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Groundwater Supply in Metro Manila: Distribution, Environmental and Economic Assessment

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Abstract

Early studies on the groundwater supply of Metro Manila have indicated inefficient resource use that could lead to the eventual decline in the groundwater level, salt water intrusion, and other similar negative externalities. Based on the preceding premise, the paper intends to present a review and assessment of how groundwater resources are developed and utilized in Metro Manila.

The study has evaluated technical reports and published literature. It has also adopted water balance models as well as Long-Run Marginal Cost methodologies in calculating the groundwater potential and cost of groundwater pumping. Through these methodologies, the study requires the incorporation of environmental externalities in valuing the unit cost of groundwater extraction. Specific suggestions concerning monitoring systems, aquifer characterization, Geographic Information System application, environmental costs of groundwater pumping, and policy enforcement have been raised. The paper identifies the need to refine the methodology and data set for instituting both supply and demand relationships and projections.

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Executive Summary

This paper was aimed to present a detailed review and critical assessment of groundwater development and use in Metro Manila with respect to its distribution, environmental and economic implications. In the review, several technical reports and published literature were consulted and become the major basis for identifying gaps and suggesting remedial measures. Also, water balance models and Long-Run Marginal Cost methodologies (e.g., AIC and JICA models) were used to estimate groundwater potential and cost of groundwater pumping. From these evaluations, it was found that further improvement in methodology and data set are needed in order to establish supply/demand relationships and projections. Also the unit cost in extracting groundwater should include not only project costs but also the costs associated with environmental externalities such as groundwater depletion, saline water intrusion and land subsidence.

Based on the preceding discussions on the quantity/quality and economic aspects of groundwater abstraction in Metro Manila, a summary of suggestions are presented for policy considerations and implementation.

1. Establish groundwater monitoring systems so we can regulate the pumping in areas where piezometric heads are declining and also assess the status of existing wells in terms of its physical state or the quality of water coming from it.

2. Undertake aquifer characterization in the eastern Laguna area, from Siniloan eastward to Paete to develop a basin-wide assessment of groundwater potential. Also, well-organized water table and piezometric maps are lacking in eastern Rizal and Laguna areas.

3. Discrepancies in aquifer characteristics data from one source to another could be due to difference in data sampling and analysis. Using automatic and computerized equipment can improve the quality of data and even check the validity of previous data.

4. The JICA and NHRC 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 can be 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. Also, expanding the models into a management model will provide assessment of “what if” scenarios especially the impacts of urban/industrial developments on water quality and yield. A follow-up study that will incorporate these methodologies will provide a useful management tool for assessing and developing water resources, even on a regional scale.

5. In estimating the unit cost in groundwater pumping, not only project costs but also the costs associated with environmental externalities such as groundwater depletion, saline water intrusion and land subsidence should be incorporated in water supply marginal cost models. The two pumping cost methodologies adopted in the study (i.e., the JICA and AIC models) should be further examined since they provided different unit costs.

6. Strict enforcement of policies concerning industrial waste treatment and disposal facilities (for wastewater and garbage wastes) should be implemented to prevent further deterioration of water resources. Also both point and nonpoint sources of pollutants should be assessed to minimize its loadings to both surface and groundwater resources.

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R.S. Clemente, G.Q. Tabios III, R.P. Abracosa, C.C. David, and A.B. Inocencio*

1. Introduction

Studies on the groundwater resources of Metro Manila started as early as the 1960s to investigate the hydrogeologic properties of its aquifers as well as to determine the groundwater abstraction and recharge patterns in the region. 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.

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 the Metropolitan Waterworks and Sewerage Systems (MWSS) in collaboration with ELECTROWATT as a long range program to provide for a more effective exploitation and use of the groundwater resources in the MWSS Service Area (MSA). 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 indicate 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.

MWWS/JICA survey in 1991 indicated a total private deep wells in MSA of 3,434, of which 2216 are operational and 1218 as abandoned wells. These private wells, which produce around 841,000 CMD are concentrated in Paranaque, Las Pinas, Muntinlupa, Pasig, Quezon City,

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Caloocan City and Valenzuela. In addition to the inventoried wells, there may be another 30,000 shallow wells serving population not connected to the Central Distribution system (CDS) and other private water supply systems. Of the 265 MWSS supervised wells, only 131 wells are active as of March 1991, which produce about 82,000 CMD of groundwater for MSA. With the continued groundwater abstraction exceeding the safe yield of the aquifers, excessive drawdowns and increased salinization have been observed in the area. That is why the 131 operational wells in 1991 have been further reduced to 109 in 1995 with total production of 73,698 CMD.

Simulation studies (JICA, 1992 and NHRC, 1993) also showed a large drawdown of piezometric heads in Metro Manila especially in coastal areas such as Muntinglupa, Paranaque and Las Pinas. These have been attributed to the heavy pumpage in those areas. As such a regulated area for groundwater pumpage was recommended for the southern municipalities of Metro Manila to prevent further sea water intrusion into its mainlands. In addition, several projects are on-going and proposed to be undertaken to assess and develop the groundwater potential of the aquifers in the MSA.

2. The MWSS Service Area (MSA)

2.1 Geography

The MSA is situated at the Southern end of the Central Luzon plain. It is bounded by Manila bay in the west, Laguna de Bay and piedmont of Taal volcano in the south and the mountainous area of Sierra Madre range in the east. The area covered by MSA is 2,061 sq.km and it includes the NCR (645 sq.km.), part of Cavite province (133 sq.km.) and the entire province of Rizal (1,339 sq.km). The NCR has 7 cities and 10 municipalities, the Cavite part has 1 city and 5 municipalities and Rizal province has 14 municipalities.
Figure 1 shows the map of the MSA.

The population residing within MSA was about 11.4 M in 1995 and the population served by MWSS is around 70% (or 8.0 M). The difference is served by private wells.

2.2 Climate

The rainfall patterns in the major portion of MSA is classified under Type I (Coronona Scheme) which is characterized as having two pronounced seasons: dry from November to April and wet from April to May (PAGASA). A smaller portion of the area in the eastern part falls under Type IV which has even rainfall distribution throughout the year.

Generally, the area derives its rainfall from the warm, moist southwest monsoon as well as convergent storm cells associated with the Intertropical Convergence Zone which occurs during the wet season. The annual rainfall over the MSA varies from 1900 mm in the western part to 2500 towards the eastern highlands with a mean of around 2,000 mm.

2.3 Geology

The MSA is underlain by rocks of various origin and characteristics which consist primarily of agglomerates, pyroplastics, sandy tuff and cinder beds. These exist in association with other properties in alluvial deposits, reworked tuff and volcanic ash often displaying desirable hydrogeologic properties. Complex tectonic and volcanic events, mainly during the Late Tertiary and Quaternary periods together with large relative sea level changes have produced the present basic hydrogeologic structure in the area. (NHRC, 1993).

3. Groundwater Distribution in MSA

3.1 Aquifer Systems

The groundwater systems within MWSS service area consist of Alluvial sediments in coastal areas of Manila Bay, Laguna de Bay and Marikina Valley and pyroclastic Guadalupe sedimentary formation underlying most of the NCR.
According to JICA (1992) and NHRC (1993) studies, the aquifer system covers about 1400 to 1800 sq.km. In general, the aquifers consist of the upper water table aquifer up to 30 m depth and the lower artesian aquifer of more than 500 m thickness, separated by semi-confining layer with thickness of up to 45 m.
The major aquifer system in Metro Manila, together with the municipalities in which they are deposited or exposed are as follows:

1) Manila Bay Alluvium - deposited in the cities of Caloocan, Manila, Pasay and part of Makati and the municipalities of Valenzuela, Navotas, Malabon, Paranaque, Las Pinas, Bacoor, Imus, Kawit, Noveleta, and Rosario

2) Marikina Valley Alluvium - deposited in the municipalities of San Mateo, Montalban, Marikina, Pasig, Cainta, Taytay, Pateros, and Taguig

3) Guadalupe Formation - exposed in Quezon City, San Juan, Mandaluyong, part of Makati, and Muntinlupa.

4) Laguna Formation and Pre-Quaternary Formations - exposed in the towns of Antipolo, Angono, Baras, Binangonan, Cardona, Jala-Jala, Morong, Pililia, Tanay and Teresa.

The Antipolo aquifer is an isolated groundwater basin which is part of the Guadalupe Formation, underlain by pre-Quaternary rocks as basement. Although the maximum thickness of the formation is 230 m, the useful water in the confined aquifer is limited to depths from 100 to 120 m below the surface.

3.1.1 Geohydrology of the Aquifers

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

The storage coefficient (S) of the main aquifer varies from 0.1 (or 10%) in the southern end of NCR where phreatic (water table) aquifer is assumed to prevail to 0.0001 in the northern end where aquifer is assumed to be under artesian (pressurized) conditions. Higher values of 0.002-0.006 are found along the western and northern side of Laguna de Bay which indicates the influence of leakage from phreatic aquifer on S. Where drawdowns of more than 50 m have occurred due to overpumping the main artesian aquifer has been converted into a water table aquifer and the S value is in the range of 0.05-0.1, which is characteristics of pyroclastic sediments of the Guadalupe Formation. Higher storage coefficient values mean that the aquifer is able to release more water from a unit volume for a unit change in head.

Leakage coefficient or the ratio of aquitard (semi-confining layer) permeability to its thickness varies from $1x10^{-11}$ sec to $3x10^{-9}$ sec. The upper water table is separated from the main artesian aquifer by semi-impermeable layer (aquitard) with thickness ranging from 15-45 m. This layer is thicker in southern (Las Pinas), western (Manila) and northwestern (Caloocan, Malabon, Navotas, Valenzuela) part of Metro Manila while it is thinner in the Quezon City area. The head in artesian aquifer was higher than the head in water table aquifer (esp. in coastal areas and some areas in Marikina Valley) which resulted in upward leakage, as indicated by free-flowing wells in these areas.

Details of the geological and hydrogeological characteristics of the Metro Manila aquifers can be found from localized studies such as Sonido (1992), SOGREAH/MWSS (1989); NEPC (1987), NWRC (1983, NIA (1975) and regional studies namely MWSS/JICA (1992), NHRC (1993), Sandoval and Mamaril (1970) Haman (1996), and Quiazon (1971).

3.2 Groundwater Withdrawal

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 (thus, the aquifer system referred to here includes the Guadalupe aquifer and the Antipolo aquifer). Figure 2 shows a profile of the groundwater withdrawal and population growth in Metro Manila .

By 1990, the total groundwater withdrawal had reached about 930,000 cum/day, of which 841,000 cu.m./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 cu.m./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 cu.m./day. This is equivalent to about a five-fold increase in groundwater withdrawal since the early 1970s.

The withdrawal from the main aquifer is estimated in 1995 at 970,000 cum/d (354 MCM/yr) of which 10% is by MWSS and the rest by private users. Compared with aquifer replenishment of about 191 MCM/yr, this indicates groundwater mining of about 164 MCM/yr. This has been going on since 1977.

Note that the estimates above apply to the whole of the Guadalupe aquifer system, including both the main (artesian) aquifer and the water table aquifer. The groundwater modelling done by NHRC (1993) for the main (artesian) aquifer indicated a withdrawal rate of only about 235,000 cum/yr. This indicates that 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.

Another indicator of groundwater abstraction is the resulting drawdown of piezometric surface due to pumping. Figures 3 and 4 show the groundwater situation in Metro Manila in 1955 and 1994, respectively as indicated by the piezometric heads. In 1955, we can see that positive piezometric heads exist in Northeast of Manila which ranged from +10 to +180. This indicates that the groundwater surface in these areas (which covers the municipalities of Cainta, Taytay, Antipolo, Marikina, up to Caloocan City) are above the reference sea level. But as you go down south to the coastal municipalities of Paranaque, Las Pinas, and Bacoor (at the Manila Bay side) and the municipality of Muntinlupa at the side of Laguna de Bay we can see that negative piezometric heads (around -10 m) exist which means that the water levels in these areas are below mean sea level. With the increase in population and water demand, we can expect a different groundwater situation in the 1990s.

This is the groundwater situation in Metro manila in 1994. We can see that the piezometric heads in northeast of Manila are still positive, but it has gone down from +180 m to +120 m. Looking at the coastal areas, the situation had really worsen because the piezometric heads had gone down to -100 m from only -10 min 1955. These have been attributed to the contineous heavy pumpage along the coastal areas during the past 4 decades. These results will be compared later with the simulated piezometric heads from two water management models i.e. JICA (1992) and NHRC (1993).

3.3 Aquifer Recharge

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). 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. Another source of groundwater recharge is leakage from MWSS pipes.

The main aquifer average recharge is estimated to be 191 MCM/yr originating from rainfall, leakage from pipelines downward leakage from water-table aquifer and induced infiltration from Laguna Lake.

3.4 Assessment of Groundwater Potential

Groundwater potential (GWP) is approximately equal to groundwater recharge. GWP depends on the relative surface area, hydrogeology and the amount of precipitation the area receive. There are a number of methods for assessing groundwater potential. Hamill and Bell, (1986) suggested several approaches for assessing aquifer yield/discharge or groundwater recharge, namely a) water budget studies, river hydrograph analysis, water level fluctuations, flow net analysis, pumping tests and mathematical models. In this study two methods were used such as a) water balance calculations and b) rainfall isohyetal maps.

3.4.1 Water Balance approach

In the recent groundwater development study in Metro Manila, recharge was estimated using water management models by JICA (1992) and NHRC (1993). While NHRC employed a detailed water balance model that includes baseflow separation, JICA used a simplistic model that only relates Rainfall, Runoff, Infiltration and ET. Effective infiltration is considered as the recharge to groundwater. Details about the models can be found in JICA(1992), NHRC(1993) while Abracosa and Clemente (1997) compared and evaluated the two models in terms of its capabilities, input requirements and underlying assumptions.

One of the principal objectives of the studies 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. From the water balance simulation, large volume of excess water (1348.11 MCM/yr or 38% of rainfall; see Table 1) 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. It should be noted also that the study area for JICA was only 140 sq km. which is smaller compared to the 1780 sq .km area used by NHRC. If we use an adjustment factor for area, we get a recharge of 205 MCM/yr for JICA (1992) which is very close to the 206 MCM/yr obtained by NHRC (1993). So both studies indicate 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. So 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. 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.

Results of the simulations also give the contour maps of the piezometric head for 1990 from both models. Piezometric heads represent the water level in observation wells with the mean sea level as the datum of reference. So a negative piezometric head indicates that the water level is below mean sea level and it is positive when it is higher than the mean sea level. It can be seen from Figure 5 that both models gave similar piezometric distribution. For instance, the piezometric heads in the Muntinlupa, Las Pinas and Paranaque areas ranged from 0 to -60 m and 0 to -50 m as simulated by NHRC and JICA, respectively. A more visible representation of the piezometric distribution is presented by NHRC through a 3-D form which is shown in Figure 6. From this, it can be observed that the higher piezometric 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 the areas with higher piezometric heads can constitute as inflows to the Laguna Lake which lies beside the piezometric depression areas of Paranaque, Las Pinas, and Muntinlupa.

3.4.2 Isohyetal maps

In this approach, recharge was estimated using empirical method previously used by NWRC. Studies by NWRC 1979-1983 indicated that groundwater recharge is around 10% of the basin average rainfall. These values were estimated using rainfall data and isohyetal maps from the previous reports.

For Cavite study, direct recharge of study area was about 153.6 mm (6.1% of mean annual rain which was about 2,499 mm) in northern part of Metro Manila and 114.7 mm (5% of mean annual or 2,308 mm) in southern part of Metro Manila. The latter one estimated that groundwater recharge was only 3.9% of the annual total rainfall. Thus the groundwater recharge rate of the annual rain varied from 3.9 to 6.1 (or 5% on the average)

To further refine the recharge rate, land use/irrigation was considered as well as the reduction in recharge due to urbanization. Urbanization reduces recharge due to increase in land area covered by concrete, asphalt, and other non-porous materials in addition to water dependent human/industrial activities.

4. Environmental Issues and Analysis

4.1 Current Problems Associated with Groundwater Use

Because of the increasing exploitation of groundwater for potable water supply, especially by private and self-supplied users, some consequential environmental problems and externalities have been recognized. Four major externalities associated with groundwater use include: a) aquifer depletion, b) groundwater pollution, c)land subsidence and d) salinization (Munasinghe, 1992). These adverse phenomena are commonly encountered concurrently, and their causes and impacts are discussed in the following subsections.

4.1.1 Groundwater depletion

Over-extraction of groundwater systems is now a pressing problem in Metro Manila especially in the coastal areas where heavy pumpage have been going on for some decades. These have been demonstrated by the lowering of piezometric heads throughout the region (Figures 4 and 5) which suggests that we have been mining our groundwater. Also, a growing number of consumers use deeper boreholes and more powerful pumps at the expense of rural or poor peri-urban communities who can only avail of hand-dug wells and hand pumps. Since overpumping leads to sea water intrusion of the aquifer and land subsidence, then it is imperative that we determine the sustainable extraction levels and regulate pumping in areas whose aquifer yield are already being exceeded. This can be attained if we improve our database on yield potential and recharge rates to our aquifers. Where applicable, water prices could be increased to reduce demand and pay for better water conservation measures (Munasinghe, 1992).

4.1.2 Groundwater pollution

According to Munasinghe (1992), there are three main sources of groundwater pollution in developing countries namely: a) sewage and seepage from inefficient sanitary facilities, b) industrial discharges or urban effluents, and c) agrochemical residues (fertilizers and pesticides).

Although soils are considered as natural purifiers, there can be some risks of direct migration of pathogens to underlying aquifers. Also, seepage from on-site sanitary structures such as latrines, septic tanks, aeration lagoons or sewerage spreading areas, can pose a pollution threat to adjacent subsurface water systems. Some urban areas are deprived of sewerage systems so wastewaters such as spent oils and solvents can leach through soils and reach the underlying aquifers.

The intensification of agricultural production to increase productivity is often accompanied by increased usage of agrochemicals such as fertilizers and pesticides. However, studies indicate that residues of nitrate and herbicides have been detected in our groundwater resources.

For instance, the International Rice Research Institute (IRRI) has expressed concerns about the impact and adverse effects of agrochemicals (e.g pesticides) on rice ecosystems, on the environment, and on human health (Lampe and Lash, 1993). A case study reported by Bhuiyan and Castaneda (1995) indicated that groundwater in shallow aquifers underneath intensively cultivated irrigated rice fields in Pampanga and Laguna are receiving a large number of pesticides used by farmers for crop protection. Clemente (1996), in his study of chemical leaching in agricultural watersheds, found that one year after application, Diuron reached the bottom profile with concentration of 0.0038 mg/l (or 3.8 ppb). This exceeded the tolerable limits for most pesticides which has a range of 0.5 to 3 ppb as set by EEC and WHO. Also, although the dissipation of the chemical through runoff and erosion was quite high, some of the chemical has leached down the soil profile quite fast. The environmental implication of this is that ground water resources underlying watersheds which have low sorption capacity and belong to high rainfall patterns can be subject to agrochemical contamination especially if the topography allows for higher infiltration and leaching. The problem is even aggravated by continuous application of the chemical where accumulation in ground water can be expected.

4.1.3 Land subsidence

Land subsidence, as the name implies, is the decline in land surface elevation due to consolidation of water bearing geological strata or clayey sediments in the aquifer. It is observed mainly in wide plain areas and is caused mainly by overpumping or groundwater mining. Land subsidence may not only result in the collapse of buildings and other infrastructures, but it can also cause flooding of sewerage and storm drainage systems during high tides as well as breakage of pipelines. This problem was observed in Bangkok where water levels dropped 10-12 meters in three years since 1985 (Nair, 1988).

4.1.4 Saline water intrusion (SWI)

There are a number of reasons that can cause an aquifer to become saline and render it unsuitable for irrigation or drinking purposes. The reuse of agricultural drainage water, deforestation coupled with high evaporative demand and overpumping can lead to build-up of salts in aquifers which is commonly referred to as saline water intrusion (SWI). SWI can be induced and become more serious in areas where overexploitation of groundwater is accompanied by insufficient recharge rate. Figure 7, which was taken from Munasinghe (1992), shows the dynamics of saline water seepage into aquifers. From this Figure we can see two distinct types of water bodies (i.e. salty and fresh water) which differ in density and are relatively immiscible. Also there is the brackish water interface beyond which there is no migration of salts. Without human interference the intrusion front can either move away from or back towards the sea depending on the amount of recharge from inland. When this natural equilibrium is disturbed by human activities such as overpumping (i.e. more groundwater abstraction than recharge), the saline water will move inland replacing the depleted freshwater (Munasinghe, 1992).

4.1.4.1 Simulation of saline water intrusion

In the JICA model, the movement of saline water was also investigated under steady state conditions using 1990 input discharge and recharge data. The simulation period was 10 years. Results are shown in Figure 8 which 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. 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 alluvial plain where consolidation of clayey deposits may result from groundwater depletion.

JICA (1992) also simulated different pumping scenarios to compute future piezometric heads at 30 time-steps (i.e., 30 years from 1981 to 2010). The five scenarios considered are based on schedule of completion of surface water supply projects and the future groundwater pumpage. Scenarios 1-3 consider that ongoing projects are completed on schedule, and scenario 4 considers a two-year delay in completion. The pumpage scenarios include an increasing pumpage for Scenario 1, constant pumpage after year 2000 for Scenario 2, constant pumpage after 1995 for scenario 3, scenario 4 is the same as scenario 1 and scenario 5 considers discharge in 1990 of 316.57 MCM continues up to 2010.

In these simulations, the piezometric heads are computed as a result of water balance in the aquifer system. So the groundwater levels indicate a balance between the quantity of water supplied to and extracted from the basin. Results of the simulations can be summarized that the maximum drawdown of 50 m will occur even in Scenario 3 (Figure 9) where the discharge is the smallest among the future groundwater use plans. This is expected to cause severe saline water intrusion and damage even in inland areas. Details of these simulation outputs are presented in Volume 3 of the Supporting Report of JICA (1992).

5. Economic Evaluation of Groundwater Use

Groundwater use in the Metro Manila area has grown rapidly during the past three decades (Munasinghe, 1992 and Haman, 1996) that natural recharges have been far exceeded, leading to the so-called phenomenon of groundwater mining. Because of its geographical setting, the consequential effect of groundwater depletion is the encroachment of saline water into the coastal aquifers. Aquifer mining coupled with water quality deterioration, and perhaps land subsidence constitute a significant economic loss to the society. In effect, each groundwater user will continue to impose external dis-economies or costs on all other existing and future users (Munasinghe, 1984). These environmental externalities will become more serious if overpumping of our aquifers is allowed to continue. So there is a need to calculate long-run economic costs of groundwater use, over and above the cost of pumping or groundwater extraction. These are additional costs imposed by any given user on all other potential present and future groundwater users.

5.1 Well Survey Data

In groundwater use and assessment, well surveys can provide a direct and reliable tool for water demand analysis and forecasting. These surveys aim to collect a broad data base of information from which estimates of the likely pumping patterns of a given consumer group over the lifetime of the well systems in use can be made as well as the estimates of the costs associated with its development.

Commonly, the volume of water extracted from wells can be determined from a water or electric meter. However, in cases that water and power consumption by pumps are not monitored, especially in private wells, the pump capacity (described as pump discharge per unit time, e.g. gpm) is used as an indicator of water consumption. Performance curves of manufactured pumps (e.g. Figure 10) provides a relationship among pump capacity, total dynamic head (TDH), Efficiency, and Horsepower. It can also be calculated from the equation:

BHP = (GAMMA x Q x TDH x Eff) / 550   1)

where BHP = brake horsepower, GAMMA = 62.4 lbs/cuft, Q is pump capacity (cfs), TDH = Total dynamic head (ft), Eff = Pump Efficiency (fraction) and 550 is a conversion factor.

To estimate the output of a well and the cost involved in producing such amount, a combination of some of the parameters in Figure 10 and Equation 1 must be available or collected. In view of these data needs, the Philippine Institute for Development Studies (PIDS) has embarked on an actual survey of well users to evaluate the water consumption patterns of household, industrial and commercial sectors (which is later referred to as user). The study involved the collection of well data by interviewing respondents coming from different user groups as regards to well depth, number of wells per user, operating hours, water requirements, pump capacity, etc. Details of this are presented in David et. al. (1998).

5.2 Cost of Groundwater Pumping

5.2.1 JICA model

JICA proposed a simple estimation procedure to determine the cost per cubic meter of water for rehabilitating or constructing new wells. It is written as:

$$C = (A*a + B) / Q \qquad 2)$$

where C = cost of water per unit volume, A = total project cost, a = capital reduction rate, B = annual operation and maintenance cost and Q = annual pumpage. The capital reduction rate (a) can be estimated from:

$$a = (i(i+1)^n/((i+1)^n -1) \qquad 3)$$

where i = rate of interest, and n = useful life in years

Given the following data:

i = 0.055; n = 20 years for a new well; construction cost = 12,700 pesos per meter, including submersible pump and pumphouse so a well with a depth of 200 m costs 2.54 million pesos (=A). With a = 0.080 and B not included, the cost per unit volume can be calculated from Equation 2:

$$C = (2,540,000 \text{ pesos} * 40 \text{ wells} * 0.080) / 27,400 \text{ CMD}*365 \text{ days/year}$$

$$= 0.81 \text{ peso per cubic meter}$$

For a rehabilitated well (totaling 100, n = 10 and a = 0.129)

$$C = 0.70 \text{ peso per cubic meter}$$

The above calculations suggest that rehabilitating existing wells is more cost effective than constructing new wells for the same output, for a 10-year operation. Haman (1996) also suggested that drilling new wells for monitoring purposes is unnecessary because existing wells can become permanent observation wells.

However, it should be noted that this construction cost is based on the early 90's price and the annual operating and maintenance cost was not included. The current cost per well is now around 3.5 Million pesos (but this can vary depending on well depth). So if this is reflected in the equation above, the new unit cost of water from a new well will be P1.12 per cubic meter. Also, the equation does not account the costs associated with externalities such as cost involved in treatment of contaminated sources. So the equation can be modified for this purpose.

5.2.2 AIC model

The average incremental cost (AIC) of water supply is another approach for estimating unit economic costs of water produced as per Munasinghe, (1992). AIC can be regarded as a good approximation of the Long-Run Marginal Cost (LRMC) of water supply and is defined as the ratio of the present value of incremental costs of producing water over the present value of volume of incremental water produced. It can be defined further if we consider the average incremental cost of water produced at the headworks, which is written as:

$$AIC_H = \frac{\sum_{t=0}^{T} (I_{lt} + R_{lt}) / (1+r)^t}{\sum_{t=L}^{T+L} Q_{lt} / (1+r)^t} \qquad 4)$$

where I_{lt} is the investment at the headworks in year t; R_{lt} is the incremental operating and maintenance (O&M) cost of the headworks in year t; Q_{lt} is the incremental water produced at the headworks in year t; and r is the discount rate (e.g. opportunity cost of capital). From Equation 4 it can be seen that AIC is the unit cost which equates the present discounted value of water and the supply costs. It should be noted that the supply during peak and off-peak periods and water losses at the headworks are not reflected in Equation 4. Also, headworks, when referred to groundwater supplies, covers the well boreholes, pumps and pumphouses. Details of the AIC concept can be found in Chapter 8 of Munasinghe (1992).

The two pumping cost methodologies presented above were used and compared with regards to the unit cost of the wells constructed for industrial/commercial operations in Metro Manila. It was found that the AIC model provides higher values of unit costs compared to the JICA model. Details of these comparisons are presented in David et. al. (1998).

5.3 Cost of Externalities

5.3.1 Groundwater depletion models

Some of the effects of groundwater depletion are lowered water table (increased Total Dynamic Head, TDH) and higher salinity (reduced life span of wells). Because of data limitations, only two scenarios are presented as per (Munasinghe, 1992), to determine externality costs due to groundwater depletion. First is the depletion case as the base scenario which will prevail if present MWSS policies or groundwater use operations continue in the next two decades. The other case is the conservation scenario which is the result of a centrally managed groundwater extraction policy. In both scenarios, it is assumed that all withdrawals in Metro Manila are made from a common aquifer which is physically defined in MWSS (1983a).

In the depletion scenario, a withdrawal level of 730 MLD starts in year 0 until year 6 and the aquifer yield declines linearly down to 620 MLD in the year 16. Then withdrawals drop to 0 in year 26 due to progressive mining of the potable water. Figure 11 shows the increase in costs with increasing depletion of groundwater. Specifically, the average costs of withdrawal will rise linearly from US$ 0.13 per cum of water in year 0 up to US$ 0.27 in year 26. In the conservation scenario, it is assumed that an equilibrium stage is attained where recharges equal total withdrawals. In this hypothetical case, extraction rates decline from 730 MLD in year 0 to 200 MLD in year 16 which is estimated as the safe yield for potable water. Once the equilibrium stage is reached, pumping can continue at this rate without mining the groundwater and costs will also remain constant at US$ 0.13 per cum, as can be seen in Figure 11.

From the above comparisons, there is no doubt that the conservation scenario is less costly, and more environmentally friendly. However, under present policies, the depletion scenario have been going on during the past decades. While the physical model and extraction scenarios provide a benchmark value for externality costs of depleting an aquifer, not much information, however, is available about the consumption patterns and economic behavior (especially water demand curves) of groundwater users (Munasinghe, 1992). And it is based on this premise that PIDS have been conducting surveys and water demand analysis to develop water pricing schemes for Metro Manila. Details of these studies are found in David et al (1998).

5.3.2 Environmental impacts and costs

Long-term economic effects of groundwater extraction are the depletion costs, the deterioration of groundwater quality (due to sea water intrusion) and damages to infrastructure (due to land subsidence) which might impose further costs on future water users. So the total cost of using a water resource is the sum of three components, namely: a) conventional resource cost of extraction, treatment, storage, distribution and disposal, b) depletion cost due to higher expenditures imposed on future users of the same water source, and c) additional costs due to environmental degradation and damage or cost of mitigating such adverse impacts.

Costs associated with environmental protection are already being passed on to consumers in a number of developing countries. In Manila, for instance, 60% surcharge is being levied on the combined water and sewerage tariff to account for environmental protection (Munasinghe, 1992). Using Manila as an example, an approach to account for pollution costs in the case of groundwater extraction has been developed. The Long-Run Marginal Cost (LRMC) concept can be employed using the Average Incremental Cost (AIC) which was described earlier in this paper.

5.4 Water Pricing Scheme

The objective of the survey conducted by PIDS is to come up with a pricing scheme based on total consumption and costs (capital, and O&M) for each well developer/user. However unit cost of water may include some forms of user charges to reflect equity considerations and externalities such as groundwater depletion and pollution.

According to Munasinghe (1992), any realistic pricing framework must incorporate both economic efficiency and equity considerations. He added that household users consume smaller volumes of water for their basic needs compared to industrial and commercial well owners who are using large volumes of water as input to their profit making ventures. In the case that well owners pay drilling and licensing fees, then only the user charges will apply for their respective use of water.

The system of user charges appear to be one of the measures that MWSS can implement in order to safeguard groundwater for future users and purposes. The system shall be based on a social demand curve which accounts for environmental and externality costs. Considering the geographical movement of saline front and the depletion of the aquifer, a surcharge may need to be imposed in critical zones in addition to defined user charges.

By determining the overall cost (which includes capital, O&M, and externalities) for the total volume of water consumed by each user from the different sectors, then guidelines as to the optimum price per unit volume of water may be recommended to MWSS and its concessionaires. This is the overall objective of PIDS and details of the water demand projection, analysis and pricing scheme is presented in David et al. (1998).

6. Groundwater Development and Management

6.1 Existing Projects

6.1.1 Metro Manila Groundwater Distribution Project

This project was initiated in 1990 under JICA assistance to expand water supply by groundwater development to where CDS was not extended. This short term water supply plan of MWSS involves the rehabilitation of active and inactive wells of MWSS to provide groundwater up to year 1995 or 2000 to the municipalities of Antipolo, Montalban, San Mateo, Muntinlupa, Cavite City, Imus, Kawit and Rosario. The components of the project consist of the following:

rehabilitation of 100 existing MWSS wells in MSA
construction of seven new deepwell pumping stations and six
elevated water tanks in Antipolo
construction of 50 monitoring wells around MSA
conduct detailed hydrogeologic survey or study in Rizal province through
groundwater exploration and well drilling

The program aims to augment groundwater supply by about 27,400 CMD through rehabilitation of the 100 MWSS wells. Approximately 40 new wells with average yield of 700 CMD per well must be drilled to supply the same volume of water. The total project cost is 317.4 M.

6.1.2 Rizal Province Water Supply Improvement Project (RPWSIP)

This project is aimed to improve and construct waterworks systems in 9 municipalities of Rizal such as Angono, Baras, Cardona, Jala-jala, Morong, Pililia, Tanay, Taytay and Teresa by utilizing groundwater and Laguna de Bay as sources. The project was mandated in 1988 by Batas Pambansa 799 directing MWSS to hasten integration of waterworks in the 9 municipalities into its service area under a French Government aid.

Sources of water will be groundwater for Cardona, Teresa, Baras, Morong, Jala-jala, Pililia, and Tanay and the rest are Laguna Lake. 20.338 MLD will come from groundwater upon completion of the project which has total cost of 523.88 million pesos. For Cardona, Teresa, Baras, Jala-jala and Morong, there will be two units deep wells, elevated water tanks and distribution pipes; and for Pililia and Tanay, nine units of deep wells and an elevated water tank will be constructed.

Table 2 presents a profile of existing groundwater development projects. It can be seen from the Table that groundwater development is not that expensive as reflected in the lower cost per cubic meter of water coming from the constructed wells. However, the methodology is quite simple (as explained in 5.2.1) and the values in Table 2 does not reflect other costs such as operation and maintenance and the cost associated with improving water quality. But the model is quite flexible and can be modified easily to reflect these additional costs as data become available.

6.2 Alternative Sources

6.2.1 Antipolo Aquifer

Present water supply and service area

There are 10 operational MWSS deep wells and 26 private deep wells in Antipolo area. Private wells provide water for domestic/industrial use while MWSS wells supply water directly to Antipolo consumers via a pipeline system. The system in Antipolo has no booster pumps, no reservoir, no ground or elevated tanks.

The population of Antipolo in 1990 was 207,842 and 84,823 live in Antipolo plateau and only 34% of this or 28,000 are supplied with water from the distribution system. Effective volume of water supply is 3,288 CMD, so per capita water consumption is 114 lpcd. The service area is limited to a part of the Antipolo plateau.

Future groundwater supply

From computer simulations, the optimal pumpage of the Antipolo groundwater basin is about 28,000 CMD and this is estimated to meet the demand until 1998. The present abstraction of wells is around 20,000 CMD so an exploitable volume of water is 8,000 CMD. Since rehabilitation of 10 existing wells can increase the supply by 2,000, so the pumpage from new wells cannot exceed 6,000 CMD.

6.2.2 Marikina lower basin aquifer

Catchment area

This basin includes the valley of the Marikina river extending from Montalban gorge to Laguna de Bay herein referred to as the Marikina valley, and the catchments of the streams which are tributary to that reach of the Marikina River. The total basin and valley areas comprise about 390 sq km and 108 sq. km respectively. The valley is about 30 km long whose width varies from about 3 km in the upstream reach, narrowing to 1.5 km at Marikina and widening to nearly 10 km at Laguna de Bay. Figure 12 shows the map of Marikina lower basin including the 9 municipalities it covers.

Well data

43 MWSS and private wells with significant data available were analyzed in terms of its transmissivity and specific capacities. Most of the specific capacities are less than 1 l/s indicating a maximum production of less than 20 l/s with 20 m drawdown. These have been attributed to poor design and construction of the wells rather than an indifferent well.

Potential for development

The only part of the basin suitable for development of groundwater to meet or exceed local demand is the northern reach of the Marikina valley, from Montalban to San Mateo where wells could yield 30 l/s or more. Various indications of high potential recharge are noted as follows: Soil tends to be coarse texture and infiltration from precipitation is large, and terrain reveals very large proportion of sand and gravel with little clay in stream beds.

Development plan

a) exploration program to quantify aquifer parameters and potential river discharge
b) feasibility and design studies
c) construction of well field and exploit safe yield of aquifer
d) operation and monitoring
e) expansion if greater safe yield than designed for.

The prefeasibility studies will consider the exploration and a concept works for supply of 1.5 m^3/s which is considered as the safe yield based on available data. The works consist of 52 production wells with connecting pipelines two booster pump stations simple water treatment facilities consisting of a chlorinator at the downstream pump station and a transmission pipeline to join the central MWSS system at Rosario bridge.

Costs

The estimated cost for developing 1.5m^3/s groundwater supply in northern Marikina valley is 134.8 x10^6 pesos in 1979 excluding allowances for annual interest during construction which is anticipated to be three years. The cost of water is derived from present worth analysis, discounting the water produced and recurring costs is 10% per annum. The cost is 0.73 pesos per cubic meter if water is delivered to Rosario bridge at the hydraulic grade line of 85 m (MWSS datum) or 0.66 pesos at 40 m datum.

This development, like the proposed project in the lower Marikina River had been deferred because of the completion of Angat-Novaliches system. But a recent project called the Manila Northeast Water Supply Project (MNESP) aims to reactivate and regulate the dam upstream of the Old Wawa dam for further provision of water supply to the Municipalities of Montalban, San Mateo, and Marikina.

6.3 Other source options

Haman (1996) suggested that possible sources of groundwater are the Quezon City and San Juan area because of its high piezometric surface and they far from the coastal areas. In addition, he mentioned the idea of tapping the Laguna lake bed by infiltration wells which will provide 38-91 MCM/yr of water but reducing water level in the lake by 4-9 cm resulting in a reduction of flow from the lake to the Pasig river during dry season. Also, connate water exists in the area so higher chloride may be present in groundwater.

7. Conclusions

This paper was aimed to present a detailed review and critical assessment of groundwater development and use in Metro Manila with respect to its distribution, environmental and economic implications. In the review, several technical reports and published literature were consulted and become the major basis for identifying gaps and suggesting remedial measures. Also, water balance models and Long-Run Marginal Cost methodologies (e.g. AIC and JICA models) were used to estimate groundwater potential and cost of groundwater pumping. From these evaluations, it was found that further improvement in methodology and data set are needed in order to develop a water pricing scheme that are based on supply/demand analysis and projections. Also the unit cost in extracting groundwater should include not only project costs but also the costs associated with environmental externalities such as groundwater depletion, saline water intrusion and land subsidence.

8. Comments/Suggestions

Based on the preceding discussions on the quantity/quality and economic aspects of groundwater abstraction in Metro Manila, a summary of comments/suggestions are presented for policy considerations and implementation.

1. Establishment of groundwater monitoring system so we can regulate the pumping in areas where piezometric heads are declining and also assess the status of existing wells in terms of its physical state or the quality of water coming from it. Sustained monitoring of on-going andoperational projects should be enforced to identify gaps and employ remedial measures.

2. The only gap in aquifer characterization exists in the eastern Laguna area, from Siniloan eastward to Paete. This needs to be addressed to develop a basin wide assessment of groundwater potential.

3. Well-organized water table and piezometric maps are available for Metro Manila except for eastern Rizal and Laguna areas.

4. 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 and groundwater 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 in both models. Also leaching of agrochemical residues can reach the groundwater especially during those times when rainfall events are heavy and this has not been assessed by the two models. These pollution pathways have been assessed by Clemente (1996) at the Siniloan watershed and found considerable amounts of pesticide residues carried by runoff and that are leached to groundwater. Incorporating this chemical transport in surface and subsurface systems will provide a better assessment of the effects of land use and management practices on surface and ground water resources.

5. 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.

6. 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.

7. Discrepancies in aquifer characteristics data from one source to another could be due to difference in data sampling and analysis. Using automatic and computerized equipment can improve the quality of data and even check the validity of previous data .

8. 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.

9. The JICA and NHRC 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 can be 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. Also, expanding the models into a management model will provide assessment of "what if" scenarios especially the impacts of urban/industrial developments on water quality and yield. A follow-up study which will incorporate these methodologies will provide a useful management tool for assessing and developing water resources, even on a regional scale.

10. Strict enforcement of policies concerning industrial waste treatment and disposal facilities (for wastewater and garbage wastes) should be implemented to prevent further deterioration of water resources. Also both point and non-point sources of pollutants should be assessed to minimize its loadings to both surface and ground water resources.

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Definition of Abbreviations/Acronyms and some terms

JICA	-	Japan International Cooperation Agency
MWSS	-	Metropolitan Waterworks and Sewerage System
NHRC	-	National Hydraulic Research Center
UNDP	-	United Nations Development Program
cumecs	-	Cubic meter per second
CMD	-	Cubic meters per day
MCMD	-	Million cubic meters per day
MCM/yr	-	Million cubic meters per year
MLD	-	Million liters per day
l/s	-	liters per second
mg/l	-	Milligram per liter
mm	-	Millimeter
amsl	-	Above mean sea level
msl	-	Mean sea level
P	-	Rainfall
PET	-	Potential Evapotranspiration
sq.km.	-	Square kilometer
sq.m./d	-	Square meter per day

Transmissivity	-	Transmissivity (T) is the product of average hydraulic conductivity (or permeability) and the thickness of the aquifer. It is the rate of flow through a cross section of unit width over the whole thickness of the aquifer and has a dimension of sq.m./d
Storage Coefficient	-	The storage coefficient (S) is the volume of water stored or released per unit surface area of the aquifer per unit change in component of head normal to that surface. This property refers to the confined parts of an aquifer and is dimensionless.
Leakage coefficient	-	Leakage coefficient (L) is the reciprocal of hydraulic resistance (R) or the resistance against vertical flow and is a property of semi-confined aquifers. Since R is the ratio of the saturated thickness of the semi-impermeable D and the hydraulic conductivity (k) of the semi-pervious layer; so $R = D/k$ and $L = 1/R = k/D$ has a unit of per time.
Piezometric head	-	The water level (m) below or above mean sea level as measured from observation wells. Negative piezometric heads indicate that the water level is below mean sea level, and vice versa.

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

Figure 1
THE STUDY AREA

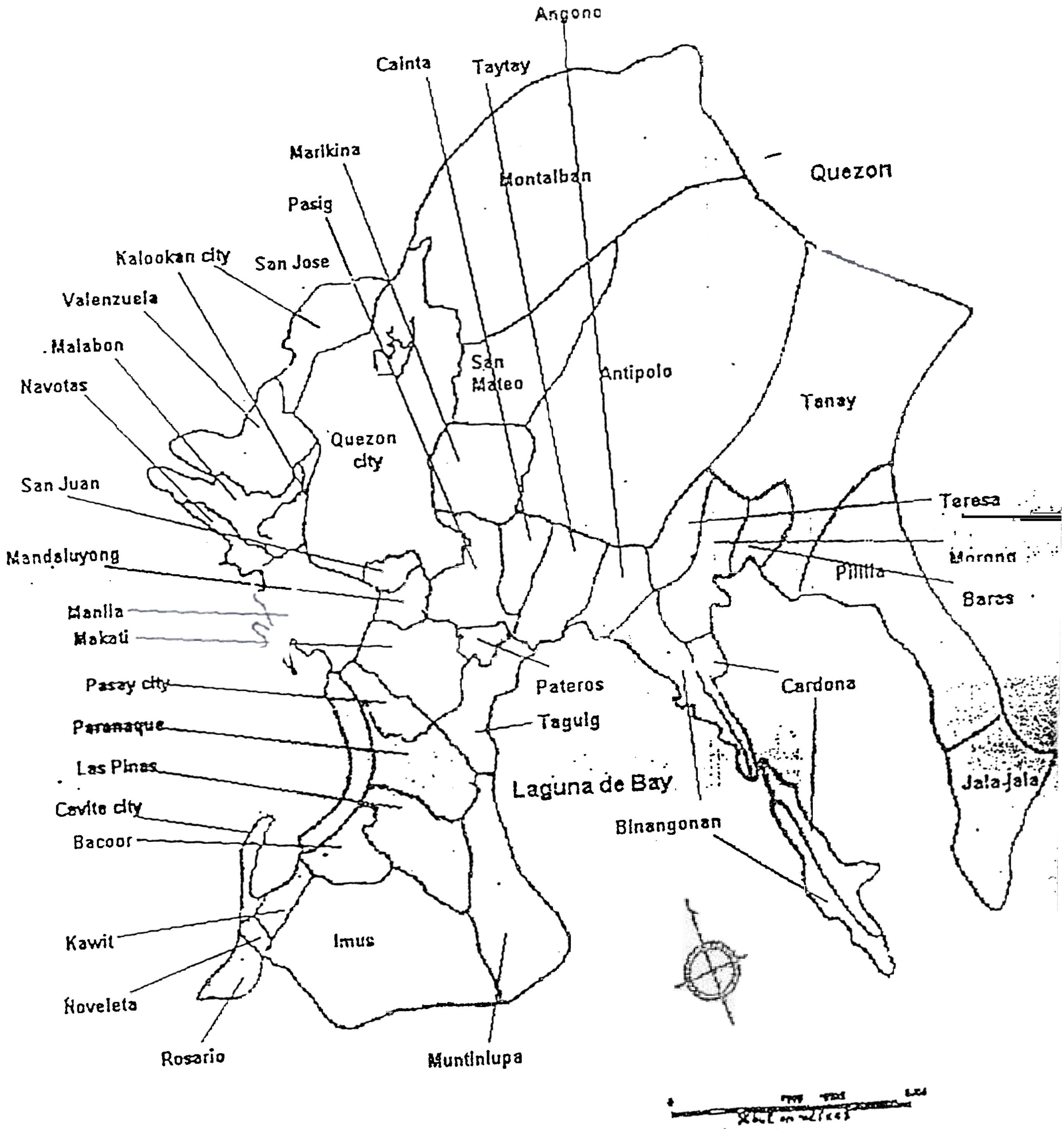
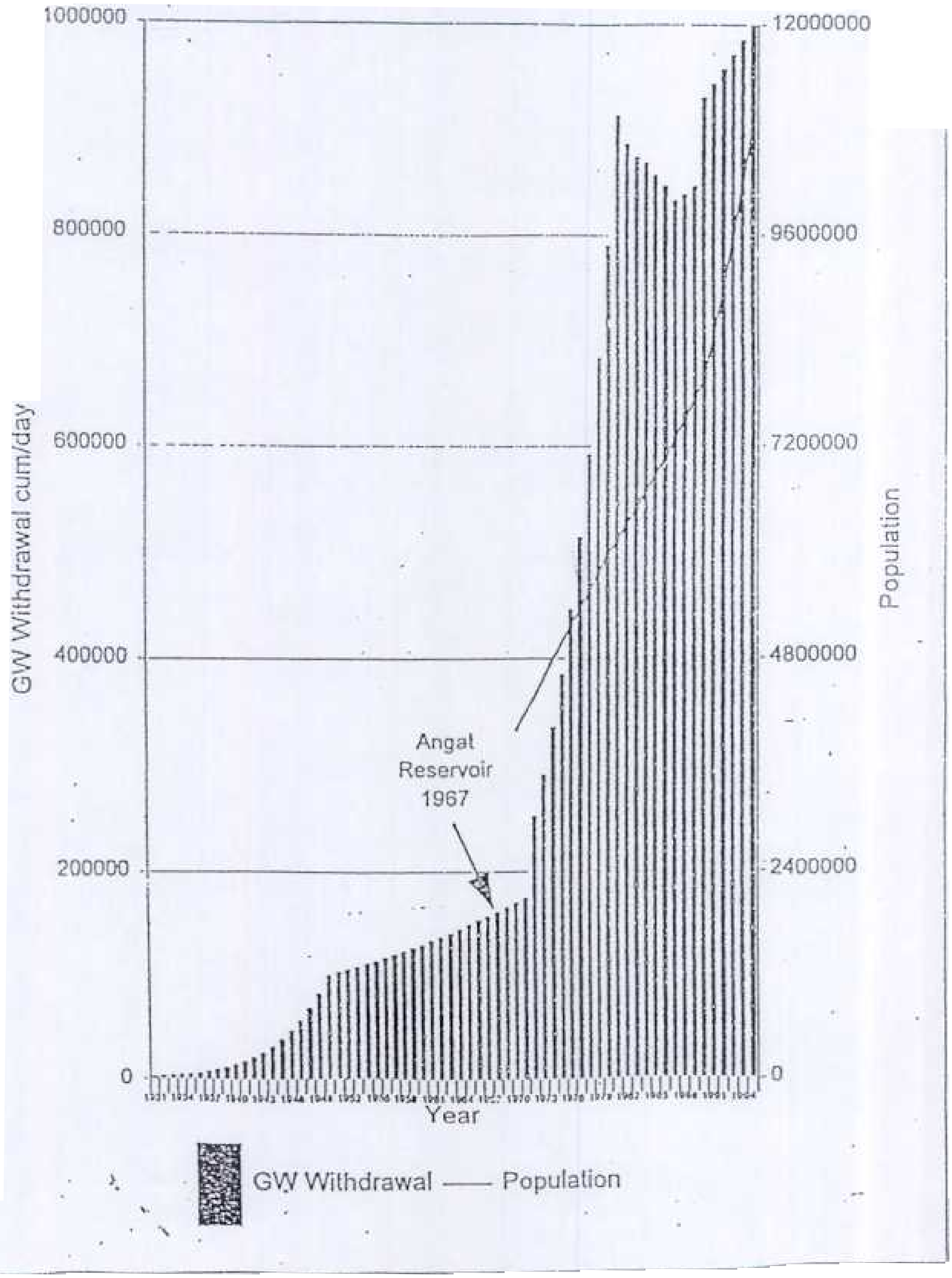
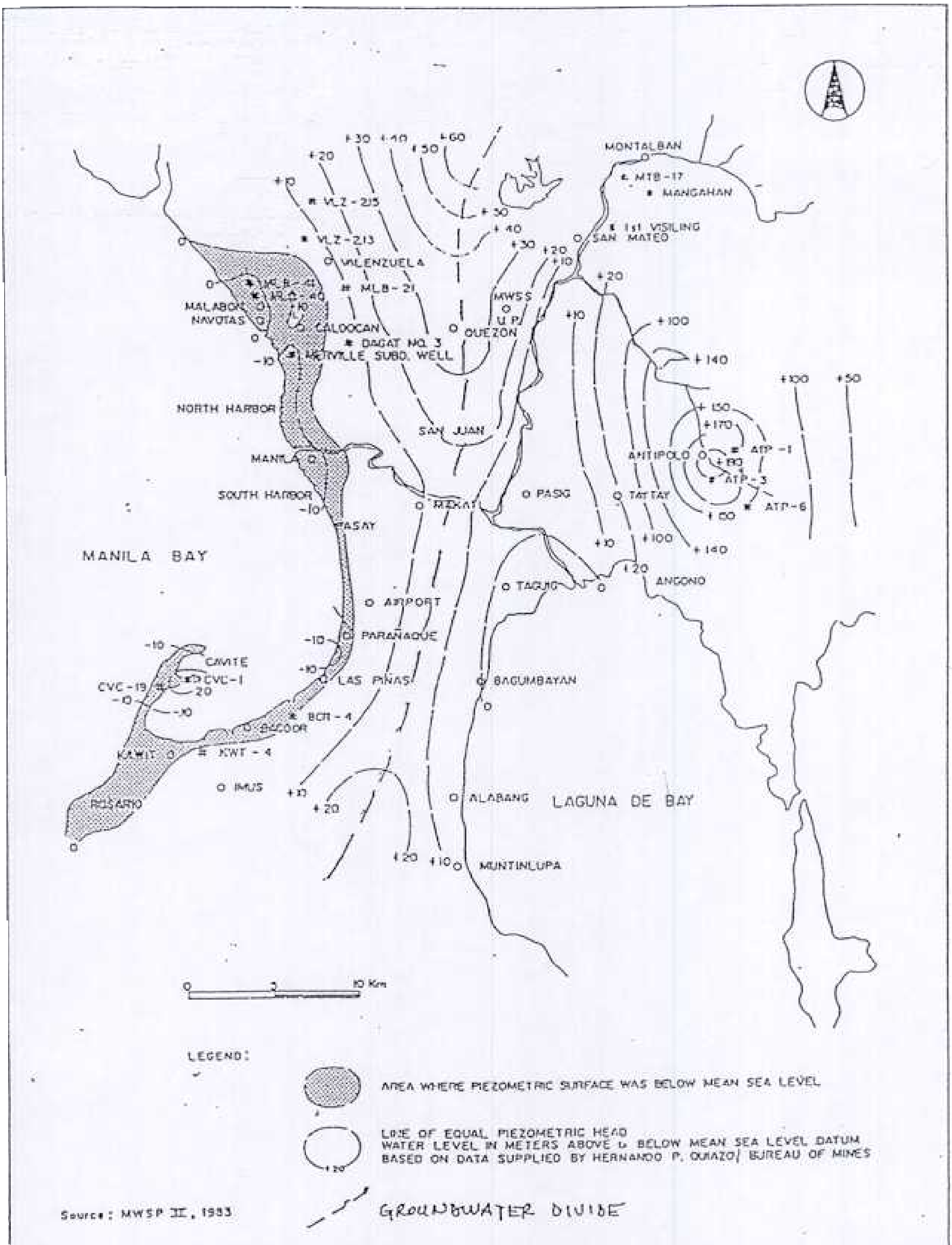


Figure ~~3~~ 2
ESTIMATED GROUNDWATER WITHDRAWAL WITHIN NCR AND POPULATION WITHIN MWSS SERVICE AREA



~~Figure 9~~



STUDY FOR THE GROUNDWATER DEVELOPMENT IN METRO MANILA	Fig. 3 ~~Figure~~ PIEZOMETRIC SURFACE OF AQUIFER SYSTEM IN METRO MANILA, 1955
JAPAN INTERNATIONAL COOPERATION AGENCY	

Figure 2-4

GROUNDWATER CONDITION IN METRO MANILA

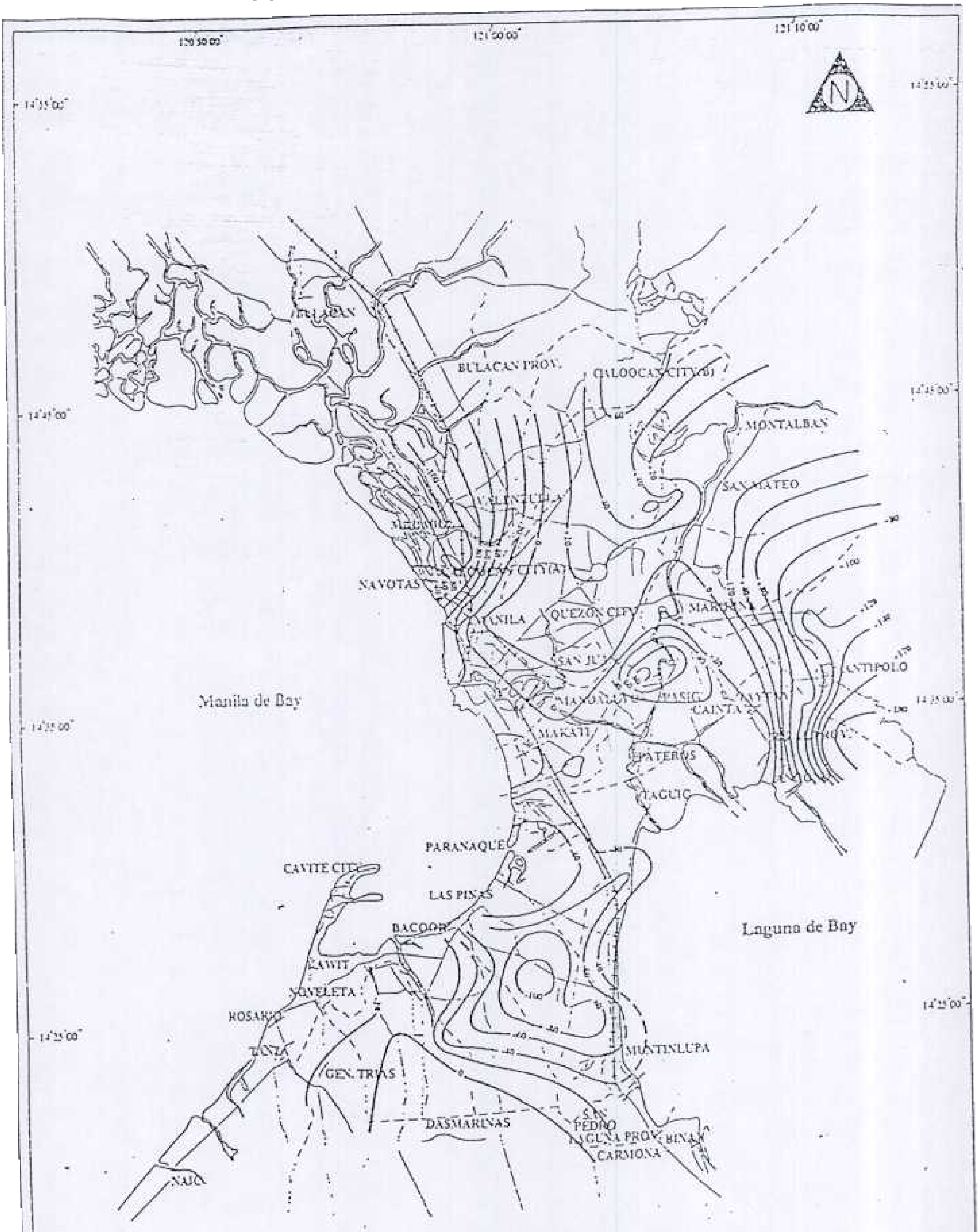
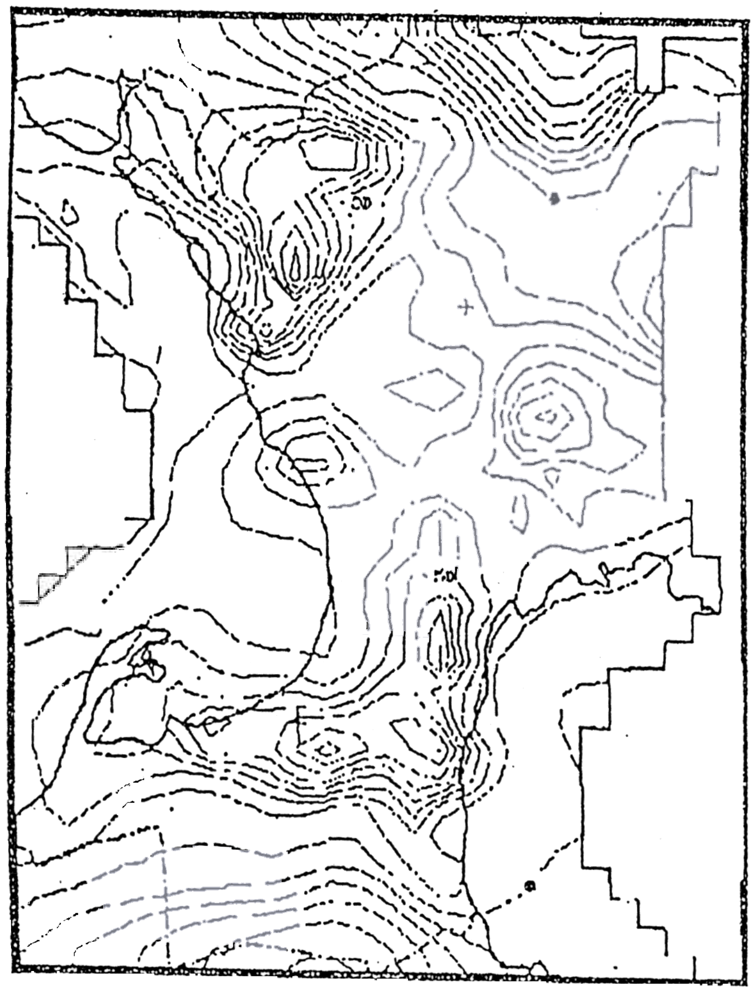


Figure 2-29 GROUNDWATER CONDITION IN METRO MANILA
(Data Source : MWSS, as of 1994)

F A 5



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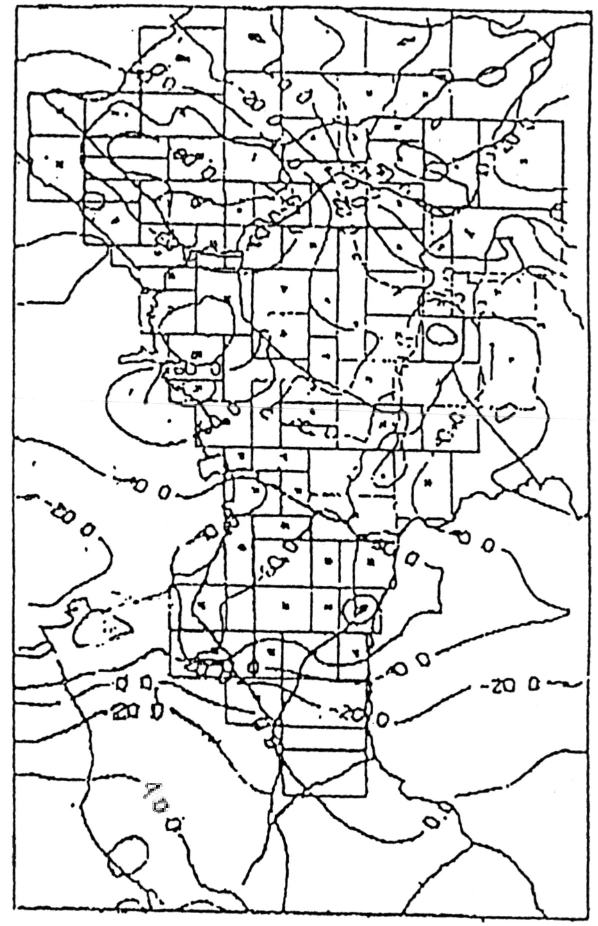

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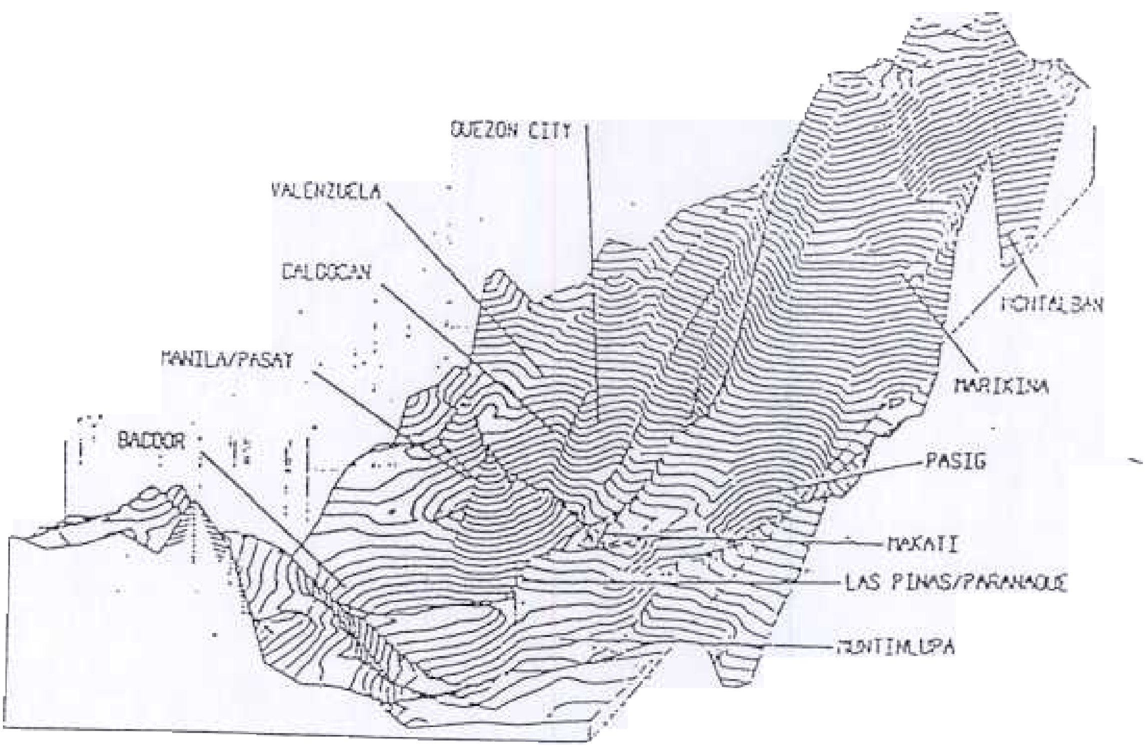
Figure ~~5~~ 6
THREE-DIMENSIONAL VIEW OF THE COMPUTED 1990 PIEZOMETRIC SURFACE FOR METRO MANILA



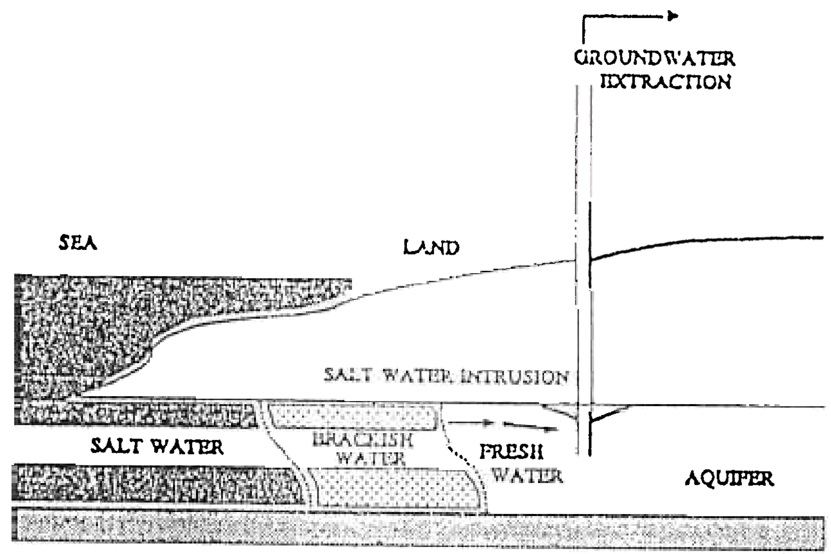
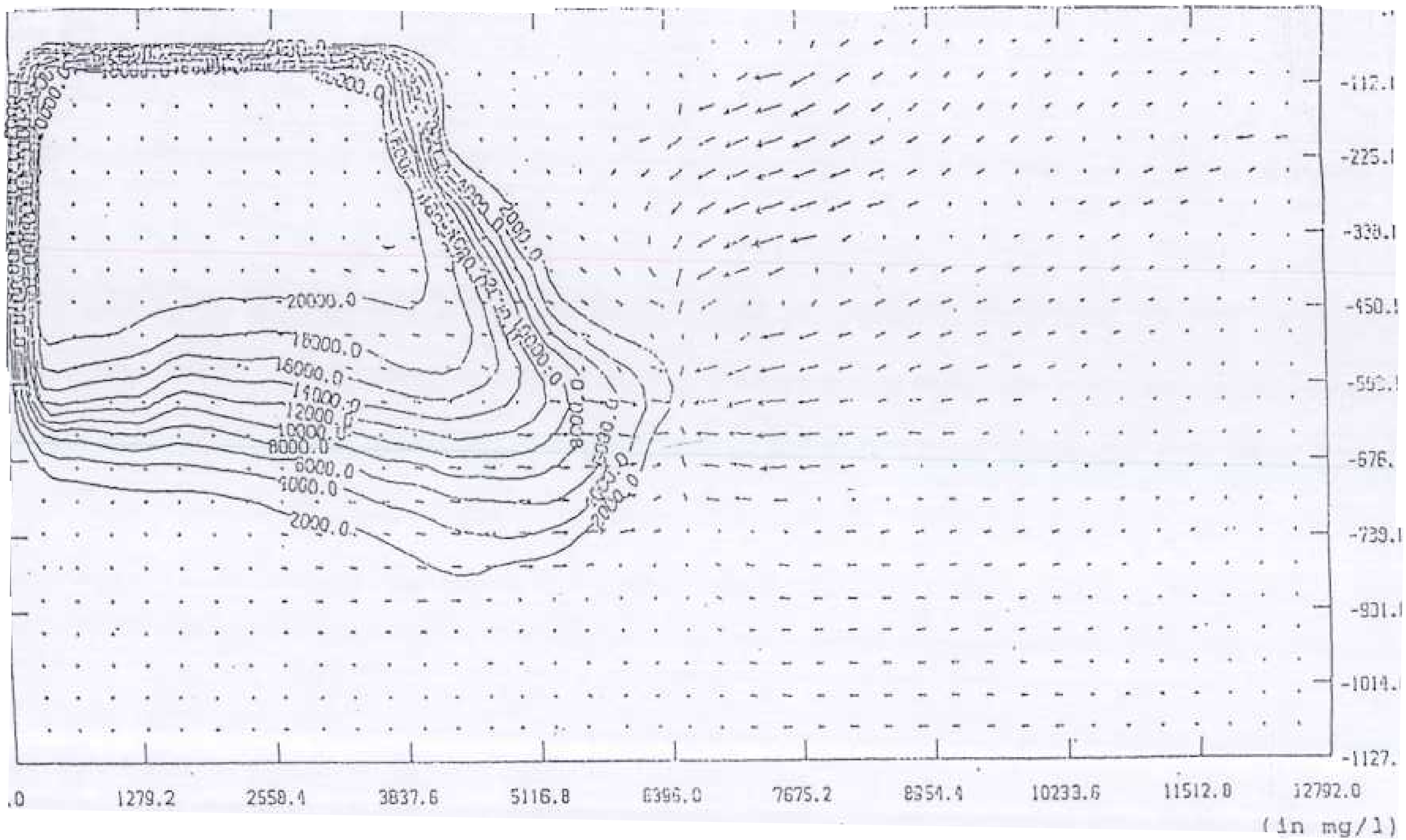
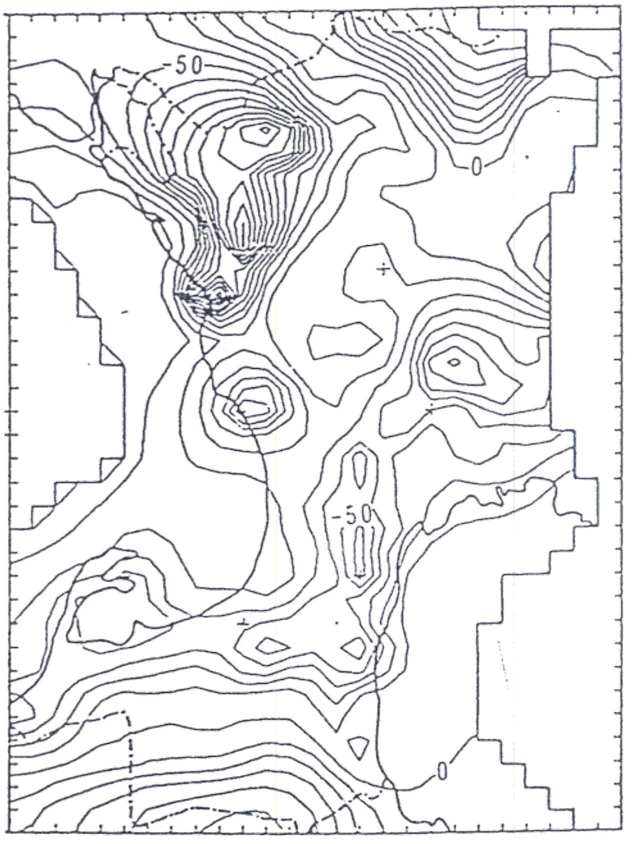


Figure ~~5.1~~ Schematic Diagram of Salt Water Intrusion in an Aquifer

7

Figure ~~6~~ 8
COMPUTED CHLORIDE CONCENTRATION AFTER
10 YEARS SIMULATION





a) Scenario 3
(Contour Interval: 10m, Unit: masl)

STUDY FOR THE GROUNDWATER DEVELOPMENT IN METRO MANILA	FIGURE 9
JAPAN INTERNATIONAL COOPERATION AGENCY	SIMULATED PIEZOMETRIC HEADS IN 2010 (Scenario 3

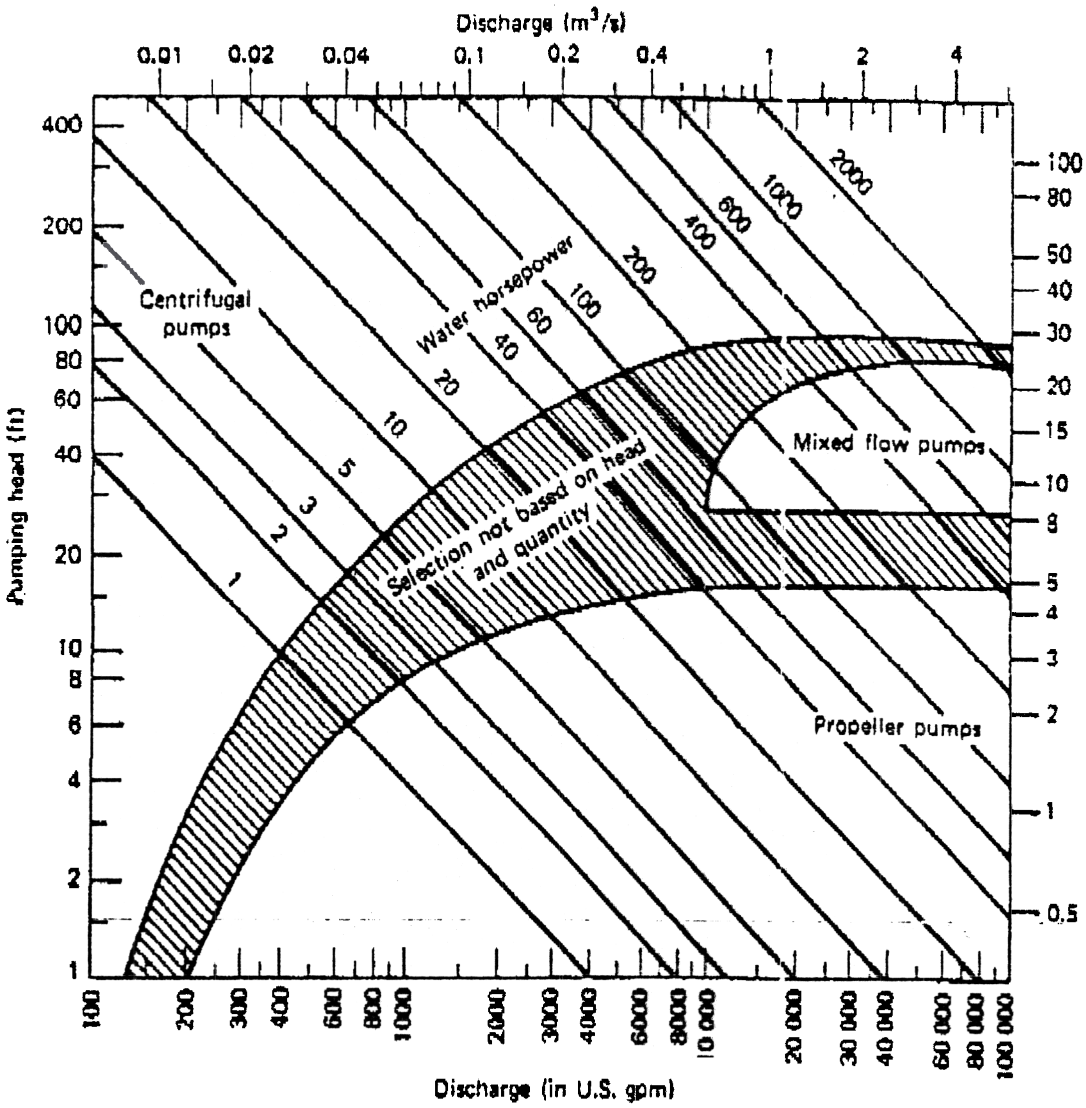


Fig. 16.8. Pump selection chart by discharge and head. (Redrawn from U.S. Soil Conservation Service, 1973.)

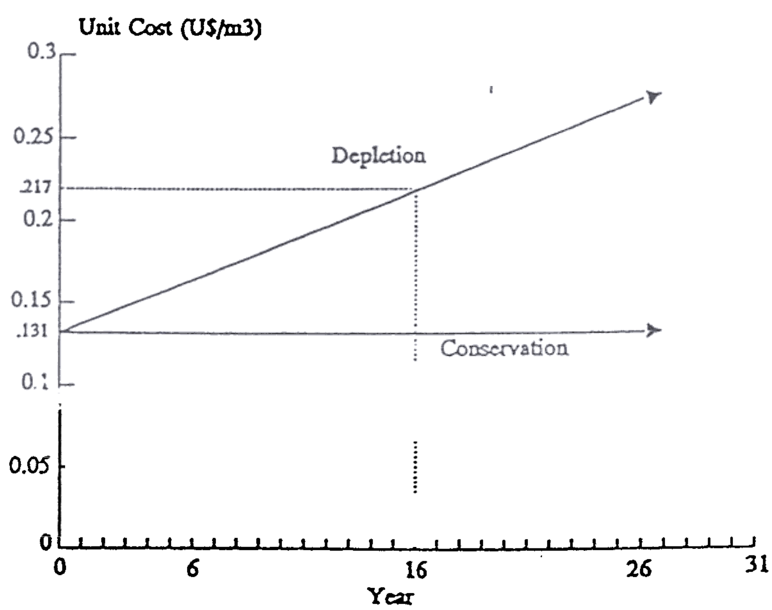


Figure ~~13.2~~ 11 Long-Run Supply Costs for the Depletion and Conservation Scenarios