A STUDY OF GROUNDWATER RESOURCES AND LAND SUBSIDENCE IN THE TOLUCA VALLEY, MEXICO

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ABSTRACT
The Toluca valley, situated within the high plateau of Central Mexico, experiences heavy groundwater extraction. Currently there is a net loss (recharge – extraction) of 166 M m$^3$ per year of groundwater within the upper Lerma basin aquifers. Ongoing work involves quantifying and predicting land subsidence associated with the lowering water tables and the high clay content found in the metropolitan area and the industrial corridor of Toluca.

1. INTRODUCTION
The sustained growth in population in the Toluca Valley and neighboring Mexico City has primarily depended on the continuous development of both local and regional water resources for industrial, agricultural and domestic use. The Upper Lerma Basin, covering an area of approximately 2000 Km$^2$ (Figure 1), is the focus of this study. Currently there is a significant net loss of water within the Upper Lerma Basin primary due to groundwater pumping, and the discrepancy is increasing with time. Stress on the aquifer has caused significant changes on the regional water flow patterns, a general reversal in the direction of hydraulic gradients, the disappearance of artesian springs and wetlands, and noticeable land subsidence within the basin.

This paper focuses on the excessive groundwater extraction occurring in the valley. We examine various changes in regional flow patterns, and ever decreasing groundwater levels throughout the valley. We examine modifications in the regional groundwater flow. We also estimate the current water balance deficit occurring in the upper Lerma basin.

A follow up study will include the quantification and prediction of aquifer compaction in the Toluca valley. Neighbouring Mexico City’s land subsidence problems have been well documented. However, no comprehensive studies exist for the Toluca Basin. Of concern in this region is the total magnitude of the land subsidence and the future subsidence rate that is likely to result from current groundwater extraction.

The upper basin of the Rio Lerma has an approximate area of 2000 km$^2$. It is located entirely in the state of
Mexico. The entire Lerma River is 560 km long and crosses 5 states before ending in the Pacific Ocean.

The Toluca valley is where the Lerma river’s headwaters originate; this valley is an important urban center with major industry occurring along with significant agricultural activities. Industrialization has led to an increase in the number of inhabitants over the course of the last four decades.

2.2 Climate

The following section gives an overview of the major climate parameters. Precipitation, Temperature, and Evapotranspiration were examined by looking at 39 climate stations located throughout the valley. Data was somewhat irregular and sometimes incomplete, however averages were obtained from the years between 1946 and 2000 (SICHEM 2004). See Figure 2 for the average annual precipitation, temperature and evapotranspiration recorded by a climate station located in the central plane of the valley. Climate stations in higher altitudes had considerably different data and will be discussed in the following sections.

2.2.1 Precipitation

Total annual rainfall varies from 1,300 mm in the highest areas to 750 mm in the center of the valley. The most intense rainfall is in the highest sectors, where 80 to 120 mm can fall in a single day. Rainfall over the rest of the area is between 60 to 80 mm/day. Approximately 90% of the rainfall occurs between May and October (SICHEM 2004).

2.2.2 Temperature

In the Toluca valley the annual average temperature ranges from 12 to 16 °C, with May being the warmest month (14–15 deg C) and January the coldest (11–12 deg C), while in the mountainous areas the annual average is 12–14 deg C, with a minimum in the Nevado de Toluca (annual means from 2 to 5 deg C) (SICHEM, 2004).

2.2.3 Evapotranspiration

Estimates of real evapotranspiration, using Turc’s Method, range from 754 to 453 mm, with an average of about 579 mm, where maximum values were recorded in April and May and minimum ones in January and December (SICHEM, 2004).

2.2.4 Infiltration

Vertical recharge due to infiltration has been estimated to be between 2 % and 11% of total precipitation (Lesser 1992, CNA 1996b, CNA 2000, GTZ-CAN 2004).

Current work involves discretizing the infiltration pattern throughout the valley using discretized soil, precipitation and evapotranspiration data. This will be used to obtain a more accurate recharge rate occurring in the valley. We have also installed a network of pressure transducers that take a water level reading twice daily. These levels will also enable us to better measure the recharge due to infiltration.

Figure 2: Annual precipitation, temperature, and evapotranspiration at a climate station in the central plain of the Toluca Basin. Averages taken for the years between 1971 to 1999.
2.3 Geology

The Lerma River Basin is located within the Transmexican volcanic belt in central Mexico (CNA 1996a). This region was a tectonically active zone in the Upper to Mid-Tertiary period (around 23 million years ago) forming a series of northwest-southeast trending fault systems throughout much of southern Mexico (DGCOH 1992).

deposited in the Pliocene period (around 3 million years ago) and extends from the flanks of the Sierra de las Cruces mountains in the east across the basin floor to the foot of the Nevado of Toluca volcano (Figures 1 and 3) (DGCOH 1992). This formation is a heterogeneous mixture of volcaniclastic materials (DGCOH 1992). The basaltic flows of the Chichinautzin formation were deposited in the eastern portion of the Lerma River Basin in the Pleistocene and Holocene periods (CNA 1996b). This formation is composed of volcanic flow and ash materials and has a lower fracture density than the Tarango formation (DGCOH 1992).

The Nevado de Toluca volcano (figures 1 and 3) is primarily composed of dacite and andesite lava flows with a core of andesite. During the Pleistocene, cinder cones formed atop the flanks of the volcano after which andesitic and basaltic lava flows were deposited in the Holocene (CNA 1996b). Basaltic lava flow materials from the Sierra de las Cruces mountain chain along the eastern edge of the basin, and the Nevado de Toluca volcano to the west, are interbedded with erosional deposits from the surrounding mountains. These sediments are further overlain by younger fluvial deposits from the Lerma River and lacustrine sediments from the ancient lakes that extended throughout the basin interior (Figure 3) (CNA 1996b).

Volcanic alluvium, eroded from the flanks of the surrounding highlands, is composed of sand and gravel (DGCOH 1992). Lacustrine materials, consisting of fine sand, silt and clay (DGCOH 1992) were deposited in the Late Pliocene, above the alluvium (CNA 1996b). The fluvial sediments are composed of fine to coarse sand sized particles and are interbedded with the lake sediments (DGCOH 1992). Alluvium thickness increases towards the basin interior to a maximum depth of 200 m (CNA 1996b).

2.4 Population density

The largest single factor controlling future growth and development of the State of Mexico is considered to be the availability of water for irrigation of agricultural fields, potable drinking water and industrial use (Diez Perez 1998).

Figure 4 demonstrates the rapid growth occurring in the Toluca valley, an area of approximately 2000 km² where since the 1960’s the population has approximately doubled every 20 years. This growth has had a deep impact on the groundwater resources in the Toluca Valley.

Figure 3: General basin geology: west-east cross-section (A-B) (see figure 1) through the southern Lerma River Basin from Nevado de Toluca volcano to the foothills of the Sierra de las Cruces mountains. The primary recharge areas and general direction of groundwater flow are also indicated in the diagram. Modified from Rudolph et al. (2006) and CNA (1996b).
If the population continues to increase at the same rate as the current one, there is no question that there will be a shortage of water in the foreseeable future. This problem is similar to the problems of Mexico City where, ironically, in the late 1960’s Mexico City started importing water from the Toluca Basin, now the Toluca basin can no longer support its own or Mexico City’s water demands. The end result is that people will either have to move away from the urban center or water will have to be imported from abroad.

3. HYDROGEOLOGY AND GROUNDWATER EXPLOITATION

The following section is divided as follows: regional flow, population density, groundwater extraction, water balance in the Toluca valley, and regional depletion of groundwater levels and reversal of vertical hydraulic gradients.

3.1 Regional flow

Precipitation in the higher altitudes infiltrates to recharge the Lower aquifer unit of the Tarango formation, where the volcanic sediments are exposed to the surface. Recharge to the Upper aquifer system is thought to be along the flanks of the highlands surrounding the Lerma River Basin, and in the basin interior where the Lower aquifer is covered by low permeability clay (DGCOH, 1992).

Infiltration from the Nevado de Toluca volcano travels east, below the valley floor, towards the location of the ancient lakes and the Lerma River (Gobierno del Estado de Mexico 1993, Lesser 1992). Groundwater flows from the volcano also travels to the north towards Ixtlahuaca (Lesser 1992). Recharge waters within the eastern mountain chain of Las Cruces, flow west to the foot of the range, towards the Laguna Almoloya and the Lerma River (Gobierno del Estado de Mexico 1993).

3.2 Groundwater extraction

Groundwater extracted in the Lerma River Basin is divided between local use and exports to Mexico City. Locally, water is used as a potable water resource, irrigation of land and supplies industrial practices. In a 2002 census, a total of 448,476,824 m$^3$ was calculated to have been extracted during that year through the 930 wells and springs that are tapped within the whole basin (IMTA 2003). Most of the extraction is occurring in the metropolitan area of Toluca and the Industrial corridor.

The Industrial Corridor is located on the main highway between Mexico City and Toluca. The Corridor is a newly developed and highly concentrated industrial zone. After the destructive 1985 earthquake in Mexico City, many industries, previously located in the Valley of Mexico were displaced to the Toluca Basin to more stable ground (Garfias Soliz 1997).
3.3 Water balance in the Toluca Valley

With excessive extraction occurring in the Toluca valley an accurate water budget of the system has become an important parameter in determining ways of managing the aquifer’s resource and minimizing negative impacts. Several attempts have been made to properly determine the water budget, with varying success.

The water budget can be written as (from Healy and Cook (2002):

\[ P + Q_{on} = ET + \Delta S + Q_{off} \]  \[ \text{[1]} \]

where \( P \) is precipitation plus irrigation; \( Q_{on} \) and \( Q_{off} \) are surface and subsurface water flow into and out of the basin; \( ET \) is the sum of bare-soil and open-water evaporation and plant transpiration; \( \Delta S \) is change in water storage; and all components are given as rates.

Table 1. Assessments of the availability of water in the Toluca Valley Aquifer. All values in Millions of m\(^3\)/year. Modified from CNA, 2000.

<table>
<thead>
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<tbody>
<tr>
<td><strong>Entrants</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Groundwater (Nevado)</td>
<td>-</td>
<td>94.5</td>
<td>94.6</td>
<td>94.6</td>
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<tr>
<td>Groundwater (Las Cruces)</td>
<td>-</td>
<td>63</td>
<td>63.07</td>
<td>63.07</td>
</tr>
<tr>
<td>Vertical recharge</td>
<td>98</td>
<td>177</td>
<td>177</td>
<td></td>
</tr>
<tr>
<td><strong>Total Entrants</strong></td>
<td>342.1</td>
<td>256.5</td>
<td>336.76</td>
<td>336.76</td>
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<tr>
<td><strong>Flow out of the Basin</strong></td>
<td></td>
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<tr>
<td>Groundwater outflow</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td>extraction</td>
<td>353.9</td>
<td>327.4</td>
<td>422.34</td>
<td>449</td>
</tr>
<tr>
<td>Evapotranspiration</td>
<td>-</td>
<td>14.7</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Natural discharge</td>
<td>-</td>
<td>-</td>
<td>53.6</td>
<td>53.6</td>
</tr>
<tr>
<td>(rivers and springs)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total output</strong></td>
<td>359.9</td>
<td>342.1</td>
<td>475.95</td>
<td>502.6</td>
</tr>
<tr>
<td><strong>Water Balance Deficit</strong></td>
<td>-13.8</td>
<td>-65.5</td>
<td>-139.19</td>
<td>-165.84</td>
</tr>
<tr>
<td>* no data</td>
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<tr>
<td>* 2000 data except for extraction</td>
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</table>

Several studies have examined the water balance in the Toluca Valley including OEE (1970); Lesser (1992); CNA (1996b); CNA (2000); and most recently GTZ-CNA (2004). Some of the studies are incomplete and lacking a detailed analysis. However, a more rigorous estimate of recharge and discharge has been estimated in the 1996 and 2000 studies respectively. Table 1 displays four studies that have examined the water balance of the Toluca Valley Basin.

The CNA (1996b) study is used to estimate recharge and discharges such as groundwater discharge and river and stream discharge. IMTAs (2003) study, determined that 449M m\(^3\)/year was extracted from the valley, and this value was used for the extraction parameter. This rate has a considerable effect on the water balance.

Using the data from the 2000 study and modifying the extraction rates using the IMTA (2003) data, the water balance deficit would be placed at 166 M m\(^3\)/year. This deficit will only continue to rise due to the expected population increase.

3.4 Regional depletion of groundwater levels and reversal of vertical hydraulic gradients

Regional groundwater flow was previously primarily from south to north from the Toluca Basin to the Ixtlahuaca/Atlacomulco Basin (CNA 1996b). Increased pumping of deep wells throughout the basins has, however, altered groundwater flow directions in the Lerma River Basin forming a depression cone in the metropolitan area of the valley.

Historically, groundwater levels in the Lerma River Basin were near-surface and emerged above the land surface in the vicinity of the ancient lakes on the eastern basin floor (Lesser 1992). Evidence of flowing artesian conditions has been documented by the National Water Commission (CNA) through water level measurements in deep monitoring wells in the middle of the basin. Lowering of the regional water levels, presumable due to heavy groundwater extraction in the basin, has been recorded in many studies (Gobierno del Estado de Mexico 1997, DGCOH 1992, DGCOH 1997, UAEM 1993, CNA 1997, CNA 1996b, CNA 2000, GTZ-CNA 2004).

Several attempts have been made to properly determine the water budget, with varying success. The CNA has recorded hydraulic heads with the use of multilevel piezometers of depths ranging from 10m to 150m from 1968 to 2006 in over 50 wells within the Toluca Basin. This valuable data has enabled researchers and water management experts to evaluate the ongoing depletion of groundwater in the Toluca Basin. The drawdown occurring between 1970 and 2004 throughout the valley is displayed in Figure 6. The metropolitan area of Toluca is also noted in the figure.
We notice a systematic decrease throughout almost the entire valley with maximum drawdowns (43 m) occurring around the City of Toluca.

The Systema Lerma, situated along the upper section of the Lerma river, gathers a large portion of the recharge water entering from the sierra las Cruces (figure 1).

![Figure 7: Change in hydraulic gradient between 1970 and 2004. Gradients were taken between upper and lower aquifers and the gradient values of 2004 subtracted from the values of 1970 to obtain the differences. Gradients were obtained between 150 m to 15 m depth. Positive values show an increase in gradients upward and negative values show an increase in gradients downward. Ticks represent UTM coordinates and are marked every 5 km on the X and Y axis.]

There is evidence of downward hydraulic gradients between the shallowest and deeper wells. As a general rule the hydraulic gradients in 2004 were downward and in 1970 were more upward, neutral or only slightly downward. The resulting difference shows that a majority of the region has had an increase in downward vertical hydraulic gradients (Figure 7). In the North West part of the valley, away from the City of Toluca, upward gradients were stronger. The strongest decreases in hydraulic gradients were noticed close to the metropolitan area of Toluca.

4. LAND SUBSIDENCE

This next section examines land subsidence. A more detailed paper on subsidence will be presented once all data is assembled and treated. The land subsidence section is divided into: Background of subsidence in the Toluca Valley, Theory, and Ongoing Work.

4.1 Background of subsidence in the Toluca Valley

Directly related to the drop in groundwater levels is the occurrence of land subsidence throughout the valley. We have observed several sites in the Toluca Valley where land subsidence is occurring. This takes place in the form of vertical land movement and the occurrence of fractures, usually in areas where there is heavy groundwater extraction. The village of San Pedro Totaltepec, 7km East from the center of Toluca and adjacent to the industrial corridor, has experienced severe land subsidence in the past 10 years. Many buildings have cracked walls or foundations, and several houses are no longer livable.

The clay content combined with heavy groundwater extraction in the central part of the Toluca basin is conducive for land subsidence and the occurrence of fractures (ICGA 1977a). Several sites, especially in and around the industrial corridor have had severe problems associated with land subsidence. The lacustrine clay and alluvial deposits reach 150 m in thickness in these areas implying that there is a large potential for compaction.

Very few studies have been carried out on subsidence in the Toluca valley. However, some studies examined the effects of the fractures on the structures of the valley (ICGA 1977a, ICGA 1977b Consultec 1978, Consultec 1979).

The dependency on the semiconfined aquifer system within the Toluca Valley will likely remain high or even increase into the future. Due to this fact, accurate predictions of long-term land subsidence phenomena will be crucial.

4.2 Theory

Subsidence is often caused by groundwater extraction. Groundwater pumping entails a drop in the pressure head or hydraulic head and an increase in effective stress. This was first noted by Meinzer and Hard (1925) and Meinzer (1928). At the same period Terzaghi (1925) established that:

\[ \sigma = \sigma - p \]

\( \sigma \) = total stress
\( \sigma \) = effective stress
\( p \) = water pressure (positive for compression)

Terzaghi's one-dimensional theory was then developed by Biot (1941) who considered consolidation as a three dimensional phenomenon. Biot's formulation has a simultaneous solution for two variables: water pressure and deformation within the matrix. In this case horizontal and vertical displacement can be obtained at each point within the 3 dimensional domain. Biot's approach is probably the best way for calculating surface deformation but it is mathematically intensive because it accounts for the two parameters (water pressure and deformation) in three dimensions. Biot's approach was later extended to encompass anisotropic material properties (Biot 1955; Carol 1979).
4.3 Ongoing work

Ongoing work includes the examination of regional land subsidence with the use of InSAR (Synthetic Aperture Radar Interferometry) images obtained from the European Space agency’s ERS-1, ERS-2 and Envisat Satellites.

InSAR (Synthetic Aperture Radar Interferometry) is a new remote sensing method used in several fields to measure displacements on the ground. The development of the InSAR techniques, using radar satellites, gives us the possibility of measuring vertical displacements of the ground surface with a precision of one centimetre to a few millimetres on areas extended with very good space details (10-100 km²) (Amelung et al. 1996, Galloway 1998, Hoffman et al. 2001, Hoffman 2003). Data from years 1995, 1996, 2001, 2002, and 2006 will be used to produce subsidence maps of the Toluca Valley.

The study of land compaction will be done on a regional scale on Toluca valley. Our findings will be verified by in-situ extensometers (Roctest ltd. R-4, Montreal Canada) installed in the industrial corridor where the most significant drops in groundwater levels are found. From field observations, San Pedro Tololtepec has had at least 2 m in subsidence in some areas over the past 10 years. This is where the first extensometer has been installed. This extensometer measures compaction in the upper 80 m of the clay and alluvium. The second extensometer has yet to be installed but will be placed throughout the clay and alluvium media (up to 150 m) to use the bedrock as a benchmark for measuring vertical movement.

The final aspect of this study will be to incorporate a subsidence module (based on either a 1-D Terzaghi model or a 3-D Biot model) into the HydroGeosphere finite element model (Therrien and Sudicky 1996) whereby future land subsidence occurrences will be simulated and predicted.

5. CONCLUSIONS

We have seen that heavy groundwater extraction is occurring in the Toluca valley and will likely continue and even increase in the future. A modification of the groundwater flow system including the lowering of water levels, the reversal of vertical hydraulic gradients, the disappearance of springs and the occurrence of land subsidence are all indications that the current rates of pumping are not sustainable. There is currently a water budget deficit of over 166 M m³/year in the Toluca basin.

Deep monitoring wells have experienced a drop of over 1.4 m/year, the highest drawdown’s being in and around the metropolitan area of Toluca and the industrial corridor. The occurrence of land subsidence in the industrial corridor and the metropolitan area of the city of Toluca is of concern. Ongoing work will add to the quantification and prediction of land subsidence occurring in the Toluca Valley.

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