REGIONAL FLOW SYSTEM MODELLING OF THE MANAGUA AQUIFER, NICARAGUA

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Abstract: The Managua Aquifer is the sole water supply to 1.2 million inhabitants of the City of Managua. The aquifer is part of a regional system of volcanic materials of the Pleistocene-age Las Sierras Formation. A numerical modelling study was conducted on the aquifer to understand the impacts of pumpage, define well recharge areas and estimate long-term sustainable yield. The model was calibrated with historical pumpage and head data compiled over more than 30 years. Eight distinct calibration periods, each with a distinct set of pumpage and aquifer head data, were defined resulting in a more unique calibration than is typical for groundwater modelling studies. It is apparent from the model that "natural" recharge is insufficient to reproduce heads at the levels observed in the field. The optimal solution is obtained when recharge is increased below urban areas to account for the significant urban water losses typical of a city like Managua. This increased recharge helps to provide a hydraulic barrier between the pumping wells and the highly contaminated Lake Managua. A safe aquifer yield based on various amounts of urban system losses is predicted.

Keywords: Volcanic Aquifer, Groundwater Modelling, Aquifer Sustainable Yield

INTRODUCTION

The Managua Aquifer is the sole source of water supply to the more than 1.2 million inhabitants of the City of Managua (Figure 1). Municipal pumpage of the aquifer began in 1925 with pumpage from Laguna Asososca, a large volcanic collapse crater on the west side of the city, which functions as a large groundwater-fed well. Increasing demand over the years led to a corresponding increase in pumpage from Laguna Asososca (Table 1). Overtime, increasing numbers of municipal production wells were constructed throughout the city to supplement Laguna Asososca. The first major well field was constructed in the mid-1970s near the Las Mercedes airport to the east of the city. By 1996, there were 89 municipal production wells producing 315 x 10^6 m^3/d. Currently there are over 120 municipal production wells including several very large well fields. In recent decades, there have been various hydrogeologic studies that estimated the sustainable yield of the Managua Aquifer (e.g. Hazen and Sawyer, 1964; Hazen and Sawyer-Chan, 1971; Montgomery-Chan, 1979, Krasny and Lopez, 1989; INAA/JICA, 1993). These studies all lacked good field information and based their predictions on the amount of "natural" recharge and did not consider urban water losses. Only the INAA/JICA (1993) study used numerical modelling but did not compile sufficient field data for calibration. This paper presents the results of a groundwater modelling study conducted by Cruz (1997).

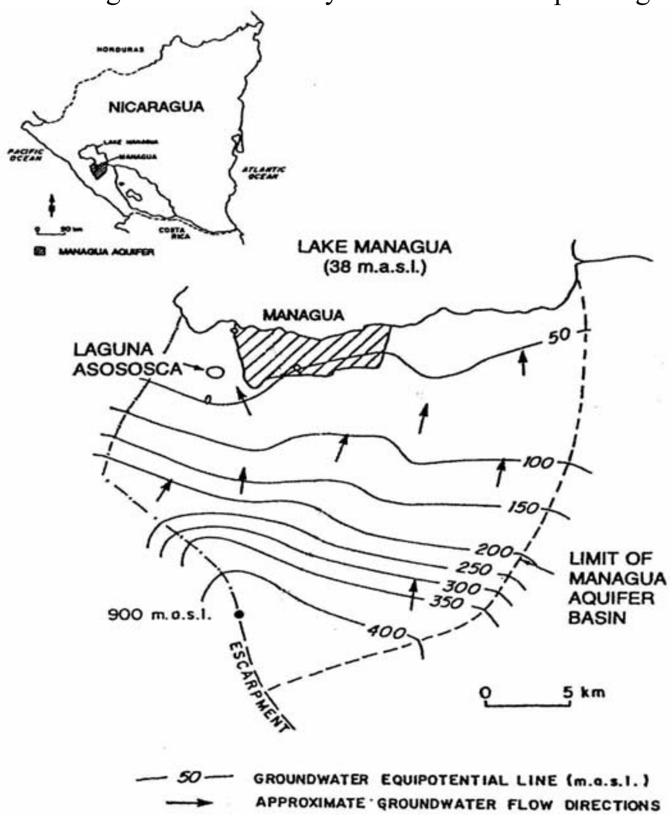

Figure 1: Location Map and Equipotential Map of Managua Aquifer (adapted from Bethune et al, 1996)

Table 1: Sources of Water Supply for the City of

Managua 1955-1996 (10^6 m^3/year)

Location	1955	1963	1972	1975	1980	1985	1990	1991	1996
Asososca	12.4	16.6	25.1	33.9	27.2	31.1	25.9	24	10.9
Las Mercedes	-	-	-	-	20.0	21.4	20.2	21.9	30.0
Sabana Grande	-	-	-	-	-	-	4.4	5.5	7.6
Veracruz	-	-	-	-	2.1	2.1	3.2	3.9	5.6
Other Wells	1.6	2.8	-	-	5.1	10.1	40.8	46.7	77.3
Total	13.9	19.3	25.1	33.9	55	64.6	97.0	102.0	131.4

Site Description

The Managua Aquifer consists of a 400 to 600 m thick semi-consolidated, highly transmissive, pyroclastic sequence of the Pleistocene-age Las Sierras Formation. It is underlain by low permeability Tertiary limestone and shale (Zoppis Bracci and del Guidice, 1958; Kuang, 1971). The pyroclastics are dominated by ignimbrite (a welded tuff formed by the widespread deposition of volcanic ash), which can be very transmissive where fractured in this tectonically active area. Although deeper formations are apparently artesian at some locations and minor perched aquifers are found at higher locations, the Managua Aquifer is generally well connected and behaves as a single water-table aquifer (Hazen and Sawyer, 1964). The aquifer is recharged immediately south of the City of Managua on the large Nicaraguan Depression and discharges into Lake Managua in the central lowland of the depression. Recharge occurs throughout the entire watershed but increases significantly with elevation due to higher precipitation. The regional flow system is therefore primarily fed at higher elevations (except where slopes are very steep) and lesser recharge occurring at lower elevations. Laguna Asososca is one of several craters within a north- south trending line of volcanic cinder cones and collapse craters located on the west side of the City of Managua. The craters are filled with highly permeable semi-consolidated volcanic pyroclastic material up to 500 m thick, which act as highly productive aquifers.

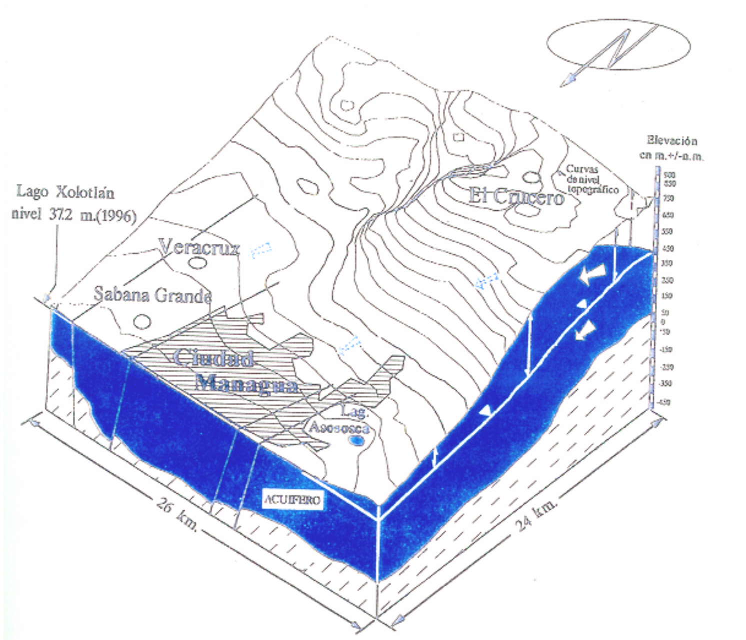

Figure 2: Cross-section of Managua Aquifer (from Cruz, 1997)

Methodology

Existing hydrogeologic information was compiled from various sources. Historical pumpage and aquifer head data were compiled by INETER for eight calibration periods (Table 2).

Table 2: Model Calibration Periods

Calibration Period	Pumpage (10^6 m^3/year)
Pre-1925	0
1963	48.5
1965-70	79.0
1971-75	102.9
1976-1980	193.4
1981-85	220.4
1986-90	303.2
1995-96	365.5

The calibration periods covering a five-year range are based on taking average pumpage rate and average aquifer head measurements for the given range. An equipotential map was drawn by hand for each calibration period with observation and pumping wells located. The commercial modelling software FLOWPATH (Waterloo Hydrogeologic Inc., 1996) was used to simulate aquifer conditions. FLOWPATH is a steady state, two-dimensional numerical simulation package that can calculate hydraulic heads, pumpage, drawdown and well capture zones. The model was first calibrated to the natural state before pumping of Asososca began in 1925. Heads were obtained from Asososca (where the original head is known) and observation wells located outside of the zone of influence of Asososca with head data predating the construction of the large municipal production wells. Calibration for each time period is achieved when simulated hydraulic heads at each time period sufficiently match heads observed in the field. An acceptable amount of error was decided to be <1 meter *mean error* with a fairly even special distribution (Table 3). The next calibration period (1963) was then simulated requiring further adjustments to input parameters to optimally satisfy both the first and the second time periods. The remainder of the time periods were gradually incorporated in the optimisation producing a calibration that has the least amount of mean and spatial error for all eight calibration periods. Input parameters were adjusted based on reasonable ranges of uncertainty defined before the modelling as well as their sensitivity to influence hydraulic heads.

Table 3: Calibration Errors for each Calibration Period

Calibration Period	Average Error	Absolute Average Error	Average Squared Root Error
Pre-1925	0.446	1.555	1.448
1963	-0.338	1.006	1.330
1965-70	-1.086	1.819	2.683
1971-75	-0.560	1.496	2.074
1976-1980	-0.442	1.954	2.555
1981-85	-0.419	1.768	2.137
1986-90	-0.116	1.965	2.898
1995-96	-0.009	0.881	1.172

Notes: Average Error=$\sum r/n$, Absolute Average Error= $|\sum| r/n$, Average Squared Root Error= $\sqrt{\sum r^2/n}$

Results and Discussion

In order to optimally satisfy the eight calibration periods it was necessary to increase natural recharge below the urban areas, which cover most of the northern half of the watershed. The optimal solution is obtained when recharge below urban areas is significantly higher than natural recharge (Table 4). This is not unexpected as it is well-known that municipal water systems are typically inefficient leaking up to 40% of total pumpage.

Table 4: Calibrated Recharge for City of Managua

Calibration Period	Area (10^6 m^3)	Leakage Recharge (10^{-4} m/d)	Total Recharge (10^{-4} m/d)	% Leakage Recharge	% Natural Recharge
Pre-1925	<<27	Not estimated	3.0	0	100
1963	27	5.4	8.4	64	38
1965-70	30.6	5.8	8.8	66	34
1971-75	36.0	6.6	9.6	69	31
1976-80	37.9	9.2	12.2	76	24
1981-85	46.7	11.0	14.0	78	22
1986-90	53.7	12.5	15.5	81	19

Notes: Natural recharge is estimated to be 3.0 x 10^{-4} m/d.

Since the majority of system leakage occurs in the older parts of Managua closer to Lake Managua, the increased recharge also helps to provide a hydraulic barrier between the pumping wells and the highly contaminated Lake Managua. The wells near the lake are thus less likely to draw polluted water from lake and all wells below urban areas have less drawdown than without the additional urban recharge. The only municipal well that could potentially draw water from Lake Managua is San Antonio, which is about 1 km from the lake.

Conclusions

The study concluded that in 1996, the Managua Aquifer was clearly not in a condition of over-exploitation whereby pumping exceeded recharge (natural and urban) leading to excessive drawdown or pumping-induced aquifer contamination was occurring. The model predicts a safe long-term aquifer sustainable yield of 677,655 m^3/d, which is sufficient to meet the expected demand until at least 2010. This is clearly higher than the yield what would be predicted if municipal system losses were not considered (e.g. JICA/INAA, 1993).

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