INVESTIGATION OF THE STATE AND CONDITION OF SALTWATER INTRUSION IN CEBU CITY AQUIFERS IN THE PHILIPPINES

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Abstract - In the Philippines, Cebu City has been declared as among the major cities with the most critical balance conditions suffering from the depletion of groundwater sources and the incidence of saltwater intrusion. Well-monitoring and plotting of isohaline contours have been conducted by the Metro Cebu Water District (MCWD). However, not much attention had been given to construct a groundwater model of Cebu City with updated data. This paper presents a simplified analytical model of the Cebu City aquifers to determine the current position of the presumed sharp saltwater-freshwater interface, as well as visualize the drawdown and upconing conditions. Ten representative wells were assessed individually regarding the likelihood of saline contamination. Moreover, the upconing of these ten wells has been simulated considering the effects of well interference. In defining the freshwater head and the distance of the toe of the freshwater-saltwater interface from the shore, the Glover relation was primarily used. Simulation results are illustrated by two- and three-dimensional representations. Calculations and graphical representations were all carried out using Microsoft Excel spreadsheets. Three of the ten wells were shown to be contaminated, while two more are threatened. Simulations with 2014 groundwater data also show an alarming drawdown condition in the aquifer. Aside from the contribution to a greater public awareness of the threat of saltwater intrusion, the findings may serve to guide the policy-making of MCWD with regard to establishing allowable rates of groundwater extraction.

Keywords - Saltwater Intrusion, Aquifer, Drawdon and Upconing Conditions

I. INTRODUCTION

Saltwater intrusion into groundwater aquifers of shorelines and coastal areas is a threat to the quality of the freshwater supply. Generally, coastal groundwater aquifers are vulnerable to seawater intrusion due to their hydraulic connection with the sea, and are responsive to various factors. Many studies and research initiatives have tackled the phenomenon of saltwater intrusion and correlated it with what they found as the rapid ascent of mean sea levels due to the continuous effect of climate change around the world. Some factors are tidal oscillation, seasonal changes, and geological formations in the coastal areas, which contribute to variable evaporation and recharge rates and so affect the extent of saline contamination (Kashef, 1971).

According to Barlow (2003), saltwater intrusion is defined as the lateral and upward movement of saltwater. Principally it is the lateral encroachment of saltwater, which is often due to groundwater extraction near coastal areas. Additionally there can be an upward movement of water brought up from deeper saline portions by pumping wells. Under normal conditions, freshwater flows seaward: from inland aquifers and recharge areas to coastal discharge areas and finally to the sea. Moreover, groundwater generally flows from areas with higher hydraulic heads – i.e., higher groundwater levels – to areas with lower hydraulic heads. This natural movement of freshwater towards the sea prevents saltwater from entering freshwater coastal aquifers. Nonetheless, saltwater intrusion is a natural phenomenon in some coastal aquifers: since seawater is denser than freshwater, saltwater could push itself inland and settle underneath freshwater. Their boundary is not strictly distinct, however; the saltwater-freshwater interface exists as a transition or dispersion zone and is constituted by brackish water, a saltwater and freshwater mixture. Moreover, human activities such as pumping from coastal groundwater wells and navigation channels, and natural phenomena such as storm surges and sea level rise, contribute to exacerbating saltwater intrusion by rendering the sea water pressure higher than that in the aquifer and allowing saline water to infiltrate inland, thus encroaching the freshwater stored in the coastal aquifer.

A persistent condition of saltwater intrusion would render the groundwater supply unusable for human consumption, ultimately affecting the water security of the community. Besides this, other problems could also follow such as damage to the subterranean marine environment. The over-pumping of freshwater, oil drilling and lack of rain are known to lead to the salinization of freshwater, where a surge of sodium ions in both water and soil occurs: an organism exposed to such an accumulation of ions would lose water in favor of the surrounding region of greater salt concentration, leading to eventual dehydration and death (Kaushal, 2007), and impacting the ecological conservation effort. Land subsidence is also caused by the decrease in pressure brought by the over-withdrawal of groundwater.

In the Philippines, according to the Environmental Management Bureau (2005), the landward movement of seawater is an effect of excessive groundwater extraction that results to the lowering of the water table, fundamental to retaining the hydrostatic pressure at the freshwater side and preventing the encroachment of seawater into the aquifer.Excessive pumping of groundwater in coastal areas in Cebu City was observed in recent years, brought about by extremely high water demand (GMA News, 2011). In this light, the Metro Cebu Water District (MCWD) had identified saltwater encroachment in the coastal aquifer near Barangay Talamban in Cebu City (MCWD, 2014). The joint investigation of WWF-BPI (2011) even indicated saltwater encroachment in coastal areas to an extent of five kilometers inshore.

Prior studies have determined the cause of saltwater intruding into the coastal freshwater aquifers of Cebu City to be the continuous, unregulated groundwater extraction (Abracosa et al., 2001; UNESCO-IHE, 2014). To compound the matter further, groundwater recharge is deemed insufficient to replenish the supply: Maghaway Valley, for instance, only registered an annual rainfall rate of 1.4 million cubic meters with an addition inflow of 1.1 MCM from riverbeds, a figure considered by Abracosa et al. (2001) as inadequate in meeting the growing water demand from the many sectors of Cebu City.Such a persisting condition of saline intrusion brought about by excessive groundwater discharge threatens the water security of the people of Cebu City, and the construction of an adequate groundwater model such as what the current study currently undertakes is a valuable step towards integrated water resources management in the coastal area of the metropolis. Furthermore, the study aims to assess the extent of saltwater intrusion in the coastal aquifers of Cebu City by means of an analytical model of groundwater flow with considering a sharp interface between saltwater and freshwater.

II. MATERIALS AND METHODS

2.1. Study Area

The Philippines, being an archipelago, in principle has abundant water resources to tap into. Levinson et al. (2008) quantify it at 478 billion cubic meters of renewable water resource, including both surface water and groundwater sources. However, the country's supply of freshwater is under stress due to rapid urbanization and insufficient replenishment of groundwater. Due to unregulated groundwater extraction, the water table has been lowered in several parts of the country, especially the coastal areas of urban regions (National Economic Development Authority, 2011). In past years, the island of Cebu (Fig. 1) has been beset by problems in the sufficiency and quality of the water supply (Codilla, 2014), where cities like Bogo, Carcar, Toledo, Talisay, Naga, Danao, Mandaue, Lapu-lapu and Cebu City depend mostly on the available groundwater supply. Relying solely on groundwater reserves for water needs may accelerate saltwater intrusion into the aquifers of Cebu. According to the report of the Japan International Cooperation Agency (JICA) and the National Water Resources Board (NWRB) in 1998, the lowering of the water table results in inadequate water availability and saltwater intrusion in several areas in Cebu, a main part of which includes Metropolitan Cebu, the central urban district of the island province and the regional center of Central Visayas.

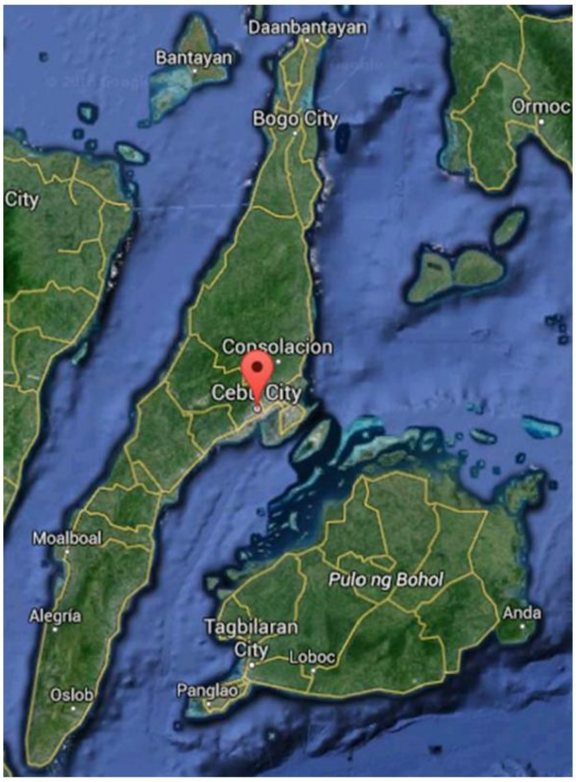

Figure 1.Geographical location of Cebu City in the island province of Cebu.

Also, a study commissioned in 2004 by the Department of Environment and Natural Resources (DENR) and conducted by CEST, Inc. classified in particular, Cebu City, the center of Metropolitan Cebu and the provincial capital, as one of the major cities in the Philippines with critical water balance conditions. It is also reported that parts of Cebu City have lowered to a ground elevation of about one to two meters above mean sea level (WWF-BPI, 2011) due to subsidence attributed to undue groundwater extraction. To meet the community's water demand in Cebu City, MCWD also primarily relies on groundwater sources, though in recent years has been exploring alternative sources: a bulk water supply project is being prepared as a joint investment between the Provincial Government of Cebu and the Cebu Manila Water Development, Inc. (CMWDI) to obtain water from the Luyang River. Nevertheless, as of August 2015 there is still a need for 250,000 cu. m. per day for MCWD to cater to the total demand of its service area. In the interim period of shifting to freshwater sources, the groundwater supply will continue to be tapped into; hence there is a need for groundwater resources to be replenished or otherwise utilized on a decreased scale, since the recharge rate does not measure up to current rates of extraction (Pinili, 2014).

2.2Secondary Data

Data from the 1980s and onwards was acquired from recorded water quality measurements of multiple wells across the study area, gathered from Local Water Utilities Administration (LWUA) and MCWD. Sections of the study area were taken in order to visualize the groundwater profile. Changes in the profile over time are also observed. Analytical solutions were used to calculate and plot the profile of the saltwater-freshwater interface in the unconfined aquifer, both before and after the presence of pumping wells.

2.3 Procedure

A study area was defined that encompassed a square region seventeen kilometers on each side, with vertical cross-sections taken at 2-kilometer intervals and oriented 128 degrees from the positive x-axis. Values had been set for the mass densities of freshwater ($\rho\_fw=1.000$ g/cm^3) and seawater ($\rho\_sw=1.025$ g/cm^3), the dimensionless relative density of saltwater ($\Delta p=0.025$), the horizontal flow of freshwater to the seaward direction ($q= 1.2864$ m^3/day/m), and the hydraulic conductivity of the aquifer (limestone: $k= 5$ m/day). Beginning with 1989 and for every five years hence, the extent of the upconing of the saltwater-freshwater interface was considered. For each mark of the five-year time interval, the Glover relation was used as an analytical means of determining h_f, the head of fresh groundwater above mean sea level; z, the depth of the saltwater-freshwater interface from mean sea level; and x_o, the distance of the toe of the saltwater-freshwater interface from the shore. Contour lines of equal depths were generated for each of the vertical cross-sections of the study area, but prior to generating the contours, z values had been interpolated between every 25-m depth for a smoother curve.

Ten wells in the study area (Fig. 2) have complete characterization information – such as the specific capacity, well diameter, distance from the shore and well depth – and so they have been designated as the reference wells: around them was employed the Thiessen polygon method for interpolation of data (Boots, 1999), in particular, that of water level and yield/discharge.

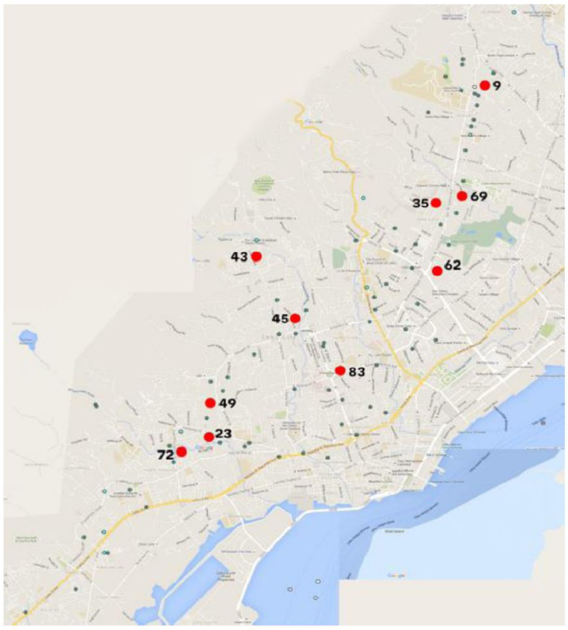

Figure 2. Map of the study area with representative wells plotted.

The total drawdown is then computed as the quotient of the discharge and the specific capacity of the well. The study supposes a 2-km effective radius of influence and the 200-m aquifer thickness; the hydraulic conductivity K is then determined based on the formula byMuskat (1937) as cited in Kashef (1987), expressed accurately as;

$$K = \frac{Q \ln \frac{r_e}{r_w}}{\pi\left(h_u^2 - h_w^2\right)} \quad [1]$$

where:
K = hydraulic conductivity of the aquifer; 5 m/day
Q = rate of flow (steady rate of well pumping), m^3/s
r_e = radius of influence of well at steady state of flow, m
r_w = effective radius of well, m
h_w = height of water level in well above impervious boundary
h_u = depth of undisturbed water table, m

which in turn is used to determine the drawdown H.

$$H^2 - h_w^2 = \frac{Q}{\pi K} \ln\left(\frac{R}{r_w}\right) \text{or} \quad [2]$$

where:
Q = constant abstraction rate, m^3/s
H = elevation from original water table to the impervious layer, m
h_W= well water depth from the impervious layer, m
R = influence radius of well field, m
K = hydraulic conductivity of the aquifer; 5 m/day
r_w = well radius, m

It is a conservative assumption that upconing of saltwater is directly proportional to the drawdown of freshwater in the well despite the density difference. The depths of the points that comprise the sharp saltwater-freshwater interface are given by Equation 3. The critical rise established by Equation 3 marks the boundary past which the saltwater in the particular scenario of the study would inevitably contaminate the pumping well. The profiles of upconing and critical rise per well were plotted for comparison and analysis.

The zone width through which the abstraction of freshwater into the sea was generated through this equation from the Glover method (Cooper et al., 1964):

$$x_o = \frac{\rho q}{2\,\Delta\rho\,K} \quad [3]$$

where:

x_o = interface distance to shore, m

ρ = density of water (1.000 g/cm^3)

q = horizontal flow freshwater, m^3/day/m; equivalent to the product of R and the aquifer thickness of 200 meters

R = recharge rate of Cebu city (1.28642 m^3/day/m)

K = hydraulic conductivity of the aquifer (5 m/day)

III. RESULTS AND DISCUSSION

3.1. Saltwater Intrusion

Three-dimensional drawdown contour maps were generated to simulate the drawdown condition of the ten representative wells in 2009 and 2014, also considering the effects of well interference Due to lack of water level data, however, drawdown depths are reckoned from the mean sea level indicated by zero elevation for the purposes of visualizing the drawdown 3D profile.

The drawdown of the groundwater level and upconing of the saltwater-freshwater interface can be plotted considering all wells operate at their maximum abstraction rates. Such a scenario shows the greatest effects well abstraction will have on the saltwater intrusion phenomenon. Figure 3 illustrates the drawdown due to maximum abstraction while Figure 4 shows the extent of upconing due to operation of wells at maximum pumping.

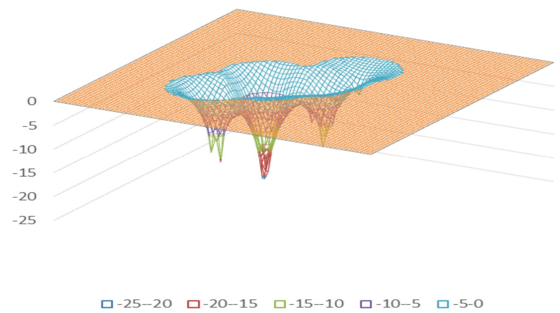

Figure 3.Drawdown due to maximum pumping with water level at 0 m MSL.

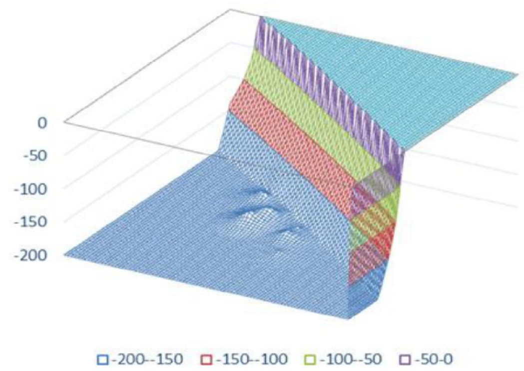

Figure 4. Saltwater upconing due to maximum Abstraction

It is evident in Figure 4 that the interface converged with parts of the upconing due to the maximum abstraction of the wells. This shows that the abstraction rates per well exceeding the computed maximum pumping rate will cause a more pronounced upconing and movement of the interface. In addition, only ten wells are analyzed in this model. If all operating wells contribute to the upconing, there could be a possibility of the saltwater-freshwater interface to move landward. The summation of the values of all wells in an assigned region can exceed the computed value of maximum abstraction. Using those values could show a better representation of the movement of saltwater-freshwater interface.

Simulated saltwater upconing in the Wells 43, 45 and 83 in 1989, 1994, 1999 and 2004 are observed to exceed the critical levels, thereby indicating their susceptibility to the intrusion of seawater. Extending the projection further, critical areas where saline intrusion may occur even after 2004 are Well Areas 23 and 35. This finding is further supported by the fact that within the vicinity are nine wells that were abandoned in 1992 because of confirmed saline contamination (Fig. 5), where chloride concentration exceeded the 250-ppt limit set by the Philippine National Standards for Drinking Water.

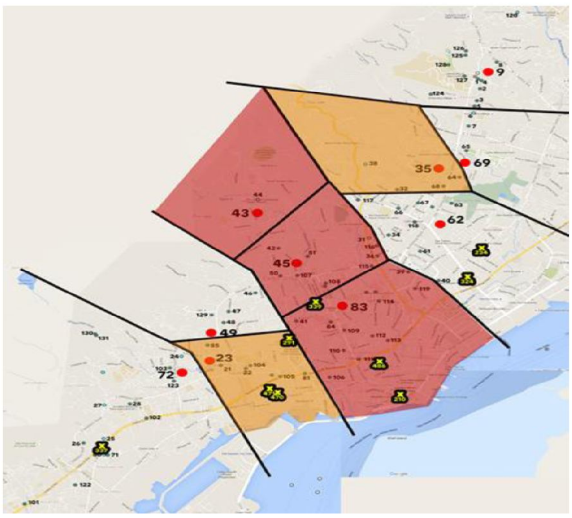

Figure 4. Overlay of simulated critical areas and the location of intruded wells

Well areas 9, 49, 62, 69 and 72 are not yet considered critical areas since these areas recorded a distance from upconing peak to the critical rise of more than 5 m. Most of the well regions that were not yet considered under critical areas were located at the northeastern portion of Cebu City except for well region 35 and 23.

CONCLUSIONS

Drawdown contours were generated to simulate the condition of simultaneous extraction of the ten representative wells in the years 1989, 1994, 1999 and 2004, and subsequently converted to three-dimensional renderings of the extent of groundwater drawdowns. Moreover, projected drawdowns in 2009 and 2014 point to an alarming condition of the groundwater supply. The hypothesis that well abstraction contributes to the gradual advance of the saltwater-freshwater interface is confirmed from the three-dimensional renderings of the extent of saltwater upconing and its influence on the sharp interface. The merely gradual movement is attributed to the limitation of considering the effect of only ten pumping wells instead of the entire wellfield. Nonetheless it is also notable that the discharge rate is the primary determinant of the total drawdown, the saltwater upconing level, and the gap between critical rise and peak of the cone of ascension as observed in the analysis of the drawdown and upconing profiles of each of the ten representative wells

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