial deposits of the Santa Catarina River. Another significant amount infiltrates directly into the cretaceous limestone of the deep aquifer system that form the ranges of the fold belt and generally receive the highest rates of precipitation. Dynamic levels in the aquifer system respond almost immediately to these high rates of recharge. Hurricane Gilbert (1988) brought the limestone (deep) aquifer back to its artesian conditions, indicating a complete recharge. All these factors do not appear in the hydrological balance that is based on 538 mm mean annul precipitation, so that long term aquifer reserves are considered to be significantly higher, implicating that extraction from the Buenos Aires wellfield can be considerably higher than 1,600 lps without overexploiting the aquifer system.

Hydrogeology of the Buenos Aires Wellfield

The aquifer system being exploited by the Buenos Aires wellfield consists of three separate hydraulic units:

- The deep artesian system is made up of fractured and locally karstified limestones of Upper Cretaceous age (Aurora and Cupido formations, also referred to as Upper and Lower Tamaulipas formations, and the overlying Cuesta del Cura formation)
- The shallow porous system consists of coarse gravels of the Santa Catarina's alluvial deposits
- The stratigraphically deepest, but morphologically exposed system of limestones of Upper Jurassic age (Zuloaga formation)

The deep artesian system is known to be locally in direct contact with the gravel unit and interact with the alluvial porous aquifer. The alluvial system serves as a hydraulic connection between the limestone aquifers. The geological formations within the "Curvatura de Monterrey" are heavily folded, exposing the Aurora and Cupido limestones in the ranges of the fold belt. Hydraulic conductivity calculated from pumping tests conducted after the drilling process resulted in $1x10^{-2}$ m/s for the gravel unit, $1x10^{-3}$ – $1x10^{-2}$ m/s for the cretaceous aquifer, and $1x10^{-3}$ m/s and lower for the Jurassic aquifer (PLANIMEX 1975). Actual hydraulic conductivity can vary to a great degree in the cretaceous aquifer due to the existence of more or less fractured or karstified zones. The situation of wells relative to their tectonic setting was also found to be an important element in determining the phenomenon of the "dry" wells: wells drilled close to the axis of the synclines proved to be no productive whereas some of the most productive wells are located in the flanks of the syncline. Although the "dry" wells are located in fractured zones the fractures seem to be closed and do not permit groundwater circulation. Piezometric levels instead suggest a groundwater flow in the flanks, explaining the sometimes close vicinity of unproductive and highly productive wells.

The Buenos Aires wellfield is designed to exploit all three aquifer systems. The alluvial aquifer is extensively being exploited by means of an infiltration gallery that is located just at the outlet of the basin at a depth of 55 meters, intercepting the groundwater flow in the porous (upper) aquifer. The deep artesian system is penetrated by a series of deep wells (down to 1,900 meters), some of them originally being boreholes for hydrocarbon exploration by PEMEX, and later used for groundwater extraction.

Piezometric levels were evaluated by using well records (SERVICIOS DE AGUA Y DRENAJE DE MONTERREY 1999) of dynamic and static levels from the beginning of pumping in 1974 up to date. Piezometric maps for the deep aquifer system were constructed for the historically lowest and highest as well as the artesian levels. The location of known springs was also taken into account. In any case a steep hydraulic gradient results that generally drives groundwater flow from the central parts of the "Curvatura de Monterrey" into northeastern directions, varying locally due to areas of very low permeability that correspond to the most compressed zones of the tightest synclines. Piezometric levels suggest that the anticlines and their flanks represent the zones of trespassing of groundwater from one sub-basin into the other. Piezometric contours for the alluvial system suggest an interaction with the Jurassic aquifer in a way that the Zuloaga formation is being recharged by groundwater from the alluvial deposits in times of high piezometric levels and vice versa in times of lower levels. Dynamic levels of the limestone aquifer of the cretaceous system rise quickly as a reaction to high rainfalls. Aquifer discharge, however, is much slower so that a great amount of recharge from precipitation is available for extraction over longer periods of time.

The results of the assessment of the Buenos Aires aquifer system were visualized in a hydrogeologic map (HELLWEG 1996) and a hydrodynamic map as well as an additional map of geologic cross sections (MEDINA ALEMÁN 2001). These maps fundamentally differ from common concepts of hydrogeologic maps for several reasons: The reference level for the construction of the hydrogeological map is the groundwater level. The parameter visualized is hydraulic conductivity at groundwater level, while all strata above groundwater level are removed. This type of hydrogeologic map clearly highlights productive areas potentially suitable for exploration (MASUCH OESTERREICH 2000). This map also was of great help to identify the distance of the wells in the deep cretaceous system from the axis of the syncline as an important factor for their (un)productivity. While this map basically is a static representation of hydraulic conductivity at groundwater level, the hydrodynamic map approaches the aquifer as a dynamic system by identifying flow systems. Recharge areas, zones of transitional flow, and discharge areas of the Buenos Aires wellfield are clearly outlined. The cross section map visualizes fold structures and the tectonic setting of the wells. Geographic Information System software was used to integrate available geologic, hydrogeologic, and hydraulic data of the wellfield. The digital system has an open structure that allows maintenance and updating of the database.

Conclusions and Recommendations

The most important conclusion of the assessment of the Buenos Aires wellfield is that, in contrast to former opinions, the aquifer system is not overexploited and is not at risk of depletion. Although dynamic levels can significantly vary in short terms the wells in the deep system are hydraulically well connected to the high yield aquifer systems in the central parts of the "Curvatura de Monterrey". Within the integrated Monterrey water supply system of dams, springs, and wellfields the Buenos Aires wellfield is considered to be presently the safest and most dependable water resource for the city of Monterrey. Whereas the amount of water available from the Cerro Prieto and El Cuchillo dams highly depends on climatic factors the Buenos Aires basin is considered to hold long term groundwater reserves significantly in excess of 51 x 10^6 m^3/year. This corresponds to an extraction of more than ~ 1,600 lps that can safely be pumped at any given time. The Buenos Aires wellfield can be managed in a dynamic way in response to the water available from the dams. It can function as a groundwater reserve in times of scarce precipitation by increasing exploitation and then decreasing it in times when surface water abounds.

References

HELLWEG, F. (1996): Untersuchungen zur Grundwasserneubildung im Canyon Huasteca als Beitrag zur Wasserversorgung des Großraumes Monterrey, NE-Mexico.- Tesis de maestría del Departamento de Ingeniería Geológica de la Universidad Técnica de Aachen; 102 pp., 35 fig., 4 tab., 2 anexos; Aachen, Alemania.

MASUCH-OESTERREICH, D. (2000) A Methodical Approach to GIS-Based Hydrogeologic Mapping.- Revista Mexicana de Ciencias Geológicas, vol. 17, número 1, pp. 24-33. Universidad Nacional Autónoma de Mexico; Ciudad de Mexico.

MEDINA ALEMAN, J. J. (2001): Desarrollo de un sistema de información hidrogeológica para el Campo de Pozos Buenos Aires, Cañón La Huasteca, Santa Catarina, N.L.- Tesis de licenciatura, Facultad de Ciencias de la Tierra, UANL.

PLANIMEX INGENIEROS CONSULTORES S.A. (FINK, M., COLUMBUS, N. & NAOR, H.) (1975): Estudio del Potencial de las Fuentes de Agua Subterránea de Monterrey.- Reporte interno de la Comisión de Agua Potable de Monterrey, Servicios de Agua y Drenaje de Monterrey.

SERVICIOS DE AGUA Y DRENAJE DE MONTERREY (1999): Relación de Información de los Sistemas Huasteca, Mina y Santiago.- Reporte interno de los Servicios de Agua y Drenaje de Monterrey.