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Metro Manila and Metro Cebu Groundwater Assessment

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Abstract

This paper describes the methodologies adopted and the results obtained in assessing the groundwater resources of Metro Manila and Metro Cebu. Also some early and recent studies on the aquifer systems in the two metropolis are presented to draw some comparisons on the assessment and data acquisition methods and identify some gaps involved and the improvements needed. Some of the indicators used in assessing groundwater potential and associated problems include storage coefficient, transmissivity, safe yield, and salt water intrusion. The complex and expensive nature of actual field monitoring and analysis has encouraged the use of mathematical models in this study. Specifically, models adopted by NHRC and JICA were used and their respective capabilities, data requirements and modeling results for water balance are described. Although the two models have specific inputs unique to each model and the NHRC model used secondary 9 year data (i.e. 1982-1990) while JICA used one-year actual data (1990), the models gave similar results as far as recharge to groundwater and piezometric heads are concerned. It was found that Metro Manila gets an annual recharge of 206 MCM which is basically due to the high rainfall events during the wet season. Inflows from Laguna lake and leakage from MWSS distribution systems have been also identified as contributors to the recharge. It was also found that due to the over pumping of wells in some coastal areas in Metro Manila, sea water intrusion of aquifers is now becoming a serious problem. The same holds true in Metro Cebu where water for all types of uses comes from groundwater. That is why the annual recharge from rainfall to the aquifer of the Maghaway valley in Cebu amounting to be 1.4 MCM plus an additional inflow of 1.1 MCM coming from riverbeds, are believed to be insufficient to cover the increasing demand for water from all sectors of the society.

It is envisioned that a regional scale groundwater and environmental planning scheme for the two metropolis needs to be developed by linking the models with GIS so groundwater data base maps can be overlaid with land use, management practices, recharge distribution and mass loadings of chemicals. A follow-up study which will incorporate this methodology will provide a useful management tool for developing water resources on a regional scale.

Metro Manila and Metro Cebu Groundwater Assessment

Executive Summary

Metro Manila

The first part of the paper was aimed to evaluate two project studies conducted to assess the surface and groundwater resources of Metro Manila. These studies have focused on the development, adoption, calibration and use of water balance and groundwater flow models to simulate the recharge rates in the study area. In effect, the analysis used some basic criteria to compare the modeling approach adopted in the two studies. These criteria include model capabilities, assumptions, input requirements and simulation outputs. Also, the extent at which the study objectives have been achieved has been also assessed.

The two methodologies (i.e. JICA and NHRC models) provided comparable simulation results for recharge rates and piezometic heads for Metro Manila. For instance both methodologies have estimated higher piezometic heads at Quezon City, Caloocan and Manila/Pasay, and low values at Paranaque and Las Pinas. While this phenomenon suggests that the excess water (runoff/baseflow) from areas with higher piezometric heads can constitute as inflows to the Laguna Lake, it was found by the solute transport model that the increase in pumpage will result in sea water intrusion into the piezometric depression areas such as Paranaque and Las Pinas. An optimal groundwater development plan was therefore proposed that regulates pumping at the coastal areas of Metro Manila.

Some issues/suggestions concerning the methodology adopted

For both water and solute transport in the unsaturated zone, the issue of bypass flow in preferential flow pathways (due to macropores) have been ignored which is a major limitation. Also, the sensitivity of the models to important parameters have not been assessed. Future modeling effort should include new algorithms (for macropore flow and non-equilibrium sorption) and sensitivity analysis to make the models more comprehensive and useful.

The neighboring towns of Metro Manila have agricultural watersheds which have been earlier assessed as a possible source of chemical loadings to the Manila Bay and Laguna Lake. However, it appears that the 2 methodologies have failed to consider or estimate the effect of agricultural runoff on the quality of surface water courses. Direct runoff was estimated as part of the water balance but the loss of chemicals and sediments in runoff/erosion, whose ultimate destination are surface water courses, was not included. Also, in these estimates, the effect of urbanization on the long term recharge patterns was not considered in the computation. A modification/ testing of the model to incorporate these factors and mechanisms will certainly increase the reliability and significance of future water resource studies.

A follow-up study to analyze the rainfall-runoff-evapotranspiration-infiltration relationships in the Metro Manila Basin is recommended using updated or measured data. The NHRC water balance model should be used for this purpose since it has more in-depth treatment of the water balance components (e.g. base flow separation, etc). From this, more accurate assessment of groundwater depletion or recharge can be obtained, and a Master plan to regulate pumping in areas with piezometric depressions (i.e, overpumping) can be implemented.

Metro Cebu

In the second part, a brief assessment of the groundwater resources of Metro Cebu is presented. It can be seen that the analytical approach employed in the analysis is quite simplistic and has more limitations compared with the water balance and numerical groundwater flow models adopted by JICA and NHRC for Metro Manila. For instance, the analytical model cannot provide accurate estimation of drawdown when transmissivity value changes due to change in saturated thickness of the aquifer. Also, the calculations are based on non-steady state pumping by using groundwater storage only. If pumping is carried out under steady state conditions (i.e., constant head provided continuously by storage in the infiltration basin), discharge rate per well can be increased. In effect, the total number of production wells can be reduced considerably since change in aquifer saturated thickness does not represent a limiting factor under such conditions of withdrawal (Cebu Consultants, 1984).

Because of the above limitations, it is recommended that a digital or numerical model need to be developed and employed for proper design of wellfields for any development scheme in Metro Cebu.

Metro-Manila and Metro-Cebu Groundwater Assessment

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1. Introduction

This paper presents an overview and assessment of the groundwater resources of the two major metropolis in the Philippines, namely: Metro Manila and Metro Cebu. Because of rapid growth in population and industrialization in these urban centers during the past two decades, consequential problems such as groundwater depletion and pollution are now being experienced in the region and this prompted the Government, through its water agencies, to investigate the current and projected status of the region's aquifers. A detailed discussion of the methodologies adopted for assessing the groundwater resources of Metro Manila and Metro Cebu will be the main focus of this paper.

2. The Groundwater System of Metro-Manila

2.1 Confined Aquifers

The groundwater system of Metro-Manila is found in groundwater formations underneath the Guadalupe Plateau and the Antipolo Plateau. The main aquifer is the one formed by the Guadalupe formation which covers 472 square km and which also covers much of the area of the NCR. It is believed to extend beneath the bed of Laguna Lake. Groundwater is stored and transmitted in this main aquifer by openings and fractures in the tuffaceous formation. This main aquifer is under pressure (thus the term artesian). It is separated from the overlying material by a semi-permeable or semi-confining layer, also called an aquitard. The thickness of this layer varies from 15 to 45 m.

The semi-permeable layer separates the aquifer below (thus the term confined aquifer) and is responsible for creating a pressurized condition. However, in some parts of Metro-Manila where drawdowns of more than 50 m have been caused by verpumping, the main aquifer has been converted to a water table aquifer (i.e, the aquifer is no longer pressurized).

The Antipolo Plateau is also underlain by a separate groundwater basin with an area of about 30 sq km. The thickness of the Antipolo formation is about 250 m. Piezometric elevations in the Antipolo area range from 16 to 170 m above msl. Depth to the water table is from 30 to 40 m. Farther to the east, the MWSS service are is underlain by older (Pre-Quaternary) formations which have poor storage and water transmitting properties, with the exception of basalts which may form local aquifers and springs.

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2.2. Unconfined Aquifers

Water is also stored in the earth material above the confining layers of the main aquifer (so-called phreatic or water table aquifers). This water occurs in a non-pressurized state. Alluvial sediments derived from erosion of the Guadalupe formation provide the medium or material for water table aquifers. Such alluvial sediments occur in three areas within the NCR: the Manila Bay deltaic plain, the Marikina Valley, and the alluvial deposits found at both the periphery and bottom of Laguna Lake. The alluvial sediments occur as irregular lenses varying in form and thickness (i.e., from about 50 m along the Manila Bay shore to about 100 m near and underneath Laguna Lake).

The layers confining the main pressurized aquifer in the predominantly tuffaceous strata and the water table aquifer in the overlying alluvial formation are not totally impermeable, however. Some “leakage” is believed to take place between the main pressurized (or confined) aquifer and the overlying water table aquifer.

2.3 Studies Conducted on Metro-Manila Groundwater System

2.3.1 Early Studies

Studies on the water resources of Metro Manila started as early as the 1960s to investigate the hydrogeologic properties of its aquifer systems as well as to evaluate various alternatives for optimizing usage of existing water supplies and for harnessing potential sources from adjacent surface and ground water systems. For instance, hydraulic properties (e.g. transmissivity and storage coefficients) were analyzed from pumpimg tests at the aquifers of the Laguna Lake Basin by several researchers (Sandoval, 1969; Quiazon, 1971; LWUA, 1982; Sandoval and Mamaril, 1970; FAO/UNDP/NIA, 1976; MWSS/SOGREAH, 1989; and JICA/MWSS, 1991). Results indicate a regional transmissivity in the range of 200-1000 sq.m./day and a general decline in permeability towards Laguna Lake. Detailed findings of the different studies have been summarized by NHRC/IDRC (1993). Further studies were conducted to determine the withdawal distribution and recharge patterns of the aquifers and wells in the Metro Manila region and results are summarized below.

Quiazon (1971) reported a total pumpage for Metro Manila and suburbs of 65 to 105 million gallons per day (110-175 MCM/yr) from about 950 operating wells indicating an annual average groundwater production of 0.07 to 0.18 MCM per well. However, he added that in an area of around 300 sq.km. of the pumped zone between Guiguinto (Bulacan), Manila, Quezon City and Marikina Valley, the decline of the groundwater level had reached 2 to 50 feet per year and he warned that many pumpwells may become inoperative within 10 years.

In 1980, the Groundwater Development - Manila Water Supply Project II (GWD-MWSP II) was launched by MWSS in collaboration with ELECTROWATT as a long range program to provide for a more effective exploitation and use of the groundwater resources of Metro Manila area. The Master Plan of this study was envisioned to project the future conditions of the groundwater in the region and to identify priority projects and determine potentials for groundwater development in unexplored portions of the aquifer systems. To achieve this goal, a water management model was adopted to simulate groundwater movement in the Manila Bay aquifer system.

Results of the simulation above indicated that if pumpage were continued to year 2000 at the 1982 rate, the mean water level would approach 90 m below MSL which is more than twice the 1982 depth. The model also projected a water level recovery rate of 2 m/yr even pumpage is completely stopped in 1990. The implication of this is that the aquifer parallel to the Manila Bay would be vulnerable to sea water intrusion for several decades.

FAO/UNDP/NIA (1976) projected up to year 1984 an annual groundwater withdrawal for western Laguna of 54 MCM to supplement an annual river diversion of 222.2 MCM to meet the water needs of 6,334 and 2,033 has of croplands planted to lowland rice and sugar cane, respectively. a preliminary report by MWSS/JICA (1991), on the other hand, found that out of the 258 MWSS wells, 131 were operational (43% of which are located in Metro Manila) which produced 32.75 MCM of water in 1990. Combining this with the 306.85 MCM for 2,216 private wells in Metro Manila, this means a total production of 339.6 MCM or an annual average of 0.145 MCM per well.

The replenishment of the water withdrawn and pumped from Metro Manila wells and its aquifer systems have been also investigated by various researchers. FAO/UNDP/NIA (1976) indicated that the artesian aquifer system of the Laguna Formation is recharged directly by precipitation under unconfined conditions in the higher ground west of the Marikina fault, and by vertical leakage under semi-confined conditions over large agricultural areas. The report also gave annual recharge estimates equal to 7% of rainfall for the driest year (1968) and 14% for the wettest year (1972). NEPC (1986, 1987), on the other hand, estimated the recharge to the Metro Manila area by considering rainfall, groundwater inflow, and induced recharge from Laguna Lake. In its approach, the 5% value selected by Quiazon (1968) as the proportion of rainfall which was effective recharge, was used. An interim report by MWSS/JICA (1991) estimated the recharge to Metro Manila from 9.3% to and 19.6% of annual rainfall.

2.3.2 Recent Studies

More recently, two major foreign-assisted projects were completed which also evaluated the water resources of the Metro Manila basin. One was sponsored and undertaken by JICA experts in cooperation with MWSS staff. The other study was undertaken by NHRC through the sponsorship of IDRC of Canada. The JICA/MWSS study did actual sampling and analysis of hydrogeological properties, well lithological data, and withdrawal/recharge patterns (initial results were earlier reported by JICA/MWSS (1991). In the NHRC/IDRC (1993) study, on the other hand, hundreds of volumes of technical reports, maps and some parameter estimations were compiled and analyzed. The common goal of the two project studies was to develop, integrate, calibrate, verify, and adopt surface and ground water models to estimate groundwater recharge rates as well assess surface and ground water quality in the study area.

Results of these recent studies are summarized in the next secction. A comparative evaluation of these recent studies is presented later in the paper, along with recommendations on ways to improve understanding of Metro-Manila’s groundwater conditions.

2.4 Summary of Aquifer Conditions

2.4.1 Aquifer Characteristics

Results of recent studies indicate that the average value of the transmissivity coefficient in Metro-Manila's Guadalupe formation is 58 sqm/day, with a range of 50 to 100 sqm/day, characteristic of an aquifer with slightly moderate water transmitting properties. Zones with high transmissivity (up to 200 sqm/day) are found locally in coastal areas along Manila Bay and Laguna Lake, as well as in the Marikina Valley.

The storage coefficient in the main aquifer varies from 0.1 in the water table aquifer located south of the NCR to 0.0001 in the northern part where the aquifer is believed to be under artesian (pressurized) conditions. However, in parts of the main aquifer where leakage from the water table aquifer occurs, higher values of storage coefficient are observed (i.e., 0.002 to 0.006). Higher storage coefficient values mean that the aquifer is able to release more water from a unit volume for a unit change in head.

As mentioned earlier, in parts of the main aquifer where overpumping has occured, the aquifer has been converted to a water table aquifer with correspondingly higher storage coefficient values. In these areas, storage coefficient values of 0.025 to 0.05 are consistent with the estimated overpumping rate of 250,000 cum/yr over 19 years and with observed changes in piezometric levels over the period (i.e., up to 110 m below mean sea level).

2.4.2 Recharge to the Aquifer System

The semi-confining layer or aquitard separating the main artesian aquifer below from the water table aquifer above has a leakage coefficient that varies from $1x10^{-11}$ to $3x10^{-9}$ per sec, which is a measure of the water transmission rate across the aquitard. Before large scale pumping took place, the pressure head in the artesian aquifer was believed to be higher than that of the water table aquifer in some parts of Metro-Manila (particularly near the coast and around Laguna Lake), resulting in upward leakage (and even free flowing wells in certain areas). With pumping, however, the pressure or head in the artesian aquifer is reduced. When the water pressure in the artesian aquifer becomes lower than the hydrostatic head of the upper (water table) aquifer, leakage occurs in the downward direction. In this way, the overlying water table aquifer recharges the artesian aquifer below, a process that is believed to have be happening in the Metro-Manila aquifer system.

In fact, because of overpumping, groundwater levels in the main aquifer have been lowered below the bottom of the semi-confining layer. In this case, maximum downward leakage would have been attained and no further increase in recharge to artesian aquifer from the overlying water table aquifer can be expected. The estimated leakage from the water table aquifer to the main aquifer is about 421,000 cum/day or 154 million cum/yr. In turn, recharge to the water table aquifer comes from rainfall that infiltrates into the ground. This occurs over an area of about 650 sq km.

Aside from rainfall, recharge to the Metro-Manila aquifer system (consisting of both the water table aquifer and the artesian aquifer) comes from other sources. For instance, deep cones of depression created by pumping along the Manila Bay coastline and along the western shore of Laguna Lake have the effect of inducing inflow to both the water table aquifer and artesian aquifer. Along the Manila Bay coast, however, this process induces saltwater intrusion. There is also inflow coming from contiguous aquifers located in the North and South where the piezometric surface is higher. Yet another source of groundwater recharge is leakage from MWSS pipes.

Overall, it is estimated that the total annual recharge to the groundwater system is about 217 million cum/yr or 594,000 cum/day. Much of this amount comes from precipitation over a 790 sq km area (148 m cum/yr). Induced flow from Laguna Lake is estimated at 22 m cum/yr; inflow from the North, at 12 m cum/yr; and inflow from the South, at 10 m cum/yr. Recharge from MWSS pipeline leakage is estimated at 25 m cum/yr.

2.5 Rates of Groundwater Withdrawal

A 1991 MWSS/JICA survey of private deep wells in the MWSS service area resulted in a total inventory of 3,343 wells, of which 2,216 were operational and the remainder were in abandoned state. The survey also found 258 wells being operated by the MWSS, of which 131 were in use. These deep wells draw water from the main aquifer (artesian aquifer). A much greater number of private wells draw water from the water table aquifer, albeit at lower capacities (i.e., LI system with hand pump). Haman (1996) estimates the number of these shallow wells to be around 30,000; they are predominantly owned by households that are not connected to the MWSS central distribution system or which use these wells to supplement the MWSS supply. Shallow wells are not usually registered with the NWRB.

Using data from various sources (JICA, 1991; Electrowatt, 1983), Haman (1996) has come up with a consolidated chart showing the rate of groundwater withdrawal from the aquifer system in the NCR region including the Antipolo-San Mateo area from 1931 to 1994 (i.e., the aquifer system referred to here includes the Guadalupe aquifer and the Antipolo aquifer). Figure 1 shows a remarkable rise in groundwater withdrawal from 1973 to 1980, attributed to the rapid growth of population in Makati, Pasig, and Quezon City which could not be supplied by the MWSS. The rate of increase in groundwater withdrawal during the 1980s and early 1990s were relatively less steep.

By 1990, total groundwater withdrawal had reached about 930,000 cum/day, of which 841,000 cum/day were pumped by private deep wells and the remainder by MWSS wells. The distribution of private withdrawal during 1990 was as follows: 71,000 cum/day commercial, 356,000 cum/day industrial, and 414,000 cum/day for public and institutional use. As of 1995, the estimated groundwater withdrawal from the NCR aquifer system was about 1 million cum/day. This is equivalent to about a five-fold increase in groundwater withdrawal since the early 1970s.

Of the 1 million cum daily groundwater withdrawal, 973,000 cum is taken from the Guadalupe aquifer. The estimated recharged rate of the Guadalupe aquifer is 594,000 cum/day, indicating an over-pumping rate of about 379,000 cum/day (Haman, April 1996). In subsequent paper (dated October 1996) Haman adjusted this estimate of the over-pumping rate to about 307,000 cum/day after accounting for the effect of induced infiltration potential in areas along Laguna Lake. Based on historical puming data, it appears that groundwater withdrawal in excess of recharge—or groundwater mining--has been occurring since 1979.

Note that Haman's estimates above apply to the whole of the Guadalupe aquifer system, including both the main (artesian) aquifer and the water table aquifer. Groundwater modeling done by the National Hydraulic Research Center for the main aquifer indicated a withdrawal rate of only about 235 m cum/yr. If Haman's estimate of total withdrawal from the entire Guadalupe aquifer system is correct (i.e., 930,000 m cum/yr as of 1990 and nearly 1 m cum/yr by 1995), it would appear that withdrawal from the water table aquifer is nearly four times the withdrawal from the main (artesian aquifer). This seems unlikely, and suggests a need to further examine possible discrepancies in groundwater withdrawal estimates for the NCR.

2.6 Changes in Groundwater Levels

As a result of over-pumping, piezometric levels have been reduced to below sea level in many part of the Guadalupe plateau (which spans much of the NCR). In Las Pinas, Paranaque and Muntinlupa, the piezometric surface is from 70 to 80 m below mean sea level; in Pasig and Quezon City, 50 to 60 m below msl; and in Valenzuela, an alarming 110 m below msl. This has caused saline water from Manila Bay to enter the aquifer. Indeed, sea water intrusion into the aquifer has reached up to 5 km from Manila Bay's coastline. Overpuming in the Pasig and Taguig areas has also resulted in the upconing of saline connate water (i.e., highly mineralized water stored deep underground) which also contaminates wells. Contour map of the groundwater elevation (piezometric surface) for 1994 as reported by JICA (1997) is shown in Figure 2.

It is suggested that some improvement in groundwater levels occurred particularly in the central part of the NCR. This is attributed to the completion in 1987 of the Manila Water Supply Project II which nearly doubled the supply in the metropolitan service area, and which alleviated groundwater withdrawal allowing pressure levels to recover.

The seasonal fluctuation of groundwater levels in the Guadalupe Plateau is about 2 m in the south and 6 meters in the north. This seasonal fluctuation indicates the effect of recharge from rainfall. However, in the central parts of the Guadalupe Plateau, the groundwater level is continuously declining at an estimated rate of 6 to 12 meters per year (Haman, 1996) as a result of over-pumping. Note that this is considerably higher than the NHRC's estimated average decline of 2.4 m/yr.

2.7 Saline Water Intrusion

Saline water intrusion in coastal areas of Metro-Manila, stretching from Las Pinas to Malabon, has been observed since the late 1960s. In these coastal areas, the shallow water table aquifer is in direct contact with the sea. By the early 1980s, the groundwater level in the Guadalupe aquifer system was observed to be declining at a rate of 5 to 12 meters per year, with deep cones of depression appearing in areas of heavy groundwater withdrawals. These cones of depression caused saline water intrusion as well as upconing of connate water in the Guadalupe aquifer. Seepage of brackish water along the Pasig River and along the Marikina fault also contributes to salinity build-up.

The MWSS/JICA study in 1991 indicated that most samples from the coastal area were salinized and contained more than 200 mg/l of Chloride. In Las Pinas, Chloride concentration in test wells was found to exceed 17,000 mg/l. However, in some parts of Metro-Manila--particularly Manila and Malabon--the extent of saline intrusion was found to have improved compared with conditions during the early 1980s. This reduction was attributed to a partial recovery of the groundwater level, in turn caused by the coversion of water source to surface water in these areas following completion of the Manila Water Supply Project II in 1987.

In Quezon City and some parts of the Guadalupe formation, chloride concentrations were found to be less than 50 mg/l, indicating these areas were not yet contaminated by saline water. JICA samples from the Antipolo area also did not show signs of saltwater contamination. Similarly, with samples from the upper Marikina Valley. However, samples from the Lower Marikina Valley--particularly in Cainta, Taytay, Pasig, Pateros and Taguig--showed chloride concentrations in excess of 600 mg/l. This was attributed to probable contamination by connate (fossil) saline water that was originally trapped deep underground but is now transported to near the surface through upconing as a result of overpumping. In fact, along the eastern portion of the Lower Marikina Valley, wells drilled deeper than 180 m encountered saltwater. Eastward from the junction of the Pasig and Marikina Rivers, saltwater occurs at depths of about 50 m (Haman, 1996).

Seepage along the Pasig River is another cause of saline intrusion, that is, when seawater moves upstream into the River during periods of high tide and low river flow. Moderately high chloride concentrations have been observed in the shallow water table aquifer along the Pasig River. However, it is not possible to attribute the high chloride values found at depths below 200 m in these areas to seepage of sea water into the Pasig riverbed.

Overall, the groundwater from the shallow aquifer and upper portions of the confined aquifer in the coastal area along Manila Bay contain Chloride levels in excess of potable water quality standards. The saline build up in these areas is due to intrusion of seawater from Manila Bay, which is a result of overpumping of the aquifers. However, JICA results show that groundwater tapped by 300 m deep wells is as yet unaffected by salinity even if these wells are located near the coast. In the Lower Marikina Valley, Chloride levels also exceed drinking water standards. Here, the salinity is caused by upconing of connate water. In other areas of the Guadalupe aquifer and the Antipolo aquifer, Chloride levels are still within standards set for potable water. The extent of saline water intrusion in Metro-Manila’s aquifer is shown in Figure 3.

2.8 Evaluation of Completed Groundwater Studies

2.8.1 Purpose of Evaluation

This remainder of this report provides a detailed comparison of the two water management models which were used to assess the ground water resources of Metro Manila. The two methodologies consist of the "Water Resources Management Model" adopted by the National Hydraulic Research Center (NHRC) of UP Diliman and the method employed by the Japan International Cooperation Agency (JICA) in their "Study for the Groundwater Development in Manila". These two aprroaches, which basically focus on surface and ground water balance accounting for the combined sub-basins surrounding Metro Manila, will be referred to in this section as JICA and NHRC models, respectively.

Basically, this comparison is aimed to evaluate the relative capabilities or drawbacks of the NHRC and JICA models in terms of modeling approach, underlying assumptions, data quantity/quality and performance. Thus, this comparative analysis will provide the following:

a) Establish the accuracy of ground water withdrawal/recharge estimates obtained by the two methods based on the criteria used in the evaluation,

b) Identify modeling and data gaps/inadequacies which will provide a basis for developing appropriate measures and undertaking follow-up studies,

c) Provide new insights on ground water modeling by proposing additional options that need to be incorporated to improve reliability of estimates

d) Generate conclusions as to the relative applicability and flexibility of the two methodologies,

e) Formulate recommendations that will validate or improve the methodology for assessing surface/ground water quantity and quality in the region.

2.8.2 An Overview of Groundwater Management and Transport Models

The development and use of water management and solute transport models have proliferated during the past three decades. This is in recognizition of the need for an alternative and cost effective methodology which can evaluate the quantity and quality of surface and ground water resources. The simulation of soil-water-chemical interactions under various climatological, geological and management scenarios can also provide guidelines and timely decisions as to what Best Management Practices (BMPs) can be adopted to develop, conserve or protect our natural resources. Moreover, the application of this approach becomes increasingly important in watersheds where field investigations can be very costly and tedious because of the diverse and diffuse nature of sediments and chemical migration to adjacent or underlying water resources.

There are now thousands of water balance and environmental process models that are available and are still being conceptualized and developed worldwide (Wurbs, 1995). These simulation models have the common feature that they attempt to represent and describe natural processes through mathematical functions that have been derived from the theories of conservation of mass, continuity equation, Darcy Law, reaction rate kinetics, etc. The differential equations describing non-steady movement of water and contaminants are commonly solved using numerical techniques subject to initial and boundary conditions in the problem domain. However, there still remains some skepticism concerning the applicability of existing models. Dilemmas are identified with reference to physically-based algorithms, parameter estimation, data requirements and model validation (Dickinson, 1987). Also, the usefulness of computer models depends on the availability and quality of input parameters and its representation of the different soil physico-chemical processes.

Some of the more widely known water balance and solute transport models which are currently in use and being tested by various researchers worldwide include SWACROP (Wesseling et al., 1989); DRAINMOD (Skaggs, 1978); FEMWATER (Yeh and Ward, 1980); FEMWASTE (Yeh and Ward, 1981), MODFLOW (McDonald and Harbaugh, 1988), MOC (Konikow and Bredehoeft, 1978; U.S. Geologic Survey); Q3P (an expansion of the 2-d areal flow of a homogeneous compressible fluid through a non-homogeneous anisotropic aquifer of Pinder and Bredehoeft (1968); GLEAMS (Leonard et al. 1987), LEACHM (Wagenet and Hutson, 1987), and PESTFADE (Clemente, 1991; Clemente et. al 1993). For a comprehensive listing and description of environmental and water resources model, you may refer to Wurbs (1995), Anderson et al (1993) and Jorgensen et al. (1996).

2.8.3 Criteria Used for Evaluation

The two studies will be compared based on the modeling approach employed, initial and boundary conditions considered, the underlying assumptions involved, the input/output data files and the model performance.

Modeling Approach. For the modeling approach, we assess the components and flow equations in the model that represent the different hydrologic processes in the watershed. Also the computational techniques for solving the governing equations for water and solute transport and the verification schemes for validating the model are evaluated.

Initial and Boundary Conditions. The initial, upper or bottom boundary conditions describe how the model represents the physical or chemical conditions at the beginning of the study, at the soil surface and at the bottom profile of the site under study. For groundwater systems, the boundary conditions represent the aquifer's hydraulic interactions with other portions of the hydrologic cycle. The conceptual model of the aquifer system is based on the assumption of a two-dimensional regime (Willis and Yeh, 1987) where boundary effects are then assumed to be uniformly distributed over the vertical thickness of the aquifer. This criteria determine the relative flexibility of the model.

For solute transport, the initial condition is the chemical concentration at the beginning of the simulation and the external boundary is considered impervious to mass flow so change in concentration at the bottom boundary is zero.

Underlying Assumptions. Although underlying assumptions and limitations are inherent in all models, the nature of these drawbacks can determine the overall accuracy, applicability and flexibility of the models.

Input/Output Data Files. The data files consist of the parameters that are measured or derived from literature which are required as inputs to the models (e.g. storage coefficient, transmissivity, rainfall, hydraulic conductivity, etc). Some input files are output from submodels (e.g. moisture content, piezometric heads, or soil temperature distribution). The availability and quality of these data are very critical in the validity of model predictions.

The output files consist of the estimates generated by the model (e.g ground water recharge, piezometric heads, solute concentration, water balance, etc.) The relevance and accuracy these output files determine the usefulness of the model estimates.

Model Calibration and Performance. Model calibration is part of a validation scheme where selected input parameters for which data are not available are estimated or adjusted until reasonable agreement between model and field data is achieved.

The performance of models are evaluated by comparing model predictions (e.g moisture content, solute concentration, or ground water recharge) with measured data both qualitatively and quantitatively. Also, they can be compared with other models using the same data set. Once the model has been succesfully validated under various field conditions, then it can be regarded that the model is performing satisfactorily.

Fulfilment of Study Objectives. This criterion is aimed to assess whether the specified targets and goals of the study were all fully satisfied or partially accomplished.

2.8.4 Brief Description of Methodologies Used in Two Recent Studies

JICA/MWSS Study

Study Objectives. The main objective of the study is to evaluate the ground water resources in Metro Manila using groundwater flow and solute transport models for confined aquifer systems. The modeling activity is undertaken to predict future groundwater movement and to describe the hydrogeologic conditions that led to heavy decline of groundwater heads as well as enhanced saline water intrusion. Also, the study is aimed to estimate the movement of ground water resulting from alternative schemes of future aquifer utilization or regulation.

Study Area and Activities. The study area covers the MWSS Service area (MSA) which comprise of five (5) cities and thirty two (32) municipalities which has a total area of 4678 sq .km. The Metro Manila ground water basin is composed 4 cities (Manila, Pasay, Quezon and Caloocan) and 13 municipalities which has a total area of 636 sq. km. For simulation purposes the domain area used was about 1404.7 sq.km. The study started in Aug. 1990 and was completed in March, 1992. This duration was divided into three stages, namely: 1) Basic survey, 2) Detailed survey and 3) analysis and planning. The physical hydrogeology of the area has been previously described (JICA/MWSS, 1992; NHRC/IDRC, 1993).

The activities involved to meet the objectives consist of the following: 1), conceptualization and quantification of groundwater regimes to analyze groundwater flow; 2) estimation, collection, and processing of input parameters and data files; 3) coupling of the groundwater flow model (Q3P) with a solute transport model (MOC); 4) model calibration and 5) model verification. The study was conducted from 1981 to 1990.

NHRC/IDRC Study

Study Objectives. The main objective of the study is to develop a Water Resources Management Model for Metro Manila and its environs that takes into account both surface and ground water resources in the region. This is to be achieved through specific goals such as determining aquifer characteristics in Metro Manila; establishing basin groundwater boundaries, properties and yield; illustrating the resulting hydrologic cycle based on conjunctive use of surface and ground water resources in the region; determining actual and potential recharge; making the integrated model Manila-specific; demonstrating the viability of the Manila Model; and disseminating project results through workshops and conferences.

Study Area and Activities. The study area consists of the Laguna Lake Basin (3758 sq. km.) and other adjacent smaller watersheds in Metro Manila (702 sq. km.). The three-year study started in May 1990 and was completed in April 1993. The physical hydrogeology of the area has been previously described (NHRC/IDRC, 1993, and JICA/MWSS, 1992).

The above objectives will be achieved through nine research activities namely; 1) study of BUH model; 2) gathering of available data; 3) review of data quality; 4) verification of data in selected areas; 5) definition of basin properties; 6) analysis of water balance; 7) BUH model adaptation, 8)calibration and validation of Manila model; and 9) demonstration of the use of the model.

2.8.4.1 Comparison of Modeling Approach, Boundary Conditions and Assumptions

Modeling Approach

JICA Model. For groundwater flow, the JICA/MWSS study used a quasi-three dimensional model (known as Q3P model). This is an expansion of the 2-d areal flow of a homogeneous compressible fluid through a non-homogeneous anisotropic aquifer of Pinder and Bredehoeft, 1968), which can be applied to 2-d or 3-d problems including multi-aquifer systems. It is based on the concept that the groundwater in the main confined aquifer is supplied by lateral flow through the aquifer and by vertical flow through the aquitard from the overlying phreatic aquifer. The model computes changes in piezometric heads over time caused by changes in groundwater pumpage.

For solute transport, the 2-d solute transport and dispersion model originally developed by Konikow and Bredehoeft, (1978) was used. This was also adopted by the U.S. Geological Survey which they called MOC (Method of Characteristics) and used in this study to compute changes in the spatial solute concentration distribution over time that are caused by convective transport, hydrodynamic dispersion, mixing or dilution from recharge and chemical reactions.

NHRC Model. The NHRC model consists of three surface water models namely: 1) NHRC First-Order Linear Baseflow model to estimate recharge from baseflow; 2) Watershed Water Balance Model to compute monthly water balance at lumped subbasin scale, and 3) Laguna Lake Water

Balance Model to estimate monthly net inflow/outflows after evaporation losses. These surface models were coupled with the Bangkok Urban Hydrogeological (BUH) model to estimate well drawdown, aquifer head radial front and average subsidence height. The linked surface/ground water and hydraulic-subsidence model was improved and augmented to develop the integrated Manila model called CUWARM which stands for Conjunctive-Use Groundwater Resources Management Model. CUWARM was calibrated only for the Metro Manila area because of the absence of adequate data in the remaining portions of the study area.

For surface and ground water quality, NHRC/IDRC (1993) only identified potential sources of contaminants (e.g. refuse dumpsites, industies, and underground storage tanks) from published data. Solute transport was not included in model development/application.

2.8.4.2 Initial and Boundary Conditions

JICA Model. The initial conditions employed by the water flow model consists of the actual piezometric heads measured at the beginning of the study in 1981. Also, storage coefficient was assigned an initial and uniform value of $1x10^{-3}$.

Three boundary conditions were considered which include no-flow boundary at the eastern margin of the basin, a constant flow at the northern and southern perimeters where the aquifer extends out of the modeled area, and a constant head boundaries to Manila and Laguna de Bay at the place where the distance from coastlines is about 5 km.

NHRC Model. The starting lake gage heights or stage are used as initial conditions in the Lake Water Balance model to compute changes in lake and floodplain stored volumes. In the BUH model, the initial hydrostatic conditions at the start of pumping which were represented by pressure heads in the aquitard/aquifer layers are assigned zero values.

A continuous head exists at the aquifer/aquitard layer, while on top of the aquitard under excess pressure head, a non-permeable boundary condition is assigned. Also, excess pressure heads in both layers are considered zero when the radial coordinate from a pumping well is at infinity.

2.8.4.3 Underlying Assumptions

JICA Model. The confined aquifer was modeled as main confined aquifer which is hydraulically connected to the overlying phreatic aquifer through confining layer. The model assumes that hydrogeological parameters such as transmissivity, storage coefficient and leakance are not affected by changes in piezometric heads, and those parameters, the boundary conditions and phreatic levels are assumed to be constant over time.

For solute transport, the model assumes that fluid density variations, viscosity changes and temperature gradients do not affect the velocity distribution. Also the model assumes that linear or equilibrium adsorption exists between the soil particles and the solutes.

NHRC Model. The BUH model consists of the hydraulic model which gives the hydraulic pressure profile in the aquifer/aquitard layers under pumping conditions and the subsidence model which provides the subsidence arising from hydraulic pressure changes in the aquitard and aquifers.

In developing the BUH model some of the assumptions include: 1) the geological system is represented by a two layer (aquitard-aquifer) profile; 2) water flow in the aquifer is mainly horizontal under pumping conditions; 3) Darcy's law applies to both aquitard and aquifer systems and 4) subsidence is taken as a basin average quantity and is mainly due to consolidation of the aquitards.

Assessment

Table 1 summarizes the features and capabilities of the two methodologies. It can be seen from Table 1 that the two models exhibit different model components, approaches and assumptions. However, the models used in these studies appear to be well tested and applicable to local conditions being simulated. The NHRC model used the base flow separation technique to compute recharge while the JICA model used a simple water balance model where effective infiltration is considered as the recharge to groundwater.

Analysis of streamflow hydrographs for baseflow separation can be useful in basins where interval between storms is short and where groundwater flow reaches the stream quite quickly (Linsley et al. 1988). The NHRC water balance model was developed along this line which could be more applicable to our local conditions where bursts of rainfall can be closely spaced. However, the NHRC overall model (Manila Model) appears to be an integration of several models and inaccuracies inherent in each model can result to an accumulation of errors in the integrated model.

The boundary conditions adopted by the two models (e.g. no flow, or constant head/flow which are invariant with time; and no changes in head) seem to be limiting and site specific. The model did not specify what other boundary conditions can be employed to tackle other geohydrological environments . A water balance model developed in the Netherlands (SWACROP, Wesseling, 1989) can analyze seven bottom boundary conditions which make it very flexible and applicable to all regions in the world. This model can be used in future water resource studies to take advantage of its added capabilities. Also, it can be compared with the JICA and NHRC water balance models using a common data set to establish the relative performance of each model.

For modeling solute transport, it appears that NHRC model has no provision for this which is a major limitation as compared to JICA. However, even JICA uses a sophisticated model (MOC) to analyze solute transport, it however uses a linear or equilibrium model to decribe sorption kinetics which is a major drawback because of the non-equilibrium nature of adsorption mechanisms specially in prefential flow pathways (Clemente et al. 1993). Also, macropore flow was not included in model development which is a major limitation especially in soil systems which have a large number of dessication cracks or worm holes where rapid mass flow can occur during heavy rains.

2.8.4.4 Comparison of Input Data Files for Models

JICA Model Input Data

For the JICA groundwater model, the input parameters consists of transmissivity, storage coefficient, aquifer thickness, leakance, initial heads, and recharge/discharge data. These inputs were collected/measured by the study team. The required data for solute transport includes bulk density, sorption coefficient, half-life, porosity, dispersivity and initial concentration.

Transmissivity was estimated from specific capacity of existing wells data and pumping tests results. Storage coefficients were initially and uniformly assigned as $1x10^{-3}$ because of lack of data. The aquitard thickness is obtained from the clay content map which was prepared from the well columnar sections. The permeability of the aquitard is unknown but was determined from model calibration then inputted into the model to compute leakance. The phreatic level was estimated from geomorphological analysis and assumed to be invariant during the simulation. The values of direct recharge were obtained from the water balance study mentioned in section 3.5 of the Main Report (JICA/MWSS, 1992). The input average recharge is 183 mm/yr which is about 8% of annual rainfall.

NHRC Model Input Data

The input parameters of the model were derived from 396 technical reports on groundwater which include well and pumping tests data base, rainfall data from 17 PAGASA stations, streamflow data from 29 Lake stations and water quality data Also, 234 maps were used to determine topographic, soil/hydrogeologic properties, land use, well locations and other cartographic information.

For surface water balance models the input parameters consist of daily total streamflows, monthly rainfall, monthly pan evaporation and potential evpotranspiration; soil moisture storage, and streamflow data such as monthly gage height and discharge.

For hydrologic modeling, the map-defined properties include sub-basins delineation, lake-depth area, flood plain elevation-area, and land use types. The groundwater parameters consist of aquifer and hydraulic properties, piezometric surfaces, water table, discharge/recharge patterns and withdrawal distribution. The estimation of of the model parameters namely permeability and compressibility was based on Metro Manila transmissivity and storage coefficient data as well as generalized rock properties from literture.

The overall Manila Model (CUWARM) requires as input a whole array of physical parameters and input data such as rainfall, evapotranpiration, withdrawal rates, soil type, land use, basin topography, surface geology, and presence of lake/sea body.

Assessment

Table 2 summarizes the different input parameters used by the two models. It can be seen from Table 2 that the two models require similar and extensive input data sets. However, it appears that the acquisition methods or sources of the data are not the same resulting in a wide discrepancy in input values for the same parameter. For instance, in the JICA model, the transmissivity value ranging from 22-274 sq.m./d was obtained from actual pumping tests while in the NHRC model, a literature value of 5-1000 sq.m./d was used. Total rainfall for 1990 of 2329.7 mm was used in JICA model, while a 9-year average of 3756.98 MCM was used in the NHRC model. Because of these differences, only the adequacy, extent, and quality of data will be used in the analysis.

It is evident from Table 2 that NHRC used secondary data acquired from literature. However, the NHRC compiled data were diagnosed and quantitatively assessed using specialized geologic software. JICA, on the other hand, did actual field measurements and analysis of its data suggesting that the sampling schemes adopted by JICA conforms with its model input requirements as far as quality and adequacy are concerned. In fact they have also conducted statistical analysis of the collected data for quality evaluation.

However, for both methodologies, some data are inadequate and they should have performed data adequacy analysis. For instance, the well sampling points are quite sparse (there are 5659 wells for the whole study area of 4460 sq.km. which is equivalent to 1.25 wells per sq. km.). With this density in sampling points, the effect of spatial variability in soil/hydrogeologic properties on water flow and solute transport are not fully accounted for. In addition, measured values of rainfall are monthly or annual averages and this has an associated assumption that rainfall events are uniformly distributed resulting in the low rainfall intensities used in the model. As such, the effect of actual rainfall patterns on infiltration and water distribution may have not been adequately represented especially during intense storms of short duration (Clemente et al. 1994).

2.8.4.5 Comparison of JICA and NHRC Model Outputs

JICA Model

The JICA model estimates include the water balance components, withdrawal rates, and piezometric heads. The solute transport model assesses sea water intrusion by calculating changes in chloride concentration with depth and time. Table 3 and Figures 4 and 5 summarize these outputs in comparison with the NHRC model predictions. Details of results can be found in the Final Report of JICA/MWSS (1992).

NHRC Model

The simulation outputs consist of daily baseflow and recharge rate (from base flow separation model); output hydrologic series such as actual evapotranspiration, soil moisture storage, direct flow, total flow (from Watershed balance model); output hydrologic series such as monthly net inflow or outflow (from Laguna Lake Water Balance model); well drawdown, aquifer/aquitard heads, subsidence height (from BUH model) and hydraulic head (or piezometric surface), groundwater flux and subsidence depth from the overall CUWARM or Manila model. Table 3 and Figures 6 and 7 summarize these outputs in comparison with the JICA model. Details of results can be found in the Final Report NHRC/IDRC (1993).

Assessment

Table 3 and Figures 4 to 7, provide a comparison between the simulation outputs of JICA and NHRC models. In Table 3, the simulated water balance components such as AET, Runoff, Baseflow and Recharge are presented. By multiplying the JICA values by the study area and using some conversion factors, the units of mm/yr have been converted to MCM/yr and given in the parenthesis. It can be seen from Table 3 that the water balance components predicted by JICA were quite different from the NHRC model. For instance the predicted recharge rate for Metro Manila was 161.96 MCM/yr for JICA and 206.16 MCM/yr for NHRC.

This discrepancy could be due to the differences in input values used, the model assumptions involved and the representation of the hydrogeologic system. For instance, the use in the JICA model of a runoff coefficient of 0.6 (to represent Manila runoff conditions) resulted in high values in runoff causing the recharge to be lower than that estimated by NHRC. It is interesting to note, however, that the water balance variables are expressed in volumetric flow per unit time which is a function of the area of the project site. It can be seen that the study area in JICA is 1404.7 sq.km. which is smaller than the study area of NHRC (1780 sq. km), thus the lower recharge prediction by JICA.

Figures 4 and 5 illustrate the piezometric heads obtained by the JICA model for Metro Manila from 1981 to 1990 and the contour map for piezometric heads in 1990, respectively. Figures 6 and 7, on the other hand, show the contour map for piezometric head, and a 3-d view of the piezometric surface for 1990, respectively, which was obtained by NHRC.

Figure 4 summarizes the 10 year piezometric heads simulated by the JICA model and some trends can be established. For instance, the piezometric heads in some areas in Metro Manila had decreased with time and in the other areas they had increased during the period. Specifically, these parameters increased from 1981 to 1990 in Northern to Central part of Metro Manila (i.e. Caloocan (CLC), Quezon City (QCT), Pasig (PSG), and Cavite City (CVC)), and they decreased in the southern part (i.e. Paranaque (PRN) and Las Pinas (LPS). These increase and decrease in piezometric heads with time have been attributed to the reduction and increase of groundwater discharge during the same period. It should be noted that piezometers are installed to measure the depth of water table or groundwater level from the soil surface.

For 1990, the values of piezometric head ranged from -25 masl (Quezon City) to -85 masl (Paranaque). This has been illustrated in detail in Figure 5 which gives the contour of the piezometric head for 1990 (JICA model). Figure 6 can be compared with Figure 5 which gives the piezometric heads simulated by NHRC for 1990. Although the pattern of piezometric distribution is not quite visible in Figure 6, it is however presented in 3-d form in Figure 7. From the 3-d graph presented by NHRC, it can be observed that the higher piezometic surfaces at Quezon City, Caloocan and Manila/Pasay, compared to Paranaque and Las Pinas, is similar to the findings of JICA as discussed above. This also confirms the conclusion earlier that the excess water (runoff/baseflow) from these areas with higher piezometric heads can constitute as inflows to the Laguna Lake which lies beside the piezometric depression areas of Paranaque and Las Pinas.

In the JICA model, the movement of saline water was investigated under steady state conditions using input discharge and recharge 1990 data. Simulation period was 10 years. Results indicate that after 2 years, saline water intrudes the aquifer along the flow direction towards the low piezometric heads (coastal towns). After 10 years, the 2000 mg/l contour reaches the center of piezometric depression (Fig. 8). Since the future movement of saline water is governed by future pumpage in the area, it is predicted that if the existing depression of piezometric heads moves more inland, the saline water will also move deeper inland. The lowering of groundwater levels due to pumping may also cause land subsidence, particularly in the alluvian plain where consolidation of clayey deposits may result from grondwater depletion. However, the model has no provision to simulate this phenomenon, so comparison with the NHRC simulation results will not be presented.

Although the NHRC model has no solute component, the study has indicated that the potential sources of groundwater contamination have been identified (e.g. refuse dumpsites, industries, and underground storage tanks). The water quality parameters analyzed by MWSS include: date of sampling, pH, turbidity, total chloride/hardness/iron, residual chlorine, bicarbonate, and free carbon dioxide. The increase in phosphate and turbidity and the decrease in dissolved oxygen and total dissolved solids have been detected which indicate increasing contamination.

2.8.4.6 Comparison of Model Calibration and Performance

JICA model

The model was calibrated by specifying and identifying some poorly reliable hydrogeologic parameters. Specifically, leakance (or aquifer permeability), an unknown parameter and some boundary conditions were adjusted until good performance of the model is achieved (i.e., prediction of piezometric heads compared closely with actual values).

NHRC model

The calibration of CUWARM or the Manila model was performed by fine adjustments of hydraulic parameters, recharge coeficients and withdrawal rates based on reasonable levels of withdrawal capacity factors (0.5 to 0.67) of well cells. The goal is to reproduce on a regional scale the observed end-of-1990 piezometric levels in Metro Manila given the initial conditions provided by the 1981 piezometric levels from the same source (i.e MWSS). The calibrated values of the input parameters such as aquifer and aquitard permeability and compressibility and deep well withdrawals are summarized in NHRC/MWSS (1993).

From the calibration period from 1981-1990 for Metro Manila, the annual water balance provided the following outputs: hydraulic heads and subsidence depth. Calibration results indicate that maximum computed drawdowns occurred in the Metro Manila areas tapping the Guadalupe Formation. This indicates that the model calibrated parameters provided reasonably accurate predictions of water withdrawal in Metro Manila. However, due to the absence of piezometic data in 1990, the calibration of the Manila Model has not been carried out for Laguna, Cavite, Batangas, and Rizal portions of the aquifer. Detailed results can be found in NHRC/MWSS (1993).

Assessment

It appears that both models have been properly calibrated and its predictions have been successfully tested by measured values. However, both methodologies did not present a detailed sensitivity analysis. A model is said to be sensitive to a particular input parameter if the model output changes considerably when the values in specific input are varied by some percentage greater or lower than measured or representative values. A sensitivity analysis is therefore performed to determine what major factors or inputs have a direct effect on model estimates of water balance or solute concentration.
In JICA, it was mentioned that leakance is the most sensitive parameter but it was not specified how the sensitivity was done and what other parameters were analyzed for sensitivity.

Many researchers have examined the effect of transport parameters (e.g. hydraulic properties, evapotranspiration, flux, macropores, sorption coefficient, and rate constant) on water and solute transport. For instance, Clemente et al. (1993) and De Jong et al. (1992) found that water flow in unsaturated zone is greatly affected by evapotranspiration, flux and macropores, while Clemente (1991), found that the sorption coefficient Kd has a major effect on the leaching of pesticides to groundwater. Without a sensitivity analysis, it will be difficult to assess the degree and relative effect of important parameters on model predictions.

Future studies which will concentrate on the data collection and sampling of parameters at which the JICA or NHRC models are sensitive, can increase the reliability of the model applications.

2.8.4.7 Comparison of Model Effectiveness

One of the principal objectives of the two studies evaluated above is to investigate if surface water resources (e.g. Laguna Lake) can be tapped as an alternative source of water for Metro

Manila or can recharge its groundwater systems. Using the overall NHRC model, a net groundwater mining rate of 28.84 MCM was obtained. From the water balance simulation, large volume of excess water (1348.11 MCM/yr or 38% of rainfall; see Table 3) was also obtained. Part of this excess water goes as inflow to the Laguna Lake through direct runoff (915.85 MCM/yr) and baseflow (226.09 MCM/yr). The remaining excess water (206.16 MCM/yr or 5.76% of rainfall), constitutes as recharge to the groundwater systems in Manila.

Similar trend was also obtained from the JICA water balance model where recharge of 161.96 MCM/yr was obtained which is 4.9% of rainfall. This recharge value is quite lower than that obtained by NHRC model, and this could be due to the high percentage of rainfall going to runoff (i.e 60%) assumed in the JICA model. Both studies, however, can draw a common conclusion that the Laguna Lake basin can be a future source for the domestic, municipal and industrial requirements of Metro Manila. However, since the Laguna Lake receives significant municipal, industrial, and agricultural wastes from tributaries in the north, south, east, and west of the lake, its water suitability is still under question.

Although piezometric head recoveries differ from one section to another in Metro Manila this can be explained by the dynamic nature of groundwater flow and varying pumping rates. Since the simulation study shows a large drawdown of piezometric heads in Metro Manila especially in coastal areas such as Muntinlupa, Paranaque and Las Pinas, due to heavy pumpage, a development plan has to be implemented in these areas to prevent further decrease in yield and sea water intrusion. As such a regulated area for groundwater pumpage was established along these coastal areas of Metro Manila. From the various scenarios simulated, the most lenient development plan is to increase the discharge in the regulated area by 14.4 MCM/yr from 1991 to 1995, so that maximum drawdowns of 40.2 m and 28.5 are expected by the year 2010 in the northern and southern parts of Metro Manila, respectively. But due to the existence of piezometric depressions in in the coastal areas, the saline water may intrude further landward in southern Metro Manila even though the piezometric heads in the coastal areas have recovered.

It should be noted that in the JICA model, the piezometric heads are computed as a result of water balance in the aquifer system. So the groundwater level indicates a balance between the quantity applied to and extracted from the basin. At this point, it can be assessed that most of the main study objectives of the two projects have been met.

2.8.5 Overall Assessment of Modeling Studies

It appears that the models used in this study for assessing water quantity and quality are well tested and applicable to local conditions. Since they considered 2-d and 3-d flows for both water flow and solute transport, then it can be generalized that the models used in this study are quite sophisticated and more representative of actual conditions in the aquifer systems where flow can be multidirectional. However, some issues need to be resolved with regards to the inherent limitations/assumptions and future application of the models.

For solute transport, some limitations in the model representation of soil/physico/chemical processes can be identified. For instance the JICA model employed equilibrium sorption kinetics, has no provision for analyzing temperature effects on microbial degradation of chemicals other than chloride, and does not consider the effect of preferential flow pathways on mass flow of water and solutes. These factors are especially important in the unsaturated profile of a watershed where the fate and mobility of chemicals is a function of hydraulic properties such as moisture content, pressure head, and hydraulic conductivity and degradation and retention parameters such as rate constant, sorption coefficient, and temperature distribution.

It was suggested earlier that one alternative for developing the water resources of Metro Manila is the diversion, treatment, and distribution of the Laguna Lake water. With this Lake being targeted by MWSS as a possible source of drinking water for Metro Manila, a more in depth analysis of the governing factors that contribute to the contamination of the lake should have been included in the NHRC/JICA reports. It was indicated that the rise in phosphates and turbidity and the reduction in dissolved oxygen indicates a contamination problem in the lake. However, they failed to recognize the fact that a more serious and pressing problem in the basin is the continuous influx of sediments from both urban and agricultural runoff. In a runoff/erosion simulation study at the Siniloan and Mt Banahaw watersheds, Clemente (1996) found that the predicted annual soil loss of around 75-300 tons/ha is quite alarming because it drains directly into the Laguna Lake. This problem has been also recognized by the Government and its policy makers. In fact, a resolution is being discussed in Congress (House Resolution # 141) which calls for the desiltation of the Laguna Lake in an effort to improve its quality as well as to use the sediments to rehabiltate the lahar affected areas in Pampanga.

Another approach has been suggested by NHRC which involves the use of the upper Marikina River runoff or diverted Laguna Lake water from Mid Bay as artificial recharge of the Guadalupe Formation. However, detailed scientific and engineering studies of the aquifer systems are required to ascertain its technical and economic feasibility. On a regional scale, however, NHRC also pointed out that competing demands over the Laguna Lake between CALABARZON and Metro Manila may arise in the near future due to the projected growth and development of the CALABARZON areas.

These studies involved a basin wide assessment of water resources and some digitizing of hydrogeologic attributes for parameter estimation were undertaken. To develop a regional scale groundwater and environmental planning scheme for Metro Manila, the groundwater and solute models should have been linked with GIS to allow geologic, groundwater level, topographic, and well maps to be overlaid with land use, management practices, water production/ recharge distribution and mass loadings of chemicals. A follow-up study which will incorporate this methodology will provide a useful management tool for developing water resources on a regional scale.

3. The Groundwater System of Metro Cebu

At present, groundwater is the only major source of water for most of the Province of Cebu and almost the entire Metro Cebu area. The aquifers of Metro Cebu covers a total area of

180 sq.km. (30 km long x 6 km wide) which can provide 150,000 cum/d of water. However, the current groundwater extraction in the area is estimated by Cebu Uniting for Sustainable Water (CUSW) to be 234,000 cum/d which is almost twice the safe yield of the aquifer of 120,000 cum/d. And yet only around 35% of the total households in Cebu City have individual service connections; the rest is being served by private wells, communal faucets and water vendors. The Metro Cebu Water District (MCWD) was established in 1974 as a government corporation which is responsible for supplying the water of Metro Cebu (i.e. Cebu City and 7 surrounding towns and cities) which has a total population of around 1.3 million. The MCWD provides water at an average of 72,399 cum/d through 56,900 service connections. The water supply comes from 77 production wells and the existing Buhisan Dam. Although the Buhisan Dam has an actual storage capacity of 8,000 cu.m, this has been substantially reduced due to heavy siltation.

With the continued groundwater abstraction exceeding the safe yield of the aquifers, excessive drawdowns and increased salinization have been observed in the area which is now causing alarm over the sustainability of groundwater resources. In effect, the need to further study the true status of the groundwater resources in Cebu, to rehabilitate existing systems, and to explore/harness new sources to augment the supply from groundwater, have been recognized by the Government.

3.1 Geological and Structural Characteristics of the Maghaway Valley

Geophysical investigations and exploratory drilling as reported by Cebu Consultants (1984) indicate that the aquifers of the Maghaway Valley consists of Alluvial sediments, Carcar limestone and Cansi volcanics, Panda Series and Maingit formation.

3.1.1 Alluvial sediments

This formation covers the flat portion of the valley around Mananga river which has an area of 1.2 sq km or 35% of the central part of the basin. These sediments are of recent age, unconsolidated and have been deposited by the Mananga River and are products of erosion from the surrounding mountains. They consist of mixture of coarse grained (i.e., boulders, gravel, and sand) and fine grained (clay and silt) sediments.

3.1.2 Carcar (Coralline Limestone)

These sediments cover about 1.1 sq.km or 30% of the southern parts of the drainage basin and consist of poorly consolidated corraline limestone of Tertiary age. This formation is generally porous but porosity is decreased by the silty layers within limestone. The alternation of less permeable and permeable corraline sediments explains the occurrence of springs and groundwater seepages observed along the eastern part of the valley slopes.

3.1.3 Other formations

The northern part of the basin is covered by the Cansi Volcanics and Pandan series which comprise around 17% and 14% of the basin area, respectively. The rocks are consolidated and consist of lava flows, conglomerates, siltstones, breccias and other volcanic rocks.

A small outcrop of the Maingit formation, which consists of shales, conglomerates and sandstone occurs in the northeastern part of the basin and is around 2% of the drainage basin area.

3.2 Recharge to the aquifers of the Maghaway Valley

3.2.1 Recharge from the Maghaway drainage basin

The area draining directly into the Maghaway Valley is estimated at 3.5 sq.km. Assuming an average rainfall (P) of 1600 mm/yr and evapotranspiration (ET) of 1200 mm/yr, the annual average recharge (R) to the aquifer in the valley can be estimated from a simple water balance as follows:

$$R = (P - ET) \times 3.5 \times 10^3 = 1.4 \text{ MCM}$$

From monthly and daily rainfall data and water level fluctuations, it was generalized that recharge to the aquifer occurs when monthly and daily rainfalls exceed 120-150 mm and 5 mm, respectively.

3.2.2 Recharge through the riverbed and from floods

Recharge from the river is estimated using a hydrological model which assumes that that seepage into aquifer occurs when the water level in the river bed is higher than 0.3 m and when the flow in the river exceeds 5 cum/s. From this, it is estimated that the average rate of recharge is about 1.1 MCM/yr.

So the total recharge to the aquifer from both sources equal 2.5 MCM/yr and this recharge exceeds the depleted volume of the aquifer at the end of the recorded dry seasons. The positive balance (or water excess) between groundwater use and recharge is presumed to be included in the total outflow from the valley.

In addition to the inflows from the Mananga River, the Maghaway Valley receives inflows from its own subcatchments which has a total area of 3.5 sq.km. of which 1.2 sq.km consists of highly permeable alluvial deposits covering the valleys floor. The remaining 2.3 sq.km of subcatchment is covered by Carcar (Coralline) limestone (1.1 sq.km) and volcanic rocks (1.2 sq.km).

It is assumed that rainfall falling on the permeable Carcar Limestone will drain to the valley as a subterranean baseflow contribution. The net rainfall from the volcanic rocks is further assumed to drain as surface runoff to be the edge of the alluvial deposits where it will be infiltrated to the groundwater reservoir of the Maghaway Valley. It was estimted that the annual recharge from rainfall is 460 mm which comes from Southeast Monsoon (265 mm) and Northeast Monsoon (195 mm) rains. In addition to this, the alluvial aquifer in the Maghaway Valley receives inflow contribution from seepage through riverbed and spillover from floods which is estimated at a rate of about 3,700 cum/d.

3.3 Hydraulic properties of the aquifers

The Alluvial aquifers are relatively homogeneous, permeable, and bigger compared with the Limestone and other formations, and its hydraulic properties are briefly described below.

3.3.1 Storage Coefficient

Storage coefficient is associated with the specific yield (SY) of an aquifer which is the volume of water which can be recovered from storage by gravity drainage, only. This hydraulic property is estimated based on analysis of rainfall data and water level fluctuations in the different sections of the alluvial aquifer in the Maghaway Valley. The upper section of the Valley is predominantly composed of coarse materials and has an SY of 0.2 or 20%. This means that every meter of saturated material in the Upper section contains about two hundred liters of stored groundwater. So with an average saturated thickness of 18.5 m and aquifer area of 1.2 sq. km., the total estimated volume in storage in the Upper section is 4.4 MCM at the end of the recharge period.

The SY of middle section, on the other hand, is around 10%, so with saturated thickness of about 35 m, and aquifer area of 1 sq.km., it is estimated that this section contains about 3.5 MCM of stored groundwater. Although the Lower section has an SY of 5%, its water transmitting capacity is very poor so groundwater is considered a passive storage only.

3.3.2 Specific capacity

Data indicates that for each meter of aquifer penetration (from 6.5 mbg up to about 25 mbg) the specific capacity increases by about 11 cum/hr per m of drawdown. Consequently, the specific capacity of about 200 cum/hr per meter of drawdown could be expected from a well screened throughout the whole 18.5 of saturated thickness of the Upper Section of the alluvial aquifer. This value is consistent with the aquifer T-value of 0.07 m^2/sec of the Upper section obtained from pumping tests.

3.3.3 Transmissivity

Pumping tests gave transmissivity values of 0.07 and 0.0824 m^2/sec for the Upper Section, but in all tests the screen partially penetrates this section of the aquifer. So a long term T-value must be confirmed by future tests of a well penetrating over a greater thickness of the Section.

The tests lasted for 7,265 minutes which could have been enough for cone of influence to expand and involve both the alluvial and limestone aquifers. However, after about 1,400 minutes infiltrating rainfall caused increase of water level in the well and stopped further expansion of cone of influence. So it is recommended to carry out a test during dry season that will last for around two weeks.

3.4 Groundwater Model

The well configuration and production discharge per well has been evaluated using an analytical model of the Maghaway Valley aquifer as per Cebu Consultants (1984). The overall governing equation for calculating maximum drawdown in a pumping well is written as:

swt = (BQ + swl + siR + siI) + swc + CQ2

where swt = total drawdown in a pumping well (m)

BQ = formation loss (m) for t=60 min for selected discharge rate (Q, cum/s)

swl = long term drawdown in a pumping well (m) for selected duration of pumping (t)

siR = sum of interference drawdown (m) from real wells by using Theis non-equilibrium formula

siI = sum of interference drawdown from imaginary wells by using the Theis formula

swc = corrected drawdown (m) in a pumping well for decrease in saturated thickness for sum of drawdown components in brackets, by using Jacob's formula

CQ2 = well loss drawdown (m) for discharge rates of 50, 75, 100, and 150 cum/hr/3600 and well loss constant C = 300 s2/m5.

The following data and assumptions were used in evaluating the drawdown in the pumping wells of the Upper Section of the aquifer:

Length = 1,200 m
Width = 1,000 m
Saturated thickness = 18.5 m
T = 0.07 m^2/s
Sy = 0.2 or 20%
Available storage = 2 MCM

The highest static water level is 6.5 mbg at the end of wet season, and the maximum drawdown corrected for decrease in saturated thickness cannot exceed 18.5 m. Also possible storage and drainage from limestone aquifer is neglected in the analysis.

Results of the simulations using the equation above indicate a spread of drawdown values in a pumping well of different pumping rates and well configuration against time. Specifically, a well configuration with Q = 150 cum/hr per well can be selected for all schemes with intensities up to about 60,00 cum/d. For intensities higher than this, drawdown calculations are considered approximate because discharge per well would have to be decreased and the number of wells would have to be increased to withdraw the required volume of 2 MCM over a shorter period.

4. Conclusion and Recommendations

The first part of the paper was aimed to evaluate two project studies conducted for assessing the surface and groundwater resources of Metro Manila. These studies have focused on the development, adoption, calibration and use of water balance and groundwater flow models to simulate the withdrawal and recharge rates in the study area. In effect, the analysis used some basic criteria to compare the modeling approach adopted in the two studies. These criteria include model capabilities, assumptions, input requirements and simulation outputs. Also, the extent at which the study objectives have been achieved has been also assessed.

The two methodologies (i.e. JICA and NHRC models) provided comparable simulation results for recharge rates and piezometic heads for Metro Manila. For instance both methodologies have estimated higher piezometic heads at Quezon City, Caloocan and Manila/Pasay, and low values at Paranaque and Las Pinas. While this phenomenon suggests that the excess water (runoff/baseflow) from areas with higher piezometric heads can constitute as inflows to the Laguna Lake, it was found by the solute transport model that the increase in pumpage will result in sea water intrusion into the piezometric depression areas such as Paranaque and Las Pinas. An optimal groundwater development plan was therefore proposed that regulates pumping at the coastal areas of Metro Manila.

The NHRC methodology is an integration of several modeling packages to analyze surface, lake and ground water balances. Although these models are found to be well conceptualized and applicable to local conditions, it is believed, however, that the underlying assumptions and limitations inherent in each submodel used can result to inaccuracies which have not been addressed in the report. Also, the model input parameters were compilations of data bases from various sources and technical reports and these could lead to modeling inaccuracies due to experimental inconsistencies from one data source to another. As such, the discrepancies observed in the simulated outputs obtained by the two models can be attributed to the adequacy and quality of model inputs used, the assumptions involved and the inherent limitations in model development.

For both water and solute transport in the unsaturated zone, the issue of bypass flow in preferential flow pathways (due to macropores) have also been ignored which is a major limitation. Also, the sensitivity of the models to important parameters have not been assessed.

Future modeling effort should include new algorithms (for macropore flow and non-equilibrium sorption) and sensitivity analysis to make the models more comprehensive and useful.

The neighboring towns of Metro Manila have agricultural watersheds which have been earlier assessed as a possible source of chemical loadings to the Manila Bay and Laguna Lake. However, it appears that the 2 methodologies have failed to consider or estimate the effect of agricultural runoff on the quality of surface water courses. Direct runoff was estimated as part of the water balance but the loss of chemicals and sediments in runoff/erosion, whose ultimate destination are surface water courses, was not included. Also, in these estimates, the effect of urbanization on the long term recharge patterns was not considered in the computation. A modification/ testing of the model to incorporate these factors and mechanisms will certainly increase the reliability and significance of future water resource studies.

To develop a regional scale groundwater and environmental planning scheme for Metro Manila, the models used in these studies can be linked with GIS so data base maps can be overlaid with land use, management practices, water production/recharge distribution and mass loadings of chemicals. A follow-up study which will incorporate this methodology will provide a useful management tool for developing water resources on a regional scale.

In the second part , a brief assessment of the groundwater resources of Metro Cebu is presented. It can be seen that the analytical approach employed in the analysis is quite simplistic and has more limitations compared with the water balance and numerical groundwater flow models adopted by JICA and NHRC for Metro Manila. For instance, the analytical model cannot provide accurate estimation of drawdown when transmissivity value changes due to change in saturated thickness of the aquifer. Also, the calculations are based on non-steady state pumping by using groundwater storage only. If pumping is carried out under steady state conditions (i.e., constant head provided continuously by storage in the infiltration basin), discharge rate per well can be increased. In effect, the total number of production wells can be reduced considerably since change in aquifer saturated thickness does not represent a limiting factor under such conditions of withdrawal (Cebu Consultants, 1984).

Because of the above limitations, it is recommended that a digital or numerical model need to be developed and employed for proper design of wellfields for any development scheme in Metro Cebu.

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Table 1. Comparison based on model features and assumptions

Criteria	JICA Model	NHRC Model
Model Components	Linear Water balance equation 3-D groundwater flow(Q3P) 2-D solute transport(MOC)	NHRC linear baseflow Watershed water balance Laguna Lake Water balance BUH hydraulic-subsidence CUWARM (or Manila model)
Initial and Boundary Conditions	Actual piezometric heads and storage coeff. No-flow; constant flow, and constant head BCs	Lake gage heights; Pressure heads=0 at start of pumping Continuous head at aquifer/aquitard layer; Change in pressure head wrt to moving front=0; When well radius reaches infinity, pressure head=0
Assumptions	Hydrogeologic parameters not affected by changes in piezometic heads and constant with time; Boundary conditions and phreatic levels are constant with time; Equilibrium sorption for solute transport	Geological system is described by aquitard/aquifer profile; Horizontal water flow under pumping conditions; Darcy Law applies; Subsidence is due to consolidation of aquitards.

Table 2. Comparison of hydrogeological properties and input parameters

PARAMETERS	JICA/MWSS	SOURCE	NHRC/IDRC	SOURCE
Transmissivity (T) sg.m/d	22-274 mean=77.5	From actual pumping tests	5-1000 8-400	Quiazon (1971) JICA/MW (1991)
Storage Coefficient (S)	1x10-3	Assigned initial value	0.01-0.20 Unconfined 0.00001-0.009 Confined 0.003-0.68 Metro Manila	Quiazon (1991) " JICA/MW
Aquifer/ Aquitard thickness; m	Aquitard 7-53	Discre-tized from clay content maps	Aquifer 50, Manila Bay Alluvium 700, Guadalupe Formation >1000 Under Manila Bay	Literat " "
Permeability (T/H); H=200 m; m/d	1x10-3	Assigned initial value	0.025-50	Literat
Compressibility (S/H); H=200 m; 1/m		NA	5x10-8 to 5x10-5	Literat
Phreatic water level; m	10	Actual geomor-phologic analysis	NA	
Well Lithology	Alluvium consists of sand, silt and gravel	Actual well tests	Volume frac. 0-50 m depth Gravel: 0.076 Sand: 0.17 Clay: 0.428	Literat
Rainfall	Annual Total= 2329.7	Rainfall map	Annual average 3756.98	PAGASA Stations
Ave. recharge	183.1 mm/yr	Input	Computed	

Table 3. Comparison of Simulated Water Balance Components

Water Balance	JICA Model Study area 1404.7sq.km. Period:1990	NHRC Model Study area 1780sq.km. Period: 1982- 1990
Rainfall (P)	2,329.7 mm (3272.53 MCM/yr)	3576.98 MCM/yr
PET	1219.3 mm (1712.8)	2512.51 MCM/yr
AET	816.6 mm (1147.1)	2274.01 MCM/yr
Excess Water	Runoff(0.6P) 1397.82 mm (1963.5)	Total=1348.11 MCM/yr Direct Runoff 915.85 MCM/yr Base flow 226.09 MCM/yr
Average Annual Recharge	115.3 mm (161.96)	206.16 MCM
Average Annual Pumpage	339.6 MCM (for whole MSA)	235 MCM

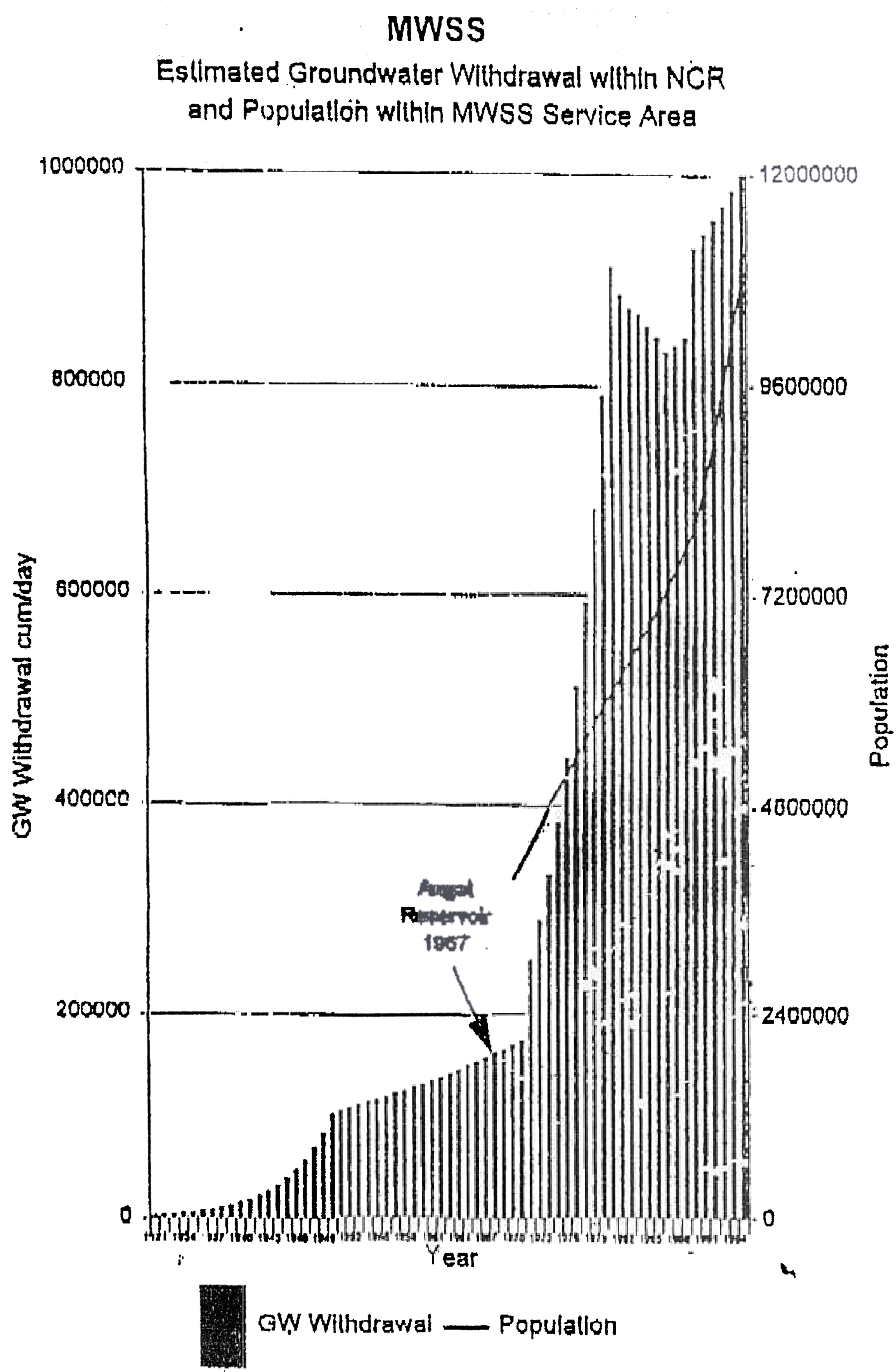

Fig. 1 Estimated Groundwater Withdrawal within NCR
And population within MWSS

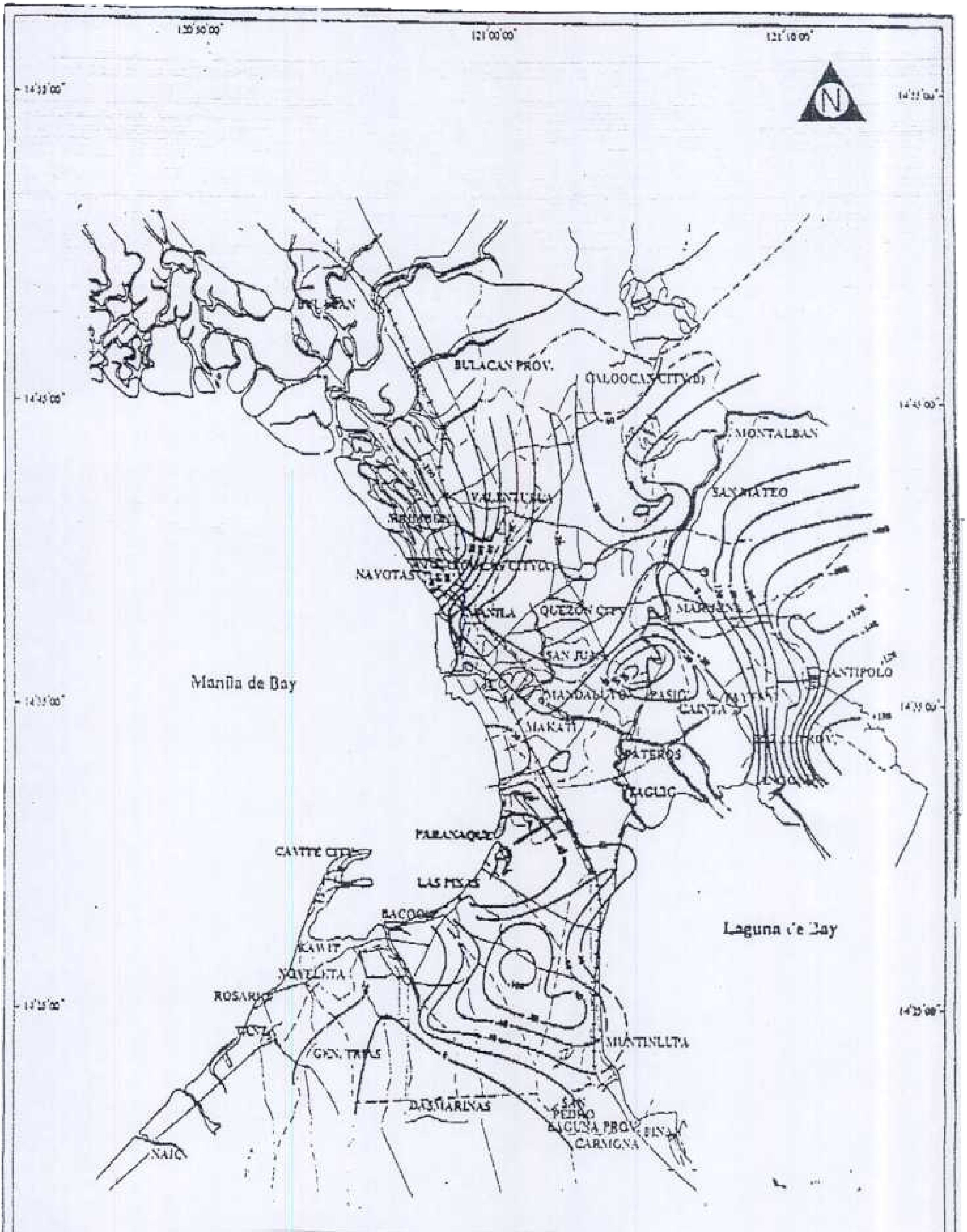

Fig. 2 Groundwater Condition in Metro Manila
(Data Source: MWSS, as of 1994)

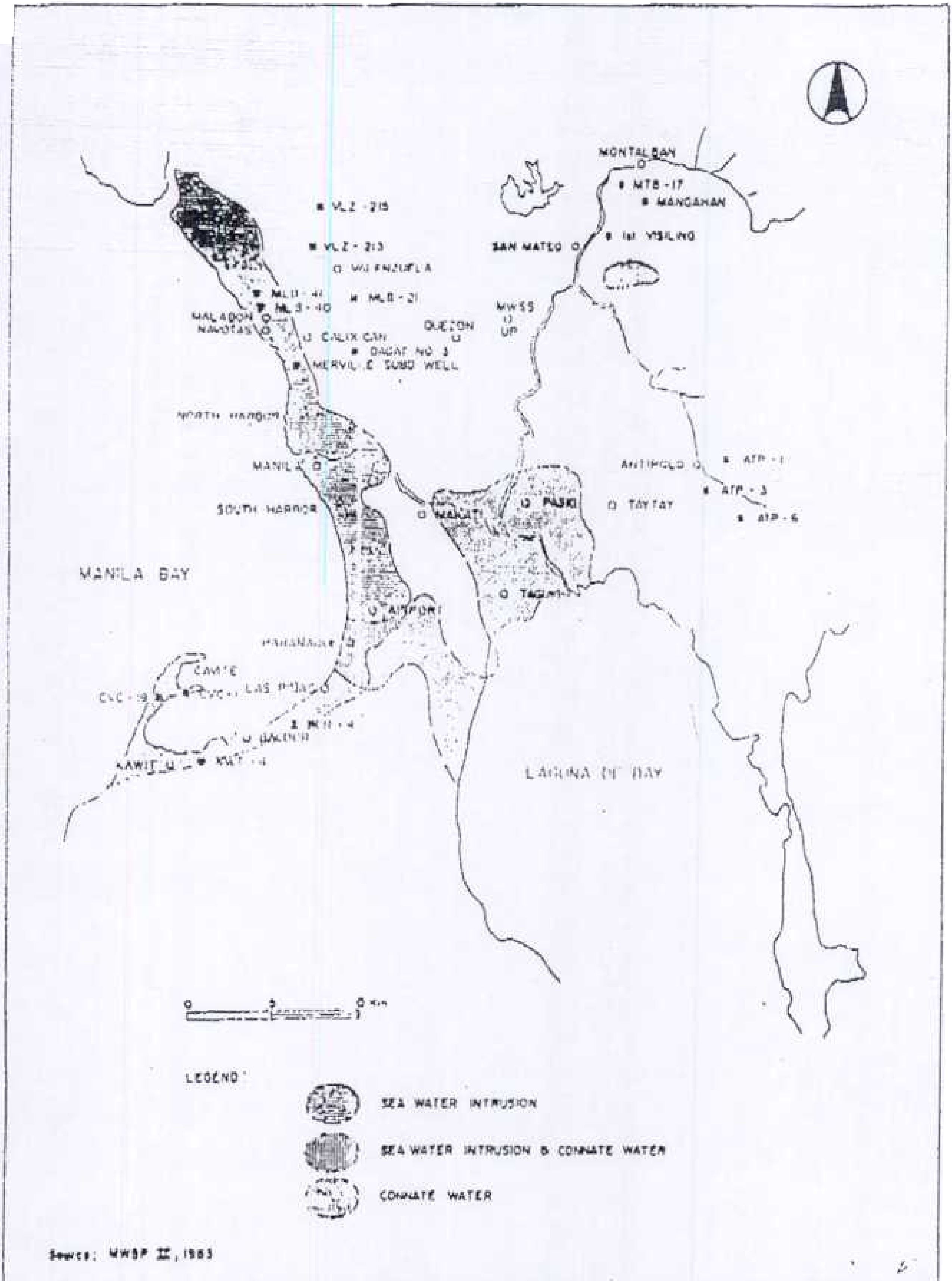

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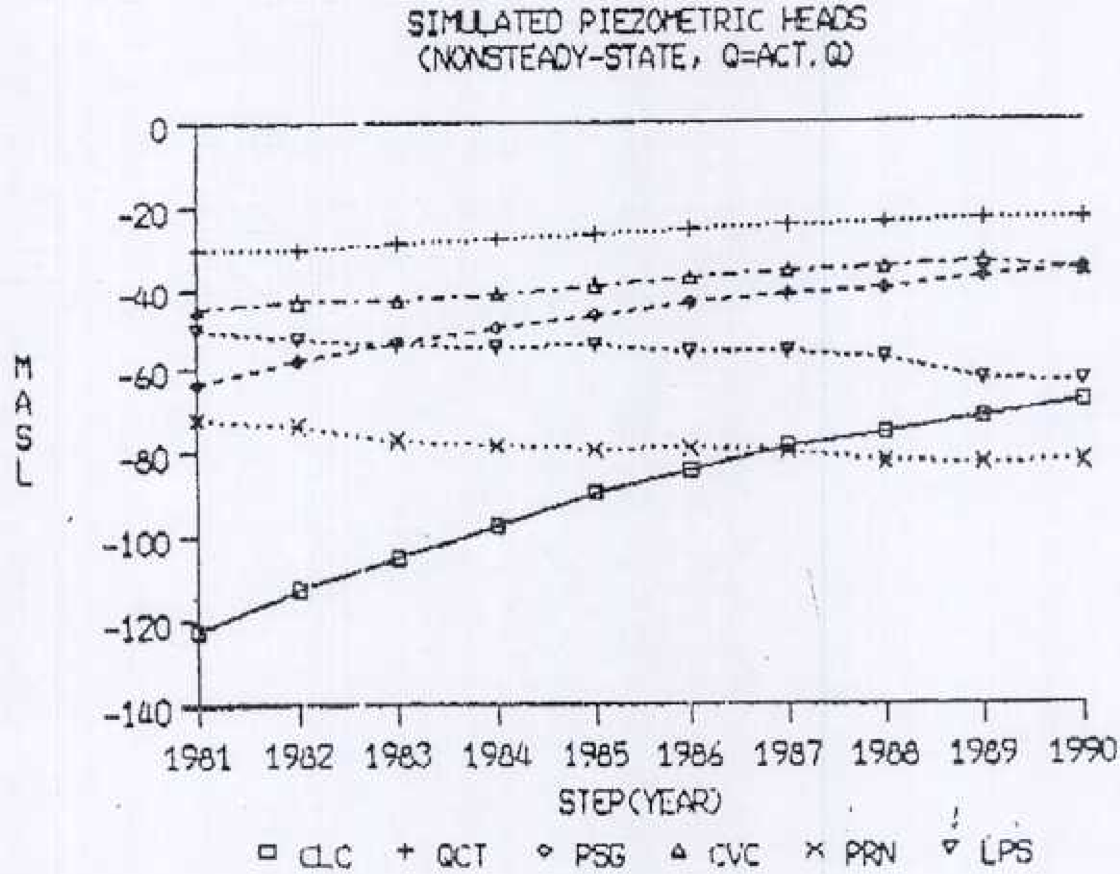
Fig. 3 Area of Saline Water Contamination IN



STUDY FOR THE GROUNDWATER DEVELOPMENT IN METRO MANILA	Fig. 4 Simulated Piezometric Heads by Nonsteady State Calculation
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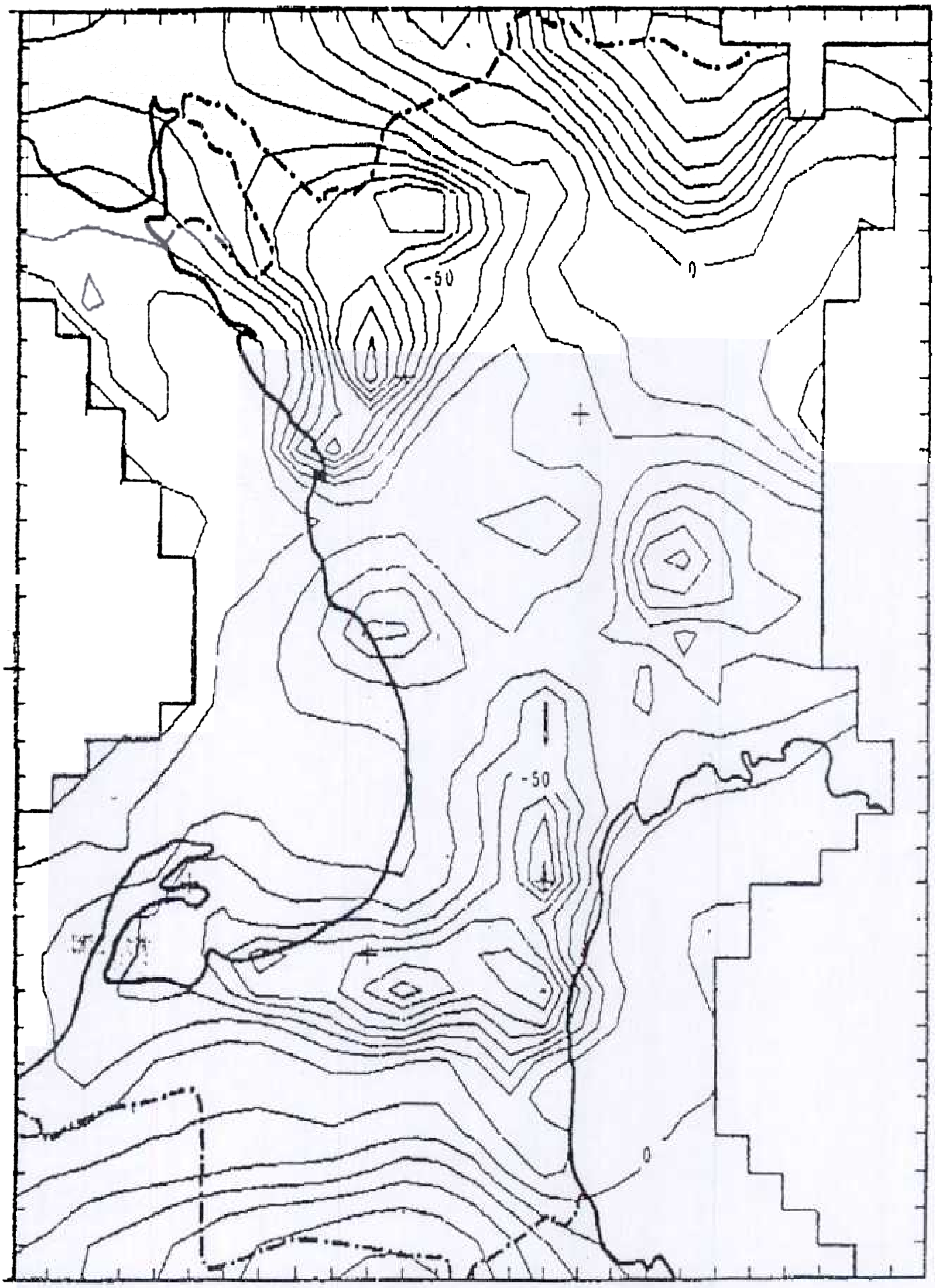

(Contour Interval: 10m, Unit: masl)

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Fig. 5 Simulated Piezometric Heads in 1990

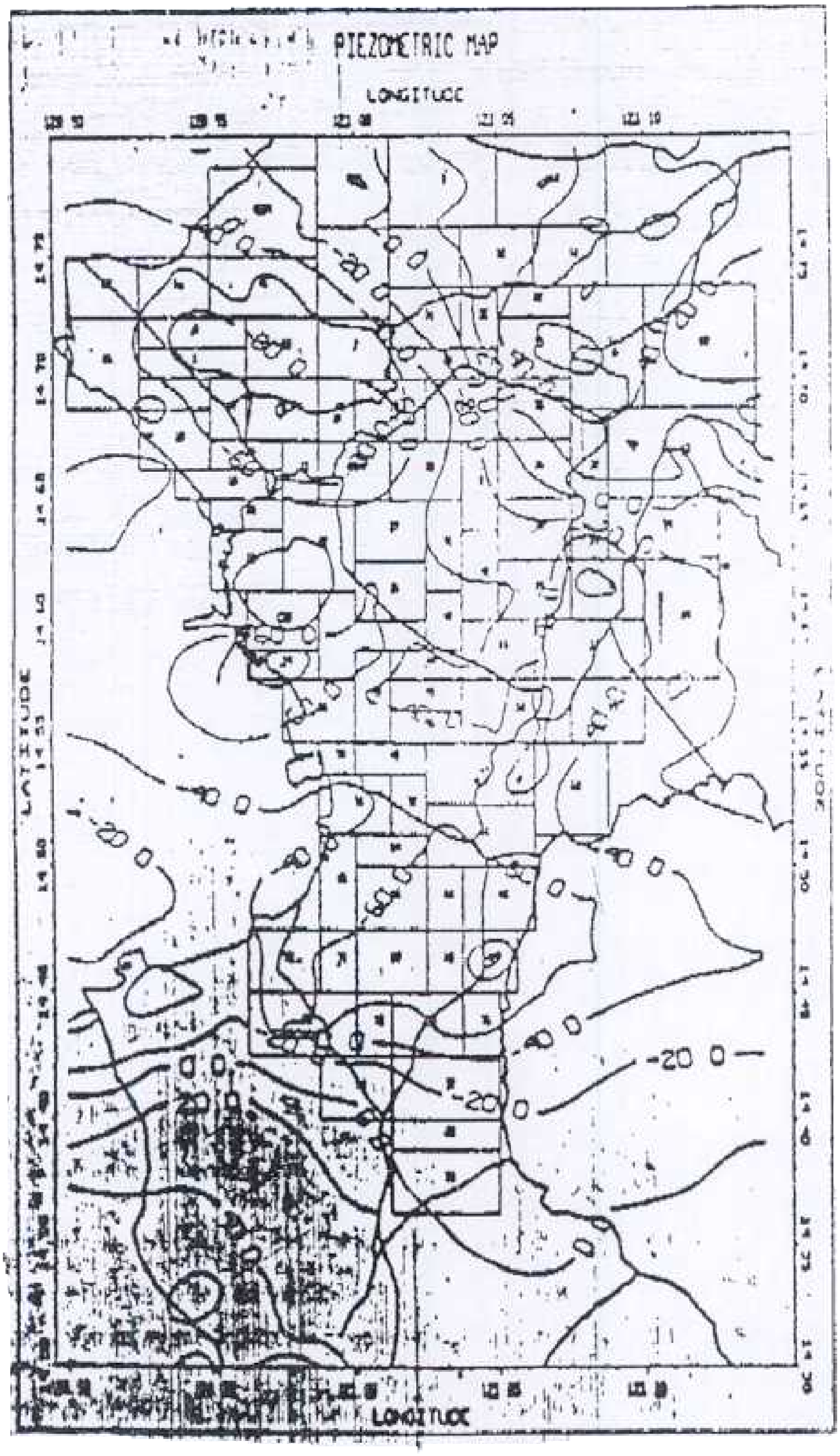

Fig. 6 Computed 1990 piezometric contour map for Metro Manila

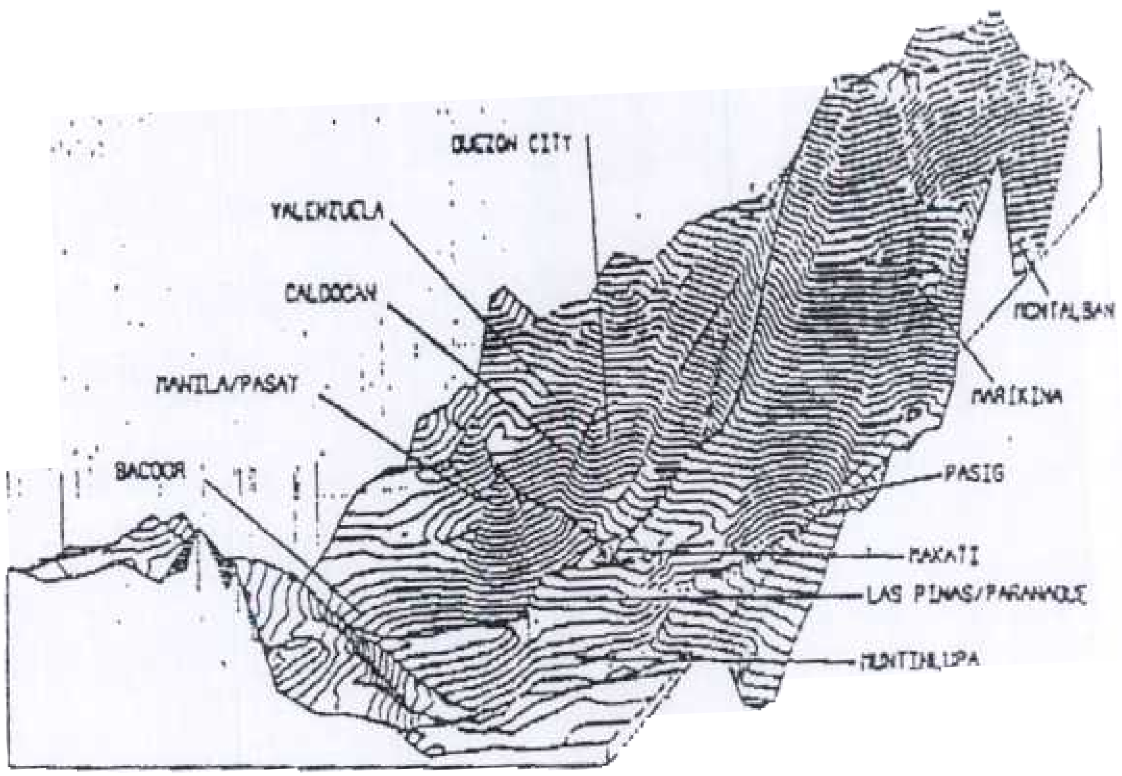

Fig. 7 Three-dimensional view of the computed 1990
Piezometric surface for Metro Manila